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PhD Thesis

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APPLICATION AND COMPARISON OF TWO ANALYTICAL TOOLS OF DECISION SUPPORT FOR THE MANAGEMENT OF RESOURCES IN A RIVER BASIN IN TUNISIA.

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APPLICAZIONE E CONFRONTO DI DUE STRUMENTI DI ANALISI PER IL SUPPORTO ALLA DECISIONE PER LA VALUTAZIONE DELLA DEGRADAZIONE DEL TERRITORIO IN UN BACINO IDROGRAFICO IN TUNISIA.

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DEDICATION

This thesis is dedicated to:

***T**he Memory of my dear father, May God bless you*

***M**y mother who has elevate me. You have been source of motivation to me throughout my life , you have been with me every time in my life, Thank you for all the love, guidance, and support that you have always given me, and helping me to succeed. Thank you for everything.*

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ABSTRACT

The objective of this study was to adapt and evaluate the applicability of a physically-based spatially distributed hydrological model SWAT (Soil Water Assessment Tool) and IWRM integrated water resources management lumped model WEAP (Water Evaluation And Planning) for simulating the main hydrologic processes in arid environments. The models were applied to the 1200-km2 watershed of wadi Merguellil in central Tunisia to investigate the hydrological response of the basin. The sensitivity analysis of hydrology, soil and vegetation parameters of SWAT and WEAP helped to identify influential parameters and this could serve as a guide in calibrating the models. The main adjustment for adapting WEAP and SWAT model to this dry Mediterranean watershed was the inclusion of water soil conservation works WSCWs, which capture and use surface runoff for crop production and aquifers recharge in upstream basins. The models were run and the simulated runoff values were compared with the measured stream-flow values. In the calibration period the Nash efficiency coefficient for the SWAT and WEAP models were respectively 0,64 and 0,41 for the runoff. The value of Nash coefficient indicates that the result of SWAT model is acceptable contrasting the WEAP model. SWAT simulation was better than WEAP in most case and could be used with reasonable confidence for runoff quantification in the Merguellil watershed. For the SWAT model, The results of the water balance simulation at monthly and annual time scales was generally good and the observed stream-flow in Zebess, Skhira, Haffouz and El Houareb flow-gages could be reproduced satisfactorily. An estimation of the suspended sediments and nutrients loads in the watershed was performed without calibration because of missing data. Several hypothetical scenarios of land use and climate change were generated by the SWAT and WEAP models in order to determine the impact of the variation of land management and climate change on water demand and supply on downstream water users.

RIASSUNTO

L’obiettivo del presente studio è quello di adattare e valutare il campo di applicazione del modello idrogeologico bidimensionale physically-based SWAT (Soil Water Assessment Tool), Strumento di valutazione di acqua e suolo, e del modello WEAP (Water Evaluation And Planning), Valutazione e pianificatione delle risorse idriche, per l’analisi integrata della gestione delle acque, IWRM (Integrated Water Resources Management), al fine di simulare i principali processi idrologici in ambienti aridi.

Nella fattispecie, i modelli sono stati applicati al bacino dello Wadi Merguellil, che si trova nella parte centrale della Tunisia e si estende su di una superficie pari a 1200 Km2.

L’analisi di sensibilità dei parametri idrogeologici, di suolo e vegetazione dei modelli SWAT e WEAP, ha permesso l’identificazione dei parametri determinanti che possono essere utilizzati come linea guida nella calibrazione dei modelli stessi.

Il principale aggiustamento per l’adattamento dei modelli, WEAP e SWAT, al bacino mediterraneo arido, oggetto di studio, è stata l’introduzione della componente WSCWs, Water soil conservation works, contenente le misure per la conservazione di suolo ed acqua; tale componente permette di catturare ed usare l’acqua di ruscellamento, per la produzione di raccolti e per la ricarica dei bacini a monte del bacino stesso.

I modelli sono stati messi a punto ed i valori di deflussi simulati sono stati paragonati a quelli delle portate di deflusso stream-flow misurate a valle del bacino.

Nel periodo di calibrazione il coefficiente di efficienza di Nash, per i modelli SWAT e WEAP ha assunto rispettivamente valori di 0.64 e 0.41, per quanto riguarda i valori di deflussi.

Secondo tali valori di Ens il modello SWAT risulta accettabile in contrasto con i risultati del modello WEAP. Pertanto. la simulazione ottenuta tramite il modello SWAT risulta migliore di quella ottenuta con il modello WEAP nella maggioranza dei casi. Il modello SWAT può essere dunque utilizzato con un livello di confidenza ragionevole per quanto riguarda la quantificazione del ruscellamento nel bacino di Merguellil.

I risultati della simulazione del bilancio idrico su scala mensile ed annuale, è stata generalmente buona e le portate di deflusso osservate alle stazioni di misura di Zebess, Skhira, Haffouz e El Houareb hanno potuto essere riprodotte in maniera soddisfacente.

Una stima quantitativa dell’erosione e del carico dei nutrienti nel bacino è stata condotta senza possibilità di calibrare i risultati a causa della scarsità di dati.

Diversi scenari ipotetici di uso del suolo e cambiamento climatico sono stati generati attraverso i modelli SWAT e WEAP, così da determinare l'impatto della variazione di tali fattori, uso del suolo e cambiamento climatico, sull' approvvigionamento idrico degli utenti a valle del bacino stesso.

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ABBREVIATIONS

CES	Conservation Des Eaux Et Du Sol.
CGCM	Generation Of The Canadian Global Coupled Model
CO2	Carbon Dioxide
DEM	Digital Elevation Model
DGF	Direction Générale Des Forêts
DGRE	Direction Générale Des Ressources En Eaux
ET	Evapotranspiration
GIS	Geographic Information System
GLUE	Generalised Likelihood Uncertainty Estimation
GTZ	Technische Zusammenarbeit Gmbh
HOF	Hortonian Overland Flow
HU	Heat Unit
HRUS	Hydrologic Response Units
IPCC	Intergovernmental Panel On Climate Change
NERC	Natural Environment Research Council
SCS	Soil Conservation Service
SWAT	Soil And Water Assessment Tool
USA	United State Of America
USDA	United States Department Of Agriculture
USEPA	United State Environmental Protection Agency
USGS	United States Geological Survey
WSCW	Water And Soil Conservation Works
PHU	Plant Heat Units
PET	Potential EvapoTranspiration
MUSLE	Modified Universal Soil Loss Equation
ESRI	Environmental Systems Research Institute
RUE	Radiation-Use Efficiency
SCS-CN	Soil Conservation Service-Curve Number
IGNF	Institut Géographique National Français
IRD	Institut De Recherche et de Développement
TP	Total Porosity
FC	Field Capacity
WP	Wilting Point
AWC	Available Water Capacity
INM	Natural Resource Conservation Service
IRCS	Institut National De Météorologie
UTM	Universal Transverse Mercator
AVFA	Agence De Vulgarisation Et Formation Agricole
Ens	Nash-Sutcliffe Model Efficiency
R2	Coefficient Of Determination
WEAP	Water evaluationand planning
CRDA	Commissariat Régional au Développement Agricole

1 INTRODUCTION

1.1 PROBLEM STATEMENT

Despite the critical importance of water scarcity, the hydrology in semi-arid regions has not received as much attention as other climatic regions and historically the hydrological data have been severely limited and can in some respects be categorized as ungauged basins. The limitation of data is due a small population density and hydrological observation networks are difficult and costly to build and maintain in such regions. Furthermore, hydrological extremes are more common than in humid climates among others due to the following: 1) precipitation is low on an annual basis but it falls as high-intensity storms of often limited spatial extent, 2) high potential evaporation, and 3) low runoff volume on an annual basis and runoff occurs as short intermittent flash floods. In order to develop a successful recharge estimation approach for a region, the effects of all the complex mechanisms must be taken into account.

Hydrological models are valuable, if not essential tools for this purpose. They have become a basic tool in hydrology. Their development, which was closely linked to increasing power of computer processing, started in the 1960s. They are now indispensable tools for planning, design and management of hydrologically related infrastructure. They can also improve system understanding which is required for decision making and policy analysis. The advantage of hydrological models is that all the terms of the water balance can be estimated over an unlimited time frame. Various model approaches have been proposed for this purpose ranging from simpler lumped and conceptual catchments models to complex distributed and physically based models. Compared with lumped models distributed hydrological models can account for spatial heterogeneities and provide detailed description of the hydrological processes in a catchment. However the main disadvantage of these models is the high demands of spatial input data.

The water management literature is rich with integrated water resources management IWRM models that have tended to focus either on understanding how water flows through a watershed in response to hydrologic events or on allocating the water that becomes available in response to those events. For example, the US Department of Agriculture's Soil Water Assessment Tool (SWAT, (Arnold and Allen, 1993), includes sophisticated physical hydrologic watershed modules that describe, among others, rainfall-runoff processes, irrigated agriculture processes, and point and non-point water watershed dynamics, but a relatively simple reservoir operations module (Srinivasan et al., 1998; Ritschard et al., 1999; Fontaine et al., 2002).

Nevertheless, the number of hydrological models now available has increased to such an extent that it has become a relatively hard task to choose one from amongst them all when a simulation is to be done. Selection of an appropriate model for a particular need is made easier thanks to several model classifications that have emerged in the past (Schulze, 1998). Hydrological models are usually distinguished on the basis of their:

- Function: prescriptive models are used to make predictions of catchment behavior and are used in engineering and regulation studies. Descriptive models

are more specifically concerned with testing of conceptual theory and mainly

applied in scientific research.

- Structure: three groups of models exist depending on their structure. Deterministic models are physically-based and describe cause and effect relationships with mathematical equations. Stochastic models use statistical properties of existing records and probability laws to solve hydrological problems. Conceptual models average inputs/outputs of an area to get rid of time and space heterogeneities that constitute a hydrological system.

- Level of spatial disaggregation: lumped models represent processes in a spatially averaged way whereas distributed models represent them in a spatially disaggregated way.

Criteria for the selection of a model are mainly linked to the nature of the problem to be evaluated and to the resources available (data, computing facilities). The naïve perception that model complexity is positively correlated with confidence in the results has faded in the recent years and the whole concept itself of physically-based hydrological modeling has been brought into question (Grayson et al., 1992): it must be kept in mind that equations underlying these models describe processes occurring in structurally stationary ‘model’ catchments which are spatially homogenous at the model grid-scale (Beven, 1989). Consequently, accuracy of the model depends on the degree of heterogeneity that is lumped in it, and improving descriptions without introducing parameter identifiability problems, this is a question that is still not resolved (Beven, 2000).

1.2 RESEARCH OBJECTIVES

Modeling can play a key role in the development of sustainable management of water resources at river basin scale. Modeling can help in evaluating current water resources, identify pollution sources (source apportionment), evaluate alternative management policies, and elaborate sustainable water allocation among various stakeholders. Various studies investigated the role of models in the implementation of the water related policies such as the EU Water Framework Directive (Wasson and Tusseau, 2003; Dørge and Windolf, 2003). Fewer efforts have been dedicated to the use of models in Northern African countries in helping the evaluation of the implementations of policies, especially those dealing with agriculture (Bouraoui and al, 2005).

The objective of this study is to investigate the spatial and temporal variation of water resources in

the semi-arid basin through hydrological modeling, the Water Evaluation And Planning (WEAP) model, a lumped model, and Soil Water Assessment Tool (SWAT) were used to simulate the hydrology of the Merguellil catchment. The aims of the study were:

- to evaluate the rainfall-runoff component of both models and to test their ability to compute natural flow data.
- to assess the impact of development on water resources by simulating water uses in the catchment.
- to provide information about two models ability to be used as a water management analysis and planning tool in the Merguellil catchment.
- to adapt the models to this dry Mediterranean environment by the inclusion of water harvesting systems (contour ridges and small dam), which capture and use surface runoff in upstream subbasins.
- To analyze the flow regime alterations and water demand under scenario of land use and climate change
- To compare the result of SWAT and WEAP models

1.3 OUTLINES OF THE THESIS

After describing the context of the study and introducing the objectives of the thesis in the **Chapter 1**, the whole purpose of **the chapter 2** is to provide a wider literature review for the research by highlighting some of components of the hydrological cycle in the watershed. The importance of scientific researches in the areas of hydrology, in the semi arid context is presented. In line with the objectives of this study, an overall presentation on the types of hydrological models and their applications in water resources management is made.

Chapter 3: This chapter is dedicated to the description of physically-based distributed hydrological model (SWAT) and the lumped model WEAP used in the study. The different hydrological processes, input requirements and outputs of the model are described. Moreover, some examples of the model application from around the world are included.

Chapter 4: The status of water resources development in Tunisia in general and Merguellil, in particular, is briefly presented in the chapter. This chapter describes the environment of the study area. It begins with the presentation of the environment of the study area in terms of its geographic and climatic characteristics. This is followed by sections on soil and land cover types and geology of Merguellil basin. An overview of the climate and hydrological systems of the study area is also included. Available data base such as the DEM, soils, land uses, and Water and Soil Conservation Works (WSCW) are presented. Analysis of the climatic data in the catchment involved checks on data quality and consistency, gap filling, and temporal and spatial characterizations.

Chapter 5: This chapter deals with the description the data required by two models. First part is dedicated to the SWAT setting parameter. The inputs required by the models including soil and land use data, (like soil hydraulic properties, digital elevation model etc) we describe the adaptation of the input data and how we model the different WSCW presented in the catchment. In the second part of this chapter, we describe the WEAP model with the different equations used and the different procedure of the simulation. The existing data related to quantification of water demand and water supply on the watershed, is explained. The required input data for the WEAP model are prepared in this chapter.

Chapter 6: Application of the two, physically-based distributed hydrological and lumped models to Merguellil catchments is presented in this chapter. As the model comprises several parameters, identification of few influential parameters is important to facilitate the calibration task. To this end sensitivity analysis of the models parameters was made and the results are presented.

An overview of methods used for calibration and validation of hydrological models is included in the first part. This is followed by the procedures used in calibrating and validating the model on the selected catchment. Comparing the measured and simulated flow in different flow gauges are reported in this chapter. The SWAT model was run at time step from yearly to monthly to daily time scale on selected catchment while The WAEP model was run at time step from yearly to monthly time scale. Determination of the water balance and suspended sediment and nutrient loads in Merguellil watershed is one of the drivers of this chapter. Finally, some scenarios of land use for the SWAT model are examined. Also scenario of climate change until 2020 year is generated with WEAP model to predict hydrologic component and water demand and supply. The modeling results and their implications are finally discussed. Finally, overall conclusion and perspectives are presented.

2 CHAPTER 2: LITERATURE REVIEW

2.1 COMPONENTS OF THE HYDROLOGICAL CYCLE

The central focus of any hydro-meteorological study is the hydrological cycle shown in figure 1. The hydrological cycle has no beginning or end and its many processes occur continuously (Chow et al., 1988). In describing the cycle, the water evaporates from ocean and land surface to become part of atmosphere; water vapor is transported and lifted in the atmosphere until it condenses and precipitates on the land or the oceans. Precipitated water may be intercepted by vegetation, becomes overland flow over the ground surface, infiltrate into the ground, flow through the soil as subsurface flow and discharges into streams as surface runoff. The infiltrated water may percolate deeper to recharge groundwater, later emerging as spring and seeping into streams to form surface runoff and finally flowing into the sea or evaporating into the atmosphere as the hydrological cycle continues.

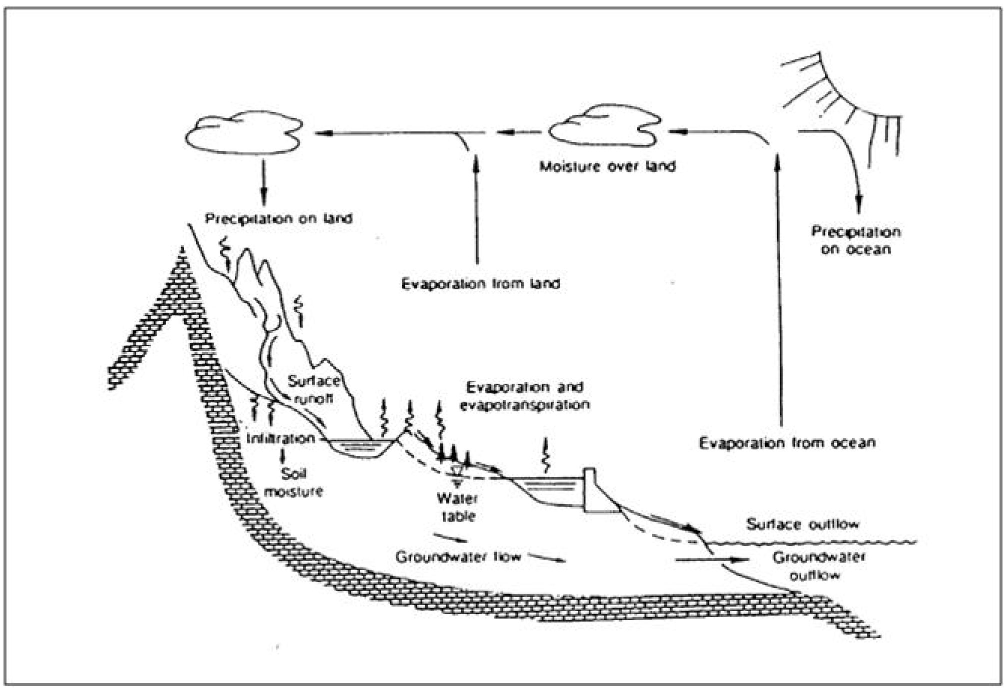


Figure 1 Elements of the hydrologic cycle (Chow et al., 1988)

It is noted that though the concept of the cycle seems simple, the phenomena are enormously complex and intricate. It is not just one large cycle but it is rather composed of many interrelated cycles of continental, regional and local extent. The major achievement and objectives of the rainfall runoff modeling is thus to study a part of the hydrological cycle, namely the land phase of the hydrological cycle on a catchment scale. Then the problem becomes to express the runoff from the catchment as a function of the rainfall and other catchment characteristics.

2.1.1 PRECIPITATION

Precipitation is the input to the system of catchment, which may have different forms, rainfall, storms, dew or any form of water landing from atmosphere. The amount of precipitation can be defined as an accumulated total volume for any selected period. Precipitation as a function of time and space is highly variable. Systematic averaging methods such as Thiessen polygon, isohyte and reciprocal distance methods have been developed to account for variations in space to obtain a representation of areal precipitation values from point observation. Singh and Chowdhury, (1986) after comparing the various methods for calculating areal averages, concluded that all methods give comparable results, especially when the time period is long. For short time step records, the conversion of a point observation to an areal rainfall has a large influence.

2.1.2 EVAPORATION AND TRANSPIRATION

Catchment evaporation demand is generally defined as that evaporation which would occur if there were no deficiencies in the availability of moisture for evapotranspiration by that area's particular plant regime. The two main factors influencing evaporation from an open water surface are the supply of energy to provide latent heat of vaporization and the ability to transport the vapor away from the evaporative surface: solar radiation and wind. Evapotranspiration from land surface comprises evaporation directly from the soil and vegetation surface and transpiration through plant leaves, in which water is abstracted from the sub soil. The third factor is the supply of moisture at evaporative surface, which brought about the definition of potential and actual evaporation. Evaporation involves a highly complex set of processes, which themselves are influenced by factors dependent on the local conditions (land use, vegetation cover, and meteorological variables). Mostly the potential evaporation is the quantity obtained either by using some simple empirical formula such as Thornthwaite, (1948), Penman formula (Penman, 1948) and a process-based model of Penman-Monteith (Monteith, 1965).

2.1.3 INTERCEPTION

The portion of rainfall intercepted by the vegetation and roofs before reaching the ground is referred to as interception. The water, which is intercepted by the leaves of vegetation and roofs eventually evaporates into atmosphere. The amount of interception could be significant in densely vegetated areas such as tropical rainforests. Such forests maintain a relatively consistent canopy and do not generally exhibit the seasonal range of interception encountered in areas where deciduous trees are dominant. It is commonly understood that if the density of the vegetation cover is sparse then this loss is insignificant.

2.1.4 INFILTRATION

The precipitation, which is not intercepted or evaporated from the land, will eventually infiltrate into the soil or flow as overland flow. Infiltration is one of the most difficult hydrological processes to quantify. The difficulty arises due to many physical factors affecting the rate of infiltration such as rainfall intensity, initial moisture content, soil property, etc. Some experimental and empirical formulas such as Horton (1939), Philip (1957), and others are available to compute infiltration rates during a rainfall event. Depending on the soil strata, the infiltrated water gradually percolates to the groundwater or either flows as subsurface flow supplying river or springs within the catchment.

2.1.5 STREAM FLOW

The rainfall that exceeds the interception requirement and infiltration starts to accumulate on the surface. Initially the excess water collects to fill depressions, until the surface detention requirement is satisfied. Thereafter when water begins to move down slope as a thin film and tiny streams which eventually join to form bigger and bigger channels. This part of the stream flow is termed as surface runoff. The infiltrated part of the rain may sometimes come as subsurface runoff, which combined with the surface runoff, constitutes the direct runoff. Hence the direct runoff is the result of the immediate response of a catchment to the input rainfall. The stream flow consists of the direct runoff (which lasts for hours or days depending upon the catchment size) and the base flow (that emerges from groundwater resources and also delayed subsurface runoff). The above description of the processes at catchment scale is schematically represented in Figure 2.

2.1.6 GROUNDWATER

Natural groundwater fluxes are typically slow; water may reside in an aquifer for as little as a few hours or for hundreds of years. Accordingly, groundwater itself is often perceived, on the average, as a relatively slow-moving reservoir in the global hydrologic cycle. At the catchment scale, however, where stream - aquifer interactions are relatively rapid and substantial, the average groundwater fluxes are relatively fast moving. They comprise: (1) the natural flow of water between watersheds, (2) the water pumped from an aquifer, (3) mountain- front recharge (seasonal infiltration of snowmelt at the base of mountain ranges), (4) event-based infiltration (infiltration from precipitation and subsequent rises in surface water levels, especially rivers), and (5) artificial recharge via anthropogenic conservation projects.

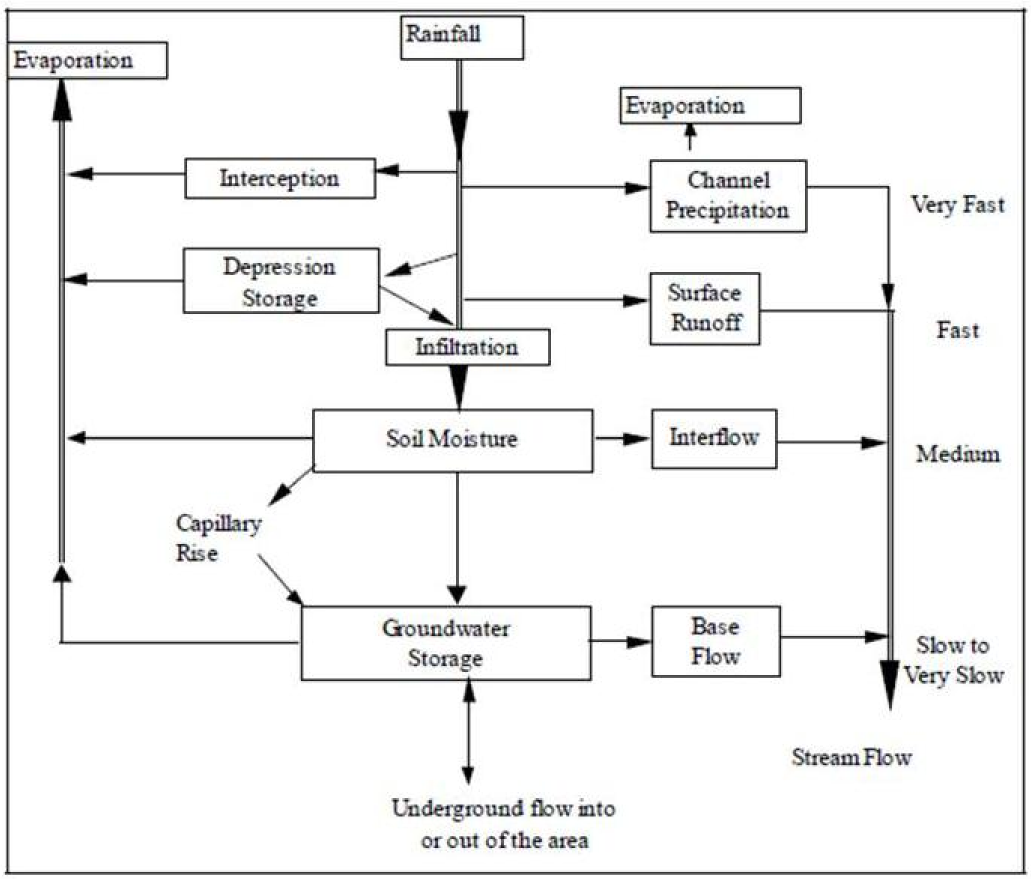


Figure 2 Schematic representation of the land phase of the water Cycle (Starosolszky, 1987)

2.2 ROLE OF HYDROLOGY AND EROSION AND SEDIMENT TRANSFER IN WATERSHED MANAGEMENT

Watershed management is concerned with the protection and maintenance of land and water resources. It is multidisciplinary and requires the involvement of various actors. Watershed management is an effective tool in dealing with one or more of the issues.

The roles of hydrological and sediment-related studies are explicit and direct in the problem formulation and evaluation of alternative plans. The problem formulation is a key step in the process and should indicate among others, the magnitude and frequency of the problem, priority problem areas, and causative factors. Appraisal and evaluation of impacts of alternative plans require information on the socio-economic and environmental burdens of proposed interventions. Hydrological inputs and analysis make important contribution in addressing problems of water quantity by providing basic information on water balance in space and time. Knowledge of the relative magnitudes of the various water balance components such as evapotranspiration, direct runoff, subsurface flow, soil moisture, etc. are essential in assessing adequacy of water for current and planned developments. It also helps decision makers to weigh the advantages of each proposed intervention on the hydrologic cycle against the disadvantages. Decisions made in the absence of basic hydrological inputs would entail immense socio-economic and ecological costs. Hydrology also allows assessment of land use and climate change impacts on water balance. The fact that the hydrological literature is filled with several water balance related studies, from catchment to global scale, is an indication of its importance in water management (Engida, 2010).

Soil erosion and sediment transport is a critical environmental issue because of its adverse socio-economic and environmental impacts such as loss of soil productivity, reservoir sedimentation and associated effects, and water quality impairment. Studies on soil erosion and sediment transfer contribute to effective management of the problem by providing basic information that includes sediment source areas, pathways, sediment yield, and other controlling factors. Such information, for instance, could be used to identify and prioritize critical areas for soil conservation measures.

2.3 WATER QUALITY ISSUES

Freshwater quality impairment has been a major issue of concern worldwide. The sources of water pollution can be point or diffuse sources. Point sources of pollution include municipal and industrial wastewaters for which specific points of entry to a receiving water body can be identified. Diffuse sources of pollution include general land runoff from urban and agricultural areas and other sources that do not have specific discharge points. Unlike point sources, diffuse sources of pollution are difficult to manage (Novotony and Olem, 1994). Due to the extensive damages that could be caused by diffuse sources of water pollution, the need for addressing the issue as an international priority of concern was already heralded long ago (Duda, 1996). Diffuse pollution is considered to be the dominant cause of water quality impairment in many developing countries due to poor waste management and environmentally unfriendly agricultural methods.

2.4 HYDROLOGICAL CHARACTERISTICS OF SEMI-ARID AND ARID AREAS

In the past, several hydrologists attempted to classify zones of the world in to humid, semi arid and arid according to the climaticological characteristics. One of the earliest indexes (Chow, 1964) used for classification is based upon the adequacy of precipitation in relation to the needs of plants whereby the precipitation analyzed month by month is just adequate to supply all the water for maximum evaporation and transpiration in the course of a year. UNESCO (1979) attributes the arid and semiarid zones as the dry areas associated with annual potential evaporation over 1000mm and further classifies according to the amount of annual rainfall they receive to hyper-arid, arid semiarid and humid. Chow, (1964) suggests that in addition to climatic characteristics other features of the land surface may also be used to delimit arid zones, since the geomorphology, soils and vegetation have their own distinctive characteristics. The objective of these classifications is mainly to study the peculiar characteristics common to a region, which would help generalization and inference for climatological and hydrological processes prevailing in these regions.

The hydrological processes operating in rainfall runoff transformation for the semi-arid and arid areas differ from those in humid temperate. Some of the distinct properties manifested in semi-arid and arid catchments are pointed out below.

2.4.1 VARIABILITY IN TIME

The rainfall in semi-arid and arid catchments is characterized by a high variability of the small amount received in space and time (Moore, 1989). A high percentage (about 80 percent of the annual rainfall) is received within the rainy seasons during 3 to 6 months. Individual rainfall events generally occur with high intensity and short duration storms. Verma (1979) points out some of the particular features of the semiarid and arid hydrological processes as:

• The marked seasonal variation in semiarid climates may require segregation of data by season. A combination of hydrological factors common in one season of the year may be virtually non-existent during another season.

• A particular combination of factors may exist for only a few days in several years and may render hydrological computation based on average values grossly erroneous.

Actual evaporation from semi-arid zones is a highly transient phenomenon with extreme variation within a day because of the available water but not over a season. The transient nature of evaporation is also controlled by the rapid growth of vegetation to climax followed by rapid die-off (Moore, 1989).

2.4.2 VARIABILITY IN SPACE

In contrast to humid climate, hydrological processes in semiarid and arid regions often vary greatly over different parts of a catchment. Especially in large catchments, the contributing area could be localized at the upper part of the catchment. In such cases, computation of areal rainfall in a lumped conceptual model leads to unrealistic average distribution over the whole area. Moreover, the sparse vegetation cover and its sharp response to the first rain have an impact on the evaporation process prevailing in such regions. The rivers in such regions are generally characterized by having long periods of low flow regime.

Another distinct characteristic of such regions is that in some cases infiltration could be very small due to outcropped rocks on the slopes of valleys whereas it could be high in areas with fractured bedrock channels. There could also be the possibility of channel infiltration from the bed of the rivers supplying the groundwater in lower valleys of the river (Sami, 1992). This fact implies that especially during low flow regime the stream flow that originates from upstream will be depleted by the channel bed before it reaches the outlet. Hence this phenomenon should be accounted for in formulating models based on the water balance of a catchment

2.5 WATER AND SOIL CONSERVATION WORKS IN THE SEMI ARID ZONE

In many arid countries, runoff water-harvesting systems support the livelihood of the rural population. Little is known, however, about the effect of these systems on the water balance components of arid watersheds (Ouessar and al, 2009). Generally, water and soil conservation works (WSCW) are built in uplands to face erosion and water scarcity problems. They consist of hillslope works reducing surface runoff and increasing local infiltration, and of small dams collecting headwater flow and providing supplemental water for irrigation. Intensive water uses are most often concentrated in alluvial plains that offer large and easily irrigable lands, better soils and abundant water resource through aquifer tapping.

By retaining upstream runoff, WSCW modify the spatial and social distribution of costs and benefits at the catchment scale. With the fast growth of WSCW-equipped areas, it becomes necessary to investigate hydrological impacts and manage resources at larger scales, especially where conflicts between upstream and downstream water uses increase. Although precise knowledge on the WSCW hydrological impacts is a prerequisite, it remains rare especially in large catchments (above 100 km2).

Many studies on WSCW hydrologic impact have been reported, according to land use/land-cover modifications:

- forestation, forest clearing (e.g., Leduc et al., 2001), in Niger, Siriwardena et al., 2006, in Australia)
- intensification of agricultural practices (e.g., Lorup et al., 1998, in Zimbabwe)
- Climate change (e.g., Séguis et al., 2004, in the Sahel)

The few investigations on WSCW effects on catchment hydrology mainly concern changes induced by large reservoirs (e.g., Batalla et al., 2004, in Spain; Güntner et al., 2004, in northeast Brazil; Thoms and Sheldon, 2000, in Australia). Studies on impacts of hillslope works (soil bunds, contour ridges, hedges, tillage) are extremely rare in large catchments as heterogeneity and data scarcity increase with catchment size. Xiubin et al. (2003) examined the correlation between the surface area controlled by WSCW and streamflow reduction in three catchments (362 000 km2, 1121 km2 and 70 km2) of the Yellow river basin in China. They found that controlled surfaces fractions of 26.0%, 28.3% and 56.3% induced runoff decreases of 49.4%, 52.6% and 49.7% respectively. Several research works were conducted either for small catchments or at the plot level. In central Tunisia, Nasri et al. (2004b) studied the hydrological impact of contour ridges in a 18.1 km2 catchment and on a 0.11 km2 hillslope. In both cases, introduction of contour ridges resulted in a runoff decrease varying between 50% and 90% for rainfall below 60-70 mm/day. In southern Tunisia, Nasri et al. (2004a) found that a traditional system of soil banks installed in a 0.26 km2 catchment reduced the runoff to essentially zero. In Cabo Verde islands, Smolikowski et al. (2001) found that runoff occurred only for rainfall events higher than 40 mm, with an intensity above 40 mm/h, in 4 m2 and 100 m2 plots with two kinds of conservation techniques (light mulching with maize haulms and hedging with bushes and grass). In semi-arid Kenya, Wakindiki and

Ben-Hur (2002) evaluated the effects of indigenous WSCW on runoff from 12 plots of 12 m2, and found that these techniques reduced the runoff by half. In all these local studies, questions of up-scaling were not considered and hydrological consequences at the regional scale were not explored. At a larger scale, identifying specifically the effects on streamflow of given environmental changes is difficult because of the diversity and variability of factors controlling the runoff response to rainfall. Opposite effects may mask each other. When changes affect only a limited area of the catchment, the moderate magnitude of their impacts makes the results statistically non significant. For instance, in Australia Nandakumar and Mein (1997) found that for the level of uncertainty of their data, 65% of a 520 ha eucalyptus forest catchment would need to be cleared before flow increase could be asserted at the 90% prediction level.

2.6 RUNOFF RESPONSE IN THE SEMI ARID AREA

Factors controlling the runoff response may be grouped into two categories relating to their time variability. The first category gathers the high-frequency factors that act at the event scale. They are essentially linked to meteorological conditions. In semi-arid areas, most authors agree that rainfall intensity is the dominant control on the runoff response (Bradford et al., 1987; Canton et al., 2001; Martinez-Mena et al., 1998), whereas initial soil moisture content generally plays a secondary role (Castillo et al., 2003; Fitzjohn et al., 1998; Karnieli and Ben Asher, 1993; Peugeot et al., 2003).

These factors induce a large variability in the event rainfall-runoff relationship, making similar rainfall depths produce a large range of runoff depths. In the second category, the low-frequency factors that progressively modify the runoff response are essentially: climate change (Servat et al., 1997), land use changes (Calder et al., 1993; Fahey and Jackson, 1997), changes in the water table level, altering the flow intensity between the surface and underground (Matteo and Dragoni, 2005) and WSCW construction. When trying to identify the hydrological impact of low-frequency factors, a difficulty consists in being able to differentiate their effects from those of high-frequency factors. Hydro-meteorological data with high time/space resolution are generally used to model the relationship between high-frequency factors and runoff response. “Unexplained”, progressive changes in the catchment behavior may afterwards be attributed to low frequency factors. When data resolution is insufficient to identify the impact of high-frequency factors, the latter act as background noise in the rainfall/runoff relationship. Due to this noise, long data series are needed to identify rainfall/runoff changes due to one or more low frequency factors.

2.7 LAND USE CHANGE UNDER CLIMATE CHANGE

Water management planners are facing considerable uncertainties on future demand and availability of water. Climate change and its potential hydrological effects are increasingly contributing to this uncertainty. The Second Assessment of the Intergovernmental Panel on Climate Change (IPCC, 1996) states that an increasing concentration of greenhouse gases in the atmosphere is likely to cause an increase in global average temperature of between 1 and 3.5 degrees Celsius over the forthcoming century. This will lead to a more vigorous hydrological cycle, with changes in precipitation and evapotranspiration rates regionally variable. These changes will in turn affect water availability and runoff and thus may affect the discharge regime of rivers. The potential effects on discharge extremes that determine the design of water management regulations and structures are of particular concern, since changes in extremes may be larger than changes in average figures (Middelkoop and al, 2001).

Land-use changes can influence hydrological processes including infiltration, groundwater recharge, base flow and runoff in a watershed. For example, watershed development reduces base flow by changing groundwater flow pathways to surface-water bodies. Global warming resulting from increases in atmospheric greenhouse gasses will alter global weather patterns and affect the hydrologic cycle. The capacity of the atmosphere to hold water will increase, leading to more precipitation and evaporation globally (Thomson et al. 2005). Changes in global climate will have significant impact on local and regional hydrological regimes, which will in turn affect ecological, social and economical systems (Dibike and Coulibaly 2005). Therefore, modeling and understanding responses of land use compositions and hydrologic components to both future land use and climate change scenarios is useful for optimizing land use planning, management and policy in a watershed. Comprehensive knowledge of land use dynamics is useful for reconstructing past land-use/land cover changes and for predicting future changes, and thus may help in elaborating sustainable management practices aimed at preserving essential landscape functions (Hietel et al. 2004).

2.8 HYDROLOGIC MODELING

2.8.1 WATERSHED MODELING

Watershed is an area having a common natural drainage course. In other words, it is an area drained by a river or stream over which the hydrological processes are integrated. The concept of watershed modeling is embedded in the interrelationships of soil, water, climate and land use and represented through mathematical abstractions. The behavior of each process is controlled by its own characteristics as well as by its interaction with other processes active in the catchment. The predominant hydrologic processes include rainfall, snowmelt, interception, evapotranspiration, infiltration, surface runoff, percolation and subsurface flow.

During the last four decades researchers have been actively involved in formulating various mathematical models to represent the various processes prevalent in the catchment. There is plethora of mathematical models available in literature. These models vary from empirical models for the evaluation of flood events to simple ones containing a certain degree of physicality, to stochastic models of various kinds and finally to the more recent distributed models.

Examples of this type of models are the SHE-model (Abbott and Bathurst) and IHDM-model (Beven et al., 1987). Practical difficulties appear in the implementation of the system and the data availability. An adequate database is costly to assemble and may be unavailable for large catchments.

2.8.2 CONCEPTS OF MODELING

In choosing between the approaches, one should keep in mind that the model must be capable of taking into account both the influence of land use and the aerial diversity on catchment hydrology. It is at least in theory possible to reach a high level of understanding of catchment hydrology using a fully distributed model, which separately describes each small sub-area of the catchment through physically consistent formulations and parameters related to measured catchment properties.

Computer based hydrological models have been developed and applied at an ever increasing rate during the past four decades. The key reasons for that are twofold: (a) improved models and methodologies are continuously emerging from the research community, and (b) the demand for improved tools increases with the increasing pressure on water resources.

Overviews of the status and development trends in catchment scale hydrological modeling during this period can be found in Fleming (1975) and Singh (1995).

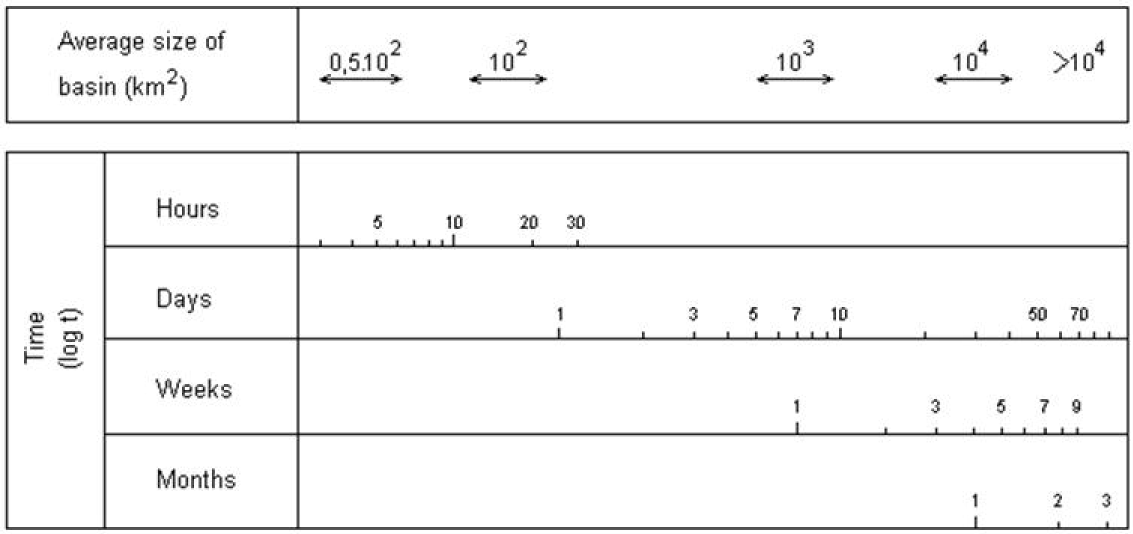
A hydrological model represents the water cycle of a drainage basin and studies the response of this basin to climatic and physical conditions (Renaud, 2004). Hydrologic models are of a major importance for the analysis of climatic change repercussions and water resources balance (Singh et al., 1995). So, they permit the evaluation of water resources and facilitate their management while valuing different choice consequences. Hydrological models of varying degrees of complexity and scale are now available ranging from basin scale models to macro-scale models approaching that of GCM scale (105 Km2) and can accept atmospheric model data as their input

2.8.3 TIME RESOLUTION OF MODELLING

Hydrological processes occur at a wide range of scales, from unsaturated flow 1m soil profile to floods in river system of a million square kilometers; from flashfloods of several minutes duration to flow in aquifers over hundreds of years (Bl¬schl and Sivapalan, 1995). There exist rainfall runoff models which represents these processes using time spans a few minutes, hours, days or even up to one year. Selection of a time step of modeling depends on:

- Catchment input characteristics such as dominant storms in the area. An area with commonly conventional type of storms with separate rainfall storms can only be modeled with time steps less than a day.
- The model structure in representing the time scale of hydrological processes. A model, which accounts for infiltration rate of loose soil, should have computation in terms of minutes. The time step is interrelated with the area of the catchment under study. Starosolszky (1987) gives an approximate representation of this relationship (Table 1)
- The scope (purpose) of the model

Table 1 Relationship between time step of modeling and area of catchment (Adapted from Starosolszky (1987)



2.8.4 HYDROLOGICAL MODELLING FAILURE IN ARID

In arid regions, an important feature of the water balance is the high proportion of incoming water which is returned to the atmosphere by evaporation from soil surface. In contrast to the humid regions, where evaporation is limited by available energy (e.g. net radiation), in the arid zone water availability is the dominant control over evaporation rates. Because of the sparse density of vegetation, direct evaporation of water from the soil is of enhanced importance, and frequently as much as half of the annual rainfall can be lost in this manner (Chow, 1964).

It is noted that the prevailing rainfall and evaporation mechanism in semi-arid and arid catchments, associated with the thin and sparse vegetation cover, alter the runoff generation of these regions in contrast to the humid regions. The runoff generated is mainly controlled by infiltration excess and is frequently localized. The runoff generated on some of the slopes and first order catchments may not always survive to contribute to the flow at the outlet of catchments of sufficient size. Hughes (1995) numerates the possible reasons why deterministic models can fail as tools for water resources estimation purposes, where failure implies the model imperfection. Apart from erroneous data inputs and poor interpretation of model results, the problems associated with the application of rainfall- runoff models to arid and semiarid areas are:

• Inadequate or inappropriate model representation of the prevailing catchment processes

• Inadequate representation of the spatial variability of runoff generation response to runoff. While this problem can be masked by spatial lumping, it may be important if the effects are non-linear and non-stationary

• Inadequate representation of the spatial variability in rainfall input, either through lumping or lack of spatial resolution in the available data.

• Inadequate representation of the temporal variability in rainfall input through the use of a coarse time interval model. This is not always a serious problem as long as the rainfall mechanisms are reasonably consistent and the durations and intensities of the major rainfall events are similar.

• Inadequate estimation of parameter values. This problem may relate to the length of the records available for calibration (Görgens, 1983) and the extent to which the rainfall-runoff relationships reflected in the observed data are sufficiently representative to allow a suitable parameter set to be quantified

In general the two interrelated underpinning problems in hydrological modeling in such regions are:

1. the model assumptions and simplifications which are not always justified in modeling in any region but over simplification of the variability in such areas,

2. The limitation of data availability as opposed to the temporal and special variability of the input to any physical or conceptual (distributed or lumped) models.

This implies that any effort in modeling such region should consider and compromise the two underlying problems that on one hand the model has to address the peculiar phenomena and at the same time it should require limited input as only limited data are available.

2.9 CATEGORIES OF MODELS

Watershed models play a fundamental role in addressing a range of water resources, environmental and social problems (Singh and Frevert, 2006). Hydrological models of different levels of complexity are invaluable tools in the planning, design, operation and management of water resources. The use of modeling studies in water management decisions is in fact increasing (Refsgaard and al., 2005). It is possible to distinguish different categories of models as shown in Figure 3:

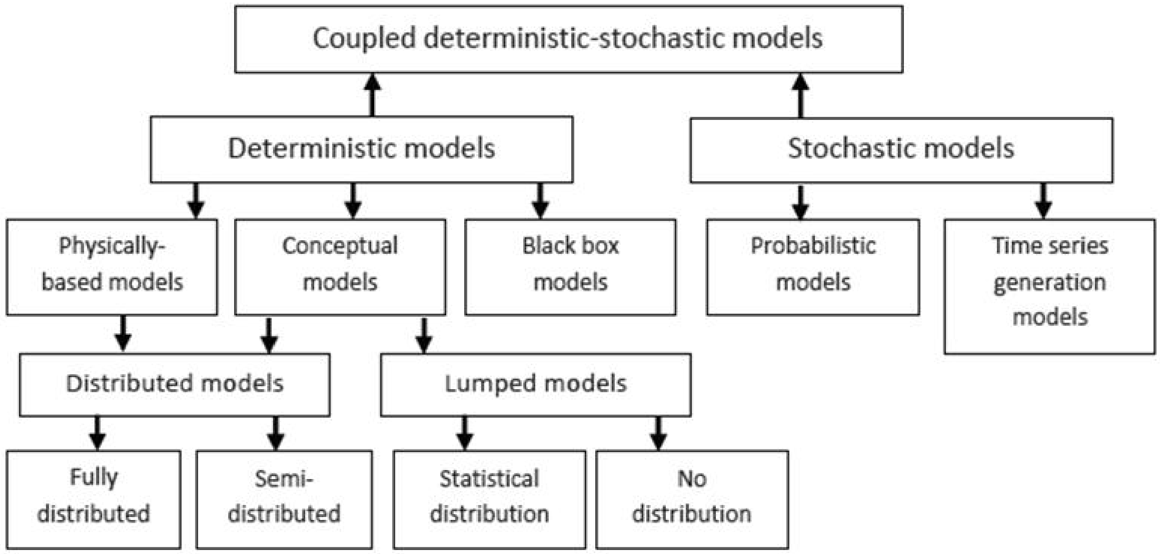


Figure 3 Classification of hydrological models. Based on Becker and Serban (1990)

2.9.1 BLACK-BOX MODELS

The black-box models describe mathematically the relation between input (precipitation) and output (runoff) without describing the physical process by which they are related and establish a statistical correspondence between input and output. These models are often successful within the range of data being available/collected and analyzed from a region. The reason is that the mathematical structure carries with it an implicit representation of the underlying physical system. Beyond the range of analyzed data, the prediction depends only on mathematical technique, since the physical significance is lost. The recent ANN models also belong to this category.

2.9.2 DETERMINISTIC MODELS

These models are based on complex physical theory and require large amount of data and computational time. Hence, the models are very costly to develop and operate (Liddament and al., 1981). The models are necessarily distributed because of the non linear partial differential equations which describe the hydrologic processes. It has been noted that analytical solutions are generally not available to solve the equations. Hence resort must be made to adopt the partial differential equations; include finite difference method (Freeze, 1971), finite element methods (Beven, 1977; Ross and al., 1979), integral finite difference and boundary integral methods which are difficult and time consuming. Simplifications have been made and kinematic wave theory was used alternatively. The models offer the ability to simulate the complete runoff and the effect of catchment changes which is particularly important in case of resource management. A noteworthy aspect of the deterministic models is that these models offer the internal view of the process which enables improve understanding of the hydrologic system. One of the most well known distributed model of this category is the European Hydrological System, SHE (Abbott and al., 1986).

The SHE is an advanced physically based, distributed modeling system developed collaboratively by the Institute of Hydrology, the Danish Hydraulic Institute and SOGREAH (France). Spatial distribution of catchment parameters has been achieved in the horizontal direction, through an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. Each process of the hydrological cycle (snowmelt, canopy interception, evapotranspiration, overland and channel flow, unsaturated and saturated subsurface flow) has been modelled either by finite difference representations of the theoretical partial differential equations of mass, momentum and energy conservation or by empirical equations derived from independent experimental research. Interception has been modelled by a modified Rutter model (Rutter et. al., 1971) which is essentially an accounting procedure for canopy storage. Evapotranspiration has been estimated by the Penman-Monteith equation (Monteith, 1965). Unsaturated subsurface flow is modelled by the one dimensional Richards equation using an implicit finite difference solution. Overland and channel flow has been evaluated by the simplifications of the St.Venant equations and saturated zone flow by two dimensional Boussinesq equation. Considerable operating flexibility has been provided in the model by varying the level of sophistication of the calculation to match the availability of data.

Another popular model is the Institute of Hydrology distributed model (IHDM), (Beven et. al., 1987). The catchment is divided into subareas along the lines of greatest topographic slope. Each sub area is modelled using one dimensional (downslope) overland flow components, one dimensional (downstream) channel reaches and two dimensional (vertical slice) unsaturated and saturated subsurface components. Each hillslope segment is simulated independently with outflows that cascade into the channel network. This has the advantage of simplifying the calculations associated with a moving unsaturated/ saturated interface that are necessary in SHE model

2.9.3 CONCEPTUAL MODELS

These models serve as a tradeoff between the deterministic approach and black box approach. Conceptual models are formulated by a number of conceptual elements, each of which is a simplified representation of one process element of the system being modelled. Each element of the model is generally described by a non-linear reservoir with an equation for outflow; S = K * Qn where, S is Storage, Q is Outflow and k & n are Constants. The basic advantage of non-linear form of modeling is that it reflects the thresholds present in hydrological systems, which otherwise cannot be adequately incorporated in a linear model. The conceptual models can be characterized into event models and continuous models. Event models represent only single runoff event occurring over a period of time ranging from an hour or less to several days depending on the size of the catchment. The initial conditions for each event must be given as input. Event models cannot keep the record of soil moisture conditions of the basin in a continuous manner. Hence, event models are not useful for ungauged catchments. On the contrary, continuous models operate over an extended period of time determining flows during all periods irrespective of magnitude of flow.

The functioning of the model is controlled by the parameters of different processes. Hence, assigning proper values to these parameters is very essential for obtaining accurate model results for the specific area being modeled. Based on the parameters representation, conceptual models are further classified as lumped models and distributed models. Lumped models are represented by spatially average watershed characteristics, where as the distributed models incorporate the spatial variability.

2.9.4 LUMPED CONCEPTUAL MODELS

A lumped model is one in which the spatial variations of watershed characteristics are generally ignored. Precipitation is considered to be spatially uniform throughout the watershed. Average values of watershed characteristics i.e. vegetation, soils, geology or topography are utilized. Hence, the results produced by these models display the average watershed conditions. The basis of lumped models is the equation of continuity that is water balance equation. These models attempt to describe three basic processes within any watershed, namely,

- Loss of water from storage to the atmosphere through evaporation or by lateral flow across the watershed topographic boundaries,
- Storage of water in soil, vegetation, aquifers and • streams, and

- Routing of water over the surface or through the • soil and aquifers, from within the basin to the outfall.

These models need to be calibrated for their application on any catchment/watershed which necessitates the availability of long term historic data sequences. Basically, two approaches are followed for the calibration of a model: (a) Manual parameter fitting using trial and error procedure, and (b) Automatic fitting using an optimization algorithm.

The lumped catchment models are usually applied for quality control and to fill the missing data, extension of historic flow records, generation of synthetic data runs for civil engineering design work, water resource assessment, and water resources management including real time forecasting. A large number of lumped models are available in literature.

Boughton (1966) developed a model for estimating water yield from catchments in dry regions. The model used daily rainfall and evaporation data. The model contained three zones in the soil moisture storage. Upper soil storage represents moisture holding capacity of the top soil where as drainage store represents temporary zone with moisture storage in excess of field capacity. Subsoil zone is described by the remaining of moisture held in the catchment soil profile. Infiltration, which takes place between upper soil and sub soil zones, is evaluated by modified Horton equation. Runoff is produced when moisture supply is in excess of the three soil moisture storages. The original model was incomplete as it did not consider the subsurface flow contributions to runoff. The model was modified for use in British catchments which enabled it to have a complete structure. The model is represented by 14 parameters. Boughton extended his work by defining the spatially varied surface storages to obtain varying areal contribution to runoff.

Pathak et. al. (1989) used a modified soil conservation service (SCS) runoff model and a soil moisture accounting procedure to simulate runoff from small watersheds in the semi arid tropics. The soil water retention parameter which related to curve number has been estimated by using a soil moisture accounting procedure. The daily values of soil moisture content are determined by using a soil balance equation. The model has four parameters which were estimated through calibration using measured runoff and soil moisture content data. The model represents the soil characteristics which in turn have strong influence on runoff.

An in-depth analysis of all the components and their interactions within some of the known lumped models has been carried out by Franchini and Pacciani (1991). This study highlights the equivalence between these models in producing the runoff, accompanied by calibration difficulty with the more number of parameters characterising interactions between the various processes of the system.

Some limitations of the popular lumped parametric models as summarized below

- In a lumped model, average values of the watershed characteristics are utilized to represent the various processes of the hydrologic cycle. Spatial heterogeneities are not well reproduced by average parameters. By taking the average value of a certain parameter, it averages (implicitly) the process. Because of the non-linearity and threshold values, this can lead to significant error which in turn affects simulation accuracy.
- When a model is calibrated based on the available historic records, any bias existing in the data is transferred to the set of optimized parameter values. This feature restricts the applicability of the model to other catchments where a different bias may be present in the data.
- Normally, the model parameters are optimized for some rainfall-runoff events over a given watershed and the optimized values at best represent the watershed only for the events used in the optimization. No sooner does the optimization set of rainfall-runoff events change, then the optimum parameter values also change.
- Most of the lumped models have some degree of the interdependence between the parameters. Thus, the parameter values at tained through the optimisation are not necessarily the best estimate of physical values, but simply a set of numbers which give best fit to the data within the constraints imposed.
- The extensive amount of data normally required for reliable optimisation is often lacking. Hence, lumped models are not suit able for ungauged catchments.

2.9.5 DISTRIBUTED CONCEPTUAL MODELS

Distributed models take the spatial variability of watershed properties into account. The underlying principle in these models is to discretise the watershed into a number of zones that are hydrologically similar. Discretization can be made by Representative Elementary Area (REA), Hydrological Response Unit (HRU) or Grouped Response Unit (GRU) concept. REA is equivalent to the representative elementary volume concept (Freeze and Cherry, 1979). The size of the element within a watershed is defined in such a manner that within-element statistics can be considered insignificant for modeling purposes. An alternative method for describing the spatial variability is by means of HRU. The HRU is considered to be homogeneous, having distinct hydrological response. The distinction can be made on the basis of vegetative cover, soil type, slope and aspect. Another method of representation is by means of GRU. The GRU is a region in a watershed that can be grouped in a manner that is convenient for modeling of the catchment. The grouping can be on the basis of zones of uniform meteorology or on the basis of grid cells which is convenient for integrating with map coordinates and remotely sensed data. The runoff generation processes such as snowmelt, infiltration and surface runoff are modelled separately for each unit. A separate set of parameter values are needed to be specified for each unit. The computed yield is then routed through one unit to another to obtain the total catchment yield. A significant aspect is that geographic position within a watershed is preserved. The distributed models are well suited for

a) Evaluating the effects of land-use change within a watershed,

b) Evaluating the effects of spatially variable inputs and outputs,

c) Simulating the water quality and sediment yield on a watershed basis

d) Simulating the hydrological response of ungauged catchments where no data are available for calibration.

These and many more areas are offering great potential for the application of distributed models. The focus of various models may differ with respect to the initial intent with which the model was developed. There are some models which consider only infiltration and surface flow processes. Huggins and Monke (1968) used a grid system to delineate watershed elements in a distributed parameter model. They applied this concept to two areas in Indiana with a grid size of 7.5 m x 7.5 m. The slope direction for each element was used to route the runoff from one element to two adjoining elements. Computed runoff from each element was then integrated using a finite difference form of the continuity equation relating moisture supply, storage and outflow. Interception process was evaluated using Horton interception equation and infiltration by Holton equation. Soil moisture was updated after considering the balance between infiltrated and the drained moisture. This work lead to the development of a very comprehensive watershed model ANSWERS. Beasley et. al., 1980).

Bravo et. al. (1970) developed linearised distributed model to estimate catchment runoff. In this model, catchment is partitioned into subareas of simple shapes and surface runoff from each subarea is determined by solving one dimensional equations of flow. The equations of flow are non-linear, but may be linearised to obtain an analytical solution. The model can accommodate spatial variability in rainfall excess by using different rainfall input for each subarea reflecting the variable storm pattern or infiltration loss characteristics. The partial source area concept of Engman and Rogowski (1974) requires an intimate knowledge of the sub surface characteristics which control infiltration and exfiltration rates. In this approach, the sub area of the watershed expands in time and space depending on the storm characteristics and infiltration capacity distribution. Kinematic wave equation is used for routing the flow from the sub area. Soil moisture data including hydraulic conductivities and soil water diffusivities are required to track the spatial and time variation of runoff. This information can be obtained from the U. S. Conservation Service catalogued report. Although considerable data requirements may hinder the general adoption of this approach, if an alternative to the data intensive aspect is found, the partial area concept may find more widespread use.

The following are the major problems that have been involved in using the distributed models:

• The large quantity of required input data of ten renders them inefficient for everyday operational hydrology. For example, the most renowned distributed model, SHE has per formed very well on mainframe computers, but its PC applications are limited because of the large number of computations that must be made

• There is often insufficient information available about the physical characteristics of the basin to evaluate the parameters of physically-based models at the required scale (Loague and Freeze, 1985)

• There is insufficient understanding of the processes of runoff generation at the catchment scale to build truly physically base models

• Some studies have demonstrated that simple models are as successful as complex models (Loague and Freeze; 1985,).

2.9.6 SEMI-DISTRIBUTED CONCEPTUAL MODELS

In order to overcome the difficulties being faced with the distributed models the researchers started developing semi-distributed models as a compromise between lumped models and fully distributed models (Arnolds et. al., 1993). The model algorithms are simple but physically based. The spatial heterogeneity is represented by means of observable physical characteristics of the basin such as land use, soils and topography etc.

Spatial variability in hydrological processes, particularly those that give rise to rapid runoff during and immediately following rain has been taken into account in the model of Beven and Kirkby (1979). First, it combined the distributed effects of contributing areas within the model and subsequently the model parameters are estimated from measurements taken in the field.

Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) is a water quality control model for simulating agricultural contributions to water pollution (Knisel, 1980). It is specifically designed as an agricultural field scale model and as a result has limited routing capabilities. The model contains three major components, hydrology, water quality and sedimentation. The main processes included in the hydrology component are surface runoff, percolation and evapotranspiration. Runoff volume is predicted using soil conservation service (SCS) curve number technique. Ritchie's evapotranspiration model has been applied to estimate evapotranspiration (Ritchie, 1972). The percolation component uses a storage routing technique to predict flow through the root zone. Calibration is not necessary because the model is physically based. The hydrological component of Simulator for Water Resources in Rural Basins (SWRRB) and Erosion Productivity Impact Calculator (EPIC) models have been derived from CREAMS.

Kite and Kouwen (1992) applied the hydrological model separately for each land-cover class in each sub-basin and routed the resulting hydrographs to the sub-basin outlet and subsequently through lower sub-basins. The final hydrographs are compared to those obtained using the lumped model on the basin. It has been reported that semi-distributed approach is better than lumped approach. The major advantage of semi-distributed approach is that relating the parameter values to land cover characteristics provides a method of investigating impact of land use changes and allows the model to be more easily transferred to other basins. Arnolds et. al. (1993) developed a comprehensive surface and ground water flow model. The main objective of the model is to predict the impact of management changes on total water supplies. The model simulates four control volumes namely surface, soil profile or root zone, shallow aquifer and deep aquifer. The first two volumes are simulated by the original Simulator for Water Resources in Rural Basin (SWRRB) model. The percolation from the soil profile has been assumed to recharge the shallow aquifer. The percolated water is assumed to be lost from the simulated system and could not return. The developed model is continuous in time to allow simulation of land management, including factors such as climate and vegetation changes, pond and reservoir management, ground water withdrawals and stream and reservoir withdrawals.

Hughes and Sami (1994) presented a semi-distributed model HYMAS (Hydrological Model Application System) representing the variability in terms of space and time. HYMAS contains modules to extract indices of catchment physical characteristics from digital map coordinate data, estimate model parameters and compile files of time series data. The catchment is divided into sub-areas and the maximum limit is put at 30. The time interval used is variable and changes automatically according to a series of user-defined rainfall thresholds. A probability distribution approach is used to account for the spatial variation in some of the variables in the subareas.

SWAT is an evaluating tool of soil and water developed by the USDA-Agricultural Research Service (Neitsch et al., 2002). This model was developed for the investigation of watersheds with surfaces going from a few hundreds of Km^2 to several thousands of Km^2. SWAT is a semi distributed model that functions on a continuous basis with a daily time step. It requires some specific information on the atmospheric conditions, properties of soil, the topography, vegetation, procedures of earth management and it incorporates equations of regression to describe the report between variables of entry and exit (Neitsch et al., 2002). This model estimates fluxes of water, nutrients, pesticides and sediments. It was validated on several watershed of the word. Its validity has been tested for numerous basin sizes. Many parameters have been predefined according to United States data.

2.10 EXEMPLE OF NITROGEN FLOW MODELS

Many types of hydrological models are freely available. Their differences concern the types of input data needed, the temporal and spatial scale, the operating system, the compatibility with GIS, their complexity and reliability. Thus, another point of interest was to consider if the models were used widely or not. Figure 2 presents an example of different hydrological models available for the specific application of nitrogen flows (Payreaudeau, 2002). The models are classified using two parameters, the basins area and the time scale of the input data.

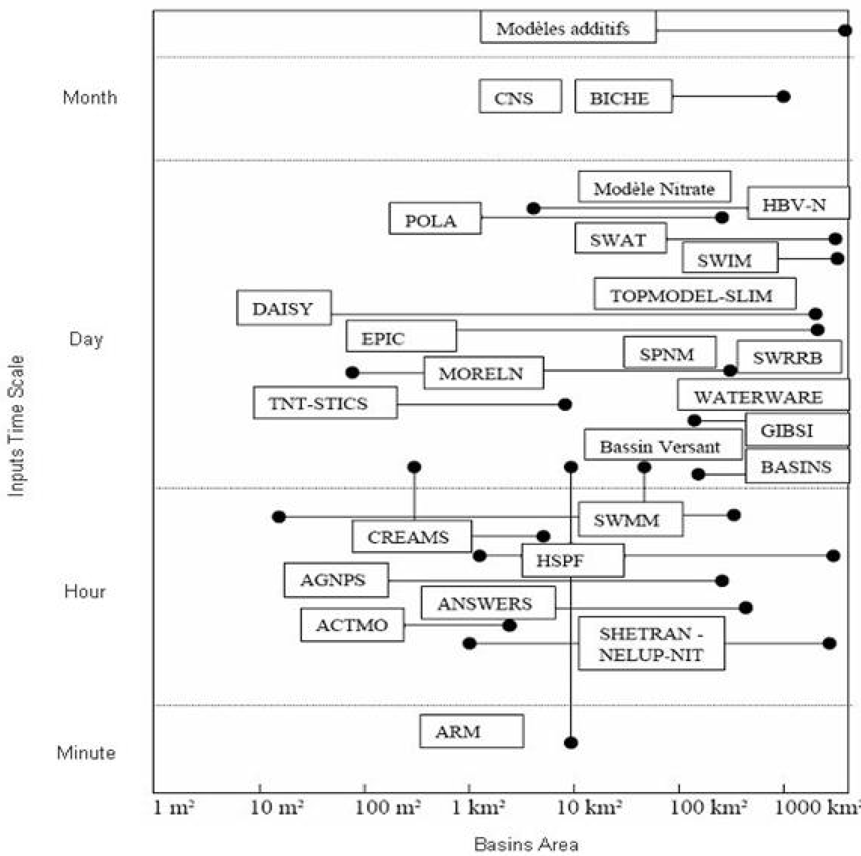


Figure 4: Overview of nitrogen flow models (Payreaudeau, 2002)

2.11 MODELS SELECTION FOR THE STUDY CASE

The literature review are reported in this chapter about severals hydrological models, it is possible now to limit the yield of existing models adapted to the objective of this work. Although the final choice of model should be made after critical analysis of some criterion:

- Spatial scale
- Temporal scale
- Associated modules
- Coupling with a GIS
- Accessibility of the data
- Management of climate change and land use scenarios

The objectives of the model also require integrating the location and diversity of WSCW on the basin in the integrated management model. Finally it was decided to test two hydrological models: WEAP (SEI, 2005) and SWAT (Arnold and al, 1998). These Models are summarized below, However, Chapter 2 will be dedicated for detailed description of two models., A first assessment the two models is reported in the Table 2

The first model is: ***SWAT*** (Arnold and al, 2002) which consists of hydrological, sedimentological, and chemical subroutines applicable to watershed scales. The hybrid model spatially based on hydrological response units includes both, conceptual and physical approaches. A central part of SWAT is the general water balance equation. Surface runoff is determined by the SCS Curve Number approach. Frede et al. (2002) found that physical soil properties affect total runoff moderately, but highly influence surface runoff in SWAT. The model was found to be less efficient in predicting runoff in relation to land cover in a semi-arid watershed, therefore calibration was strongly recommended (Hernandez et al., 2000). Nonetheless, SWAT was found suitable for predicting annual flow volumes, sediment, and nutrient loads (Borah and Bera, 2004). Monthly predictions were generally good, except for months with extreme storm events and hydrologic conditions (Borah and Bera, 2004).

The second model is ***WEAP*** (SEI, 2005), is comprehensive, straightforward and easy-to-use, and attempts to assist rather than substitute for the skilled planner. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, WEAP simulates water demand, supply, flows, and storage, and pollution generation, treatment and discharge. As a policy analysis tool, WEAP evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems. Operating on the basic principle of water balance accounting, WEAP is applicable to municipal and agricultural systems, single subbasins or complex river systems. Moreover, WEAP can address a wide range of issues, e.g., sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and streamflow simulations, reservoir operations, hydropower generation and energy demands, pollution tracking, ecosystem requirements, and project benefit-cost analyses.

Table 2: assessment of SWAT and WEAP models

Hydrological model	SWAT	WEAP
Input	Quantitative	Semi- Quantitative
Output	Water balance /Pollutio / erosion	Water balance/ water supply unmet demand / Costs and benefits
Number of parameters	286	75
Required soil Map	YES	NO
Required land use Map	YES	NO
Climate change scenario	YES	YES
Integrated Data Base	YES	NO
GIS Support	YES	YES
Simulation of flood event	YES	NO
Time scale	Daily Monthly Annual	Monthly Annual
Simulation of antropic activities and agricultural practices	YES	NO
Simulation of water quality	YES	SI
Calibration–validation	YES	SI
Diffuse pollution process	YES	SI
Sewerage	YES	SI
Erosion Simulation	YES	NO
Degital Elevation Model	YES	NO
Ungauged basin	YES	NO
Discritization in spatial unit in unità spaziale	Subbasin - HRU	NO
sources	http://swatmodel.tamu.edu/	http://www.weap21.org
Sub Model	SWRRB, CREAMS, GLEAMS and EPIC	QUAL2K
Dynamic evolution of result	NO	YES
Water management	equality	priority
Decision support tool	YES	YES
Spatial scale	Complex Watershed	Municipal, agricultural systems, individual watershed or complex sub-basin.

3 CHAPTER 3 METHODOLOGY

3.1 THE SWAT MODEL

The Soil and Water Assessment Tool is a physically based and semi-empirical model. It is based on physical laws but it also permits the addition of measurements and their use for simulations. The spatial areas that can be modeled range from hundreds to thousands of square kilometers.

Unlike other hydrologic models, the SWAT model takes into account many parameters impacting on hydrology and the water cycle, and simulates the flow and the transport of sediments or polluting elements. It has been "developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds with varying soil, land use, and management conditions over long periods of time." (Di Luzio et al, 2007) and to provide continuous-time simulations with a high level of spatial detail by allowing the further division of a watershed or river basin into hundreds or thousands of sub-watersheds. The land area in a sub-basin is then further divided into hydrologic response unit (HRUs) which are portions of sub-basin that possess unique land use, management, and soil attributes

Developed by the Blackland Research Centre, the SWAT model was originally written in C and made compatible with GRASS (Srinivasan and Arnold, 1994). A new version in Arc Macro Language compatible with ArcInfo has been created (Bian et al, 1996) and then in Avenue, compatible with ArcView (Di Luzio et al, 1997): AVSWAT. The version used is AVSWAT: this version provides an ArcView 3 extension and a graphical user interface.

3.1.1 EXISTING STUDIES OF SWAT

The SWAT model is widely used in the United States and in some European countries to solve water management problems. It has been used for a variety of applications, including water balance calculation, sediment transport and stream-aquifer interaction.

For the integrated water management of the San Joaquin River Basin in California, SWAT was used combined with GIS. The study area was 85000 km². The objective of the study was to describe the effects of land management/use on water, salt, sediment, nutrient and pesticide yields. SWAT allowed the quantitative characterization of the magnitude and geographic extent of problems and the impacts of changing land management. (Flay and al, 2000) In the catchment basin of Mercube in Haute-Savoie, France, SWAT has been used to model the phosphorus transport of a small agricultural area (Renaud, 2004). SWAT was integrated in GIS with ArcView 3.2. The different types of data required by the model were added, allowing the model to run. The calibration permitted the prediction of the behavior of the basin depending of different conditions though further work is needed in this domain.

A study to identify limitations and uncertainties of SWAT has been carried out by Sophocleous et al (2000). SWAT was combined with MODFLOW (Modular Three Dimensional Finite Difference Ground Water Flow Model). The results showed that SWAT distorted the shape of the watershed by using a mean distance of overland flow to the stream during transport processes. However, the study demonstrated that SWAT:

- Was capable of operating on a watershed scale with several sub-basins
- Allowed topographical, land use and management differences
- Was capable of simulating several management practices
- Could simulate long periods of time
- Could be calibrated through field testing

A study by Flay (2000) had the aim of understanding nitrate and phosphate dynamics in agricultural basins. It analyzed the ability of SWAT to model the effect of changes of land use patterns and practices. This study concluded on the main assets and drawbacks of SWAT.

3.1.2 COMPARISON OF SWAT WITH OTHER MODELS

Borah and Bera (2003, 2004) compared SWAT with several other watershed scale models. In the 2003 study, they report that the Dynamic Watershed Simulation Model (DWSM) (Borah et al., 2004), Hydrologic Simulation Program - Fortran (HSPF) model (Bicknell et al., 1997), SWAT, and other models have hydrology, sediment, and chemical routines applicable to watershed scale catchments and concluded that SWAT is a promising model for continuous simulations in predominantly agricultural watersheds. In the 2004 study, they found that SWAT and HSPF could predict yearly flow volumes and pollutant losses, were adequate for monthly predictions except for months having extreme storm events and hydrologic conditions, and were poor in simulating daily extreme flow events. Shepherd et al. (1999) evaluated 14 models and found SWAT to be the most suitable for estimating phosphorus loss from a lowland watershed in the U.K.

Van Liew et. al. (2003a) compared the stream-flow predictions of SWAT and HSPF on eight nested agricultural watersheds within the Little Washita River basin in southwestern Oklahoma. They concluded that SWAT was more consistent than HSPF in estimating stream-flow for different climatic conditions and may thus be better suited for investigating the long term impacts of climate variability on surface water resources. Saleh and Du (2004) found that the average daily flow, sediment loads, and nutrient loads simulated by SWAT were closer than HSPF to measured values collected at five sites during both the calibration and verification periods for the upper North Bosque River watershed in Texas. Singh et al. (2005) found that SWAT flow predictions were slightly better than corresponding HSPF estimates for the 5,568 km2 Iroquois River watershed in eastern Illinois and western Indiana, primarily due to better simulation of low flows by SWAT. Nasr et al. (2007) found that HSPF predicted mean daily discharge most accurately, while SWAT simulated daily total phosphorus loads the best, in a comparison of three models for three Irish watersheds that ranged in size from 15 to 96 km2. Nasr et al. (2005) found that both SWAT and the MIKESHE model (Refsgaard and Storm, 1995) simulated the hydrology of Belgium's Jeker River basin in an acceptable way. However, MIKESHE predicted the overall variation of river flow slightly better.

Srinivasan et al. (2005) found that SWAT estimated flow more accurately than the Soil Moisture Distribution and Routing (SMDR) model (Cornell, 2003) for 39.5 ha FD36 experimental watershed in east central Pennsylvania, and that SWAT was also more accurate on a seasonal basis. SWAT estimates were also found to be similar to measured dissolved and total P for the same watershed, and 73% of the 22 fields in the watershed were categorized similarly on the basis of the SWAT analysis as compared to the Pennsylvania P index (Veith et al., 2005). Grizzetti et al. (2005) reported that both SWAT and a statistical approach based on the SPARROW model (Smith et al., 1997) resulted in similar total oxidized nitrogen loads for two monitoring sites within the 1,380 km2 Great Ouse watershed in the U.K. They also state that the statistical reliability of the two approaches was similar, and that the statistical model should be viewed primarily as a screening tool while SWAT is more useful for scenarios.

Of late the climate change impact assessment has become a very pertinent concern of the water and agriculture sectors. The SWAT model has been modified in response to a widely acknowledged need for tools and information to help water and land managers to assess and manage the impacts of climate variability and change. The users can conduct watershed based studies of the potential implications of climate variability and change on water and land resources. Specifically, SWAT provides flexible capabilities for creating climate change scenarios, allowing users to quickly assess a wide range of “what if” questions about how weather and climate could affect their systems. The existing capabilities of SWAT for assessing the effects of land-use change and management practices have been enhanced to assess the coupled effects of climate and land-use change.

3.1.3 MODELING APPROACH AND STRUCTURE

The SWAT model operates on a daily or hourly time step and is designed to evaluate management effects on water quality, sediment, and agricultural chemical yield in large, ungauged basins as it requires minimal calibration. The development of SWAT is a continuation of USDA Agricultural Research Service (ARS) modeling experience that spans a period of roughly 30 years. Early origins of SWAT can be traced to previously developed USDA ARS models (see figure below) including the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980), the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), and the Environmental Impact Policy Climate (EPIC) model (Izaurralde et al., 2006), which was originally called the Erosion Productivity Impact Calculator (Williams, 1990). The current SWAT model is a direct descendant of the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold and Williams, 1987), which was designed to simulate management impacts on water and sediment movement for ungauged rural basins.

The model is based on a command structure for routing runoff and chemicals through a watershed. These commands allow the user to route flows through streams and reservoirs, combine flows, and input measured data (e.g., weather) and point source loading. The major components of SWAT include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. The minimum weather inputs required by SWAT for simulation of hydraulic process are maximum and minimum daily temperature and precipitation. Sediment yield is estimated by the Modified Universal Soil Loss Equation (MUSLE; Williams, 1975). Daily average soil temperature is simulated using the maximum and minimum annual air temperatures, surface temperature, and damping depth.

The SWAT hydrological model has been used to include many parameters that impact on hydrology and to simulate the flows on the study area. Figure 3.1 presents a diagram of the SWAT process.

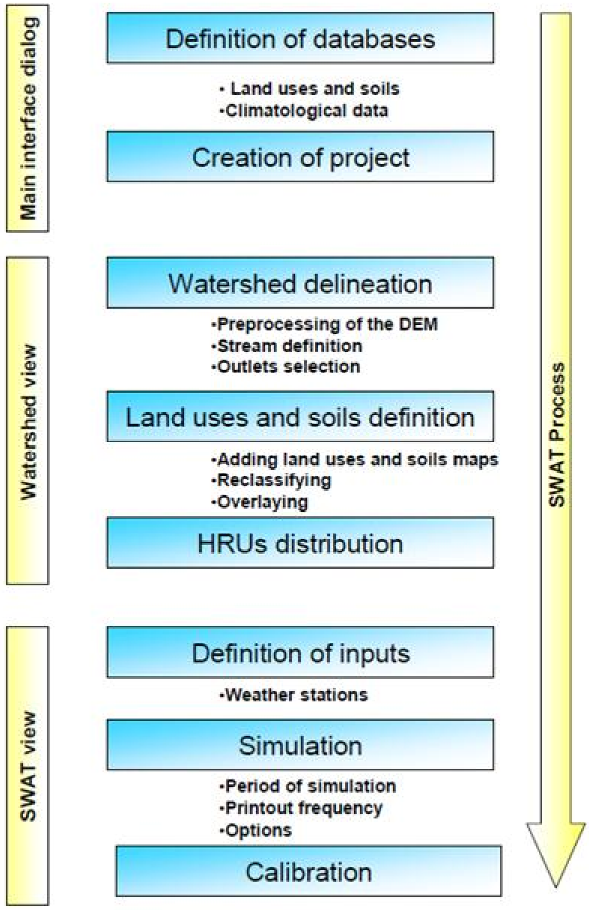


Figure 5 Representation of the SWAT model process

The preliminary step was the definition of the databases (dbf tables): soil and land use parameters, and climatological data. Each table has to be defined clearly using the nomenclature provided in the SWAT user's manual. Soil and land use parameters were modified and the climatological data were added in different files presenting each parameter and the location of their meteorological station.

The watershed delineation builds the streams and the sub-basins using the Digital Terrain Model. The burn-in option permits the use of an existing digitized stream network.

For the land use and soil definition, raster or shape files are added to the Watershed view in ArcView 3.2 and linked to the SWAT database. To use the maps provided, the SWAT interface requires a table linking the values represented to types already defined in the hydrological model. For the land use, some default categories are already provided in this version of SWAT with two themes: land cover and urban land. It is also possible to add new land use types with suitable parameters.

The table represents an example of the look-up table for the land use database. The land use mapped in the shape file is linked to default categories present in SWAT.

3.1.4 THE HYDROLOGIC RESPONSE

The basic spatial unit to the calculation is the Hydrologic Response Unit (HRU) that is the result of the combination of a soil type, a class of land cover and a sub-basin. The modeling requires that the watershed must be divided into sub-basins. Flows estimated for every HRU are added by sub-basin in order to get a global flow transmitted between sub-basins (Bioteau and al., 2002). The active processes in soil are infiltration, evapotranspiration, withdrawal by plants, lateral out-flow and outflow toward the lower horizons. The concept of the HRU is based on the assumption that there is no interaction between HRUs in one sub-basin, therefore it is only at the subbasin level that spatial relationships can be specified.

The model combines empirical and physically-based equations, uses readily available inputs, and enables users to study long-term impacts. SWAT is defined by eight major components: hydrology, weather, erosion and sedimentation, soil temperature, plant growth, nutrients, pesticides and land management. SWAT is currently being utilized in several large basin projects. SWAT provides the modeling capabilities of the HUMUS (Hydrologic Unit Model of the United States) project (Srinivasan et al., 1993). The HUMUS project simulates the hydrologic budget and sediment movement for the approximately 2,100 hydrologic unit areas that have been delineated by the USGS. Findings of the project are being utilized in the Resource Conservation Act (RCA) appraisal conducted by the Natural Resources Conservation Service. Scenarios include projected agricultural and municipal water use, tillage and cropping system trends, and fertilizer and animal waste use management options. The model is also being used by NOAA to estimate nonpoint source loadings into all U.S. coastal areas as part of the National Coastal Pollutant Discharge Inventory. The U.S. EPA is currently incorporating SWAT into the BASINS interface for assessment of impaired water bodies.

3.1.5 CURVES NUMBER

SWAT uses the curve number approach to predict runoff generation and it has been the subject of a number of critical reviews (e.g. Hjelmfelt et al., 1982; Bales and Betson, 1982). Further work is required to clarify under what conditions the method gives satisfactory predictions. Mishra and Singh (1999) show that their generalized version of the method gives better results than the original formulation, as it should, since it has two additional fitting parameters.

Hjelmfelt et al. (1982) found no strong correlation between curve number and antecedent condition for individual rainfall events, suggesting that interactions with individual storm characteristics, tillage, plant growth and temperature were sufficient to mask the effect of antecedent rainfall. Despite its limitations, the Curve Number method has been used quite widely since it provides a relatively easy way of moving from soil and vegetation data sets (such as in GIS) to a rainfall- runoff model.

3.1.6 RESERVOIRS

A reservoir is an impoundment located on the main channel network of a watershed. The features of an impoundment are shown in Figure 6. The water balance for a reservoir is:

$V = V\text{stored} + V\text{flowin} - Vf\text{lowout} + V\text{pcp} - V\text{evap} - V\text{seep}$, Where

V is the volume of water in the impoundment at the end of the day (m3 H2O),

Vstored is the volume of water stored in the water body at the beginning of the day (m3 H2O), Vflowin is the volume of water entering the water body during the day (m3 H2O),

Vflowout is the volume of water flowing out of the water body during the day (m3 H2O),

Vpcp is the volume of precipitation falling on the water body during the day (m3 H2O),

Vevap is the volume of water removed from the water body by evaporation during the day (m3 H2O), and Vseep is the volume of water lost from the water body by seepage (m3 H2O).

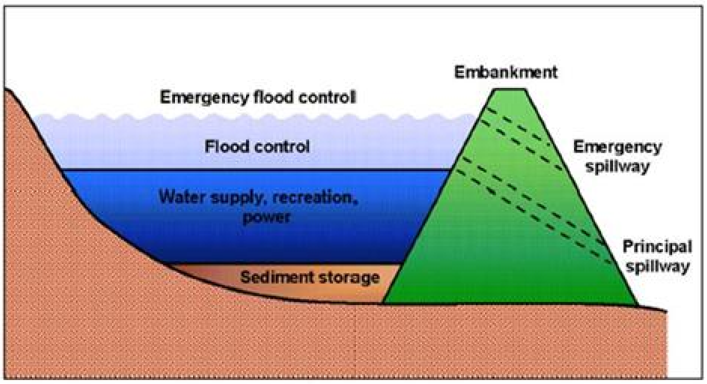


Figure 6 Components of a reservoir with flood water detention features

3.1.7 SENSITIVITY, CALIBRATION, AND UNCERTAINTY ANALYSES

Sensitivity, calibration, and uncertainty analyses are vital and interwoven aspects of applying SWAT and other models. Numerous sensitivity analyses have been reported in the SWAT literature, which provide valuable insights regarding which input parameters have the greatest impact on SWAT output. The vast majority of SWAT applications report some type of calibration effort. SWAT input parameters are physically based and are allowed to vary within a realistic uncertainty range during calibration. Sensitivity analysis and calibration techniques are generally referred to as either manual or automated, and can be evaluated with a wide range of graphical and/or statistical procedures. Uncertainty is defined by Shirmohammadi et al. (2006) as “the estimated amount by which an observed or calculated value may depart from the true value.” They discuss sources of uncertainty in depth and list model algorithms, model calibration and validation data, input variability, and scale as key sources of uncertainty. Several automated uncertainty analyses approaches have been developed, which incorporate various sensitivity and/or calibration techniques (Gassman and al, 2007).

3.2 THE WEAP MODEL

3.2.1 BACKGROUND

Many regions are facing formidable freshwater management challenges. Allocation of limited water resources, environmental quality and policies for sustainable water use are issues of increasing concern. Conventional supply-oriented simulation models are not always adequate. Over the last decade, an integrated approach to water development has emerged which places water supply projects in the context of demand-side issues, as well as issues of water quality and ecosystem preservation.

However, it is necessary to develop a better understanding of how the natural hydrologic system behaved prior to the onset of the dramatic hydrologic manipulations that characterizes many of our water resource systems today (Muttiah and Wurbs, 2002). This type of analysis relies upon the use of hydrologic modeling tools that simulate physical processes such as precipitation; evapotranspiration, runoff, and infiltration (see Figure 7 a, pre-development). Following the construction of hydraulic structures such as dams and diversions (see Figure 7 b, post-development), factors related to the management system must also be considered. These systems were put in place to govern the allocation of water between competing demands, be they consumptive demand for agricultural or urban water supply or non-consumptive demand for hydropower generation or ecosystem protection (Yate and a, 2005).

A water resource model is a conceptual representation of an actual water system that allows us to explore how the system might change in response to a range of assumptions (Harris, 2007). Because models are conceptual, they are not able to predict exactly what will happen under various proposed scenarios, but instead allow the modeler to compare the outcomes of different scenarios to each other. For example, scenarios might include different assumptions about population growth, the adoption of new technology, changes in the economy, the construction of infrastructure, or the implementation of new environmental regulations. Typically, one scenario is developed based on business as usual assumptions, which provides a point of reference against which other scenarios can be compared (Harris, 2007).

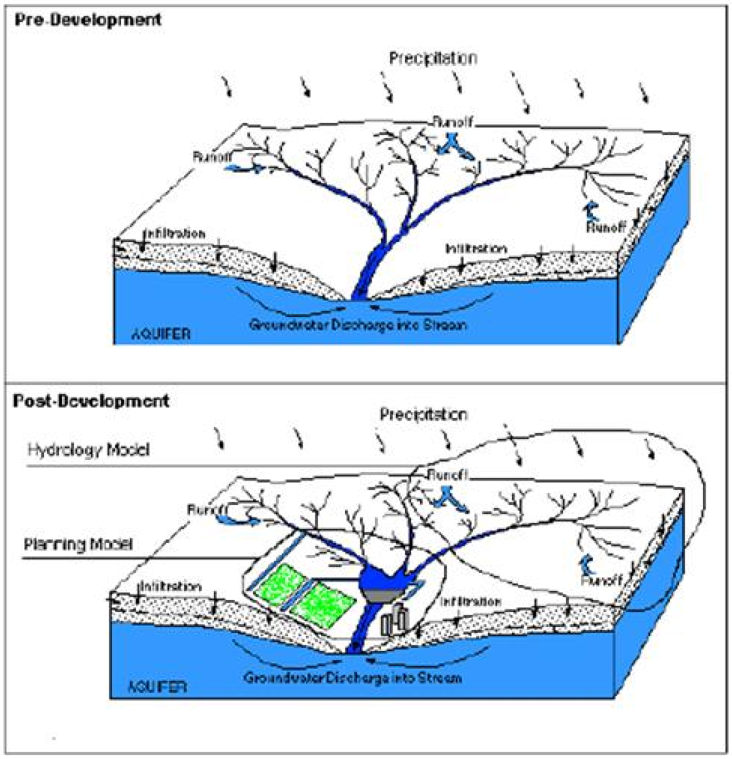


Figure 7 Characterization of (a) pre- and (b) post-watershed development that highlights the implications of water resource infrastructure on the hydrologic cycle

The Water Evaluation and Planning System (WEAP) aims to incorporate these values into a practical tool for water resources planning. WEAP is distinguished by its integrated approach to simulating water systems and by its policy orientation. WEAP places the demand side of the equation--water use patterns, equipment efficiencies, re-use, prices, hydropower energy demand, and allocation--on an equal footing with the supply side--streamflow, groundwater, reservoirs and water transfers. WEAP is a laboratory for examining alternative water development and management strategies.

3.2.2 PRESENTATION OF THE WEAP MODEL

The WEAP software was developed by the Stockholm Environment Institute at Boston. It is an object-oriented computer modeling package designed to simulate water resources systems and trade-off analysis. WEAP (Water Evaluation and Planning) is a unique water resources planning software system that allows the modeler to account for a changing climate through an internal rainfall run-off module which simulates hydrologic patterns based on climatic input. This ability to include climate change in the development of future scenarios makes it a potentially powerful tool for informing climate adaptation policy-making (Harris, 2007).

WEAP stores information characterizing a water system in a transparent and easy-to-use database. Characterization includes water use patterns, losses, environmental flows, priorities for the demand side, supply sources, hydrologic flow patterns, surface and groundwater storage, costs, and operation and allocation rules for the supply side. Rivers, canals, demand sites, water and wastewater treatment plants, conveyance and pumping facilities, local water sources, surface and groundwater reservoirs comprising the water system are quickly drawn and linked in a graphical interface and can be organized to match real geographic locations with the help of imported GIS map layers (Lévite et al., 2002)..

As opposed to historic hydrologic inputs, WEAP uses inputs such as precipitation, temperature, humidity, and wind speed. These inputs can be derived from global climate change scenarios, and are used to calculate how much of the precipitation that falls in a particular area ends up as run-off into streams, recharge to groundwater, or evapotranspiration through vegetation. With this capability, the WEAP user can build scenarios that assume, for example, higher temperatures or heavier rainfall, along with assumptions about water demand, infrastructure, and environmental regulation. These human activities are the elements that can be adapted in the future in response to climate change. For example, we might model a scenario with restricted water demand to try to minimize the predicted water shortage or improve the predicted water quality. WEAP produces results that demonstrate whether water demand is met during a particular month, the degree of water shortage if there are shortfalls, levels of storage in reservoirs for future use, and measures of water quality. WEAP also assesses the sufficiency of environmental water flows, the level of hydropower generation capacity, and the evolution of soil moisture, evapotranspiration rates, surface run-off volume, and the rate of groundwater recharge (Harris, 2007)).

3.2.2.1 APPLICATION OF WEAP

The Water Evaluation and Planning Version model attempts to address the gap between water management and watershed hydrology and the requirements that an effective IWMR be useful, easy to use, affordable, and readily available to the broad water resource community. WEAP1 integrates a range of physical hydrologic processes with the management of demands and installed infrastructure in a seamless and coherent manner. It allows for multiple scenario analysis, including alternative climate scenarios and changing anthropogenic stressors, such as land use variations, changes in municipal and industrial demands, alternative operating rules, points of diversion changes, etc.

It has been applied in water assessments in dozens of countries in North America, Europe, Asia, and Africa. WEAP applications generally involve the following steps (Yates and al., 2005):

- Problem definition including time frame, spatial boundary, system components and configuration.
- Establishing the ‘current accounts’, which provides a snapshot of actual water demand, resources and supplies for the system.
- Building scenarios based on different sets of future trends based on policies, technological development, and other factors that affect demand, supply and hydrology.
- Evaluating the scenarios with regard to criteria such as adequacy of water resources, costs, benefits, and environmental impacts. The WEAP analysis are able to project how climate change might affect water resources in order to understand what types of adaptation policies would be most likely to reduce the country’s vulnerability.

3.2.2.2 ADVANTAGES OF WEAP MODEL

The Water Evaluation and Planning (WEAP) model has a long history of development and use in the water planning arena. Raskin et al. (1992) first applied it to a study on the Aral Sea, but that version of WEAP had several limitations, including an allocation scheme that treated rivers independently, gave priority to demands on upstream sites over downstream sites, and assured demand sites that preferred groundwater to surface water were last in line in getting surface water allocations. Given these deficiencies, WEAP21 introduces major advances including a modern Graphic User Interface (GUI), a robust solution algorithm to solve the water allocation problem, and the integration of hydrologic sub-modules that include a conceptual rainfall runoff, an alluvial groundwater model, and a stream water quality model (Yates, 2005).

WEAP model simulations are constructed as a set of scenarios, where simulation time steps can be as short as one day, to weekly, to monthly, or even seasonally with a time horizon from as short as a single year to more than 100 years.

WEAP places the evaluation of specific water problems in a comprehensive framework. The integration is over several dimensions: between demand and supply, between water quantity and quality, and between economic development objectives and environmental constraints.

In specific, the following tasks and activities could be performed using WEAP system:

1- identify and evaluate the impacts of climate change on water for agriculture, recreation, hydropower generation, water for municipal and industrial use, habitat function and health, biodiversity, water purification;

2- Simulates water demand, flows, and storage, and pollution generation (environmental assessment capability). Treatment and discharge;

3- Provides through its graphical interface a simple yet powerful means for constructing;

4- Viewing and modifying the system and its data (database management, forecasting, and analysis.);

5- Detailed supply demand modeling (forecasting, planning and evaluation);

6- Assess current patterns of land development and modification (land use/land cover and population changes);

7- Examine alternative water development and management strategies including adaptation strategies.

8- Explore the physical, social, and institutional aspects that impact watershed management integrated water resources planning that may

impact the water conservation policies.

3.2.2.2.1 SCENARIO ANALYSIS

Scenarios are alternative sets of assumptions such as different operating policies, costs, and factors that affect demand such as demand management strategies, alternative supply sources and hydrologic assumptions, with changes in these data able to grow or decline at varying rates over the planning horizon of the study (Yates and al, 2005).

The scenarios can address a broad range of "what if" questions, such as: What if population growth and economic development patterns change? What if reservoir operating rules are altered? What if groundwater is more fully exploited? What if water conservation is introduced? What if ecosystem requirements are tightened? What if new sources of water pollution are added? What if a water-recycling program is implemented? What if a more efficient irrigation technique is implemented? What if the mix of agricultural crops changes? What if climate change alters the hydrology? These scenarios may be viewed simultaneously in the results for easy comparison of their effects on the water system.

Among others, the scenarios are evaluated with regards to supply sufficiency, cost, and average cost of delivered water, the meeting of in-stream flow requirements, hydropower production, and sensitivity of results based on uncertainty of key variables. These could include reductions in water demand due to demand side management, assumptions of rates of growth, incorporation of technical innovation, changes in supply (Yates and al, 2005),

3.2.2.2.2 DEMAND MANAGEMENT CAPABILITY

WEAP is unique in its capability of representing the effects of demand management on water systems. Water requirements may be derived from a detailed set of final uses, or "water services" in different economic sectors (SEI, 2005). For example, the agricultural sector could be broken down by crop types, irrigation districts and irrigation techniques. An urban sector could be organized by county, city, and water district. Industrial demand can be broken down by industrial subsector and further into process water and cooling water. This approach places development objectives--providing end-use goods and services--at the foundation of water analysis, and allows an evaluation of effects of improved technologies on these uses, as well as effects of changing prices on quantities of water demanded. In addition, priorities for allocating water for particular demands or from particular sources may be specified by the user.

3.2.2.2.3 ENVIRONMENTAL EFFECTS

WEAP scenario analyses can take into account the requirements for aquatic ecosystems. They also can provide a summary of the pollution pressure different water uses impose on the overall system. Pollution is tracked from generation through treatment and outflow into surface and underground bodies of water. Concentrations of water quality constituents are modeled in rivers.

3.2.2.2.4 EASE OF USE

An intuitive graphical interface provides a simple yet powerful means for constructing, viewing and modifying the system and its data. The main functions--loading data, calculating and reviewing results--are handled through an interactive screen structure that prompts the user, catches errors and provides on-screen guidance. The expandable and adaptable data structures of WEAP accommodate the evolving needs of water analysts as better information becomes available and planning issues change. In addition, WEAP allows users to develop their own set of variables and equations to further refine and/or adapt the analysis to local constraints and conditions.

3.2.2.2.5 URBAN WATER MANAGEMENT

One of the strengths of WEAP is that it is adaptable to whatever data is available to describe a water resources system. That is, it can use daily, weekly, monthly, or annual time-steps to characterize the system's water supplies and demands. This flexibility means that it can be applied across a range of spatial and temporal scales. Indeed, WEAP has been used throughout the world to analyze a diverse set of water management issues for small communities and large managed watersheds alike.

Historically, WEAP has been used primarily to assess the reliability of water deliveries and the sustainability of surface water and groundwater supplies under future development scenarios. This type of application of WEAP has focused on the water supply implications of proposed management and/or infrastructural changes, but has overlooked the impacts of these changes on the management of storm water and wastewater. Recent advancement of the model, however, has allowed for the holistic, comprehensive consideration of each of these facets of managing local water resources. The updated model can now be used to address questions surrounding the integration of storm water, waste water, and water supply.

3.2.2.3 OPERATIONAL STEPS

1. The study definition sets up the time frame, spatial boundary, system components and configuration. The model can be run with any time step where routing is not a consideration; for the proof-of-concept in the Basin, a monthly time step is used.

2. System management is represented in terms of supply sources (surface water, groundwater, inter-basin transfer, and water re-use elements); withdrawal, transmission and wastewater treatment facilities; water demands; and pollution generated by these activities. The baseline dataset summarizes actual water demand, pollution loads, resources and supplies for the system during the current year or some other baseline year.

3. Scenarios are developed - based on assumptions about climate change, demography, development policies, costs and other factors that affect demand, supply and hydrology. The drivers may change at varying rates over the planning horizon. The time horizon for these scenarios can be set by the user.

4. Scenarios are then evaluated in respect of desired outcomes such as water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

3.2.3 THE PHYSICAL HYDROLOGY MODULE of WEAP

The WEAP21 model includes an irregular-grid, water balance model that can account for hydrologic processes within a watershed system and that can capture the propagating and non-linear effects of water withdrawals for different uses. Our approach is informed by Beven (2002), who challenges the trend towards physically-based modeling systems.

The physical hydrology component of WEAP has been developed to account for two different hydrologic realities. The first is the notion that precipitation in sub catchments located in the upstream portions of watersheds, with complex topography, steep slopes, and abrupt hills and valleys, contributes to groundwater baseflows that serve a gaining stream year-round, with a relatively short time lag (Winter et al., 1998; Winter, 2001; Eckhardt and Ulbrich, 2003; Burness et al., 2004). Conversely, sub catchments located in lower portions of watersheds with flatter terrain tend to contribute to alluvial aquifers that are directly linked to the river system to which they can contribute flow (gaining streams) and from which they can receive seepage (losing streams), depending on hydrologic conditions. These groundwater systems can also provide storage from which users can draw water to satisfy demands (Figure 8). This schematic shows a watershed broken into two sub-catchments. SC-1 is a headwater catchment, without surface-groundwater interaction and applies the two “bucket” water balance model. SC-2 is characterized as being in a valley area, where the surface hydrology applies the single bucket water balance with recharge to an underlying alluvial aquifer which as groundwater-surface water interaction.

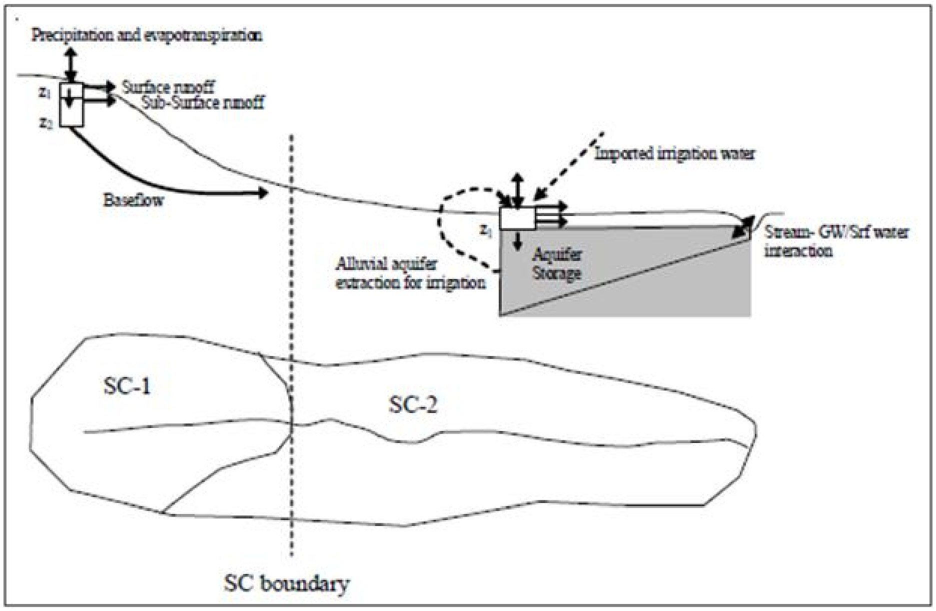


Figure 8 Physical hydrology component of WEAP21 with two different hydrologic realities. (Yates and al, 2005)

3.2.4 SURFACE WATER HYDROLOGY

The physical hydrology model consists of several conceptually simple components that are combined to be computationally efficient, but with enough specificity to capture important hydrologic process and address key water resource issues. For a given time step, the hydrology module is first run to update the hydrologic state of the watershed, and thus provides mass balance constants used in the linear allocation problem in a second procedure within the same time step. A one dimensional, 2-storage soil water accounting scheme uses empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff or interflow, and deep percolation (Yates, 1996).

3.2.5 GROUNDWATER-SURFACE WATER INTERACTION

Surface water and groundwater are dynamically linked, for when groundwater is depleted, a stream contributes to aquifer recharge (a losing stream), while a stream is considered to be gaining when there is substantial recharge to the aquifer across the watershed and flow is from the aquifer to the stream. Irrigated agriculture can complicate the picture even further, since water can be drawn from the stream, pumped from the local aquifer, or even imported from outside the basin, and thus both depletes and recharges the aquifer (Liang et al., 2003; Winter, 2001).

Capturing these dynamics is important, and the groundwater module implemented in WEAP21 allows for the dynamic transfer of water between the stream and the aquifer (Figure 9). In WEAP21, the aquifer is a stylized wedge that is assumed symmetric about the river, with total aquifer storage estimated under the assumption that the groundwater table is in equilibrium with the river. Thus the equilibrium storage for one side of the wedge, GSe is given as:

Equation 3.1 $$\mathbf{GS_e = h_d * l_w * A_d * S_y}$$

where h_d (m) represents the normal distance that extends horizontally from the stream, l_w (m) is the wetted length of the aquifer in contact with the stream, S_y is the specific yield of the aquifer, and A_d is the aquifer depth at equilibrium. A_d estimate of the height which the aquifer lies above or is drawn below the equilibrium storage height is given by y_d the vertical height of the aquifer above or below the equilibrium position. In the Figure 9, E_X refers to the water withdrawn from the aquifer to meet demands, and P refers to the watershed's contributing recharge.

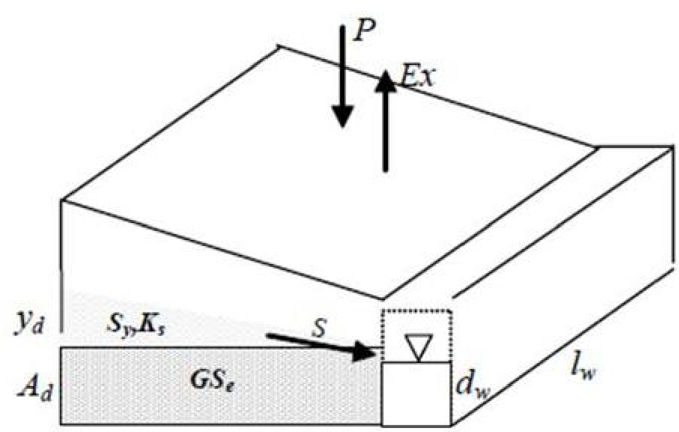


Figure 9: Schematic of the stylized groundwater system, and its associated variables (Yates and al, 2005)

3.2.6 IRRIGATED AGRICULTURE

Demand associated with irrigated agriculture shares the same surface hydrologic model as the watershed demand associated with evapotranspiration from natural land cover. A sub-catchment can be designated as containing irrigated land cover fractions, which are then assigned upper and lower irrigation thresholds. Sub-catchments with irrigation require a water source to meet that demand and these sources are identified in WEAP21 by using the drag-and-drop capability to link the water sources to the appropriate irrigation demand location.

3.2.7 SURFACE WATER QUALITY

The WEAP21 model includes descriptive models of point source pollutant loadings that can address the impact of wastewater on receiving waters. The water quality parameters are currently limited to conservative constituents that decay according to an exponential decay function, dissolved oxygen (DO), Biological Oxygen Demand (BOD) from point sources, and in-stream water temperature. The water quality of reservoirs is currently not modeled. The first-order DO and temperature models are patterned after Chapra (1997), where water quality is simulated for select rivers, chosen by the WEAP21 user interface. Mass balance equations are written for each stream segment of the selected rivers, with hydrologic inflows from rivers and groundwater sources automatically input to simulate the water balance and mixing of DO and BOD concentrations and temperature along each reach. The river network is the same for the water resources and the water quality simulation and assumes complete mixing (Yates and al, 2005).

3.2.8 THE MANAGEMENT SYSTEM: THE ALLOCATION MODULE

The starting point in a WEAP21 water management analysis is the development of watershed demands. Each demand is assigned a user-defined priority given as an integer from 1 (highest priority) to 99 (lowest priority). Each demand is then linked to its available supply sources, with each supply source preference set for each demand site (e.g. does the site prefer to get its water from a groundwater or surface water source?). The supply-demand network is constructed and an optimization routine allocates available supplies to all demands. Demands are defined by the user, but typically include municipal and industrial demand, irrigation demands from portions of the watershed, and in-stream flow requirements.

3.2.8.1 WATER DEMANDS

Demand analysis in WEAP21 that is not covered by the evapotranspiration-based, physical hydrology module is based on a disaggregated, end-use approach that determines water requirements at each demand node. Demographic and water-use information is used to construct scenarios that examine how total and disaggregated consumption of water evolve over time. These demands scenarios are computed in WEAP21 and applied deterministically to the Linear Program (LP) allocation algorithm. Demand analysis is central to integrated water planning analysis with WEAP21, since all supply and resource calculations are driven by the allocation routine which determines the final delivery to each demand node, based on the priorities specified by the user.

WEAP provides flexibility in how data are structured and can range from highly disaggregated end-use oriented structures to highly aggregated analyses. Typically, a demand scenario comprises several sectors including households, industry, ecosystems, and agriculture, and each can be broken down into different sub-sectors, enduses, and water-using devices. However, if the physical hydrology module is used, agricultural and urban turf watering demands are not included in the disaggregated demand analysis but are derived from soil moisture fluctuations.

The structure of demand data can be adapted to meet specific purposes, based on the availability of data, the types of analyses the user wants to conduct, and their unit preferences. In most cases, demand calculations are based on a disaggregated accounting for various measures of social and economic activity (e.g., number of households, water use rates per household, hectares of irrigated agriculture, industrial and commercial activity, and water use rates) and are aggregated and applied in the allocation scheme at the demand site level (Yates and al, 2005). Activity levels are multiplied by the water use rates of each activity and each can be individually-projected into the future using a variety of techniques, ranging from applying simple exponential growth rates and interpolation functions, to using sophisticated modeling techniques that take advantage of WEAP21's built-in modeling capabilities via a spreadsheet like expression builder

3.2.8.2 IN-STREAM FLOW REQUIREMENTS

In-stream flow requirements are used to represent established or new regulatory requirements of minimum flows in a river. These data objects are placed on the river and are assigned a priority and minimum flow value that must be maintained during a specified period. In-stream flow requirements can vary in time, so one can characterize a temporally changing regulatory environment, making it possible to make the in-stream flow requirements a higher priority and simultaneously raise the minimum standard of flow at any given time in the simulation. Figure 10 illustrates this, where the in-stream flow priority has changed from a 2 (lower priority) to a 1 (highest priority) in 2005, while the minimum in-stream flow requirement has been raised from 1.0 cubic meters per second (m3) to 2.0 (m3) in the same year.

3.2.8.3 SURFACE RESERVOIRS

Reservoirs represent a special object in the WEAP21 model in that they can be configured to store water that becomes available either from the solution of the physical hydrology module or from a user-defined time series of stream flows. A reservoir's operating criteria determines how much water is available in the current time step for release to satisfy downstream demand and instream flow requirements, hydropower generation, and flood control requirements and how much if any should be carried over until a later time-step. If the priority assigned to storing water in a reservoir is less than downstream demands or in-stream flow requirements, WEAP will release only as much of the available storage as is needed to satisfy demand and in-stream flow requirements, taking into consideration releases from other reservoirs and withdrawals from rivers and other sources.

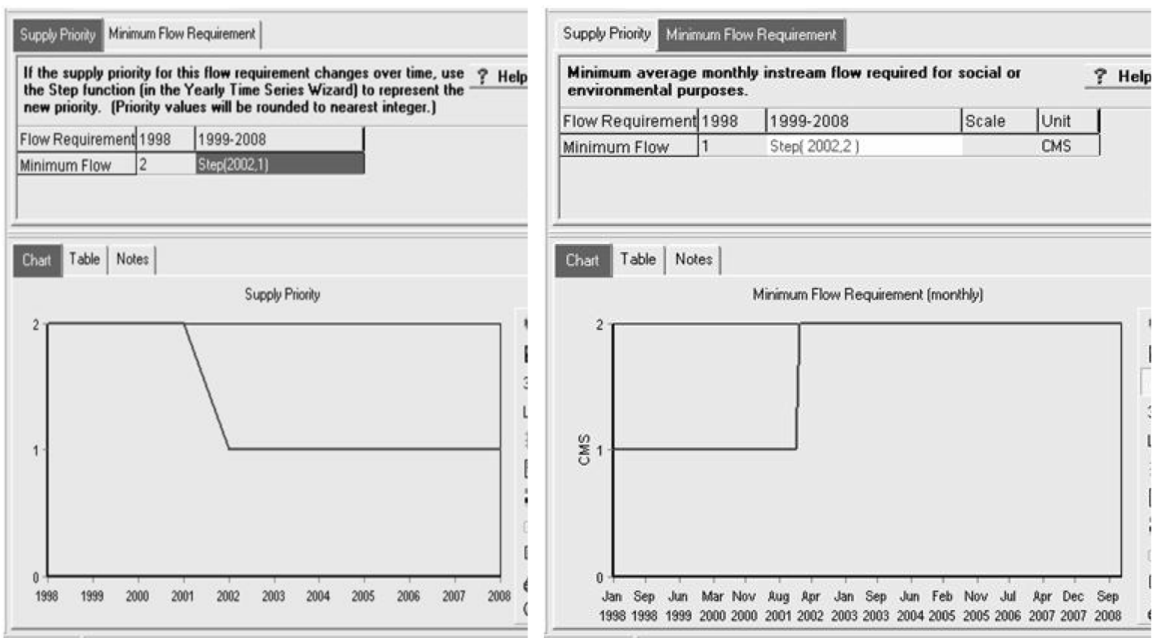


Figure 10 WEAP21's GUI for specifying in-stream flow requirements. The left panel shows the supply priority of in-stream flow, while the right panel is the actual in-stream flow requirement in m3/s that abruptly changes over time as a result of regulatory requirement

In WEAP, a reservoir is stratified according to water storage volumes as shown in Figure 10, where: 1) the flood control storage (Sf) defines the zone that can temporarily hold water but must be released before the end of the time step. In effect, it is always vacant, as additional flows that would lead to reservoir storages above the flood control storage are spilled; 2) the conservation storage (Sc) is the storage available for downstream demands at full capacity, where all water in this zone can be drawn from; 3) the buffer storage (Sb) is a storage that can be controlled to uniquely meet water demands during shortages; when reservoir storage falls within the buffer storage, water withdrawals are effectively conserved via the buffer coefficient, bc, which determines the fraction of storage available for reservoir release; and 4) the inactive storage (Si) is the dead storage that cannot be utilized. All these storages parameters can vary in time and can be used to define water conservation and flood storage/release targets. The amount available to be released from the reservoir, Sr is the full amount in the conservation and flood control zones and a fraction (defined by bc) of the amount in the buffer zone

Equation 3.2 $$Sr=Sc+Sf+(bc*Sb)$$

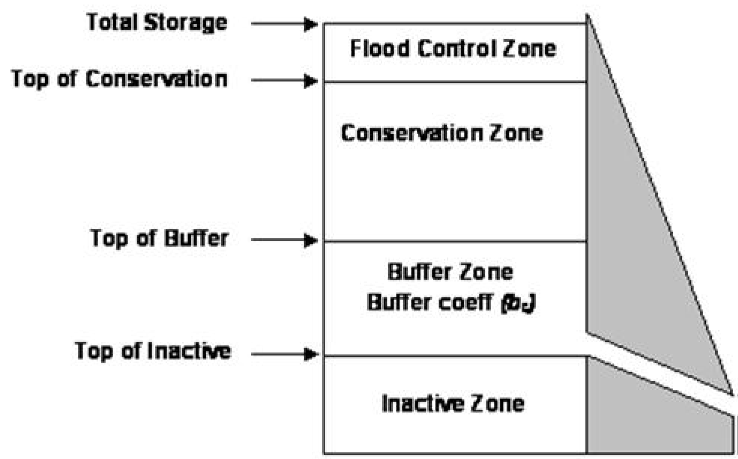


Figure 11 The different reservoir storage volumes used to describe reservoir operating

3.2.8.4 DEMAND PRIORITIES AND SUPPLY PREFERENCES

A standard linear program (Berkelaar et al., 2004) is used to solve the water allocation problem whose objective is to maximize satisfaction of demand, subject to supply priorities, demand site preferences, mass balances, and other constraints. The constraint set is iteratively defined at each time step to sequentially consider the ranking of the demand priorities and supply preferences. The approach has some attributes of a more traditional dynamic programming algorithm, where the model is solved in sequence based on the knowledge of values derived from the previous variables and equations (Loucks and al., 1981; Nandalal and Sakthivadivel, 2002).

Individual demand sites, reservoirs, and in-stream flow requirements are assigned a unique priority number, which are integers that range from 1 (highest priority) to 99 (lowest priority).

Those entities with a Priority 1 ranking are members of Equity Group 1, those with a Priority 2 ranking are members of Equity Group 2, and so on. The LP constraint set is written to supply an equal percentage of water to the members of each Equity Group. This is done by adding to the LP for each demand site:

1) a percent coverage variable, which is the percent of the total demand satisfied at the given time step;

2) an equity constraint that equally satisfies all demands within each Equity Group in terms of percentage of satisfied demand; and

3) a coverage constraint which ensures the appropriate amount of water supplied to a demand site or the meeting of an in stream flow requirement.

3.2.8.5 METHODOLOGY

In the Chapter 5, the WEAP program will be used to build an IWRM model taking Merguellil catchment as a case study. The following summarize the main steps to be followed:

1. Prepare the required information and all the input data for WEAP software to develop an integrated water resource management (IWRM) model

2. Setup GIS-based data as input for the model.

3. Suggest future scenarios related to the population growth, supply and demand changes, and other factors.

4. Build the IWRM model using WEAP Program.

5. The final results of the modeling will be formulated in a form of figures, tables and maps.

6. Make needed calibration for the output data resulted from WEAP model for the catchment.

7. Set the general comments and recommendations.

4 CHAPTER 4: CASE OF STUDY

4.1 WATER RESOURCES IN TUNISIA

Water resources in Tunisia are estimated at 4700 Mm^3 including 650 Mm^3 of nonrenewable resources or 13.8% of the total water resources. Groundwater resources represent 42.5% of the total potential. Over the last decade, records show that Tunisia experienced 12 important flood periods alternated with 17 dry periods. Droughts appear two to three times every 10 years and can last two, three or even four successive years.

Surface water resources in Tunisia are characterized by problems of quantity and quality. These resources are limited because of the semi-arid to arid climate found in most of the country, with episodic droughts, and a natural deterioration of water quality because of the salty types of rocks found within the country (Benabdellah, 2007). Tunisia receives on average 230 mm/year of rainfall; that is 36 billion cubic meters (bm^3) of rainfall. However, this volume varies between 11bm^3 during a drought year and 90 bm^3 during a very wet year. The variability of the climate under the Mediterranean influence in the north and under the Saharan influence in the south makes rainfall at the same time scarce and unequally distributed in space and time. The annual precipitation is on average 594 mm in the north, 289 mm in the center and only about 150 mm in the south. The ratio between the highest observed values and the lowest observed values of precipitation vary from 4.4 in the north to 15.8 in the south, illustrating the temporal irregularity and variability of rainfall.

Surface water resources are estimated at 2700 million cubic meters (Mm^3) distributed per year over three natural areas distinguished by their climatic and hydrological conditions as well as by rather homogeneous geomorphologic and geological aspects. The north provides relatively regular contributions evaluated to 2190 Mm^3, thus representing 82% of the total surface water potential while covering only 16% of the country. The center part, covering 22% of the area, is characterized by irregular resources. It provides 12% of the total surface water potential. The southern part of the country which accounts for approximately 62% of the total area is the poorest in surface water, providing very irregular resources evaluated at 190 Mm3 which represents 6% of the country‘s total potential of water. The quality of surface water, evaluated by its degree of salinity, varies according to the origin of the resource. Considering that a salinity of less than 1.5g/l is acceptable, and then approximately 72% of the surface resources may be considered of good quality. Water quality also varies across the country with 82% of the water resources in the north considered good quality, 48% of that in the center and only 3% in the south (Benabdellah, 2007).

Tunisia has many aquifers, storing 720 Mm3 each year in the northern and central areas and 1250 Mm3 in the south of the country (DGRE, 1995).Groundwater is distributed as follows:

- The north has 55% of the shallow groundwater resources and only 18% of the deep groundwater resources
- The center provides 30% of the shallow resources and 24% of the deep resources
- The south provides 15% of the shallow resources and has 58% of the deep resources.

Good quality groundwater is found in only 8% of shallow water and 20% of deep aquifers. If one accepts that salty water up to 3g/l can be used in the agricultural sector and for the production of drinking water, then approximately 36% of groundwater resources are not suited for these two sectors which are in increasing demand. the salinity of the water stored in shallow aquifers can reach 3.5 g/l due to overdraft as resources are drawn down for both drinking and irrigation (Benabdellah, 2007).

With a population of approximately 10 million and the availability of water resources below 500 m3/capita/year, Tunisia has been able to meet the needs of its various economic sectors, even during severe droughts: coverage of drinking water supply reaches 100% in cities and more than 80% in rural areas, without rationing, even in periods of shortage

4.2 STUDY AREA

The Merguellil catchment is located in central Tunisia, about 60 km west of the city of Kairouan (Figure 12). It is located between the parallels 39G 60N and 39G 78 N and the Meridian 7G 55E and 8 G 35 E (Kallel et al., 1975). The Merguellil catchment is characterized by a semi-arid climate. It extends on an area of about 1200 km² upstream of the El Houareb dam built in 1989 in order to protect Kairouan against floods. About 70% of the catchment surface area has slopes below 7%. Slopes above 15% cover 10% of the catchment surface area.

The water stress situation within the Merguellil catchment can be summarized as a limited resource facing an increasing water demand. Additionally, since four decades the Merguellil river basin is experiencing continuous change in its hydrologic system due to the construction of hill ponds, hill reservoirs and contour ridge (Figure 3.1) and the large El Haoureb at the outlet. After the floods of the Kairouan city in 1969, which caused severe human and material damages to the city, the large El Houareb dam was established with the main objective of protection of the city. However, besides reducing floods this dam served also to develop irrigated areas and to supply the city with potable water.

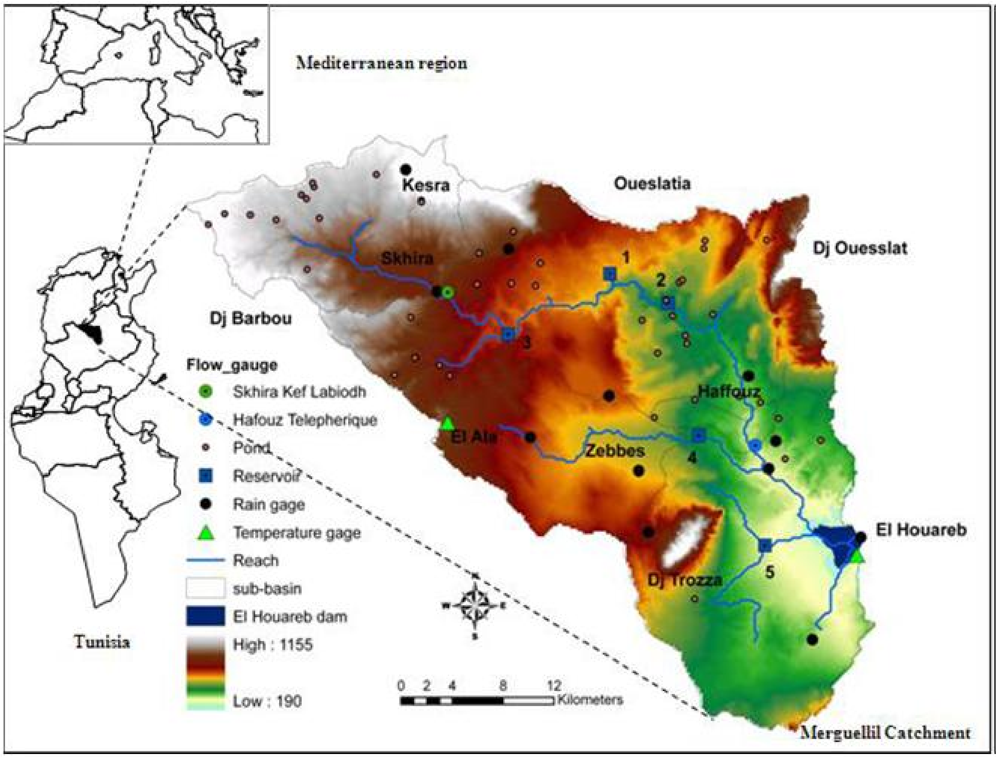


Figure 12 Location of the study area

4.2.1 MERGUELLIL ENVIRONMENT

The Merguellil catchment presents two contrasting aspects: an hilly upstream (1200 km^2), with an altitude between 200 and 1200 m, and a very flat downstream, part of the Kairouan plain that extends over more than 3000 km^2. The Merguellil catchment is endorheic and river flow is not perennial, but sometimes very violent: about 80 % of the annual flow is produced in 12 days. Before the construction of the big El Houareb dam, at the border between the upstream part and the Kairouan plain, the largest floods of Wadi Merguellil reached the Sebkha el Kelbia, a large salt lake often dried up and smaller floods vanished in the Kairouan plain by both evaporation and infiltration to the aquifer. For the period 1989-2005, the mean annual flow of Wadi Merguellil calculated at the entry of the El Houareb dam was 17 Mm^3 (extremes of 2.5 and 37.6 Mm^3). The exceptional flood of the 1969 autumn were estimated at about 175 Mm^3, with a peak flow over 3000 m^3/s, which resulted in the inundation of the Kairouan plain, high human and material losses. Groundwater resources may complement the surface water resource but they are not evenly distributed: 3 small aquifers cover the lower part of the upstream catchment; the thick and large aquifer in the Kairouan plain alluvium is the most important of central Tunisia.

4.2.2 PEDOLOGY

Four types of soils can be identified in the catchment. Immature soils are mainly inorganic and occasionally halomorphic. They are made up of silt and limestone. Associated soils consist of marl, sand and sandstone. Calcimagnesic soils gather brown, rendzina and regosol soils. Isohumic soils belonging to the brown sub-arid soil group are well suited for cereal-growing. These four soil types cover 38%, 44%, 11% and 7% of the catchment surface area respectively. In the Merguellil catchment, soil texture varies from clay to coarse sand textured. The upper basin contains shallow soil over a limestone crust rigid, the rest of the basin is composed of deep sand on sandstone. The soil map of the Merguellil catchment (Figure 13) presents four main units: poorly evolved soils, Carbonate soils (calci-magnesic), Iso-humic soils, and mineral soils resulting from erosion (association).

- **Poorly evolved soils** either wind borne or fluvial, form the best agricultural lands of south west (oasis or Ségui soils). In fact, they are deep (>1.50 m) and have silty-loam to sandy texture. Organic matter can barely exceed 0.5%. Gypsum accumulations could be present at medium depths of 40 - 60 cm and gypsum borne crust is therefore present almost everywhere at the boundaries of garaâts and chotts. Of course, salinity appears from bottom to upper layers. Its content varies according to the cultivation patterns. In most cases, these soils show spots of water logging and salinity as found in Ne-fzaoua, Gherib, Jerid, Gafsa regions (Mtimet, 2000; Mtimet, 1999, Raspic, 1999).
- **Iso-Humic soils** are brown soils with dominantly coarse texture. They are rather deep with an organic matter content ranging from 0.5% to 1.5%. On the plateau of Sidi M‘hedeb and Sfax, they have calcareous crusting, which allows them to be associated to calcicmagnesic soils. Which due to their erosion residues (high sand content) have a moderate retention capacity (60-80 mm m^{-1}) (Mtimet et al, 1996, 1997; Mtimet, 2000).
- **Carbonate soils** (calcic-magnesic) cover the north-west part of the basin where irrigation is poorly developed. Characteristically they possess a low field capacity (30-60 mm m^{-1}). They regularly cover calcareous parent materials. Their thickness is

variable following the general ground morphology. They exhibit crusted horizons or contain coarse calcareous elements (Mtimet, 2000; Mtimet, 1999).

- **Mineral soils** resulting from erosion (association). The valleys and the slopes are generally covered with calcareous or gypsum nodule-soils. This Soil type is more presented in Mountains, where the calcimagnesic soil formed a continuous cover formerly balances with a good forest cover. The outcrop of the bed rock is due to important erosion started by the degradation of the vegetation. This degradation is more visible on the broad marly outcrops located at the south of Makthar.

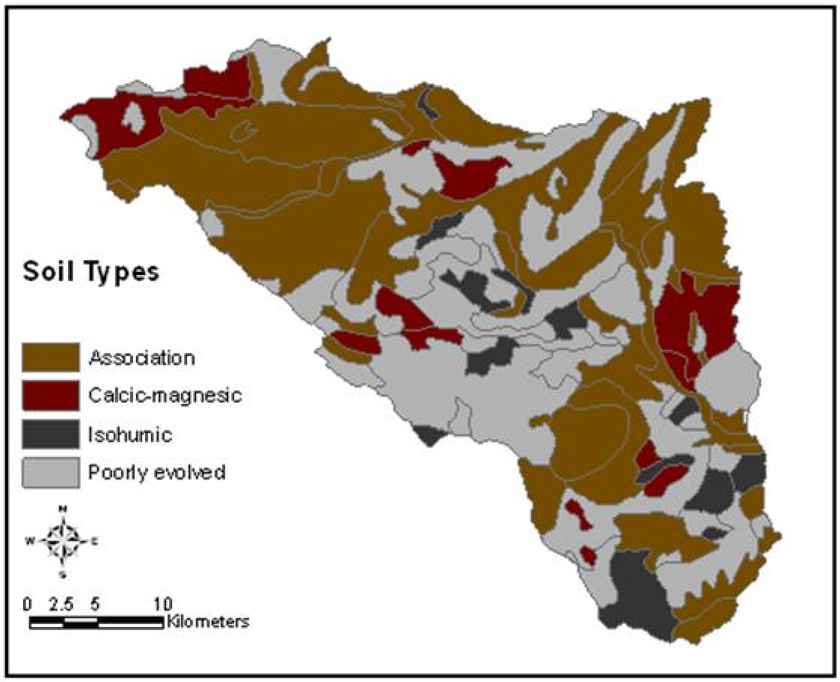


Figure 13 Soil map of the Merguellil catchment

4.2.3 LAND USE

Half of the catchment area is cultivated with annual crops (wheat, barley) and trees (olive and almond). Grazing lands cover 30%, forest 19%, and urban areas 1% (Lacombe, 2008). The Vegetation cover decreases from upstream to downstream (Figure 14). The upper part of the basin is covered by forest, which accounts for 18.5 % of the total basin area; pasture for another 21.5%, mainly in the central region, an urban area is concentrated in the small cities of Haffouz, el Ala and Kesra and presents (0.5%), water bodies (2.5%) while crops cover the remaining 57%, chiefly in the south east and north (kingumbi 1999).

The upper catchment is underlain by sedimentary deposits, mainly limestone, with alluvium along the larger valleys. In the lower catchment the Kairouan plain is a collapsed basin filled with a laterally and vertically heterogeneous sequence of Pliocene - Quaternary flood deposits bought down by the Zeroud and Merguellil rivers; these deposits are up to 700 m thick.

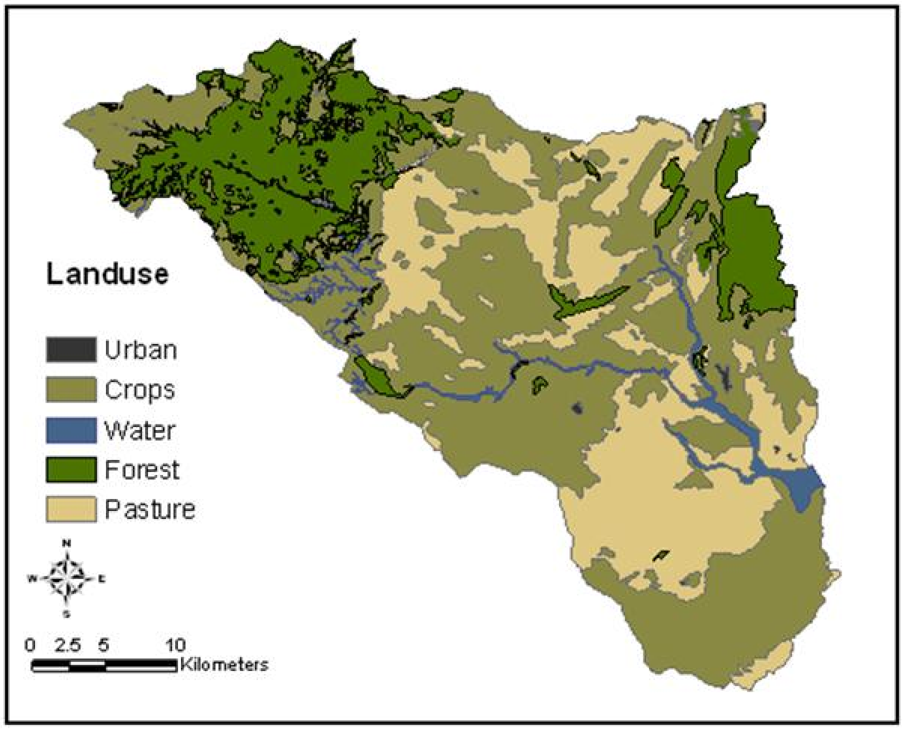


Figure 14 Land use map of the Merguellil catchment

4.2.4 CLIMATIC DATA

4.2.4.1 PRECIPITATION

The catchment area of Merguellil belongs to low rainy zone with annual precipitation from 200 to 400 mm distributed out of 40 to 70 days of rain. The mean annual rainfall (1929–2005) varies between 515 mm (for an average of 61 rainy days) at the top of the catchment (elevation = 1200 m) in the north-west and 265 mm (37 rainy days) at the catchment outlet (elevation = 200 m). About 83% of the mean annual rain falls between September and May with two peaks in October and March. Rain is extremely rare in July. Kingumbi et al. (2005) investigated the rainfall variability in the Merguellil area since 1966. They showed that while rainfall greater than 30 mm/day became more frequent after 1989 (11 days/year for the period 1966–1989, 16 days/year for the period 1989–1998), the annual mean cumulated area covered by such heavy rains has been decreasing since 1976 (2400 km2 for the period 1966–1976, below 1800 km2 after 1976). According to the Emberger classification, The North western part of the Merguellil catchment is situated in the superior and inferior semi-arid boundaries, while the rest of the basin like Kesra, Trozza and Djbel Oueslat belong to the inferior Semi-arid boundary (CES, 1986).

Precipitation varies with altitude; indeed the highest values are observed on the plate level such as that of Makthar and El Alaa, land on mountains which form the relief of the basin like Djebel Trozza. Generally, the North-western part of the catchment receives more rains than the South-eastern part . Precipitation decreases from the upstream to the downstream; the highest values are recorded at the Kesra.F and Skhira stations in the upstream of the catchment, while the lowest value is at EL Houareb rain-gage. Mean monthly precipitation over a period of 10 years (1990-2005) on the totality of the Merguellil catchment is presented in Figure 15. We note that most rainy months are September (50mm) and January (41mm). From May, monthly precipitations decrease until reaching the lowest values in July (Abouabdillah, 2010).

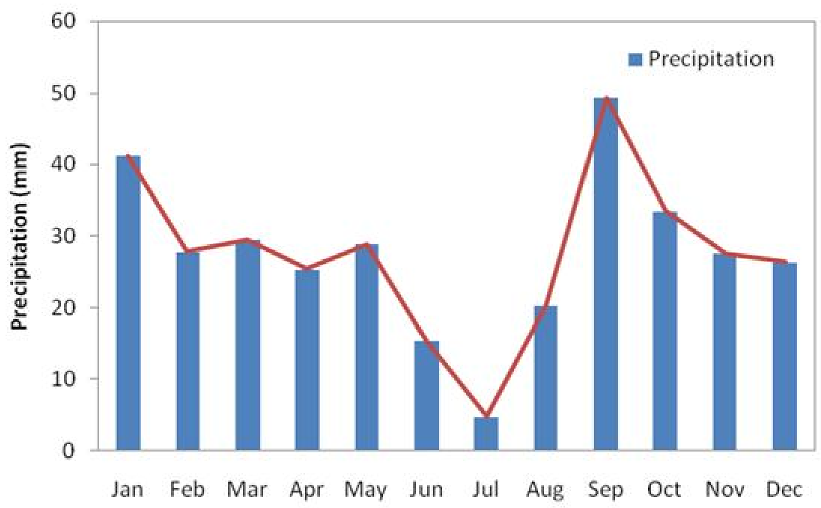


Figure 15 Mean monthly precipitations in the Merguellil catchment based on measured data in all rain-gages from 1990 to 2005 (Abouabdillah, 2010)

4.2.4.2 TEMPERATURE

No temperature gages were located within the watershed, and even the available stations in the proximity of the basin [Kairouan (1901-1979), Makthar (1901-1979) and Sbiba (1964-1982)] have records that do not cover the simulation period (1986-2005). The mean monthly temperatures within the Merguellil catchment (Figure 16) fall below 10 °C during December, January and February. They are between 10 and 20 °C during October and November and during April and May. The hottest months in the basin Merguellil are July and August. In these months, the monthly mean maximum temperatures exceeded 10 °C, but they stay below

35°C. The coldest period of the year is the winter months from December to February, with average monthly minimum below 5 °C. They remain below 10 °C during November, March and April and exceed this threshold, the rest of the year.

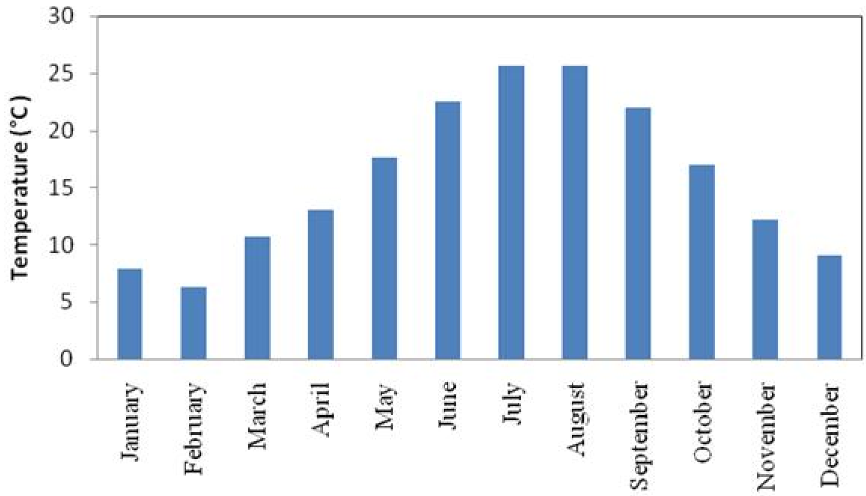


Figure 16 Mean monthly temperatures in the Merguellil catchment based on measured data in Sbiba, Makther and kairouan stations from 1972 to1982 (Abouabdillah, 2010)

4.2.4.3 HUMIDITY

Relative humidity is the ratio between the amount of water vapor in the air and maximum absorption capacity of the air at a given temperature. The mean monthly value oscillates between 55% and 70% during the cold season and between 40% and 55% during the warm season. The climate is moderately dry from September to April and very dry from May to August. Relative humidity increases in the presence of thunderstorms and lowered during sirocco (hot wind). In Kairouan, it is high during October (65%), November (61%), December (64%), January (65%) and low in June and July (48%), August (50%).

4.2.4.4 EVAPOTRANSPIRATION

The potential evaporation depends on temperature, wind and atmospheric humidity. Evaporation is maximal in summer in the plains and it is minimal in winter in highland areas with cooler temperatures. Given the lack of measures and the presence of gaps of potential evapotranspiration in the Merguellil watershed, several formulas have been adapted to determine this variable i.e. Thornthwaite and Penman formula that requires a lot of climatic parameters but better agree with the measured values in some weather gauge (Bouzaine and Lafforgue, 1986). The monthly maximum is reached in July with an average of 1000 mm and the minimum in January with 400 mm (Dridi, 2000).

4.3 DESCRIPTION OF WATER SUPPLY SYSTEM IN THE STUDY AREA

4.3.1 EL HOUEREB RESERVOIR

In 1989, the big El Houareb dam (Figure 17) was built for preventing catastrophic floods. In fact, the major part of the dam water infiltrates (and recharges groundwater) or evaporates. The reservoir has often dried up. Dam releases are very exceptional. The numerous works for water and soil conservation in the upstream catchment result in a significant decrease in the river flow, and completely modify the regional water balance. Moreover they do not represent a new reliable local water resource. Water is also taken from aquifers for providing drinking water to inhabitants of the catchment but also to remote areas, along the coast where population and tourism activities are much denser.

Figure 17 El Houareb Dam on May 2007 (left) and on May 2008 (right)

This dam has a capacity of storage equal to 95 million cubic meters (Mm^3) at its principal spillway and is strongly connected to Kairouan plain aquifer. Over 60% of the inflow collected by the El Houareb dam infiltrate and recharge the aquifer (Kingumbi et al., 2004; Leduc el al., 2007). The El Houareb reservoir represents a good hydrological ‘integrator’ of the whole upper basin, as witnessed by the dam water level; consequently it was schematized in the model. For the period 1989–2005, the mean annual flow of Wadi Merguellil, estimated at the El Houareb dam, was 17 Mm3, with a minimum of 2.5 Mm3 in 2000–2001 and a maximum of 37.6 Mm3 in 2004–2005. These values can be compared with the exceptional flood of autumn 1969, estimated at about 175 Mm3, with a peak flow of over 3000 m3/s, resulting in a severe inundation of the Kairouan plain, with high human and material losses (Bouzaïane and Lafforgue, 1986). Outflow from the El Houareb reservoir consists of evaporation (25%), pumping and releases (12%), and uncontrolled infiltration to the karts aquifer (63%). Because of this exceptional caustic loss, dam releases are very limited and the dam has completely dried up several times. Part of the reservoirs' water is pumped to supply public irrigation schemes downstream of the dam. Figure 18 represents the Water level of the El Houareb dam and reflect the inter-annual variability.

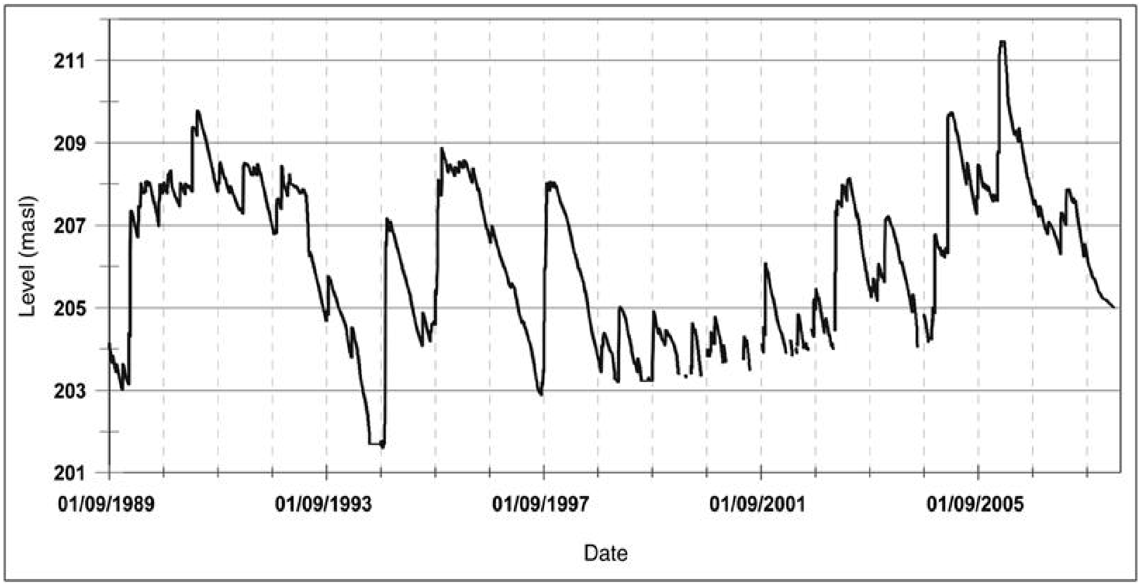


Figure 18 Water level of the El Haouareb dam (because of siltation, the lowest levels, recorded in 1994, 1997–2005 and 2008, correspond to a complete drying up of the dam).

4.3.2 GROUNDWATER

Three small, interconnected aquifers (Aïn Beidha, BouHafna, Haffouz–Cherichira) exist in the lower part of the upper Merguellil basin (Figure 34). Depending on place and time, they interact with the drainage network in both directions: springs supplying rivers or floods recharging alluvium and linked aquifers. The Kairouan plain aquifer represents a much larger water storage because of its horizontal extent and a thickness of up to 800 m of alluvium and colluvium (Nazoumou, 2004). The Kairouan plain aquifer was previously fed by the rapid infiltration of flood water, which was the major component of its water budget, and by lateral groundwater inflows from adjoining aquifers. Since 1989, the El Houareb dam has stopped most of the Merguellil flow (dam releases have represented only 6% of the dam water) and the plain aquifer is now recharged by the horizontal transfer through a karstic system that mixes water from the Aïn Beidha aquifer and from the dam reservoir.

4.3.3 WSCWs: CONTOUR-RIDGED AND SMALL DAMS

In the 1990's, the Tunisian government and international donors have subsidized the construction of WSCW (contour ridges and small dams) to reduce gully formation and allow supplemental irrigation in the Merguellil catchment (Figure 19). Between 1989 and 2005, 44 small dams were built, collecting runoff from 128 km2. Contour ridges were constructed over 234 km2 of lands, 12% of which located within the catchments of the small dams. As of 2005, WSCW collects runoff from 28% of the Merguellil catchment surface area. 97% of WSCW-controlled areas are located outside the Merguellil headwater catchment in the downstream part of the Merguellil catchment where they control 32% of the surface area. The forest in the upper sub-catchment probably explains why WSCW are almost absent from this area. Three kind of water harvesting techniques are presented in the study area: Five large reservoirs located on the main channel network; they receive the water from all subbasins upstream from of the water body. To reduce siltation in the reservoirs of the three large dams in the region, WSCW have been implemented in each upper basin. In the Merguellil basin in particular, they currently consist of 25,000 ha of contour-ridged terraces,. Presently, more than 20% of the upper basin area has been affected by conservation works.

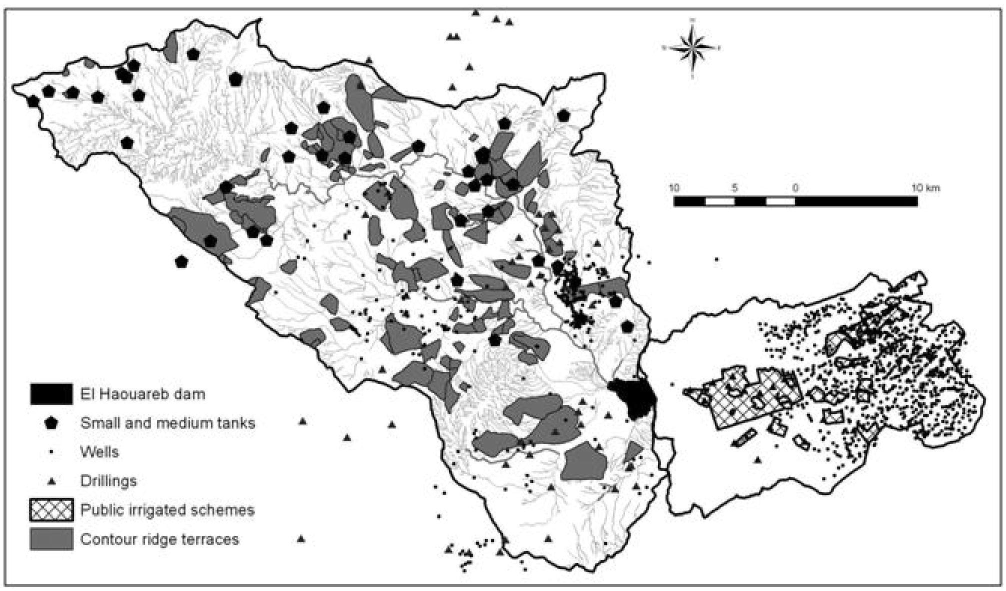


Figure 19 Water infrastructure in the Merguellil basin.

From 1990 onwards, the WSCW directorate set up a decennial strategy (1991–2000), focused primarily on the treatment of hill slopes and the construction of small tanks (Figure 19). Currently, 17% of the basin is occupied by terraces made out of dry stone or by terraces with total flow retention (tabias), in particular in the very fragile Zebes and Haffouz sub-basins (Ben Mansour, 2006). The upper basin also includes about 30 small pond (with a capacity lower than 0.5 Mm3), built and managed by the SWC directorate, which store 2.5 Mm3/ year on average, and five larger tanks, built by the dam directorate and managed by the SWC directorate. With a storage capacity above 1 Mm3, these ponds receive annual average contributions of 2.8 Mm3. These reservoirs were initially built to trap sediments but authorities later tried to select reservoir sites close to the population and exploitable land.

4.3.3.1 HILL PONDS

Hill ponds are small compacted earth dams with a height of the dam varies between 5 and 8m and length from 100 to 300 m and the average capacity is 0.1 million m3. They are equipped with floodway for 1 or 2 m from the coast to the crest and an underground fighter and sampling which crosses the dam. Largest dams are called hill reservoirs. Their heights are 8 to 12 m and can store over 1 million m^3 (Ghola, 1993). These structures (Hill ponds and hill reservoirs) have a relatively high cost compared to volume stored water: The dams are generally designed to improve local agriculture. They have an important role on the retention of sediment and protect big reservoirs from silting and water recharge groundwater (DGF and GTZ, 1994). In the absence of other techniques of water transfer, ponds are the best way to initiate a process of local development. The sites chosen are not only dictated by the characteristics of the physical environment, but also depend on the willingness of people to participate in development project of territory (Selmi and Talineau, 1995). The hill ponds have different size: 37% of these ponds were built in the sixteen‘s within an American project for the development of watershed Merguellil. They are totally or partially silted as a result of the exceptional flood of 1969. The ponds built after 1969 are partly clogged by 10% to 80%: these are the ponds that have more water resources. The ponds were built primarily to protect the reservoirs against silting (Ben Mansour et al., 1994). In the 90s the construction of large hill reservoirs that contain more important water. The biggest reservoir is El Kharroub (1.27 million m^3). Data about the hill ponds reservoirs were provided from the CES Kairouan (Direction de Conservation des Eaux et des Sols). According to some statistics collected by the Office of the Ministry of Agriculture showed that the speed of construction of these ponds is much higher than the rate of exploitation (Bouzid, 1998). The analysis of the diversity of crop management systems around the ponds made in 1996 shows that 50% of farmers have not introduced the Irrigation and retains their traditional production, 28% begin to use the water in their agricultural production function, and 22% are engaged in small irrigation (Albergel and Rejeb, 1997).

4.3.3.2 CONTOUR RIDGE

In the Merguellil catchment contour ridges were constructed over 230 km^2 of lands. Contour ridges are small earth structures constructed across the curve levels (Figure 20). The main objective for their construction is to reduce the erosive power of surface runoff resulting in the reduction of soil erosion and to increase local infiltration). The Contour ridges have been used in many parts of the world as a soil and water conservation technology. There has been a forceful adoption of this technology through many countries‘legislation as the example of Tunisia where since the 1990‘s, the Tunisian government has started to subsidize the construction of Water and Soil Conservation Works (WSCWs).

Figure 20 Contour ridges in the Merguellil catchment (Dridi, 2000)

Soil conservation implies also indirectly water conservation. In fact, since the water conservation capacity of a soil depends on the soil depth, thus when a soil profile is conserved by minimizing erosion its depth remains large and with it water holding capacity. In the Merguellil catchment, besides increasing the amount of water added to the soil profile, contour ridges intent also to protect downstream reservoirs against silting (Achour and Viertman, 1993 ; CES et al., 1995) as they constitute a good sediment traps. In addition these contours are adopted to familiarize the farmers to plant along the curve levels. The design of the ridges is done in a manner to prevent overtopping by runoff. Ridges follow the contour at a spacing of usually 1 to 2 meters. Runoff is collected from the uncultivated strip between ridges and stored in a furrow just above the ridges (Critchley and Klaus 1991). Crops are planted on both sides of the furrow. The length of contour ridges is variable since they can be interrupted by any obstruction making difficult their alignment. In the Merguellil watershed the spacing between ridges ranges from 5 m (at El Ala and Haffouz) and 8 m (at El

Hammam). Contours ridges induce considerable terrain loss; considering a contour ridges spaced of 6.5 m with a length varying from 200 to 500 m, the terrain loss per hectare oscillates between 13 and 32 % which is not negligible particularly in cultivated lands. According to CES et al (1995), it is more suitable to construct the contour ridges under the following conditions:

- Rainfall: 300 - 400 mm/year,
- Low rainfall intensity. This is not the case of semi arid climate ,
- Slopes: 4 – 6 %,
- Soils: fertile and quite deep soils (at least 80 cm) with a suitable infiltration rate.

4.4 DESCRIPTION OF IRRIGATED AGRICULTURE

4.4.1 IRRIGATED AGRICULTURE ON THE WATERSHED UPSTREAM

An investigation of 5045 farm units in Haffouz district, carried out in 2002 by the CRDA of Kairouan, identified eight main cropping systems, including irrigated systems (arboriculture and olive trees, olives tree alone, cereals, winter vegetables, summer vegetables) and rainfed systems (arboriculture and olive trees, olive trees, cereals). This survey also identified a typology of farming systems that can be considered as representative of the upper basin (Le Goulven and al, 2009).

Farms are divided into seven types according to their cropping patterns. The first four types are based on dry farming and include types T1 (farms cultivating mainly olive and almond trees); T2 (farms cultivating cereals with a large proportion of fallow and rangeland); and T3 and T4 (both cultivating mainly cereals and olive trees but with different average areas: 45.2 ha for T3 and 6.8 ha for T4). The last three types refer to irrigated cropping: T5 (irrigated vegetable cropping in rotation with olive trees and orchards); T6 (irrigated cereals); and T7 (irrigated olive trees and orchards).

The first four types make up about 90% of the farms in the district (T1 and T4 alone total 80% of farms), while farms based on irrigated crops are very few: types T5, T6 and T7 represent only 12% of the farms and are mainly found in the sectors of Haffouz, Khit El Oued and Aïn Beidha (Fig. 7.6). Type T7 includes most of the irrigated farms, which are concentrated in only a few douars. The analysis clearly shows a strong spatial heterogeneity of farming systems, related to strong differences in access to irrigation water (Le Goulven and al, 2009).

The major part of the agricultural area is cultivated with rainfed crops (cereals and olive trees). The extent of fallow lands, linked to the mode of rainfed (dry) farming, explains the low cropping intensity, between 57% and 98%, with an average of 73%. In most sectors, irrigated crops make up less than 10% of the agricultural area, except in Haffouz, where they correspond to nearly 40% of the cropped area. Vegetables and irrigated cereals are cultivated in rotation with olive and almond trees.

Agricultural uses of water in the upper basin are little developed: irrigated crops cover only 2700 ha out of 33,000 ha of cultivated land. Perennial crops and olive, almond and apricot trees cover 1700 ha, while summer vegetables are planted on less than 400 ha. Distribution and types of uses depend on access to water. Irrigation with surface water (by pumping from Wadi Merguellil in particular) is very unpredictable in summer. Aquifers are very localized and the drilling of wells less convenient than in the plain downstream because of the relief (Le Goulven and al, 2009).

4.4.2 IRRIGATED AGRICULTURE ON EL HAOUAREB DAM DOWNSTREAM

The proportion of irrigated crops varies from 24% in the Houfia sector to 88% in the Chebika sector. The proportion of summer vegetables, alone or intercropped with olive trees, varies between 11% of the cropped area in the Houfia sector and nearly 40% in the Ouled Khalf Allah sector. With the exception of the Houfia sector, which distinguishes itself by its strong proportion of rainfed crops, agricultural development is rather homogeneous in the plain downstream of the El Harouareb dam. All sectors have access to irrigation water, either through public schemes or through private wells and boreholes pumping water from the Kairouan aquifer. This results in a cropping pattern that includes 70% of irrigated crops, with 30% devoted to summer vegetables (melons, watermelons, peppers and tomatoes). This cultivation of summer vegetables is the mainstay of irrigation development because it yields handsome revenues. Its development is associated with the adoption of drip-irrigation, which is subsidized by the state at the level of 60% of capital costs for small farmers (Le Goulven and al, 2009). This irrigation technique is also very labour saving, and associated fertigation allows farmers to strongly increase yields and therefore incomes.

Farmers can increase their areas cultivated with summer vegetables, but these crops are very risky and sensitive to market variations and vagaries. For example, prices of melons and watermelons are divided by three between the first early productions and the main production season, approximately one month later.

4.5 ASSESSMENTS OF FLOWS

4.5.1 ASSESSMENT OF FLOWS ON THE WATERSHED UPSTREAM

Using studies on the El Haouareb dam (Kingumbi, 1999) and calculations made on small tanks (Lacombe, 2007), a first assessment of surface water and green water in the upper area can be made for the 2000–2004 period (Figure 21):

• Out of 409 Mm3 of rainfall, 175 Mm3 (43%) are lost by evaporation, including 41% by evapotranspiration of the natural vegetation and 2% from small dams and the El Haouareb dam.

• The larger part of rainwater (89%) is stored as green water: 48% is consumed by cultivated areas, rangelands and forests, on a total area of 605 km2, and 41% by the natural vegetation.

• Runoff water accounts for only 11% of rainfall; once evaporation in the dam is deducted the quantity of water which can be used for productive purposes amounts only to 7.8% of the basin inflow.

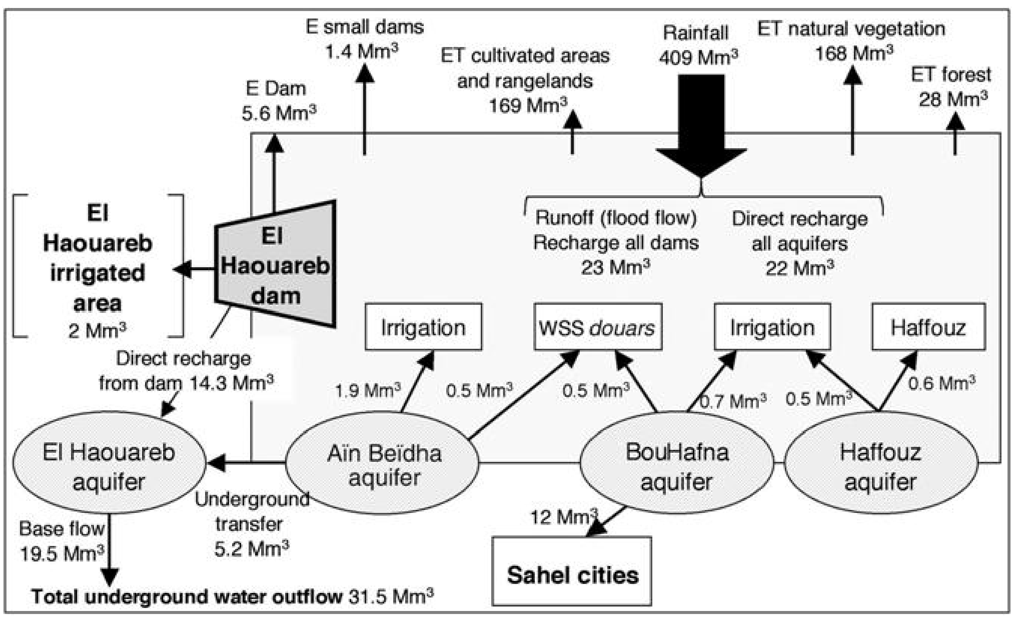


Figure 21 Assessment of average flows of the upstream zone of Merguellil basin (2000–2004) (Le Gouleven and al, 2009).

This shows the paramount importance of dryland farming, which uses the soil storage capacity (600 Mm3 for the basin, based on a reserve of 100 mm) and whose storage efficiency (88% for daily rainfall under 15 mm) is important (Dridi, 2000). If rainfed cereal production in the basin, which produces, on average, 2.6 t/ha, were to be replaced by an equivalent production under irrigation, an area of 6500 ha (at 4 t/ha) would be needed, which would require 14 Mm3 of blue water, which is 44% of the amount exported today. This gives an idea of the interest in seeking drought-resistant varieties (Luc, 2005).

4.5.2 ASSESSMENTS OF FLOWS ON EL HAOUAREB DAM DOWNSTREAM

In Table 3, the accounting of green water considers the whole area of the main plain, excluding 27,350 ha of djebels (Table 3). In the lower basin, more than 60% of rainfall is consumed by crops (Figure 22). For non cultivated areas, the overall consumption of rainwater is estimated at 25.2 Mm3. Volumes abstracted from the Kairouan aquifer for municipal and industrial uses represent a total of 15 Mm3 (values given by the Kairouan CRDA). Only the contributions from rainfall and the dam are measured values, while other variables are estimated. Urban abstraction represents almost half of agricultural use. Since water is exported and there is no return flow to the aquifer, this amounts to a net loss for the zone.

The main inflow is rainfall and groundwater flows from the upper basin; the contribution of the dam through releases of surface water is very limited. Observations of aquifer levels confirm the imbalance between inflow and outflow and point to a shortfall of 17.4 Mm3, with agriculture as the main cause for this imbalance (net consumption of 21.9 Mm3)(Luc, 2005).

Competition for water between agriculture and other activities is very strong in the plain, but all sectors do not face the same constraints. Drinking water supply is a priority according to the Water Code, and abstraction is supposed to be done only through authorized and controlled boreholes. Agricultural use in public schemes is also based on controlled groundwater abstraction, but the administration has, in fact, very little control over private wells. These wells are deepened in order to follow the decline of the aquifer and have spread out in the area, despite renewed prohibition. They came along with changes in agricultural practices through the introduction of melons and watermelons, both of which ensure a handsome income to farmers.

Table 3 Assessment of green water consumption according to rainfall.

Year	Dry	Average	Wet
Total contribution of rainfall in Mm3	49.2	82.3	99.8
Total green water consumed in Mm3	30.5	52.2	60.1
Total green water consumed (% rain)	62.0	63.4	60.2

4.5.3 URBAN CONSUMATION

The Merguellil basin overlaps with seven administrative districts (delegations) belonging to two gouvernorats (Siliana and Kairouan). In 1994, the population in the study area totaled 102,600, 85% of which resided in the gouvernorat of Kairouan (Géroudet, 2004). The population in the Merguellil catchment remains very low (1%) concentrated in the Haffouz and Zebess regions. The pattern of settlement between delegations is almost identical in the censuses of 1974, 1984 and 1994, except for the population of Chébika, which almost doubled between 1974 and 1994 (**Figure 23**). However, the last census, in 2004, showed an

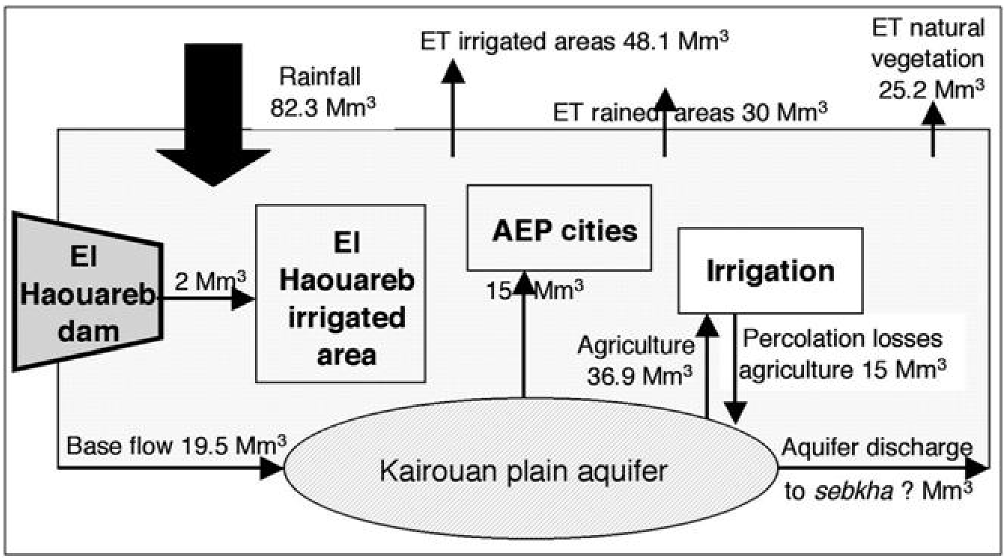


Figure 22 Assessment of average flows in the lower Merguelli basin (1994–2003) (Le Gouleven and al, 2009).

inversion in the demographic trends, which had been characterized up to that point by a regular increase in population. A decrease in the remote rural population of the basin (approximately 85% of the total) is now expected (Le Goulven and al, 2009). Before the 20th century, the little population, mainly nomadic, exploited the region as an extensive grazing area. Deep changes occurred in the last century, with a spectacular demographic growth and a rapid development of agriculture, in response to local and national incitements. Irrigation is now widely spread all over the Kairouan plain and depends on groundwater, leading to the overexploitation of the plain aquifer. In the upstream, crops are more various and irrigation less present (Le Goulven and al, 2009).

The increase in population and expansion of water supply networks has led to much larger withdrawals from aquifers, upstream and downstream. Moreover, the export of water to urban areas and tourist activities along the coast are other major factors contributing to the present overexploitation of aquifers. Deep wells tapping several aquifers in both the upper and lower parts of the basin ensure supply of drinking water to this population.

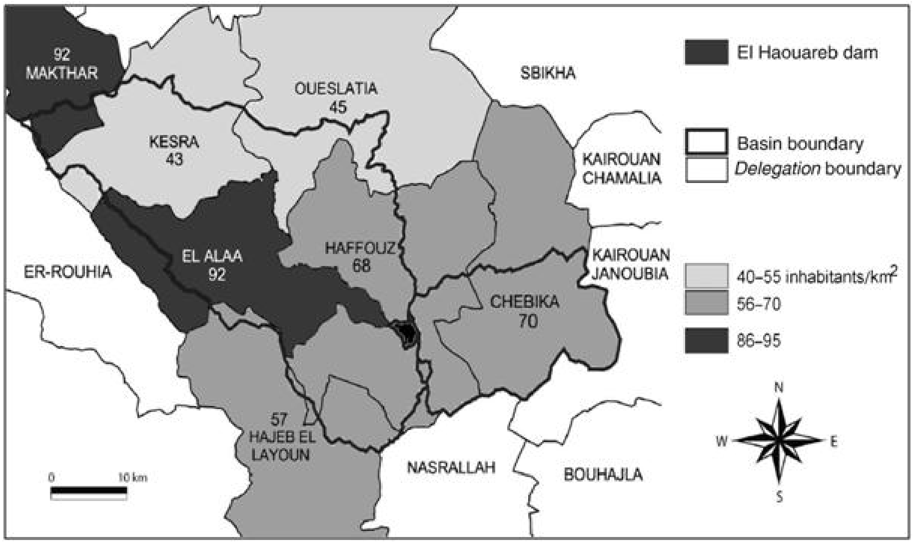


Figure 23 Population density per delegation in 1994(Le Goulven and al, 2009) .

Small water supply schemes supplying isolated communities are managed locally, while large ones are managed by the SONEDE national company. However, more than 80% of the water pumped for domestic consumption is exported out of the basin area towards the large cities on the coast. Inequalities in quantities and quality in Tunisia make water management more difficult and explain the need to transfer surface water from the north to the Sahel and the south in order to improve the drinking water supply and insure equity between regions. Withdrawals for domestic use represent more than half of the withdrawals in the upper basin and less than one-third in the lower basin (Le Goulven and al, 2009). Industrial use is marginal (less than 2% of the total).

5 CHAPTER 5: SWAT AND WEAP SETUP

5.1 SWAT SETUP

5.1.1 MODEL INPUT

The data needed relate to different types of data having effects on the flow. Precise parameters for each theme are required in physical equations. The mandatory sets of data concern topographic data, land use, soil (pedology) and climatological data. The DEM must be an ESRI Grid; however soils and land use may be either in ESRI grid, shape file, or geodatabase feature class. Climate data is entered as point data and any number of climate data points can be entered to allow for spatial variation of climate across a catchment. Pedological maps are also required to define parameters. These data are present for the United States (USDA) and the user only needs to enter the zip code of the area or the label of the segment. Outside the United States, precise soil composition and characteristics are needed.

Some climatic data are provided with the SWAT model but the weather stations are located in the United States. In different areas, users need thus their own climatic data. Two differents data types are used: statistics concerning each weather station and daily values used to model the flow.

5.1.1.1 DIGITAL ELEVATION MODEL

Digital Elevation Model (DEM) data play an important role in SWAT. The topographic attributes of the sub-basin, including area, slope, and field slope length are all derived from the DEM (Lin and al, 2010). So are channel length, channel slope, channel width, and channel depth, if the channel is automatically generated based on DEM but not previously defined

Several studies have been performed to analyze the sensitivity of SWAT outputs on DEM resolutions (Cotter et al., 2003; Chaplot, 2005; Di Luzio et al., 2005; Dixon and Earls, 2009). Cotter et al. (2003) and Chaubey (2005) evaluated the impact of resampled resolutions of DEM (30 m, 100 m, 150 m, 200 m, 300 m, 500 m, and 1000 m) on the uncertainties of SWAT predicted flow, sediment, NO3-N, and total phosphor (TP) transport in Moores Creek watershed (18.9km2) in Washington County, Arkansas, USA.

Their studies showed that DEM resolution affected the watershed delineation, stream network and sub-basin classification in SWAT. A coarser DEM resulted in decreased representation of watershed area, decreased slope, and increased slope length. A decrease in DEM resolution resulted in decreased stream flow, sediment, NO3-N and TP load predictions with short-term fluctuations. Cotter et al. (2003) recommended minimum DEM data resolution ranged from 100 to 200m to achieve less than 10% error in SWAT output for flow, NO3-N and TP predictions (Lin and al, 2010). Dixon and Earls (2009) compared the SWAT predicted stream flow at the original and resampled DEMs in the Charlie Creek drainage basin (855 km2), located in the Peace River drainage basin of central Florida, USA. The results indicated that SWAT was indeed sensitive to the resolutions of the DEMs. The calculation of the digital elevation model was carried out by Kingumbi (1996). The projection of Conique origin In conformity with Northern Lambert Tunisia was transformed into UTM zone 32, northern hemisphere (WGS). The DEM (Figure 24) was generated from contour lines provided form the Major State maps (1/50000) (IGNF, 1957) with an equidistance of 10 meters.

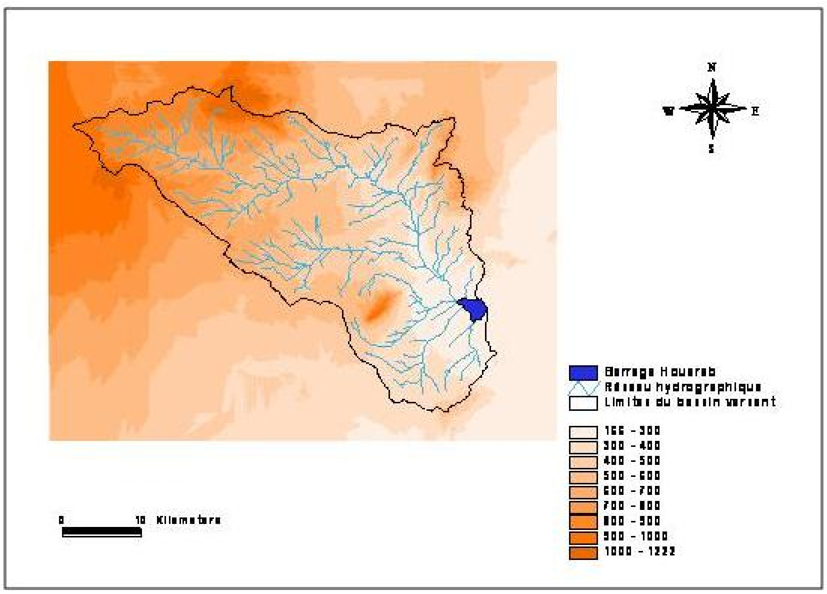


Figure 24 Digital Elevation Model of the Merguellil watershed

5.1.1.2 HYDROGRAPHIC NETWORK

The extraction of hydrological network is important step for the success of the simulation, so it is very important to take precautions and be careful during this step (Renaud, 2004). The quality of the DTM is essential for the quality of extraction. SWAT is based on the D8 algorithm for extracting of the network.

The objective is to obtain a hydrological network closest to geometrically digitized network which is considered the reference network. The improvement of resolution of the DEM and the establishment of a more effective method like the "burning option" would at once safe extraction of the finest network and therefore a better simulation of flows at the watershed outlet (Renaud, 2004). The principle of the "burning option” method is to use the drainage layer digitized from topographic maps considered as a reference for correcting the extracted network address and the flat areas classified as areas of instability (Mensi, 2005). All the physical and morphological characteristics of streams will be automatically calculated (length, slope).

The hydrological network is based on two main outputs: watersheds and streams. These two outputs are produced in SWAT using the Digital Elevation Model. Figure 25 compares the hydrographic network produced by SWAT and IDRISI elaborated within MERGUSIE project (Monat, 2000) at (1/50000) scale, for the same stream definition threshold area. the hydrographic network extracted by SWAT from the DEM were also similar with topographic maps of the area, They overlaid most of the time.

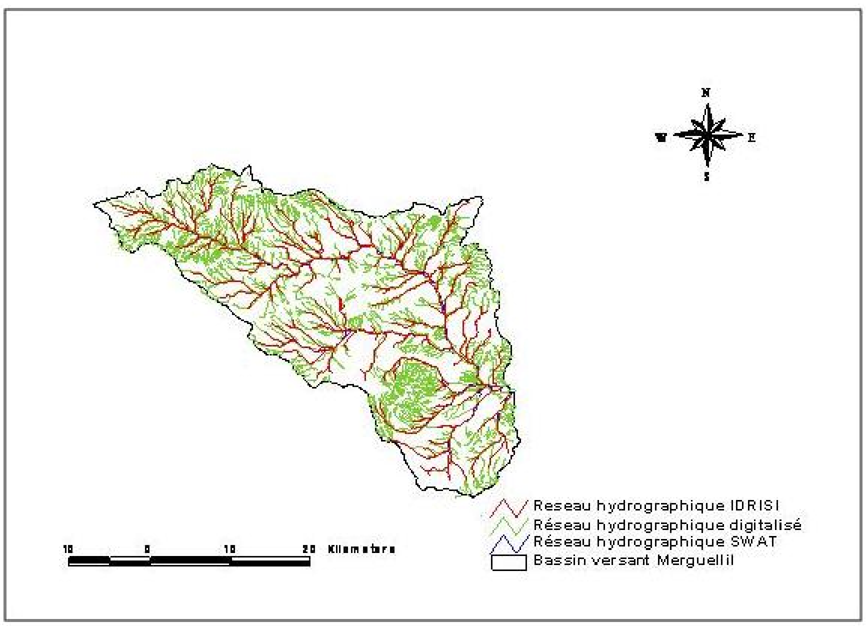


Figure 25 Comparison of stream from SWAT and IDRISI

Figure 26 and Figure 27shows two design for the hydrographic network of Merguellil watershed. Figure 26 illustrates a sample network with a threshold drainage area of 1000 ha which represents about 1% of the total area of the basin. In the Figure 27, the hydrographic Network is extracted with a surface drainage of 2100 ha which represents almost 2% of the total area of the basin. One can observe through the two figures, a difference between the two hydrographic network, the first one is more developed as a way secondary and tertiary branch can be observe more. The lower surface drainage threshold is , the hydrographic network will be more developed on the watershed. This will affect the results of the simulated flows, Suspended solids and nitrogen and phosphoric concentration.

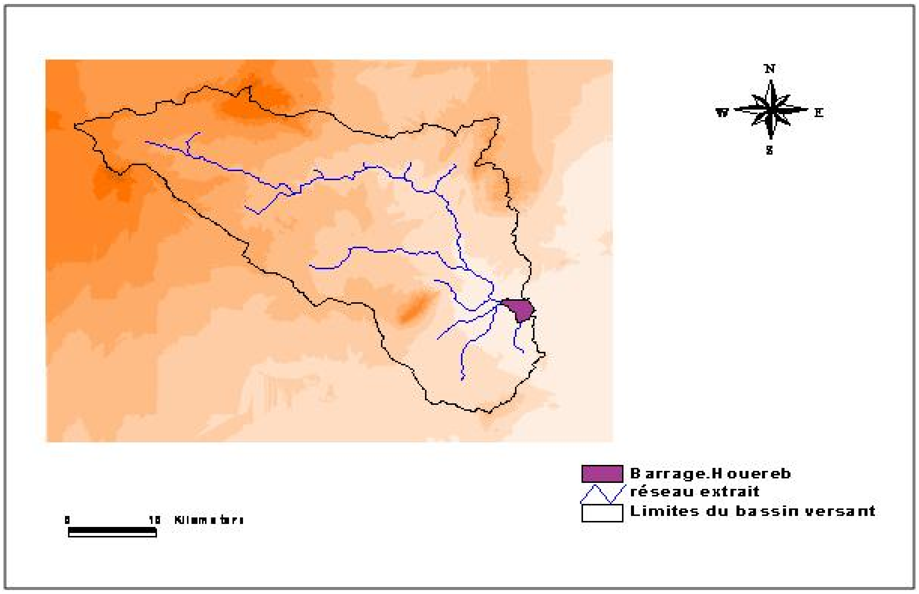


Figure 26: Hydrographic network extracted at surface drainage threshold of 2100 ha

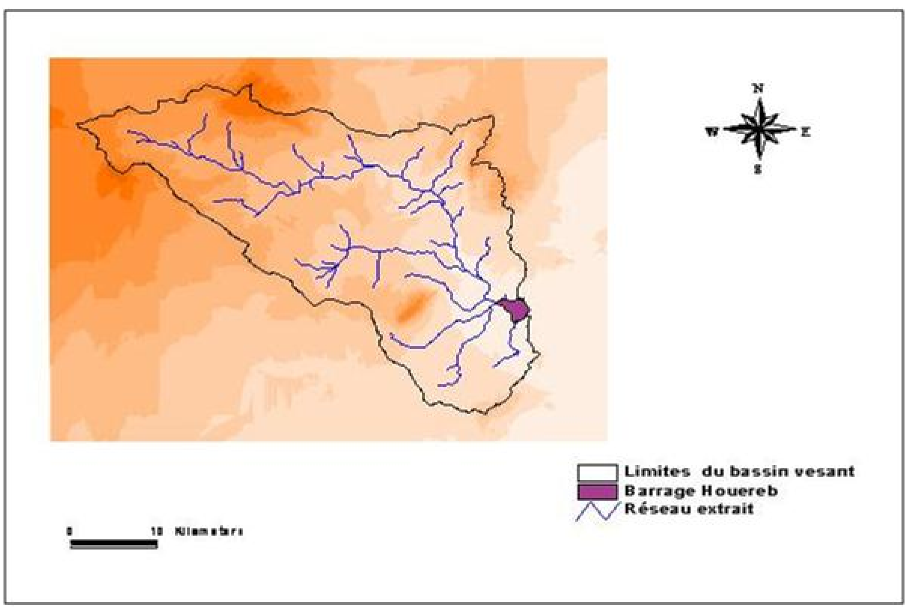


Figure 27: Hydrographic network extracted at surface drainage threshold of 1000 ha.

5.1.1.3 SUBBASIN DELINEATION

The number of sub basins depends on the threshold of drainage area (Arnold et al, 1995). Although the subdivision of a watershed into smaller units (sub-basins) is a standard practice for modeling purposes, it is almost impossible to advance an ideal level of subdivision. During the subdivision process in the SWAT model, the stream network and outlet configuration may be refined by the user. Sub watershed outlets may be added. To remedy the problem, it was necessary to determine an appropriate level of subdivision in our watershed to achieve efficient results, we referred consequently to some previous studies ie (Mensi, 2005 and Abouabdellah, 2009), we tried to subdivide the watershed Merguellil. In the successive Chapter, we will conduct a small study on the sensitivity of the model in relation of to the spatial discretization, the threshold of drainage area considered for the study was 2% of the total area corresponding to a threshold drainage area (2200 ha). Based on the sensitivity analysis (detailed in the chapter 6), this choice will ensure a stable calculation for the simulation. From digital elevation model, the SWAT model was cut into 26 subbasins.

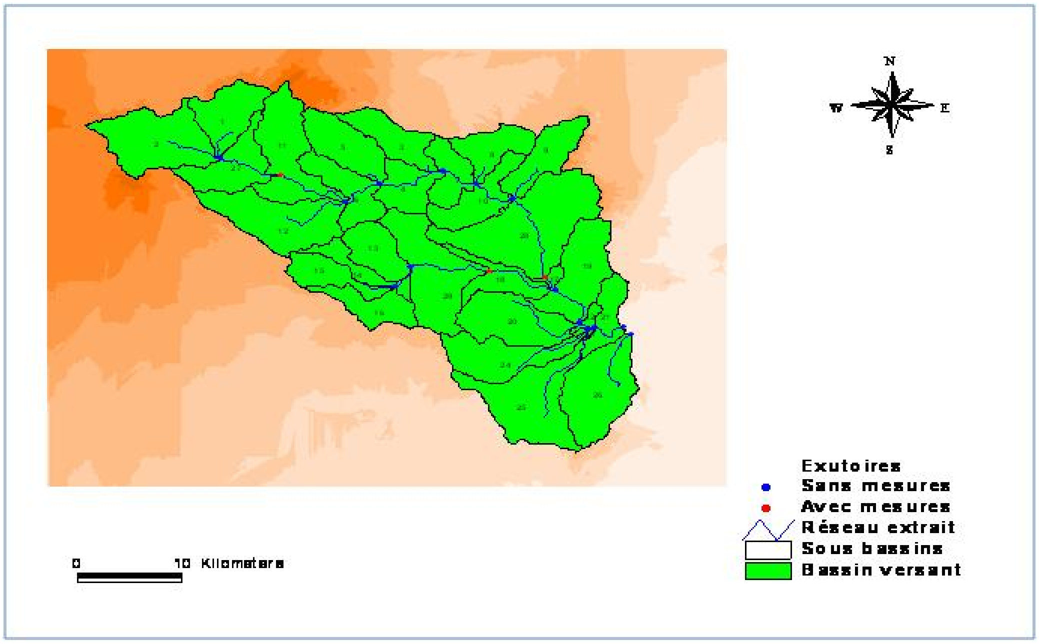


Figure 28 Subbasins delineation in the Merguellil catchment

Adding outlets at the location of monitoring stations is useful for comparison of measured and predicted flows so we decide to add three outlets corresponding to 3 point of flow measurement (red points on the map in the Figure 28): a first outlet correspond to Skhira station, the second to Zebess station and last Haffouz station. Totally, 29 sub-basins are located through the Merguellil watershed. The Sub-watershed delineation process must be completed by the definition the outlet of the watershed so the dam of El Houereb is considered the outlet of the watershed because it allow comparison of measured and predicted flows at the basin scale. The DEM and the sub-basins delineated are shown in Figure 28.

5.1.1.4 HYDROLOGICAL RESPONSE UNITS

SWAT permit in the first step the watershed to be discritise by dividing into multiple sub-basins, then each sub-catchment which are subdivided into several homogeneous units called Hydrologic Response Units (HRUs) formed by unique land use and soil combinations (Arnold et al., 1998). Flow generation, sediment yield, and nonpoint source loadings from each HRU in a subbasin are summed, and the resulting loads are routed through channels, ponds, or reservoirs to the watershed outlet.

The responses of each HRU in terms of water, sediment, nutrient, and pesticides transformations and losses are determined individually, and then aggregated at the sub-basin level and routed to the associated reach and to the catchment outlet through the channel network (Bouraoui and al., 2005). The SWAT is a incorporated with a GIS interface that delimit the sub-basins and stream networks from a Digital Elevation Model (DEM) and calculates daily water balances from meteorological, soil and land-use data. (Arnold and al, 1996). SWAT is based on two methods to create HRUs: the first is the Dominant Land Use and Soil based on creating one HRU for each subbasin by using the dominant land use and soil class. The second is The Multiple Hydrologic Response Units that will create multiple HRUs within each subbasin. The threshold level set for multiple HRUs is a function of the scale study and the level of detail desired by the modeler (Arnold and al., 1996).

The HRU can represent three-dimensional heterogeneity of the watershed. They are designed to reflect the different subsystems of the hydrological cycle of the dominant basin (Flügel, 1995). Each HRU is assumed to present an agro-hydrological homogeneous behavior. Fluxes estimated for each HRU are then summed to obtain a global flow transmitted between sub-basins (Bioteau, 2002). The concept of the HRU as a tool for hydrological modeling at the regional scale was developed based on three assumptions (Moore, 1993):

* Each class of land use located in a given soil is characterized by a homogeneous set of dynamic hydrological processes.

* The dynamics of hydrological processes is controlled by the management of land use and the physical properties of different soil types.

* The set of dynamic hydrologic processes changes very slowly within each HRU.

In order to eliminate insignificant land-uses and soils, a threshold level was selected in each subbasin of 1% and 3%, respectively. This means that if the percentage of the soil type or the land cover type is minor than this percent of the subbasin area, it is considered negligible and is therefore not included in the following analysis. Given these thresholds, 290 HRUs (unique land-use/soil/slope combinations within subbasins) were created. The list of sub-basin and HRU generated by SWAT is presented in the APPENDIX 2.

5.1.1.5 LAND USE AND SOIL MAPS

The land-use and soil maps were based on the 1/200 000 Scale) in the basin were provide by the IRD (L'Institut de Recherche et Développement). These maps were developed using previous studies done on this area (Barbery and Mohdi, 1987; Mizouri et al.1990).

5.1.1.5.1 LAND USE MAP

In the current case study, two land use maps of different scales are provided, the first map is based on the agricultural map of the governorate of Kairouan and Seliana. This map has been established in the CRA project (Agricultural Regional Map) which linked the group Studi-SCOT-Sodeteg and the CRDA (Regional Commissioner for Agricultural Development) in the central governorates of Tunisia.

This CRA project aims to develop a geographic database and develop models for the simulation of various agronomic and economic situations. This database supplies a Geographical Information System (GIS) and allows editing of maps for land use, soil physical potential and economic vocation of cultures. The second map provide from the National Project Mobilizer (PNM), Mergusie, which seeks to analyze the integrated management of water in the watershed Merguellil. This international cooperative project involves some research and training institutions, particularly DGRE and IRD.

The layer of land use issued by the first project was done at the 1/25000 scale while the second is done at 1/50000. The information are provided from the processing of Landsat satellite images combined with field survey and supplemented by analysis of the board "green" topographic maps (forest, orchards, vineyards, ...).

We consider for actual study, the layer of land use elaborated by the IRD. We are extremely conscious of the simplicity of cutting retained; however, we believe it is sufficient in the present state of knowledge of the field and in order to model the hydrological response at daily scale for a wide annual and inter-annual analysis. Finer spatialization and more realistic could be considered using the soil layer developed by CRDA but the cost of this spatialization must be taken into account in terms of data for detailed investigations. In this study there is priority to improve the performance of the SWAT model but in presence without complete input data for detailed GIS map we can't reach this objective. Thus, according to this choice, we content of 5 types of land use which composed of grain crop (winter wheat), rangeland, forest land, urban area and surface water (Figure 29).

Table 4 : Land use in subbasin (in %) in the Merguelli watershed (Dridi, 2000)

Sub-Basin	Crops	Forest	Pasture	Water body	Urban
Skhira	34	65	0,2	0,6	0,2
Haffouz	46	29	23	1	1
Morra	93	2	2	4	Very low
Zebbes	86	3	8	2	1
total watershed	52	19	26	2	1

The land-use map presents five different types: forest (19%), pasture (26 %), urban (1%), water bodies (2 %) and crops (52%), in the rest of our study, we consider a single crop: the Durum wheat. In the Table 4 below we present the repartition of land use in sub basin of Merguellil watershed

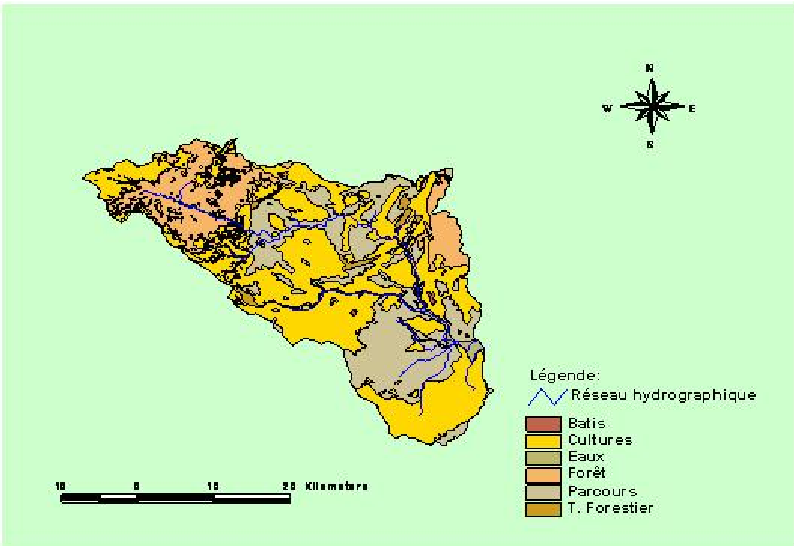


Figure 29 Land use map of Merguellil catchment extracted from GIS project Mergusie

5.1.1.5.2 SOIL MAP

There are 4 units of soils in the watershed Merguellil poorly evolved soils, Carbonate soils (calci-magnesic), Iso-humic soils, and mineral soils resulting from erosion (association) (Hervieu, 2000). Figure 35 shows the spatial distribution of the different entities soil of our study area. We have for the study area with two coats soil, one scale 1/25000 using data from the digitization of soil maps provided by the Department of Soils and Soil Science department of the CRDA of Kairouan and Seliana These data are complemented by expertise based on interpretation of satellite images on areas not covered by existing soil studies and confirmed by field survey. The second layer is at a scale of 1/50000 is from the National Project Mobilizer (PNM), Mergusie.

However, we noted that the soil layer provided by the CRDA include seventy-three sub group of soil while the map retained for the study include only four main classes of soil in the modeling and twenty four subgroups. The soil map provided by CRDA is too complex to model because the most of the soil parameters of different types of soil are unknown. Thus, we decide to choose a very simplified schematic and assuming the map on the second layer provided by IRD.

<u>The soil data required by SWAT:</u>

The GIS interface developed around the SWAT model were designed both to manage spatial data as to automate and facilitate the preparation of input data sets. These interfaces can then manipulate, extract and convert the spatial information in a format compatible with the model. They facilitate the parameters settings related to simulations.

In addition to the soil layer, SWAT requires to complete a digital database containing the different parameters for each soil type. These parameters relate to the subdivision of different backgrounds profiles:

The factor of soil erodibility (KUSLE)

- Bulk density (BD; kg/m3)

- available water capacity (AWC; mm)

- saturated hydraulic conductivity (Ks, mm / h)

- Organic matter (OM,%)

- texture of soil: clay content (C%), silt (Si;%) and sand (S;%).

All these parameters must be determined for each horizon (unit subdivision of the soil profile with similar physico-chemical, morphological and microstructural characteristic). Obviously, all fields of values for soil properties are not available due to lack of resources, we conducted two methods to generate the missing data - the use of pedotransfer functions predefined by the literature - the use of pedotransfer functions identified close to the study area.Some profiles provided from previous studies describing the soil profiles in the Merguellil catchment (Direction des sols 1963-1982),but they are insufficient for the current study because of the lack of information.

Generally, the majority data of the soil layer was not available; data was partially provided by the Soil Science department of the CRDA of Kairouan and then complemented by other soil profiles which reported from the literature of the first phase of the Mergusie project, those profile were performed on different regions of the study area. We checked on the field the compliance of these soil units with the digitized maps. In the APPENDIX 1, the list of different soil profils is reported.

Bourguignon (Bourguignon, 2002) established functions of pédotransfert and determined a spatialization of the available water capacity of the soil on the downstream of the Merguellil catchment area, from this study, it is noted some association between the soil units on downstream and the upstream of the area catchment. We based on the complementary information of this study to obtain the values of the bulk density and available water Capacity and the textural composition of the soil in particular content clay (C; %), in silt (SI; %) and sands (S; %).The Table 5 presents the main properties of different soils used in the simulation.

Table 5: Soil Characteristics of the four soil types considered in the watershed Merguellil. The texture is expressed as% of clay, silt and sand

	Soil1	**Soil 2**	**Soils 3**	**Soil 4**
Profondeur (en mm)	1000 - 2000	300 - 700	100 - 300	100 - 300
Cond. Hydraulique (m/s)	$2 .10^{-6}$	$6 .10^{-6}$	$3 .10^{-5}$	$3 .10^{-5}$
Texture (%) :	40/10/50	20/30/50	10/25/65	10/25/65
Densité apparente	1.43	1.46	1.48	1.48
Réserve utile	0.06 – 0,11	0.06 – 0,11	0.06 – 0,11	0.06 – 0,11

Soil 1 : poorly evolved soils
Soil 2 Carbonate soils (calci-magnesic)
Soil 3 Iso-humic soils
Soil 4 mineral soils resulting from erosion (association)

Consequently soil density was determined based on the textural triangle (Figure 30) (Rawls (1983) from which the mineral density was first estimated and then corrected by the organic matter content. The equation gives the expression for the density of soil (Brakensiek et al, 1983):

BD: soil bulk density (Kg/m3).

MO:% organic matter.

ρ MO: Density of organic matter (~ 0.224 g/cm3).

ρ M: mineral density deduced from the Rawls triangle Kg/m3

Equation 5.1
$$BD = \frac{100}{\frac{\%MO}{\rho_{MO}} + \frac{100 - \%MO}{\rho_M}}$$

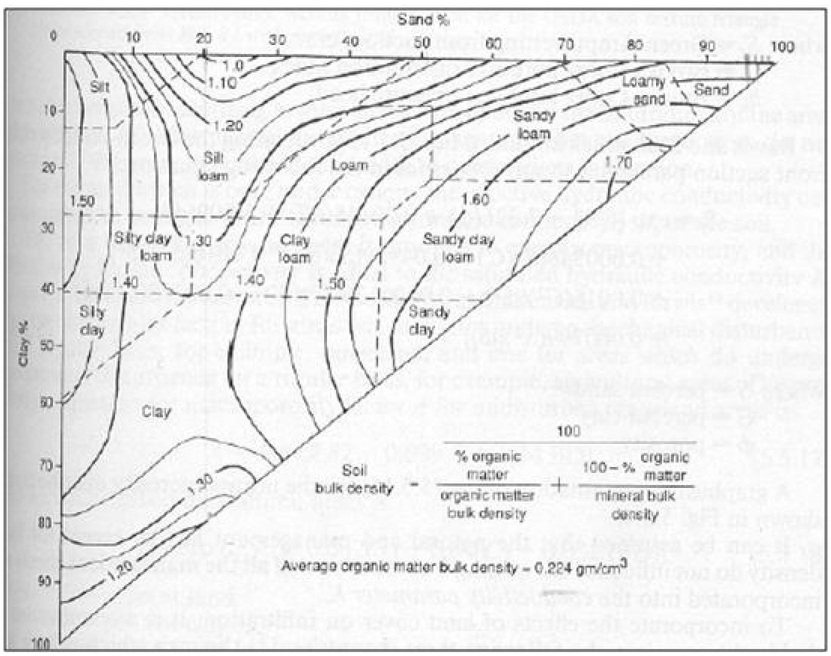


Figure 30 Textural triangle (Rawls, 1983)

Saturated hydraulic conductivity is calculated using the pedotransfer function detailed by Finke (Finke et al 1995).it is a function that requires organic matter parameter , soil bulk density and percentages of clay, sand and silt. The available water content (AWC) is calculated as the difference between the water content at saturation (pressure of soil water is equal to 1/3 bar) and water content at permanent wilting point (pressure of soil water is equal to 15 bar). The equation of Van Genughten (1980) was used in this approach:

Equation 5.2: $AWC = \frac{\sigma s - \sigma r}{[1+(\alpha h_{50})^{n}]^{m}} - \frac{\sigma s - \sigma r}{[1+(\alpha h_{15000})^{n}]^{m}}$ where

σs: Water content at saturation.

σr: residual water content.

h: water pressure in the soil.

α: scale parameter.

n, m: parameters.

- SOIL HYDROLOGIC GROUPS

The U.S. Natural Resource Conservation Service (NRCS) (1996) classifies soils into four hydrologic groups based on infiltration characteristics of the soils. They defines a hydrologic group as a group of soils having similar runoff potential under similar storm and cover conditions Soil may be placed in one of four groups, A, B, C, and D .

A: (Low runoff potential). The soils have a high infiltration rate even when thoroughly wetted. They chiefly consist of deep, well drained to excessively drained sands or gravels. They have a high rate of water transmission.

B: The soils have a moderate infiltration rate when thoroughly wetted. They chiefly are moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate rate of water transmission.

C: The soils have a slow infiltration rate when thoroughly wetted. They chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow rate of water transmission.

D: (High runoff potential). The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have high swelling potential, soils that have a permanent water table, soils that have a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. They have a very slow rate of water transmission. Based on this classification the different soil types in the Merguellil catchment are classified. Both the hydrologic group B and C are considered in this study.

Table 6 Input Soil Unit data in the Merguellil watershed

Soil Unit in the Merguellil watershed	SOIL HYDROLOGIC GROUPS
Poorly evolved soils	B
Isohumic soils	B
Carbonate soils (calcimagnesic)	C
Mineral soils resulting from erosion	C

5.1.1.6 CLIMATIC DATA REQUIRED BY SWAT MODEL

The model requires Climate data covering all the simulation period with daily steps. The data set is structured in tables "dbf". These data refer to the rainfall (mm), maximum temperature (° C), minimum temperature (° C), insolation (MJ/m2/d) wind speed (m / s) and relative humidity (%). The SWAT model requires climate stations geographically located by their coordinates in the projection system which is defined from the beginning. Climate data that will be used to simulate the basin are imported once the HRU were distributed. A special window allows the integration of all the climate data. This interface allows the user to load the location of weather stations closest and most significant for the study of the basin. In a second step the daily data of different climatic parameters can be specified. In the occurrence of lack of some parameters, SWAT can perform the simulation from the monthly data of the references station. Figure 31 shows the model interface which it is possible integrate data and table of weather stations.

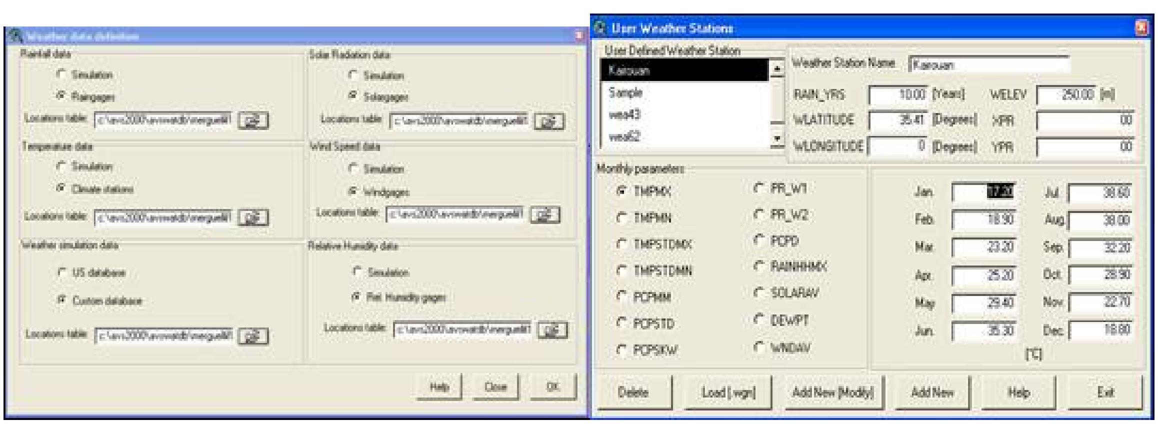


Figure 31 integration of weather data in SWAT model interface

5.1.1.6.1 TEMPERATURE DATA REQUIRED BY SWAT MODEL

The meteorological data required to structure the database of the SWAT model include the daily maximum and minimum temperatures, these data have been obtained from the database of the National Meteorological Institute (INM). Temperature data is homogeneous throughout the watershed, and there is a little spatial variability. It should be noted that according to the requirement of the model, climate station must be located in space by its coordinates in the projection set. In the case of our study there are no temperature gage within the basin of Merguellil. Therefore, The stations considered are close the basin, Makthar situed in basin upstream, Ouesletia in north east of Kairouan and the downstream basin, all of them are located in the proximity of the basin. In Table 7, we visualize the location of these gages:

Table 7 Altitude and location of temperature gage selected for the study

Station	Altitude (m)	Latitude Nord (° ‘ ‘’)	Latitude Est (° ‘ ‘’)
Kairouan	66	35° 40’ 33’’	10° 06’ 16’’
Makthar	937	35° 51’ 11’’	09° 12’ 16’’
Ouesletia	745	35° 44’ 18’’	09° 08’ 12’’

The temperatures decrease with altitude, and average temperatures are minimal for the months of December, January and February, they drop below 10 ° C for Makthar station. They are between 10° C and 20 ° C during the months of April and November and they exceed the 20 ° C during the months of June, July, August and September. For Kairouan station, temperature increases during the months of June July and August (as shown in Table 8).

Table 8: mean monthly temperatures (° C) (1979 - 2002)

Station	J	F	M	A	M	J	J	A	S	O	N	D
Kairouan	20	17	25	23	25	37	36	35	32	22	20	16

According to Table 9, the warmest period in the basin Merguellil corresponds to the months of June July and August. The average monthly maximum temperatures exceed 20 °C throughout the year, but they do not exceed 40 ° C. The coldest period of the year (Table 10) corresponds to the months from December to February, with mean monthly minimum temperatures below 7 ° C.

Table 9: Mean maximum monthly temperature (°C) average 1979 - 2002

Station	J	F	M	A	M	J	J	A	S	O	N	D
Kairouan	25	26	27	28	31	39	40	40	36	31	29	20

Table 10: Mean minimal monthly temperature (°C) 1979- 2002

Station	J	F	M	A	M	J	J	A	S	O	N	D
Kairouan	7	11	15	14	16	23	23	24	22	20	19	12

The temperature data used in the SWAT model cover the period September 1992 - August 2002. These data are supposed to be uniform across the sub-basin. We suppose that these data do not show a large spatial variability given the small area of the study area and it proximity to the climate station.

5.1.1.6.2 RAINFALL DATA

Since the seventies, the number of rainfall gages network began to increase in central Tunisia and particularly on the Merguellil watershed, which characterized by very irregular rainfall and hydrological patterns. Firstly the problem which takes place is the choice of rainfall stations. It seemed appropriate to select only the items belonging into the basin as well as those located in proximity to the boundary. After selection, In order to ensure a total cover of the study area, 20 rainfall stations were chosen. Table 11 presents some rainfall stations located within and near the watershed. The rainfall data were provided from the DGRE. They have been prepared in collaboration with personnel DGRE and CRDA of Kairouan.

Table 11 Geographical locations of rainfall gages in the watershed Merguellil (DGRE)

Rainfall Gages	Latitude (° ‘ ‘‘)	Longitude (° ‘ ‘‘)	Altitude (m)	From
Makthar PF	35 51	9 12	900	1960
Aïn Baida	35 31	9 43	297	1982
El Ala GN	35 36	9 33	466	1969
Chrichira Ecole	35 38	9 50	321	1966
Djebel Trozza	35 31	9 34	450	1978
Gueria	35 46	9 26	674	1966
Hajeb El Ayoun Del	35 23	9 32	350	1957
Haffouz DRE	35 38	9 40	280	1968
Kesra Forêt	35 49	9 21	986	1888
Messoudia-Chebika	35 37	9 55	110	1967
Ouslatia INRAT	35 46	9 35	460	1961
Skhira B16 Kef Labeid	35 44	9 23	600	1974
Sidi Saâd Jaugeage	35 23	9 41	238	1951
Ouslatia Foret	35 50	9 35	465	-
Tella	35 48	9 14	861	1980

There are some rainfall stations close to the Merguellil Watershed but they were not operational in the same periods. SWAT manual recommended in the operational file, which represent the data file serving as input in the model, it should not increasing the short-term rain-gage but get fewer rain-gage with longer series time. By merging all neighboring stations, ie by filling the missing data from a station for a given period by those of the neighboring station, often located in the same area and altitude, As Final result we obtain twenty rainfall gage with synchronized daily series of measures (see Figure 38).

These operations consisted of merging

- Stations Makthar PF and Makthar MS were merged into Makthar PF.
- Stations El Ala école and El Ala GN were merged into El Ala GN.
- Stations Haffouz SM Haffouz DRE and Haffouz Pichon were merged into Haffouz DRE.
- Stations Kesra Forest and Kesra B9 were merged into Kesra Forest.
- Stations Ouslatia INRAT, Ouslatia Forest and Ouslatia GN were merged into Ouslatia INRAT.

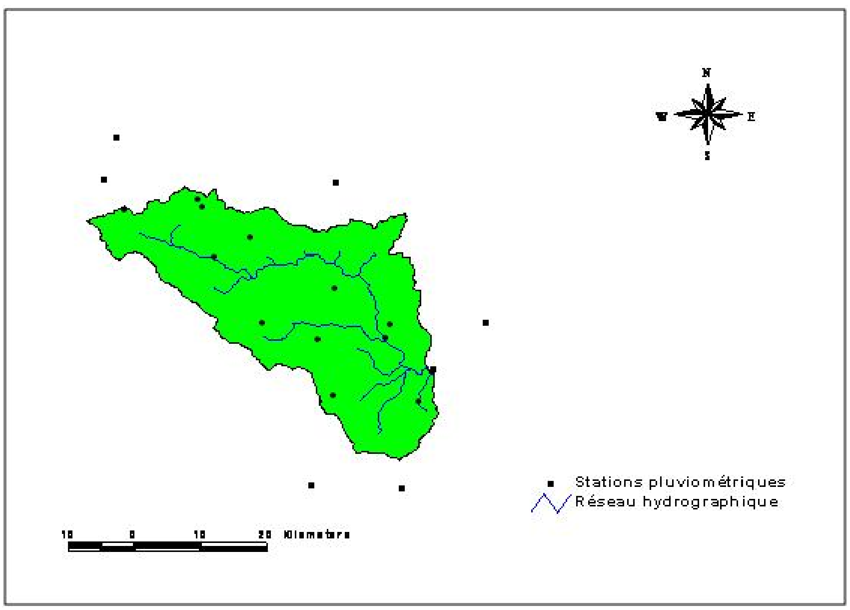


Figure 32 Localization of the rainfall stations retained for the study area.

5.1.1.7 Relative Humidity

Relative humidity is the ratio between the amount of water vapor in the air and the maximum absorption capacity of air at a given temperature. The monthly average is between 55% and 70% during the cold season and between 40% and 55% during the warm season. The climate is moderately dry from September to April and very dry from May to August. Relative humidity depends on temperature, and stations continentality (Dridi 2000). It increases in the presence of thunderstorms and lowered during sirocco (hot wind). In Kairouan city, on a monthly scale, it is highest during the months of October (65%), November (61%), December (64%), January (65%) and lowest in June and July (48 %), August (50%). During the day, the maximum relative humidity is between 18 h00 and 6h00 and the minimum in the early afternoon (Bouzaine and Lafforgue, 1986). The application of SWAT model requires daily data of the relative humidity, Therefore there is only one climate station called Kairouan MS, able to provide available data which cover the simulation period.

5.1.1.8 SOLAR RADIATION DATA

the calculation of Solar radiation data was evaluated from a of Augstrum formulate recovered from the literature (INM):

Equation 5.3

$$\frac{G}{G_0} = (A \times \frac{S}{S_0}) + B$$

where G is the global radiance (J/m2), G0 : is the extra global radiance (J/m2), S is the sunning duration (hours), S0 is the day duration (hours) and A , B are monthly factors.

5.2 WEAP SETTUP

5.2.1 DATA PROCESSED FOR WEAP MODEL

The utility of the analysis with WEAP model is to highlight the need for alternative water supplies; to quantify groundwater recharge; to evaluate water conservation and fair water allocation policies; and to provide guidelines for future nontraditional water supply projects

WEAP integrates this information on water supply and water quality with the demands from irrigation, household supply, industry, hydro-power generation and environmental flows. By integrating supply and demand with costs of different interventions, WEAP enables the analysis of the costs and benefits of different water allocation and development options. Vulnerabilities in the system, mitigation options and coping capacity may be assessed by using data from extreme years. This, in turn, can be used for cost-benefit analysis of mitigation options (Hoff and al, 2007).

WEAP applications generally include several steps. The study definition sets up the time frame, spatial boundary, system components and configuration of the problem. The Current

Accounts provide a snapshot of actual water demand, pollution loads, resources and supplies for the system. Alternative sets of future assumptions are based on policies, costs, technological development and other factors that affect demand, pollution, supply and hydrology. Scenarios are constructed consisting of alternative sets of assumptions or policies. Finally, the scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables (Figure 33).

WEAP applications generally involve the following steps:

1) problem definition including time frame, spatial boundary, system components and configuration;

2) establishing the current accounts which provides a snapshot of actual water demand, resources and supplies for the system;

3) building scenarios based on different sets of future trends based on policies, technological development, and other factors that affect demand, supply and hydrology; and

4) evaluating the scenarios with regard to criteria such as adequacy of water resources, costs, benefits, and environmental impacts.

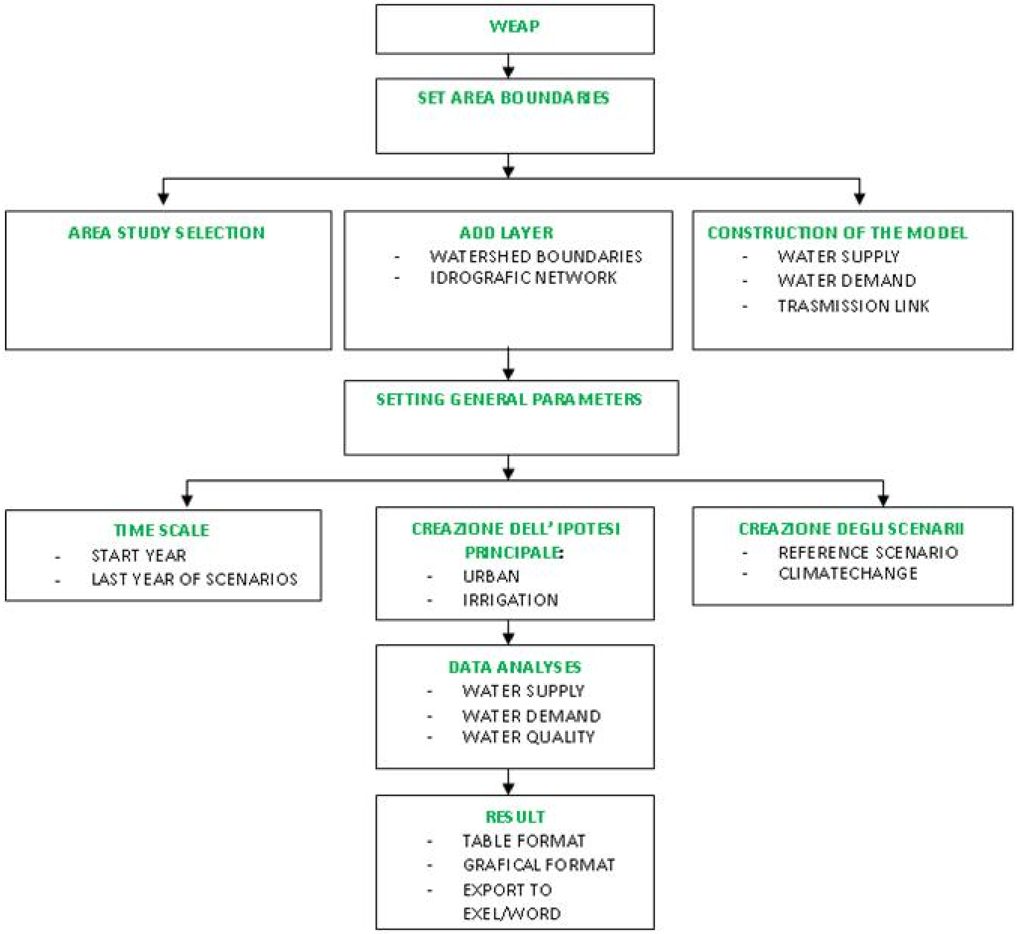


Figure 33 WEAP Software diagram

First of all, the basic parameters were defined: the current account year and forecast intervals. We chose as the reference period between the years 1992 and 2002. The current account set corresponds to 1992 while the forecast interval is 1993-2020. The data collected and reported in WEAP concern: 1) the sites of demands with their location: urban water demand (city), cultivated area, industrial zone 2) the resources and catchment sites : Diversion Dam, rivers, groundwater exploitation (boreholes, wells, tanks), hydrological data, other resources.

5.2.2 CREATING THE AREA STUDY

To setup the area, the problem under study is characterized by defining physical elements comprising the water demand-supply system and their spatial relationships, the study time period, units, hydrologic pattern, and, when needed, water quality constituents and cost parameters.

All the system considered for the study include the Merguellil watershed and a part of kairouan plain which include the Kairouan city and the downstrewam of El Houereb Dams (Figure 34). The total study area is 1570 km^2.

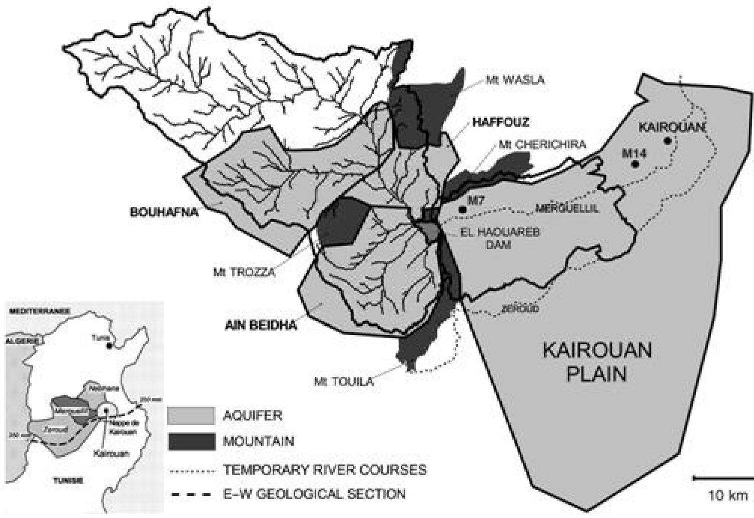


Figure 34 Location of the study area, limits of the upper and lower sub-basins and of the different aquifers

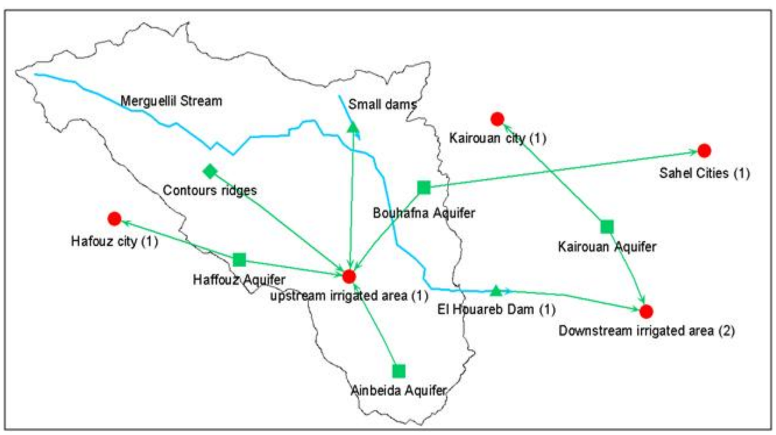


Figure 35 Construction of the model: creation of the area

5.2.3 CLIMATIC DATA REQUIRED

Most of the water resource of the study area originates from the rainfall. The mean annual rainfall is required by the model , however we have to consider that the area study is extended to the downstream of the basin include the plain.This rainfall and the Evapotranspiration data use in the WAEP model for the Merguellil watershed is provided from the same rainfall data selected for SWAT model as cited in the previous part of this chapter (paragraph 5.1.1.6.2). the yearly average rainfall is estimated to 295,5mm. The Figure 36 illustrate the monthly variation rainfall data inserted within the WEAP model.

Evapotranspiration from cultivated area and rangeland in the upstream of the Merguellil watershed are estimated to 169 Mm3 annually (Le Goulven and al, 2009). Evaporation from the El Houareb dam is valuated to 5,6Mm3.

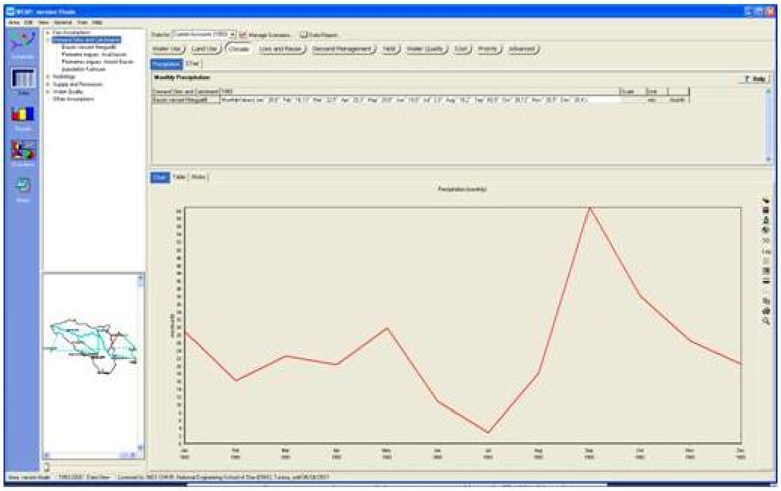


Figure 36 : WEAP input: Average monthly Precipitation in the Merguellil watershed

5.2.4 CROP DATA

Crop coefficients must be defined for each type of land use (Kc's) that multiplies the reference evapotranspiration to reflect differences occurring from plant to plant. The monthly Kc values introduced in the WEAP model are reported in the Table 12:

Table 12 Monthly Kc input for the study area

Month	Jan - Feb	Mar	Apri	May – Jun – Jul - Aug	Sep - Oct	Nov - Dec
Kc	0,57	0,66	0,80	1	0,7	0,53

5.2.5 IDENTIFICATION OF ELEMENTS OF A WEAP SCHEMATIC

Using the hydrological function in WEAP, the water supply from rainfall is depleted according to the water demands of the vegetation, or transmitted as runoff and infiltration to soil water reserves, the river network and aquifers, following a semi-distributed, parsimonious hydrologic model. These elements are linked by the user-defined water allocation components put into the model through the WEAP interface (SEI, 2006).

For the study of water supply and demand, the main data required in WEAP model are the quantity of water used for domestic, for irrigation, breeding, and numbers of users (people, livestock, ...), the cultivated area, precipitation, evapotranspiration, and stream flows. These data include firstly the water resources and secondly the main water users, we can make a simple model of water management, prioritizing the allocation request. However taking into account data of users, such as industry mining, tourism and other, makes modeling more realistic.

In the WEAP model, a node represents a physical component such as a demand site, wastewater treatment plant, groundwater aquifer, reservoir or special location along a river. Nodes are linked by lines that represent the natural or man-made water conduits such as river channels, canals and pipelines. These lines include rivers, diversions, and transmission links and return flow links. A river reach is defined as the section of a river or diversion between two river nodes, or following the last river node. WEAP refers to a reach by the node above it.

Each node (except demand sites and tributary nodes) may have a startup year, before which it is not active. With this feature you can include nodes in the analysis that may be built after the Current Accounts Year, or selectively exclude nodes from some scenarios. To exclude a node from a scenario entirely, set it to be not active in the Current Accounts, and then enter 0 for the startup year. WEAP will ignore any nodes (not active in the Current Accounts) with startup year equal to 0.

- **Demand sites**

  The objective of simulation with WEAP model is to maximize water delivered to various demand elements and in-stream flow requirements according to their ranked priority. This is accomplished using an iterative, linear programming algorithm (SEI, 2005)). The demands of the same priority are referred to as equity groups. These equity groups are indicated in the interface with a number in parentheses (from 1, having the highest priority, and 99, the lowest).

  The program is formulated to allocate equal percentages of water to the members of the same equity group when the system is supply-limited. Practically, data Demand site In the WEAP model must be selected and edited concern Water use and, Annual Activity Level, monthly variation and consummation for each activity.

Table 13 Water demand site

Demand site	Annual activity level	Annual water use rate	Monthly variation	Rate of consumption	Priority
Irrigated area on watershed upstream	2700 ha	3500 m^3/ha	Apr 5% May 10 % june 20% Jul 25 % Aug 30 % Sep 10 %	90	2
Irrigated area on watershed downstream	11000 ha	3500 m^3/ha	Apr 5% May 10 % june 20% Jul 25 % Aug 30 % Sep 10 %	80	2
Kairouan city	550000 inhabitant	100 m^3/inhab/year	Proportional to the number of days in a month	80	1
Sahel city (touristic)	12	200 m^3/inhab/year	Proportional to the number of days in a month	80	1
Haffouz city	44.000	100 m^3/inhab/year	Proportional to the number of days in a month	80	1

This Data concerns:

- The annual activity level which determines the water demand such as agricultural surface, the number of users of water for domestic or industrial purposes

- Annual water use rate : the level of water consumption per unit of activities

- Monthly variation or the monthly share of the annual demand

- The rate of consumption or % of inflow consumed.

The Information about the demand sites of the Merguellil catchment are represented in the Table 13, the Water consumption in the catchment for the years between 1992 up to 2002 is used as a yearly input data. It is assumed that the agricultural and the domestic demand sources have not the same degree of priority. For the Merguellil watershed, the priority is given to the domestic demand so we attribute 2 to the irrigated area demand and 1 to water demand of the city.

The monthly variation is expressed as a percentage of the yearly value. The values for all of the months have to sum up to 100% over the full year. the monthly variation in the water use rate selected for the irrigated area is recognized in the following configuration: 5% in April - 10% in May - 20% in June - 25% in July - 30% in August – 10 % in September - 0% for the rest of the year (Figure 37).

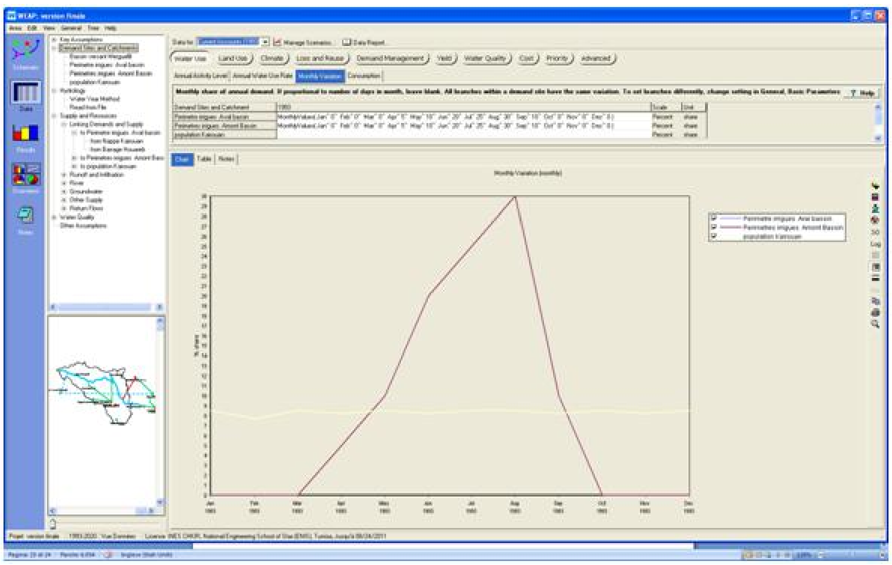


Figure 37 Monthly variation for water demand in the Merguellil Watershed

- **Groundwater data required**

The variables required to characterize the aquifers are:

- Storage capacity (Mm^3): maximum theoretically accessible capacity of the aquifer. In the Merguellil watershed

- Initial storage (Mm3): water stored at the beginning of the first month of the simulation

- Hydraulic conductivity (m/day): ability of the aquifer to transmit water through its pores.

- Specific yield: porosity of the aquifer, represented as a fractional volume of the aquifer.

- Groundwater recharge (Mm^3/month).

- Wetted depth (m): depth of the river

- Horizontal distance (m): a representative distance for the groundwater –river geometry, taken as the length from the farthest edge of the aquifer to the river.

- Reach length (m): horizontal length of the interface between the reach and linked groundwater.

- Storage capacity below river level (Mm^3): groundwater storage volume at which the top of groundwater is level with the river.

Groundwater is represented in WEAP as a wedge that is symmetrical about the surface water body. Recharge and extraction from one side of the wedge will therefore represent half the total rate.

Total groundwater storage is estimated using the assumption that the groundwater table is in equilibrium with the river (SEI, 2005). In the following table, the variables required to characterize the set of aquifers considered for the simulation. Figure 38 show the monthly nature recharge for the aquifers. The Model GW-SW flows" method was selected for the calculation of the transfer between surface water and groundwater. Finally, The input data required for the different aquifers in the Merguellil watershed are estimated and reported in the Table 14:

Table 14 Groundwater data required for WEAP model

	El Houereb Aquifer	**Ain Bidha Aquifer**	**Bou Hafna Aquifer**	**Haffouz Aquifer**
Storage capacity (Mm3)	50	7,5	9,5	19
Initial storage (Mm3)	20	5	5	10
Max.withdrawal (Mm3)	2	0,1	0,2	0,2

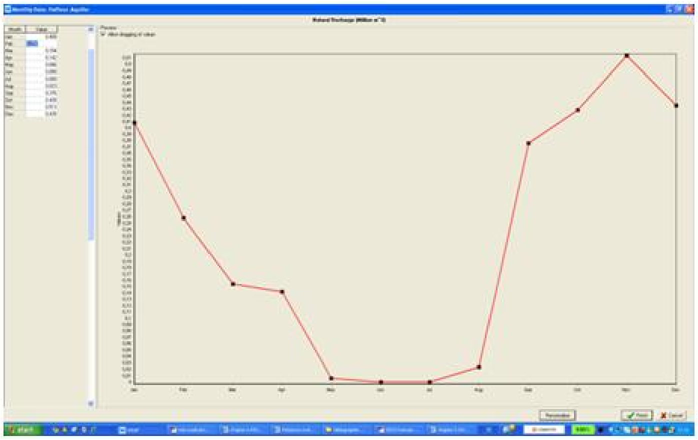


Figure 38 Monthly Natural recharge of Haffouz aquifer

5.2.6 SMALL DAMS AND MEDIUM DAMS

A main assumption is taken in account for the WEAP modeling performed on the Merguellil watershed, we consider that small dams and the reservoirs are represented in one only component schematized by the model and will be called “SMALL DAMS”. The upper basin also includes about 30 small tanks (with a capacity lower than 0.5 Mm^3), built and managed by the SWC directorate, which store 2.5 Mm^3/ year on average, and five larger tanks, built by the dam directorate and managed by the SWC directorate. With a storage capacity above 1Mm3, these tanks receive annual average contributions of 2.8 Mm^3 (Le Goulven and al, 2009).

The following information about the reservoirs are required by the model:

- the yearly inflow into the local reservoir.
- the storage capacity or total capacity of the reservoir.
- the initial storage or quantity stored in the reservoir at the beginning of the simulation.

5.2.7 CONNECT THE DEMAND WITH A SUPPLY

Through WEAP model, demand water must be satisfied; this is accomplished by connecting a supply resource to each demand site. For this reason we create a Transmission Link from the Main River to all urban and to Agriculture sites. WEAP will attempt to supply all of the demand with sources having the highest preference level, only using lower-level sources if the high-level sources do not have sufficient supply. The transmission link performed in the WEAP model applied to Merguellil watershed is resumed in the Table 15:

We have to highlight that priorities in the WEAP model can range from 1 to 99, with 1 being the highest priority and 99 the lowest. These priorities are useful in representing a system of water rights, and are also important during a water shortage, in which case higher priorities are satisfied as fully as possible before lower priorities are considered. If priorities are the same, shortages will be equally shared.

Table 15 Transmission Link between water supply site and demand site in the Merguellil watershed

	Start Point	End Point	Priority
1	Hafouz aquifer	Haffouz city	1
2	Bouhafna aquifer	Sahel city	1
3	Kairouan aquifer	Kairouan city	1
4	Mergullil watershed	Mergullil river	-
5	Mergullil watershed	Kairouan aquifer	-
6	Contour ridges	Upstream irrigated area	1
7	Hafouz aquifer	Upstream irrigated area	1
8	Ainbidha aquifer	Upstream irrigated area	1
9	Bouhafna aquifer	Upstream irrigated area	2
10	Small dams (ponds)	Upstream irrigated area	1
11	El Houareb Dam	Downstream irrigated area	1
12	Kairouan aquifer	Downstream irrigated area	1

The supply input elements related to the water balance in the catchment were studied. Data related to groundwater recharge rates, its initial storage, its specific yield, and the maximum withdrawals allowed according to annual renewal was collected and calculated based on yearly time steps for the period 1992-2002.

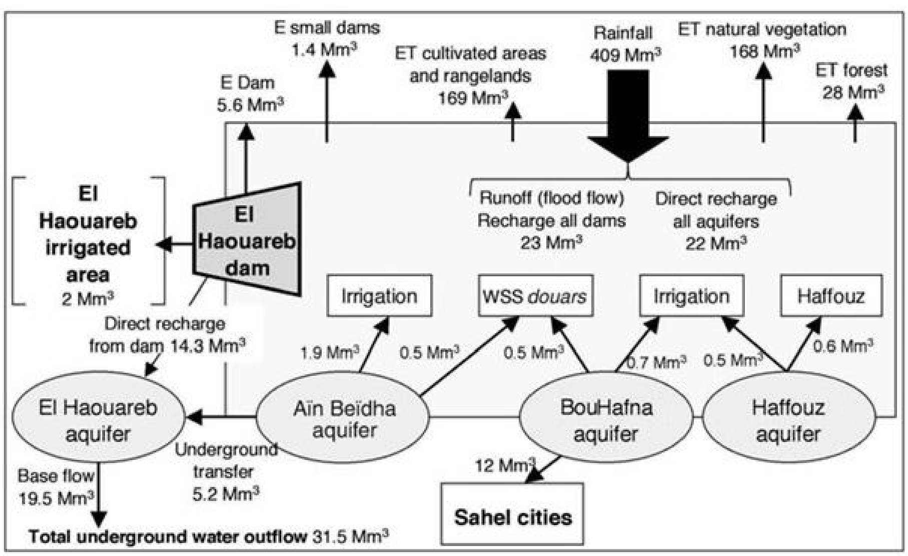


Figure 39 Water balance of the Merguellil watershed (Le Gouleven and al, 2009).

According to the water balance scheme (Figure 39) performed by Le Gouleven (2009), some assumptions were considered to complete the input data required for the application of WEAP model on Merguellil watershed. We have estimated that for the current account of the WEAP model which refer to calibration year 1992:

- The Haffouz aquifer contribute annually to the water demand of Haffouz city by 0,6 Mm3 and 0,5 to irrigated sectors (upstream area)
- The Bouhafna aquifer contribute annually of 12 Mm^3 to satisfy the water demand of Sahel city and about 0,7Mm^3 to the irrigation in the upstream area, but we don't consider the Douars Wss into the model because represent as rural community, we ignored any information about it (the number of population).
- The Ainbidha aquifer contribute annually of 1,9 Mm^3 to the water demand of irrigated area
- 5,2 Mm^3 of water is transferred on underground annually from Hafouz Bouhafna Ainbidha aquifers to El Houareb aquifer
- Kairouan aquifer contribute to the base flow by 19,5 Mm^3. It receive a direct recharge from El Houareb dam about 14,3 Mm^3.
- The total rainfall on the Merguellil watershed contribute to the recharge of all the dams by 23Mm^3 in which 17Mm^3 for the El Houareb Dam and 6 for the small and medium dams
- El Houareb irrigated area (called also downstream irrigated area) receive annually 2 Mm3 from the El Houareb dam.

For the downstream of the El Houareb Dam, some input data required by the WEAP model, have been considered from the diagram of water balance (Figure 40) realized by Le Gouleven and al, (2009).

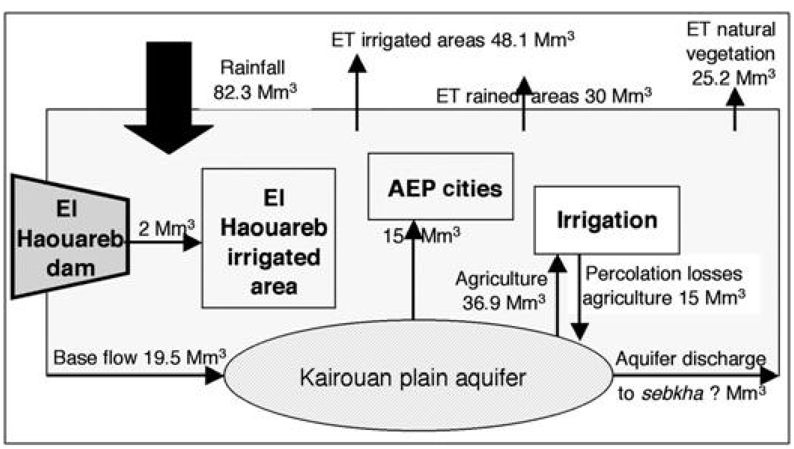


Figure 40 Water balance in the downstream of the Merguellil watershed

All the simulation step in the modeling with WEAP were finalized at the present and the main components of the system; area location, catchment size, supply and demand locations, basins or any other source of groundwater, surface water are introduced properly in the database of the model.Figure 41 shows the ultimate WEAP model for Merguellil catchment. In the next chapter we will deal with the model result and discussion. Climate change and land use scenarios will be performed in order to assess the capacity of model.

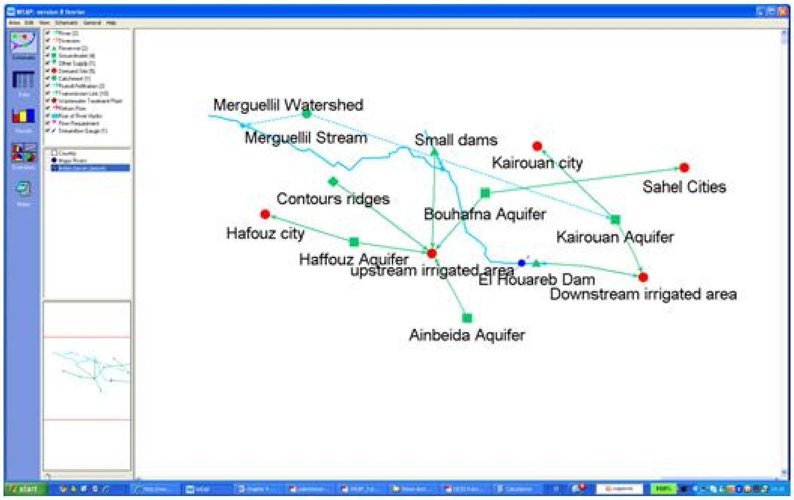


Figure 41 WEAP model for Merguellil catchment

6 CHAPTER 6: RESULT AND DISCUSSION

6.1 SWAT SIMULATION

6.1.1 SENSITIVITY ANALYSIS

Several studies have been done on the sensitivity of the SWAT model, Mulet et al (2005), Holvoet et al (2005), Huisman et al (2004), Francos et al (2003), Romanowicz et al 2005. Not all the parameters have the same weight on the model outputs: characterize the model sensitivity to different parameters to better understand the model. Some of these parameters present initial or boundary conditions while others are forcing factors. Therefore, prior the calibration, a sensitivity analysis was conducted to assess the most sensitive parameters.

The calibration of conceptual model in semi-arid region often requires long periods of calibration to obtain reliable simulation results mainly because of the highly variable flow (Görgens, 1983). SWAT applied to a semi-arid basin does no exception to this rule: it must be calibrated. This model is over parameterized but few parameters are really sensitive. The model is defined over parameterized (Ambrose, 1999) when the number of parameters it contains is much greater than the amount of data available for its calibration. The over parameterization of the models can generate the problem of equifinality (Beven, 1996). Among the sensitive parameters, some are clearly identifiable while others are not. In this chapter, we will attempt to investigate the sensitivity of model parameters related to the flow, the sediment transport, the nutrients and the threshold drainage. This is done in order to highlight the most sensitive parameters in order to give greater attention during the model calibration. A sensitivity analysis allows identifying the parameters on which the greatest attention should be paid during their valorization.

6.1.1.1 CHOICE OF PARAMETERS

We will try here to analyze the impact of the sensitivity of SWAT model to the variation of some parameters. The parameters tested are the most sensitive among others. For each parameter, we give the range of variation (max, min) and the step of variation.

The sensitivity of a parameter on an output variable can be evaluated by representing the output based on parameter values. A non-sensitive parameter is a parameter whose value has little influence on the output variable; this will be a parameter showing no particular distribution over the variable. We realize that making this type of study on the hundreds of model parameter would have been very costly in computing time, so we made first selection "manual" sensitive parameters to be analyzed.

The sensitivity analysis was done at the Merguellil station that covers 26 subbasins (1200 km^2). The most sensitive parameters are identified. A total of twenty-seven parameters are selected, listed in Tables below according to the compartment and they characterize the processes they represent. The lower and upper limits were defined based on data from literature. In total 27 parameters was analyzed by compartment of the model:

- seven parameters which concern the compartment soil-vegetation
- Five parameters which concern the Aquifer compartment
- Three parameters which concern slope compartment
- Three parameters which affect the Drainage compartment
- Five parameters which concern the Erosion compartment
- Two parameters which affect the nitrogen compartment
- Two parameters which affect the Phosphorus compartment.

For analysis of sensitivity parameters, some predefined hypotheses were considered:

- reference year for the precipitation and flows data (year 1996-97)
- Temperature (year 1996-97)
- A single HRU: one soil and one type of vegetation are taken into account
- The Penman Monteith method is selected for the calculation of evapotranspiration
- Muskingum formalism is chosen for the flow of water into the hydrographic network

6.1.1.2 SENSITIVITY OF THE FLOW PARAMETERS

Compartments include processes that affect the flow are four: the Soil-Vegetation compartment, the aquifer compartment, the slope compartment and Drainage compartment (

Table 16):

Table 16 Parameters selected for the sensitivity study

Compartment And Processes Involved	Parameters	MIN	MAX	STEP
SOIL – VEGETATION *Infiltration, Percolation, Evaporation, surface runoff.*	Hydraulic conductivity (mm/h)	8	100	10
	Available soil water capacity	0.03	0.17	0.02
	Bulk Density (g/cm^3)	1.3	1.6	0.05
	Soil depth (mm)	100	1000	100
	Clay Percent (%)	5	35	2
	Soil evaporation compensation factor	0	1	0.1
	Curve Number	40	80	5
AQUIFERS *Recharge et évaporation de l'aquifère superficiel, recharge de l'aquifère profond, contribution de la nappe au débit du cours d'eau.*	Groundwater delay time (days)	0	20	2
	Baseflow alpha factor (days)	0.1	1	0.1
	Groundwater "revap" coefficient.	0.02	0.2	0.02
	Deep aquifer percolation fraction.	0	1	0.2
HYDROGRAPHIC NETWORK *Transfert.*	Manning's roughness coefficient (Manning)	0.02	0.2	0.02
	Effective hydraulic conductivity of the channel beds (mm/h)	5	150	15

6.1.1.3 THE SOIL – VEGETATION COMPARTMENT

All the simulation results for these parameters are presented *Figure 42*. We observed a obviously different sensitivity varying from some parameters to others according to the process involved. Among the three compartments listed in the

Table 16, the two Soil Vegetation and aquifers compartments seem be to contain the maximum number parameters sensitive to variation of average flow. In fact three of the seven chosen parameters are very sensitive: the available soil SOL_AWC, soil depth and the curve number CN. The other four (bulk density, hydraulic conductivity, percentage soil clay and distribution factors on evaporation show a very low sensitivity vis-à-vis the flow.

The parameter CN is the curve number that represent a parameter established in the SCS method, The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. The CN variation given by the SWAT model is ranged between 40 and 80. It is shown from Figure 45 that the flow rate increases with the parameter CN. A 33% decrease of this parameter includes a decrease of 11% of the flow (the rate increased from $1m^3/s$ to $0.87\ m^3/s$). While in the increase of CN to a value of 80, we obtain a rate of growth rate of 7%.

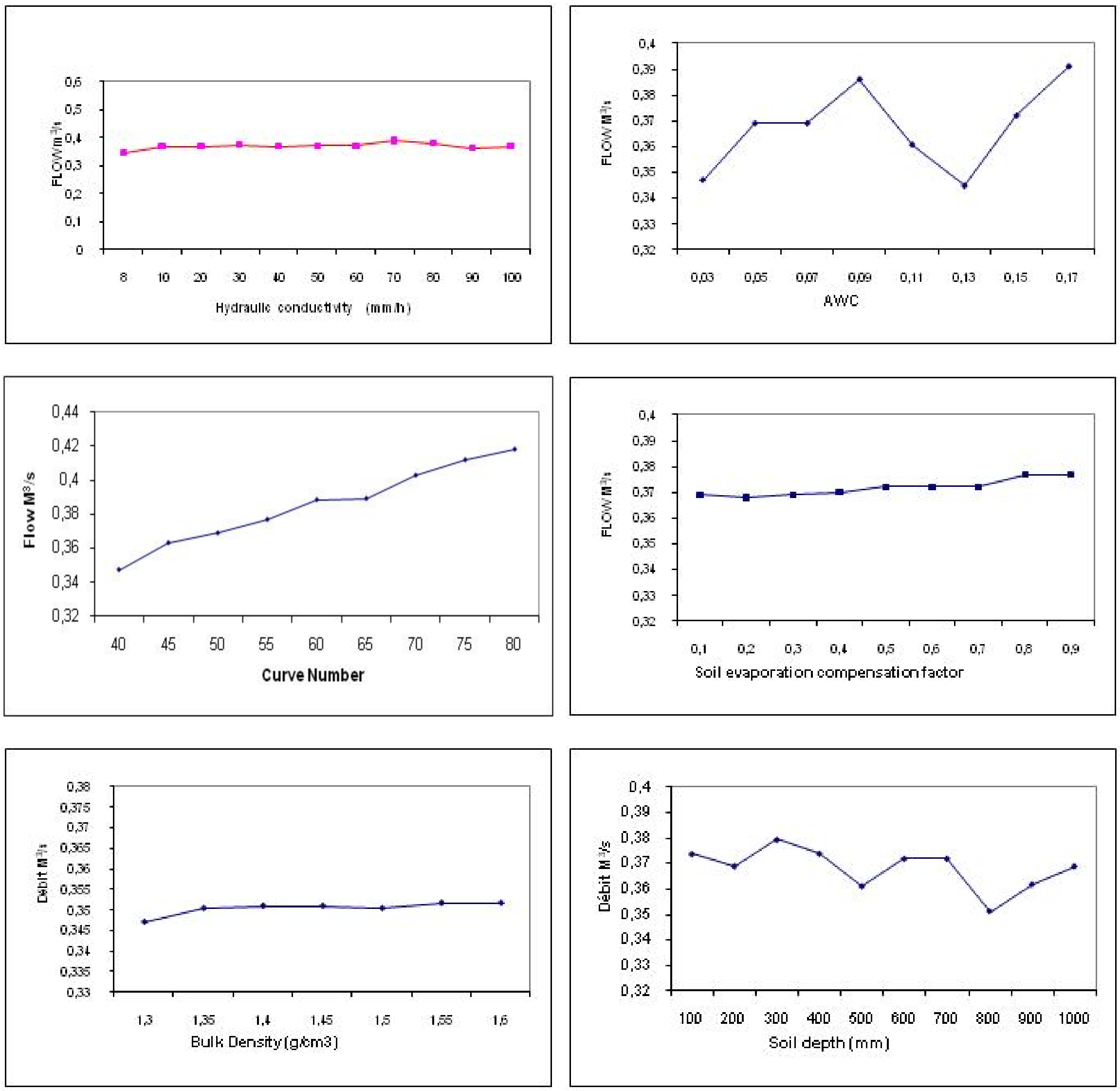


Figure 42 Sensitivity of the SWAT model to the soil-vegetation parameters

The CN parameter controls the interaction infiltration/surface runoff; therefore, it is furthermore important. According to Chaponière (2005), this parameter should be insensitive: this just compensation for low values of Curve Number between parameters and number of lateral flow delay. Indeed, when the Curve Number is high, surface runoff is high: flood peaks are important; the lateral flow has little influence. On the other hand, when Curve Number is low, the rain infiltrates in the soil and contributes to filling the soil reservoir which drains mainly through the lateral flow. The shape of the hydrograph changes according to the delay of this flow on the watershed. The delay of a low flow combined with a low CN; simulate a hydrograph almost equivalent to a high CN value and any delay value.

6.1.1.4 THE AQUIFER COMPARTMENT

Figure 43 shows the results of the analysis on the stream-flow in relation with the parameters of the aquifer compartment. The four parameters of model SWAT strongly sensitive are : the parameter of Groundwater delay time (day) GW_DELAY, the base flow alpha factor (day) Alpha_BF, the Groundwater "revap" coefficient (GW_REVAP) and Deep aquifer percolation fraction RCHRG_DP.

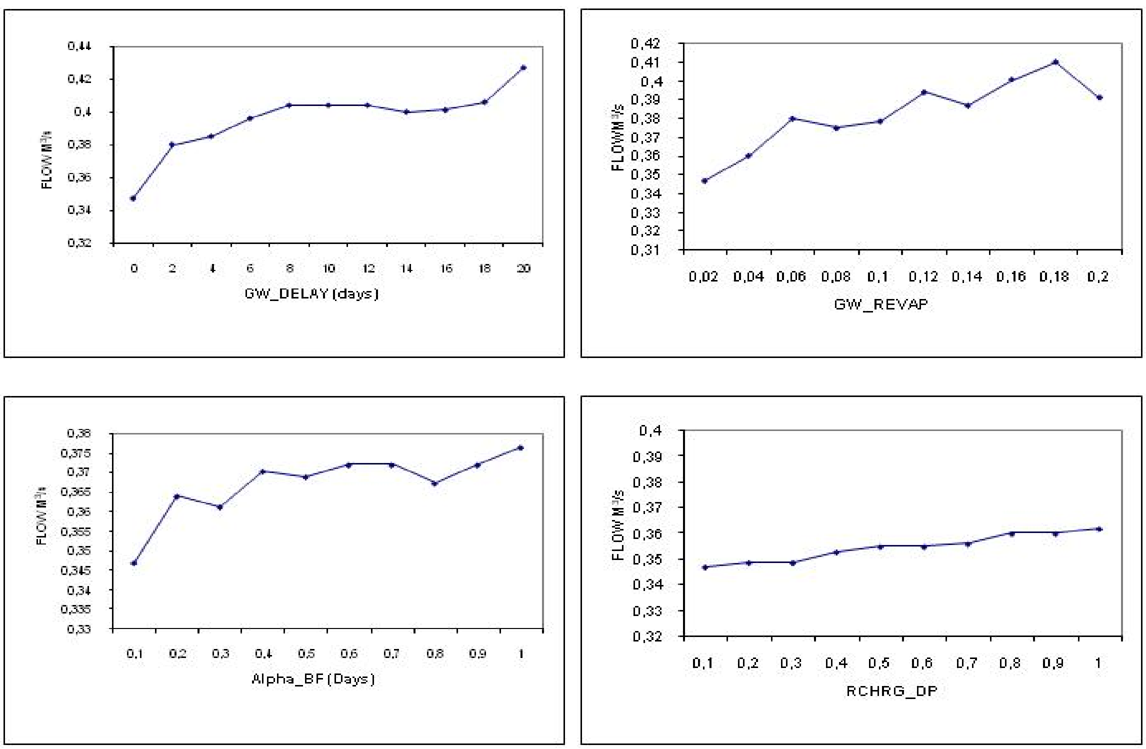


Figure 43 Sensitivity of the SWAT model to the groundwater parameters

6.1.1.5 THE HYDROGRAPHIC NETWORK

Figure 44 represent the response of the model in term of flow. to the discharge system to the variation of the parameters relating to the hydrographic network. These 2 parameters are: the coefficient of roughness (Manning) and the effective hydraulic conductivity of the channel bad (mm/h). Model SWAT does not show any variation of the flow with respect to these parameters. It should be also noted that the factor length of slope LHILL is sensitive although it does not appear in list of the parameters to adjust in the interface of AVSWAT, however the model fixes a default value at 0.05 m, according to Badas, (cited in Srinivasan and al, 2003) this value can imply a over-estimation of the lateral flow.

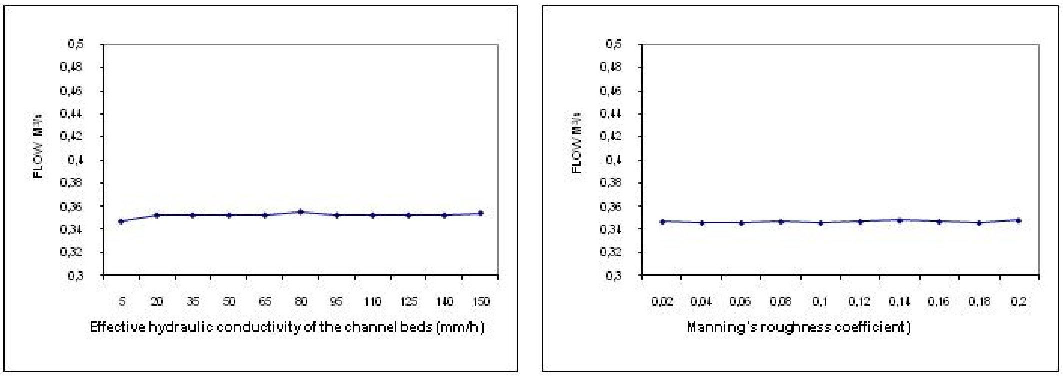


Figure 44 Sensitivity of the SWAT model to the hydrographic network parameters

We can conclude that the flow was sensitive to four parameters (ALPHA_BF, GW_REVAP, CN2 and SOL_AWC) and insensitive to both parameters REVAP_MN and ESCO. Among the four parameters assumed to influence the flow, the model shows high sensitivity for three parameters ALPHA_BF, GW_REVAP and CN2 while the model sensitivity to SOL_AWC parameter is relatively low.

6.1.2 SENSITIVITY OF THE EROSION PARAMETERS

Table 17 Erosion parameters selected for the sensitivity study

Compartment And Processes Involved	Parameters	MIN	MAX	STEP
Erosion	Average slope length (m). **SLSUBBSN**	10	150	10
	Factor related to vegetation cover included in the MUSLE equation **USLE_C**	0	0.5	0.1
	Linear parameter for calculating the maximum amount of sediment **SPCON**	0	0.01	0.1
	Channel erodibility factor **CH_EROD**	0.05	0.5	0.1
	Channel cover factor **CH_COV**	0	1	0.2

Table 17 Erosion parameters selected for the sensitivity studyreports the suspended solids parameters selected for the study of the sensitivity of the SWAT model and the range of variation of each parameter.

The simulation results for the selected five parameters are shown in Figure 45. The mass of suspended solids produced increases with increasing of SLSUBBSN, USLE_C and SPCON parameters. The decrease of 25% of the parameter SLSUBBSN imply the increasing of the mass produced from 38010 T to 33680 T, which equal to rate of 13%. When it increases by 25% the mass of solid transported increase from 38010 T to 40500 T, which represent a rate of 6.50%. The decrease of the parameter USLE_C by 25% increased the mass produced 38010 T to 34650 T, which considered as a decline rate of 9%. Although, when It increase by 25% the mass increases from 38010 T to 40230 T, about 6%. Therefore, the decrease of the parameter SPCON by 50% increased the mass produced 38010 T to 36580 T, a decline rate of 4%. An increasing of 50% of the SPCON parameter implies an increasing from 38000 to 41500 T, rate of 9%.

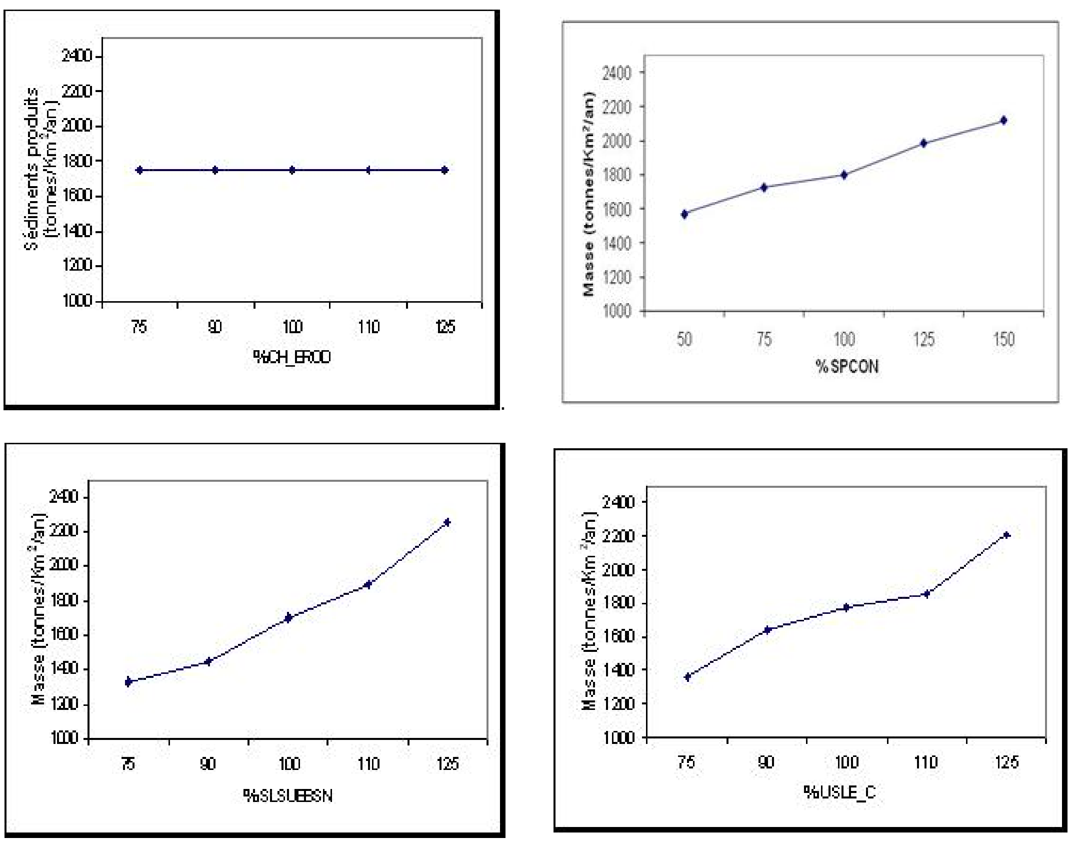


Figure 45 Sensitivity of the SWAT model to the erosion parameters

6.1.3 SENSITIVITY OF THE NUTRIENT PARAMETERS

The Table 18 summarizes the parameters tested to study the response of the model to the mass loaded (kg) of the elements nitrogen and phosphorous at the outlet of the Merguellil Catchment. The result of the analyses is illustrated in the Figure 46.

Table 18 Phosphorus and Nitrate parameters selected for the sensitivity study

Compartment and processes involved	Parameters	Min	Max	Step
Phosphorous	Phosphorus percolation coefficient (10 m^3/Mg). **PPERCO**	10	17.5	2.5
	Phosphorus soil partitioning coefficient (m^3/Mg). **PHOSKD**	100	200	20
Nitrate	Initial NO3 concentration in the soil layer (mg/kg):**SOL_NO3**	0	5	1
	Nitrate percolation coefficient. **NPERCO**	0	1	0.2

The phosphorus percolation coefficient **PPERCO** is the ratio of the solution phosphorus concentration in the surface 10 mm of soil to the concentration of phosphorus in percolate. The value of PPERCO can range from 10.0 to 17.5. The phosphorus soil partitioning coefficient **PHOSKD** is the ratio of the soluble phosphorus concentration in the surface 10 mm of soil to the concentration of soluble phosphorus in surface runoff. The NPERCO parameter controls the amount of nitrate removed from the surface layer in runoff relative to the amount removed via percolation.

The value of NPERCO can range from 0.01 to 1.0. As NPERCO → 0.0, the concentration of nitrate in the runoff approaches 0. As NPERCO → 1.0, surface runoff has the same concentration of nitrate as the percolate.

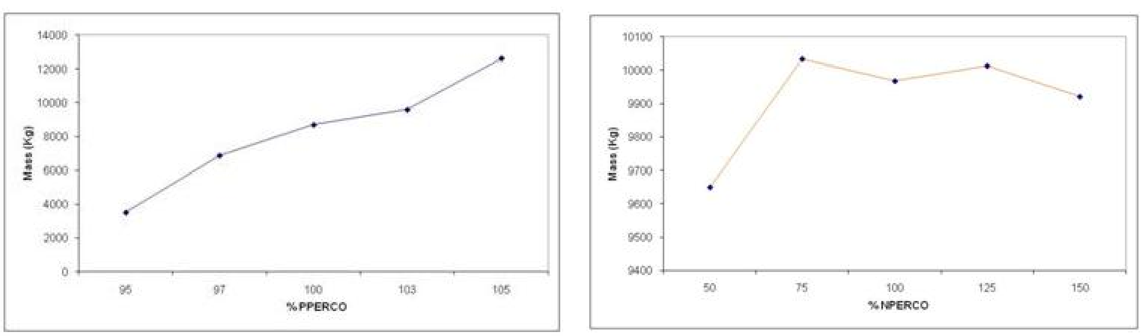


Figure 46 Sensitivity of the SWAT model to the Phosphorus and Nitrate parameters

As conclusion, the flow is sensitive to four parameters (ALPHA_BF, GW_REVAP, CN2 and SOL_AWC) and insensitive to both parameters REVAP_MN and ESCO. Among the four parameters supposed to influence the flow, the model shows higher variations in flow for three which are: ALPHA_BF, GW_REVAP and CN2. The model response to SOL_AWC parameter variation is relatively low. For parameters of the suspended solid of the SWAT model, it can be concluded that three parameters are sensitive (SLSUBBSN, and USLE_C and SPCONC) while the others CH_COV and CH_EROD are insensitive. The water quality parameter of SWAT model relative to the phosphorus and nitrogen were tested. The SWAT model is sensible to these parameters to produce the mass loaded. The Phosphorus percolation coefficient and the Nitrate percolation coefficient are the parameters of SWAT model, the most sensitive to the load of the nutrients.

6.1.4 MODEL SENSITIVITY TO THE THRESHOLDS DRAINAGE

A Series of simulations for several threshold drainage areas were performed in order to study the impact of sub-basins number on the response of sub-watershed on the variability of output parameters in terms of flow, suspended solids and nutrients ,

We consider a range of variation of the surface threshold drainage (which limits are set by SWAT) in proportion to the size of the basin. This interval admits as threshold value below a surface of 2280 ha representing 2% of the total area and 34223 ha as the maximum value representing 30% of the total area of the watershed. Between these two values, other seven intermediate values were considered as a percentage of the total [3%, 4%, 5%, 10%, 15%, 20% and 25%] (Table 19).

Table 19 Number of sub basins obtained for different threshold surface drainage.

N°of Simulation	% Total area	area (ha)	Nbr of sub- basins generated
1	2	2280	26
2	3	3422	16
3	4	4563	10
4	5	5703	8
5	10	11407	5
6	15	17111	3
7	20	22815	1
8	25	28519	1
9	30	34223	1

6.1.4.1 VARIATION OF FLOW IN FUNCTION OF SUBDIVISION

Figure 47 shows an increase of mean annual flow when the number of sub basins decrease. This trend of flow was explained by Arnold et al (1998) by two factors: the higher the subdivision of a basin is fine, the more groundwater flow is growing in opposition to surface runoff and if drainage density (length of the network system divided by the drainage area) is higher, the losses through the beds of rivers are important. A study done by FitzHug (2000) confirms that SWAT is insensitive to different levels of watershed subdivision.

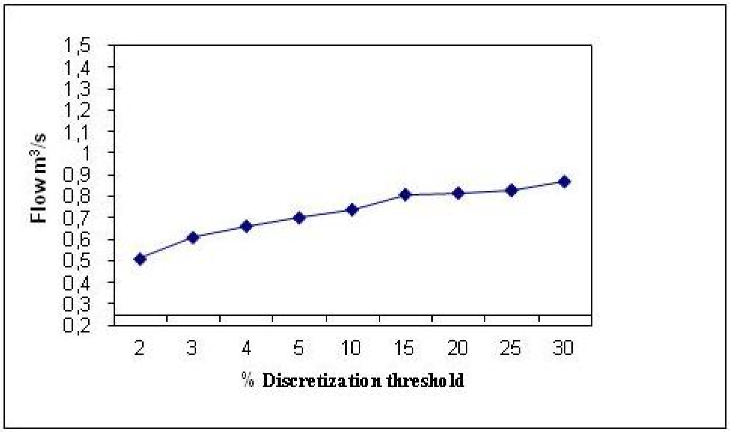


Figure 47 Flow variation for different threshold of discretization of Merguellil Watershed

For the case of watershed Merguellil, the flow obtained with the finer discretization (2%) of the total area and representing 26 sub-basins, representing about 60% of the flow obtained with the higher discretization 30 % of the total area and representing only one sub-basin.

6.1.4.2 VARIATION OF SUSPENDED MATTER

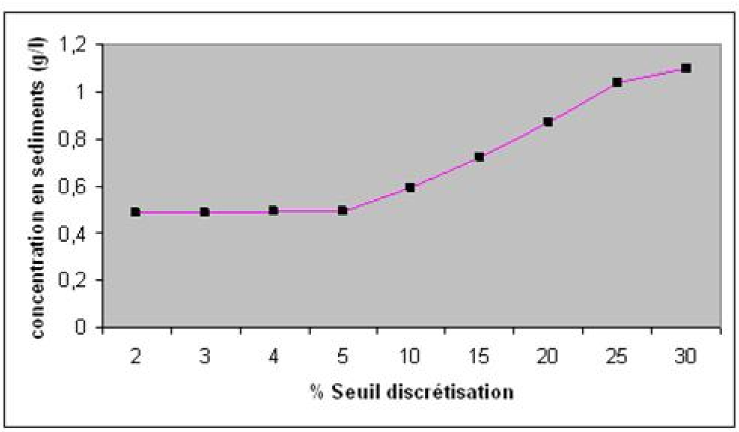


Figure 48 Variation of the concentration of suspended solids for different subdivision thresholds of Merguellil watershed

It can be seen from the results from the simulation (Figure 62) that the concentration of suspended solids has a greater sensitivity to changes in the number of sub-basins. Indeed, there is an increase of 227% of subdivision from the lowest (C = 0.48 g / l) to the higher (C = 1.1 g / l). For an efficient simulation of suspended solids, Arnold et al (1996), considers that the threshold of subdivision of 3% is the discretization threshold most appropriate to ensure stable load. Mensi (2005) also found similar results at its study in a sub-watershed to the north of Tunisia, by setting a threshold of stability of matter in suspension between 2 % and 6%. Jha (2002) explains the increase in the quantity of suspended solids produced inducing by the increase in the number of sub-basins by the fact that higher is the underground flow, the lower is the process of detachment and transport of solid particles. Similarly, the number of sub-basins increases proportionately to the drainage density, a phenomenon that results in an increase in the quantity of suspended solids deposited in the bed of streams.

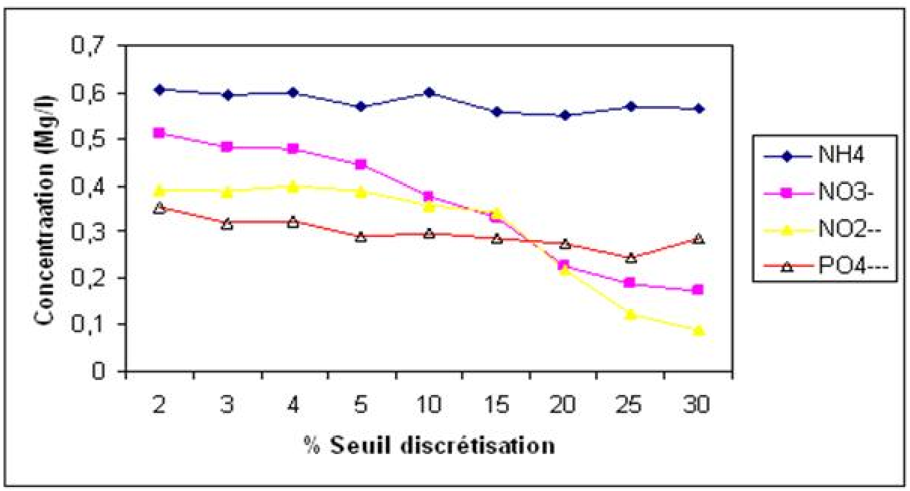


Figure 49 Variation of the concentration of nutrients for different thresholds subdivision of Merguellil watershed.

The result reveal from Figure 49, the Variation of the concentration of nutrients for different thresholds subdivision of Merguellil watershed, there is a total decrease of all levels towards a decrease in the number of sub-basins.

The rate of decrease is not constant for all nitrogen elements. The trend of nitrogen is very heterogeneous. The concentration of phosphorus analyzed in function of number of sub basins is stable. This stability is due to the fact that phosphorus is a very mobile element that does not depend on the type of flow most dominant in the basin. The level of stability extends over the interval [4%, 20%]. Ammonium shows fluctuations with a slight tendency to increase with the number of sub basins. The concentrations of nitrate and nitrite decrease considerably with the reduction in the number of sub basins, in fact we notes a drop of 23% for the concentration of nitrite between the two thresholds maximum and minimal.

6.1.5 CALIBRATION AND VALIDATION

6.1.5.1 METHODOLOGY OF CALIBRATION OF THE MODEL

The procedure of calibration/validation consists in separating the duration from the observations in two entities:

• A period of calibration during which the parameters are modified with an aim of obtaining the best adequacy between observations and simulations,

• A period of validation where, starting from the preceding values of parameters, the difference between observations and simulations are measured; indeed, an essential quality of the model is its capacity to represent the processes whatever are the climatic conditions.

The calibration is the process to identify watershed parameters of a function capable of representing and reproducing the hydrological functioning of the basin (GOUNDOUL, 1992). In the procedure of parameter calibration, it is desirable to refer to the reality of physical phenomena involved in the process of transformation of rainfall into runoff at the outlet of a basin. (Bodi, 2003). During the calibration of a hydrological model, three methods can be adopted (Refsgaard and Storm, 1995).

The application of SWAT model in a watershed requires the adjustment of parameters for the model to reproduce the best possible flow observed.

The adjustment parameters of the SWAT model is usually done by trial and error: we modify the parameters to which the model was considered sensitive and analyzed the new results, to determine whether to continue to change settings and in what sense taking into account considerations graphics and the use of statistical criteria. The tests also help to familiarize with the interactions of model parameters, ie to know the direction and magnitude of changes made hydrograph simulated by modifying a parameter. The fitting procedure varies the parameters from a watershed to another; however one can determine the steps and general rules

The calibration of the water balance and runoff must be preceded by an understanding of actual conditions mainly occurring in the watershed, this calibration is performed in the first place for average annual conditions, once all this is done, can move to monthly or daily calibration to refine its quality. (Arnold et al 2002) Indeed, we must adjust the parameters of the surface runoff and groundwater to improve the contribution of the saturated zone to the total flow.

SWAT is a physically based model for soil-plant compartment and for the most part empirical for groundwater and surface flow compartment (Ruelland, 2004). So many parameters are determined by the entries corresponding to spatial or known quantities and general values. However some parameters are according to stall the watershed studied. The values of these parameters were obtained by an iterative process aimed at optimizing the model responses as a function of measures.

6.1.5.2 ADJUSTMENT INDICATORS ADOPTED

To quantify the accuracy of the results, we adopted two indicators for adjusting. The statistical indicators used for the evaluation of model performance are the coefficient of determination (R^2) and the Nash-Sutcliffe model efficiency (NTD) (Nash et al., 1970). Neitsch et al., (2002) recommended both coefficients for the SWAT model use.

- **The R^2 coefficient of determination**

The R^2 coefficient of determination is calculated using the following equation:

$$R^2 = \frac{\sum_{i=1}^{n}(q_{ci}-\overline{q_c})(q_{oi}-\overline{q_o})}{\sqrt{\sum_{i=1}^{n}(q_{ci}-\overline{q_c})^2\sum_{i=1}^{n}(q_{oi}-\overline{q_o})^2}}$$

Where:

q_{ci} et q_{oi} : calculated and observed value of the day i.

$\overline{q_o}$ *et* $\overline{q_c}$: respective averages of q_{ci} and q_{oi} of n days used to calculate the coefficient

- **The Nash-Sutcliffe coefficient Esn**

The Nash–Sutcliffe efficiencies have been reported in scientific literature for model simulations of discharge, and water quality constituents such as sediment, nitrogen, and phosphorus loadings. (Moriasi et al., 2007)

$$Esn = 1 - \frac{\sum_{I=1}^{n}(I_{\text{mod}} - I_{obs})^2}{\sum_{i=1}^{n}(I_{obs} - \overline{I}_{obs})^2}$$

Where:

I_{obs} is observed discharge,

I_{mod} is modeled discharge.

$\overline{I}_{obs}$ is Average values measured

observed discharge at time t

This coefficient varies between - ∞ and 1(Nash et al., 1970). It tends to 1 when the calculated flow tends towards the observed flow. In general when it is negative is that it is a poor simulation. Efficiency reflects the overall performance of the model to reproduce the hydrograph. It reflects the closeness between the shapes of hydrographs (Chaponnière, 2005). Its value will be severely affected by the value of runoff badly restored. The sensitive parameters are those that regulate the shape of the hydrograph: the parameters of delay lateral and deep flow can differ the arrival of the runoff volumes produced to the catchment outlet. According to Van Liew et al. (2005), Esn value greater that 0.75 is considered good value between 0.75 and 0.36 are considered satisfactory and values below 0.36 are considered not satisfactory. Henriksen et al. (2003) categorized NSE into five classes namely; excellent, very good, good, poor and very poor and defined the limits of the classes for each of the efficiency indexes. They proposed a limit of 0.5 for a result between good and poor performance. Liden and Harlin, (2000) also state that a good simulation should have an Esn between 0.5 and 0.95.

6.1.5.3 THE CHOICE OF GAUGING STATIONS FOR CALIBRATION

The DGRE has performed flow measurements in the Merguellil catchment starting from 1969 year for some gauge flow and from the year 1996 for the other. By comparing the synchrony of climate and hydrometric data sets, an interval in which the simulation model can be determined by considering the step of calibration and validation could be established.

According on the sensitivity analysis cited in paragraph 6.1.1, the hydrologic calibration procedure was carried out referring to daily flow data at Skhira-Kef labiodh and Haffouz flow-gauges over the period 1992-1994. In particular, the most sensitive input parameters were adjusted so that measured flow match values predicted by the model during this period. Measured daily flow at the same gauges for the year 1996 was used for the hydrological validation of the model.

Before the sixties, the Hydrological Service of the Directorate General of Water Resources had only limited hydrological data. Since 1965 and especially after the 1969 flood event, the situation has improved significantly. But the quality and quantity of data accumulated and archived since those years were not sufficient to accurately identify the multiple aspects of the hydrological regimes capricious (kingumbi, 1999). Ever since the seventies, the monitoring network began to expand in Central Tunisia and particularly on the watershed of Merguellil. 5 hydrometric stations are currently measuring the streamflows of the Merguellil watershed (Table 20): Kef Labiodh station located in Skhira, Haffouz cassis stations, Haffouz telepherique station, Morra station, and Zebbess station. Therefore, measurement operations in other flow-gages like the Sidi Boujdaria station ceased formaly in 1989. The selected flow gages for the study are selected in the table below.

Table 20 : Characteristics of flow gages in Merguelli catchment (Kingumbi, 1999)

Flow gauge	Observation period		Geographic Coordinates	
	Start	**End**	**Latitude (°)**	**Longitude (°)**
Haffouz Cassis	1965	1974	35°39'13''	9°39'39''
Haffouz .Tel	**1974**	**2011**	**35°37'55''**	**9°39'39''**
Morra	1996	2011	35°41'00''	9°23'53''
Sidi Boujdaria	1974	1989	35°35'16''	9°41'58''
Skhira	**1974**	**2011**	**35°44'19''**	**9°22'57''**
Zebbes	**1996**	**2011**	**35°38'12''**	**9°36'29''**

- **Skhira - Kef Labiodh flow-gage**

The area of a watershed drained is about 188 km^2, the station of Skhira - Kef Labiodh has a measuring section completely rocked, which permit a very stable calibration. The first season of low water flow measurements took place in November and December 1966, while in flood flow measurements began only in September 1974 after the installation of the teleferic.

- **Haffouz Telepherique flow-gage,**

The Haffouz gauging station was installed on road Haffouz - El Ala, where it controls a area of 650 km^2 in 1955. The facilities were destroyed during the floods of autumn 1969 and rebuilt in December 1970. Since 1974, flows were controlled by the teleferic station located 2.5 km downstream, and drain a watershed of 675 km^2.

Four measurement series of gauging stations were considered for the calibration of the flow: it deal with the Skhira-kef Labiodh, Haffouz teferic and Zebbess stations. The fourth measurement point is located at the dam El Houereb data volume series are only available from 1989. Therefore Sidi Boujderia and Morra Stations were not selected for the validation because of the short periods of measurements, and uncertainty of measurement and large gaps in data series due to human and technical error, so we decide to not taken it into consideration.

The average daily flow series used during calibration was acquired within the Directorate General of Water Resources (DGWR) Nevertheless, data availability varies with hydrometric station, for the case of Skhira station, series of observed flow may cover widely the simulation period. For gauging station Haffouz teleferic, the data of average daily flow range from 1966 to 2001 which covers the whole model calibration over the entire phase of the simulation. The Data of the Zebbess station is limited and doesn't cover the period of simulation for the model calibration, the average daily flow series begins at 08/06/1996 and ends 31/08/2002. The data flow measured at El Houereb dam started in September 11, 1993 and ends in September 31, 2002. Representation of stations selected for calibration is shown in Figure 50.

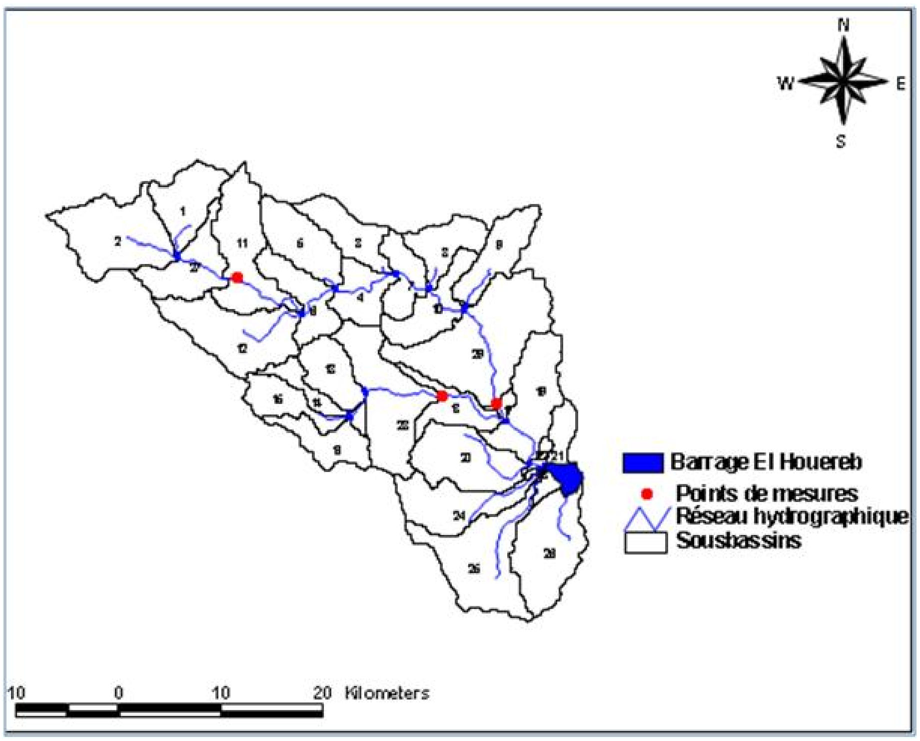


Figure 50 Flow gage (red dots) used for calibration and validation of the hydrological model SWAT

6.1.5.4 ANALYSIS OF HYDROMETRIC DATA

Analysis of hydrometric data in Watershed Merguellil were realized during the first phase of the project Mergusie, Dridi (2000) analyzed the hydrometric data for the period of 1974/75 to 1981/82 and found that the specific flow are low, in fact, the flow reached or exceeded 10 days per year is 1.44 $m^3.s^{-1}$ registered at Skhira gauge and 4 $m^3.s^{-1}$ in Haffouz gauge; while the flow reached or exceeded per 30 days per year of 0.146 $m^3.s^{-1}$ registred at Skhira and 0.268 $m^3.s^{-1}$ registered at Haffouz (Bouzaine and Lafforgue, 1986). At the monthly scale, flow irregularities foresee especially during the months of September, February, March and August. Average of eight per year floods and violent are observed with fairly short rise times of about one to two hours on average and basic time between 1 and 10 hours (Dridi 2000). The duration of the flood is short (1-3 days) (Tchatagba, 1998; Bouzaine and Lafforgue, 1986).

Floods contribute for 80% of annual runoff (Bouzaine and Lafforgue, 1986) .They appears more frequently in late summer early autumn period (August, September, October). During large floods, flows can reach a few hundred m^3. Other secondary maxima appear mainly in March and May. Such a situation is fairly typical of central Tunisia, with two peaks: one in autumn (September) and one in spring (March). In winter, the distribution of floods in the Merguellil catchment is steady and relatively January (Dridi, 2000).

6.1.5.4.1 ANALYSES OF DAILY VARIABILITY

The daily, monthly and annual hydrographs flow data for the four gauging station Skhira, Zebbess, Haffouz and El Houereb dam were established. The curves are presented in the appendix. For Skhira gauging station, measurement series of daily flow present an average of 0.233 / m^3s, a standard deviation of 1.65m^3/s and a maximum of 55.1 m^3 /s recorded on 04/08/1990. For station Zebess, it is observed a maximum flow of 12.2m^3/s recorded on 09/09/1997; however, there was no events of continuous flow in this sub-basin with the exception of a few more or less important events.

Besides, we can observe the existence of clear peaks in the hydrograph flow that occurred in 1997, 1998 and 2000 years. it can be noted that maximum flows exceeding sixty cubic meters per second recorded in 1986, 1988, 1992 and 1997, the highest value recorded was 65.6 m^3/s 17/09/1997. However there has been a lack of daily flow data during this period. Figure 70 6-30 6-31 and 6-32 show the variability mean daily flows observed over the period 1992-2002.

6.1.5.4.2 ANALYSES OF MONTHLY VARIABILITY

The monthly variability is characterized by higher flows during September (0.595 m^3/s) and May (0.333 m^3/s) for the station of Skhira. In the same way for the station of Zebess, it is noted elevated flows during the same two months (0.51 m^3/s in September and 0.30 m^3/s in May). For the station of Haffouz, the peak of flows observed was in September and October.

During July and December, concerning the station of Skhira, two low monthly mean flows were recorded (respectively 0,096 m^3/s and 0.114 m^3/s) and a flow quasi null in July for the station of Zebess, this does not make the exception for the hydrometric station of Haffouz which records the lowest monthly flow of 0,12 m^3/s. The dam El Houereb receives on average, the most important monthly contribution estimated at 5,3Mm^3 during the September and the weakest during July estimated at 0.25Mm^3.

Additionally, for the series of data relative to the four points of measurements cited above. The highest values observed, show the large inter-annual irregularity of the monthly flows which is relatively in relation with the high irregularity of the rains in central Tunisia. The figures 6-19 present the variation of monthly medium flow for the station of Skhira - Kef Labiodh.

6.1.5.4.3 ANALYSES OF INTERANNUAL VARIABILITY

From the data analyses, the mean annual flow varies very clearly from one year to another. The 1990, 1996 and 2002 years recorded the highest flow rates with a maximum flow value of 0.621m3/s for 1990. The minimum value (0.018m3/s) was recorded in 1984. For Zebess station the maximum flow was 0.28m3/s in 1998, followed by the value registered on the year 2000 about 0.15m3/s. Maximum annual runoff for Haffouz gauge is 1 m3/s in 1985. At the outlet of watershed Merguellil, contributions in the waters of the dam are higher in 1990 and 1989 of about respectively 40.61 and 39 million cubic meters. The year 1996 represents an exceptional lowest contribution to the dam in term of water estimated at 6.22 million m3. Figure 51 shows the variation of mean annual flow.

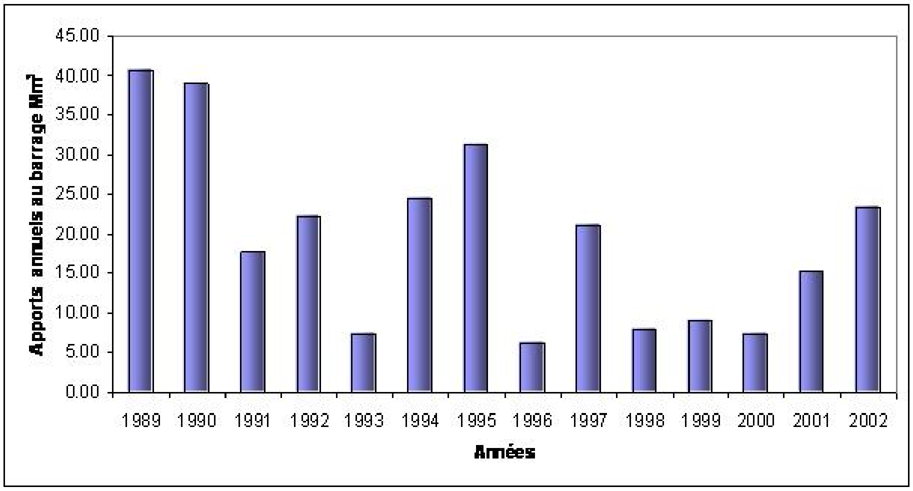


Figure 51: Annual variations of average inflows of the El Houareb dam (Mm^3)

6.1.5.5 MODELING OF WATER HARVESTING IN SWAT

To assess the impact of WSCW on the water balance, the hydrological regime on the entire watershed, and in order to determine the role of these developments on the dynamics of erosion and pollution point and diffuse, we considered two types of physical development in the stage of the simulation. The question was: how to model the physical characteristics of these structures spatially and temporally during the simulation phase,

The problem encountered during this study is to simulate the effect of contour ridges on the surface runoff; in effect these works reduce runoff and increase infiltration relatively, thus changing the dynamics of local water soil. Little literature cited this kind of problem, especially those who have used the model SWAT. Bracmort (2003, cited in Srinivasan and al, 2003) recommends changing the values of some specific parameters in the SWAT model to simulate a number of agricultural practices, such as grassed waterways, structures, stabilization of rivers and parallel terraces.

We can note that in the Merguellil catchment, the contour ridges and ponds reduce about 30% of the flow on the sub-basin Haffouz (Dridi, 2000). The contour ridges retain more water than lakes or dams because the last one are constantly subjected to siltation, which reduces their storage capacity. However the impact of erosion on the contour ridges is less obvious: the contour ridges can contribute to the solid yield, especially if they are built on ground dominated by marl material, on bare land subject to overgrazing.

While when contour ridges are built on calcareous formation they can be more effective on erosion control (Dridi 2000). In our study, two distribution WWSC GIS format maps of development in the watershed Merguellil are available, the first was realized from Dridi during the Merguellil project (Dridi 2000), which also expand the spatial evolution of these structures into four period: 1970, 1980.1990, and 1998 . The other GIS map provide from the CRDA and established in 2003 (Figure 52), however the two GIS layers are not compatibles. For further SWAT model simulation, details about WSCW provided by GIS layer developed by Dridi (2000) will be considered.

To consider such structures in the SWAT modeling, approach was performed in 3 steps:

- The first step was to divide the simulation period according to the timing of spatial evolution of contour ridges throughout the period (Table 21)
- The second step is to calculate the contour ridges area in each sub-basin by overlay the two maps according to operational date starting.
- The last step is to specify the HRU concerned with the distribution of these structures in each sub basin at the end to estimate the calibration parameters of the model (eg reduce the curve number (CN) in the homogeneous unit to reduce runoff).

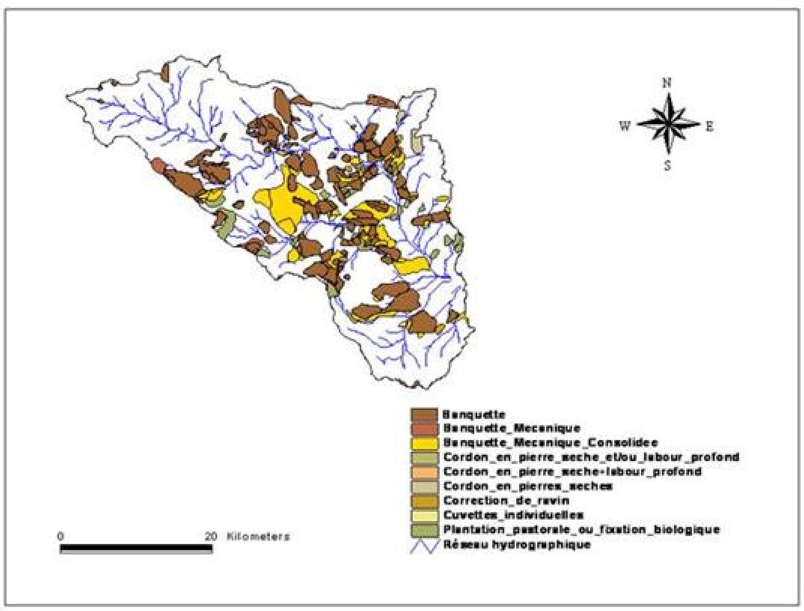


Figure 52: contour ridges map of Merguellil catchment on 2003 (CRDA KAIROUAN-IRD)

In 1998, area managed by contour ridges full retention cover, on the Merguelli catchment, covered an area of 196 km^2 which 70% was located in Haffouz and Zebbess subbasin and only 2% in the Skhira subbasin characterized by forest domination (Dridi 2000).

Table 21 Simulation period based on WSCW distribution

Simulation period	WSCW Area (ha)	Number of concerned subbasin	Number of concerned HRU
1992- 1998	9743	8	20
1998-2002	19600	12	55

We have considered during the calibration phase of the reduce of the parameter, curve number CN and similarly decrease of soil available water capacity S_AWC to release the percolation of water flow towards the deep layer. (Jha et al, 2003 cited in Srinivasan and al, 2003) done a study on a catchment area of 9500 km^2 and shown that the reduction of the curve number 8% and field capacity of soil of 0.04 mm results a proportion of 60% for base flow and 40% for the runoff on an annual basis, (Melo de Souza, 2003 cited in Srinivasan and al, 2003) have also explained the effect of parameter CN reducing runoff. According to Arnold et al (2002) model is particularly sensitive to CN, the available soil and a coefficient of evaporation. The coefficient of transfer of groundwater to the stream (base flow alpha) is also significant, so it is important to adjust it to reproduce at best the flood and low flows.

6.1.5.6 MODELING OF PONDS IN THE SWAT MODEL

The Merguellil catchment suffers regular water shortage aggravated by current drought with different degrees of frequency, intensity and severity. In addition, the natural hydrological regime is continuously altered by the construction of 44 small dams (hill ponds) and 5 large dams (hill reservoirs) and contour ridges. These reservoirs are frequently completely dry especially during the summer period. However, they constitute good traps for sediment loading and protect then the outlet (El Houareb dam) against silting.

Mishra (2003) (abstract cited in Srinivasan and al, 2003) analyzed the potential applicability of the SWAT model in a semi arid watershed, with 3 ponds installed built on uncontrolled streams, the SWAT model illustrates these three points as the reservoir type "impoundment". The difference a reservoir or a pond is modeled in the SWAT model is explained through the calculation of water balance of each one. For the SWAT model simulations, we considered only the mapping of 34 small dams because their hydraulics characteristics data are available (Figure 53).

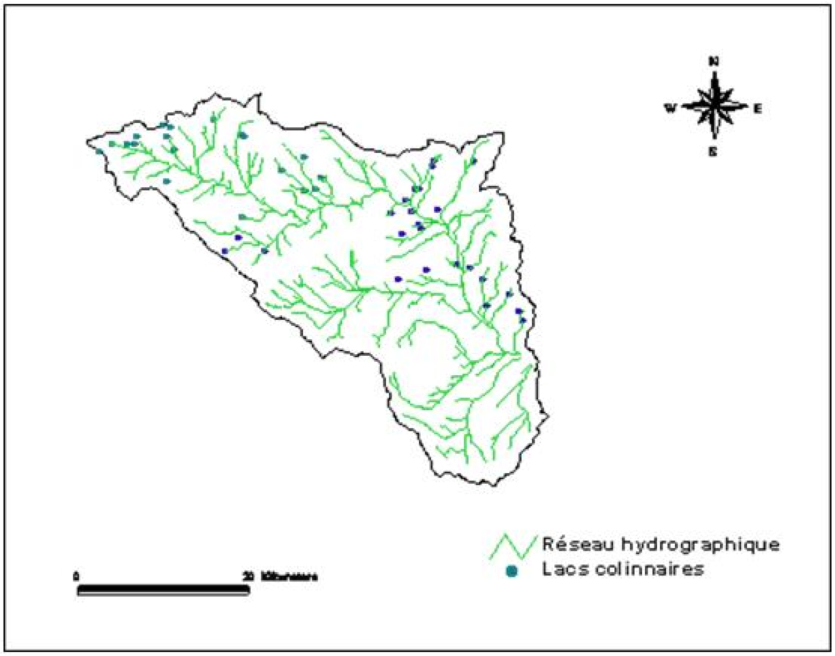


Figure 53 Location of small dams within the Merguellil watershed

These small dams have generally a relatively small area compared to the sub-basin area. The SWAT model can take into account of the water points in the sub-basin including tanks, small lakes and marshes, especially a specific input file with extension (. PND) is dedicated to this task. This file contains information about the parameters used in the model to simulate the water balance, sediment and nutrients to these water points (Arnold, 1993).The variables of these files are:

- Fraction of subbasin area that drains into ponds
- Surface area of ponds when filled to principal spillway (ha).
- Volume of water stored in ponds when filled to the principal spillway (10^4m^3).
- Surface area of ponds when filled to emergency spillway (ha).
- Volume of water stored in ponds when filled to the emergency spillway (10^4m^3).
- Initial volume of water in ponds 10^4m^3.
- Initial sediment concentration in pond water (mg/L).
- Hydraulic conductivity through bottom of ponds (mm/hr)

Four areas only between the areas identified for selected small dams in the basin, are published by the direction of the WSCW. To estimate the missing areas, two alternative can be selected: firstly to find a relationship between the area of the reservoir and watershed area based on small dams observed by the IRD or to adopt an average height for a reservoir that is obtained by dividing the mean volume of the reservoir by its height, so the size of the storage is obtained.

The first solution not permits a well-known relationship between them (logarithmic or others). However, the second solution seems more interesting, since it reflects the physical shape of the dam, rather than looking purely a mathematical concept. Then assumption is considered that a relationship exists between the area of the storage at emergency spillway and the capacity of the storage, ie by dividing the volume of the storage by this height, area of the reservoir can be as a result estimated. ElEuch, (1999) estimated at 3 m the average height of water filled at the principal spillway, the same values is considered for the next our work of the thesis.

The details of the 34 lakes and their relative fraction area to the sub-basin area are reported in the table 27. Since some sub-basins contain more than one ponds and others sub-basins contain no one, the areas of water bodies on each sub-basin are summed, the date construction of these works varies from 1968 until to 2003, although this fact has complicated the simulation procedure, since simulation was done from 1992 to 2002, as solution, So as suggestion SWAT model was apply in different time intervals between 1992 and 2002, and then by introducing step by step the ponds in the model according to the effective operation date. In the chronological order, Small dams were implemented on the basin on 6 in time intervals (see Table 22). Initially, SWAT simulation for Merguellil catchment has considered nineteen small dams which existed already in September 1992, followed by two other ponds in 1993 then, 4 others in January 1993 and two others until January 1994 and up in January 1995 and January 1996 and finally 3 other small dams until January 2002.

Table 22 : Distribution of the small dam's period of simulation sub-basin

Scénario	Start of simulation	End of simulation	Name of small dams introduced in the SWATmodel
1	Septembre1992	December 1992	El mouta, Dagla, Knouch,Ben Houria, Abda, Khalifa, Ben Jaballah, Salem Thabet , El Marrouki, Dahbi, Bouksab, El Maiz, El Hoshas, Fidh Ben Naceur, Fidh Ali, O.El Habsa, O. Fidh M'barek, O.El Guatar
2	January 1993	December 1993	El mahbes, Ben Zitoun
3	January 1994	December 1994	El Absa, Ain smili 1, Ain Faouar, Sidi sofiane
4	January 1995	December 1995	Ghtatis, Dj.Hallouf
5	January 1996	December 2001	El Gasâa, El Hamra, Aîn Smili 2, El Masref
6	January 2002	December 2002	Brahmia, Ghouil, Dakhlet

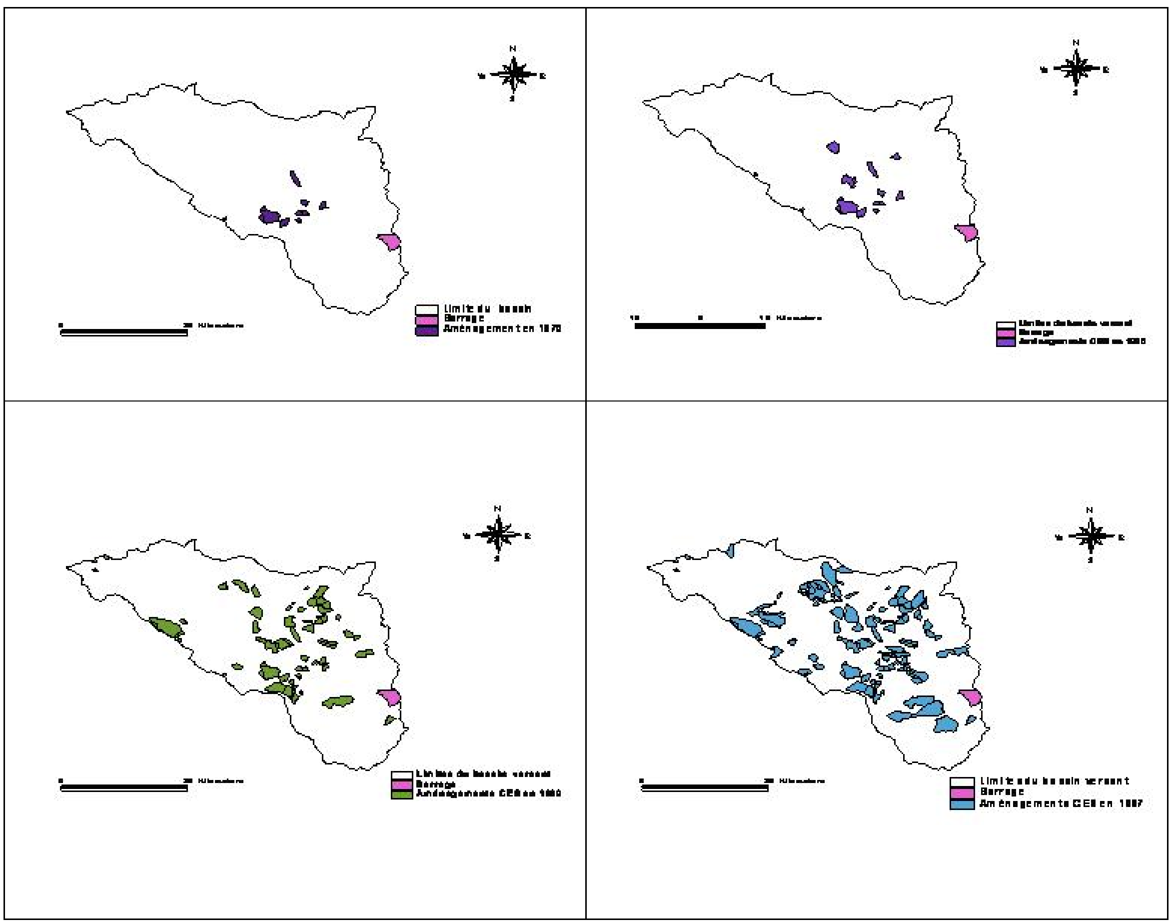


Figure 54: Evolution of contour ridges map of Merguellil catchment (Dridi, 2000)

Table 23 Small Dams on the catchment Merguellil

	Small dams Name	Volume m^3	Principal spillway height m	Area (ha)
1	O,El Habsa	45 000	8	0,6
2	El Absa	35 000	6	0,6
3	Brahmia	67 000	9	0,7
4	El Gasâa	104 800	8	1,3
5	Ben Houria	17 000	4	0,4
6	O, Fidh M'barek	53 000	6	0,9
7	Ghtatis	106 000	7	1,5
8	Fidh Ben Naceur	100	8	0,0
9	O,El Guatar	150	7	0,0
10	El mahbes	180 000	8	2,3
11	Fidh Ali	127	9	0,0
12	El Maiz	44 500	10	0,4
13	El Hamra	160 000	10	1,6
14	Ben Zitoun	50 000	7	0,8
15	Ain smili 1	130 000	8	1,6
16	Aîn Smili 2	35 000	7	0,5
17	Bouksab	500 000	6	8,3
18	El hamam	80 000	9	0,9
19	Ain Faouar	66 000	7	0,9
20	El Hoshas	130 000	7	1,9
21	Sidi sofiane	40 000	8	0,5
22	Abda	63 000	3	2,1
23	Dahbi	60 000	4	1,5
24	Salem Thabet	63 000	6	1,1
25	El Marrouki	56 000	7	0,8
26	Ghouil	153 000	9	1,7
27	Dagla	56 000	6	1,0
28	Knouch	26 000	4	0,7
29	Khalifa	70 000	7	1,1
30	Ben Jaballah	18 000	7	0,3
31	Dakhlet	520 000	13	4,0
32	El Masref	160 000	8	2,0
33	Dj,Hallouf	95 000	8	1,2

Particularly, six simulations with the model were performed which correspond according to six intervals; the result of simulation was regrouped in a unique graphic representing the entire period of simulation 1992-2002. As hypothesis, the initial volume of water stored for each pond built at the beginning of the simulation was considered null. However, some consideration taken in account that means that the initial volume of water in each pond to introduce as input in the consecutive new period of simulation was kept equal to the volume obtained as output of the precedent simulation done. The minimum value of the initial concentration of sediments in pond has been provided by the model as the default because of the lack of data. Each parameter varies in a range of values provided by the model and based especially on literature. Some input data such as phosphorus and nitrogen parameters remain undefined by because there is no data monitoring, it has also been taken by default by the model, and it was uncertain how it can affect the simulation results.

As describe above, SWAT model simulations will be performed from 01 September 1992. Until 31August, 2002 on daily, monthly and Yearly step, All the climatic database required related to model input parameters (wind speed, Relative Humidity, maximum and minimum temperature...). Calibration and validation concern only hydrological parameters of the model because of lack of observed data relative to nitrogen, phosphorus and sediment concentration.

Starting with simulation, the model interface proposed different equations for calculating evapotranspiration (Penman-Monteith, Priestley-Taylor and Hargreaves). These equations are more or less complicated and do not require the same quantity of data. Chaponnière, 2005 analyzed the sensitivity of the model of the three methods vis-à-vis the simulated flow and evapotranspiration simulated, she cited that the Penman-Monteith formula is most suitable for semi-arid environment. Based on her analyses, The Penman-Monteith method was selected for the Merguellil catchment, and especially all data parameter required are available in this case.

Concerning the flow process, the SWAT model offers two methods to estimate it. These two methods are more or less adapted to local context; we have decided to choose the method of Variable Storage which calculates the difference between the inflow into the basin and outflow as a function of elapsed time. This preference is based on the conclusion of the study done by Chaponnière (2005) on the sensitivity of the SWAT model vis-a-vis these two routing methods, the results of analyses, expressed in flow, explain that both methods give the same results in a semi arid contest.

Generally, the SWAT model provides a continuous three time steps for simulation: yearly, monthly and daily. In the case of our study to better understand the variations of flow, transport solid and the load of nitrogen and phosphorus. In the first instance, simulations based on annual scale were initiated, in order to incorporate the effect of WWSC on the flow regime. In a second step, simulations based on monthly and daily scale were conducted to refine the calibration. Usually, SWAT output files are well structured and the format is easily converted in Excel file, some macro file were performed with excel software during analyses of SWAT result in order to repeat fast the extraction of the output file subsequent to each new simulation. This method cans also make simplification to the calculation of R2 and Nash coefficients.

6.1.6 RESULT OF FLOW CALIBRATION

The SWAT model is built with state-of-the-art components with an attempt to simulate the processes physically and realistically as possible. Most of the model inputs are physically based. Flow calibration was performed for the period from 1992 through 2002 for annual, monthly and daily simulated flows using observed flows provided from the DRE gauging stations. This calibration was based on available measured daily stream flows through 3 gauging stations (Zebbess, Haffouz, and Skhira) and watershed outlet (inflow El Houereb dam). Severe parameters such as curve number (CN), soil available water capacity AWC, and groundwater parameters) were adjusted by trial and error to reduce the differences between simulated and measured values and to obtain better fit on hydrograph recession. When measured streamflow data are available, calibration can be used to determine optimal values for the unknown parameters by minimizing the difference between modeled and observed streamflow. The hydrological parameter of the model was calibrated by adjusting the runoff curve number CN in order to optimise the runoff. This parameter is not well defined physically in SWAT model (Conan and al., 2003). Also we adjust the slope length parameter (Lhill) in the SWAT model because as cited in Badas,(2003, cited in Srinivasan and al, 2003), the AVSWAT fixes this parameter at a very low value of 0.05m, implying an overestimation of the lateral flow as well as a shortage of available soil water required for groundwater recharge. Consequently a reasonable value of Lhill for Merguellil catchment based on the topographic data and the subbasin discretization would be more then 50 m.

To minimize as much uncertainly as much in the model results, the following parameters were changed during calibration: ALPHA_BF, Delay, RevapMN and Rchdp, CN, ESCO, GWQMN, GW_REVAP, SOL_AWC, SOL_K, SOL_Z and SUR_LAG. All others variables were kept constant.

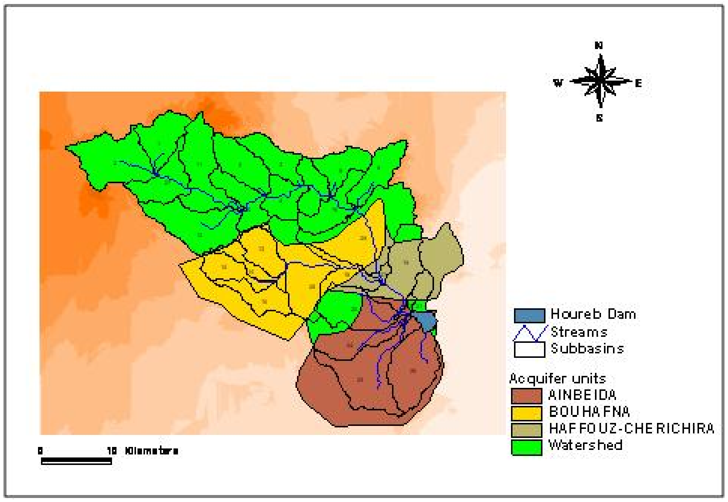


Figure 55 overlaid aquifers maps and subbasin map generated by swat

The calibration of the aquifers components of swat presented some major difficulties, Brett m Watson (2nd conference) refer to the fact that swat only requires a small number of input parameters to model groundwater which is hugely advantageous because extensive field work is not required to obtain inputs. Canon 2003 cited that it is better to assume a unique set of calibrated parameters all around the catchments creating soil/land-use/aquifer association, this contradict by Brett and al, 2003 (cited in Srinivasan and al, 2003), using a constant set of ground water parameters for each land use class across the entire catchment was not entirely adequate for modelling groundwater flow. According to Brett and al 2003, cited in Srinivasan and al, 2003) varying the parameters sets for too many subbasins would be problematic for at least two reason: firstly because of the big uncertainly that would be created in the model output. Secondly these changes would not necessary reflect actual conditions. For our study, the groundwater parameters Alpha, Delay (days), Revap and Rchdp are adjusted for the different aquifer units (Table 24). According to figure 5, the aquifers map is overlaying partially the watershed map. The aquifer of Bouhafna covers totally the four subbassin (13-14-15-16) and partially three subbasin (18-28-29). Also Chrichira aquifer covers totally one subbasin (17) and partially 5 subbassin (19-20-21-22-29). Consequently more importances were given to groundwater parameters adjustment in these subbasins.

Table 24: Groundwater parameters after adjustment: coefficients for recession (alpha), evaporation (revap) and recharge to the deep aquifer (rchdp), response delay and Threshold to allow base flow to the river (gwqmin in mm)

Aquifer unit	Alpha_b	Delay (days)	Revap	Rchdp
BOUHAFNA	0.061	200	0.08	0.10
Chrichira	0.080	120	0.14	0.05
Ain Bidha	0.100	130	0.23	0.08

A map of the water harvesting technique WHT was overlaid to the subbasins map in order to identify the WHT area in each subbasin. However several problems were encountered for SWAT modelling in presence with those water harvesting and soil conservation techniques, the incertitude of the WHT area within this subbasin which covering partially these subbasin. Additionally WHT differ from subbasin to another and are also related to the lithollogy.

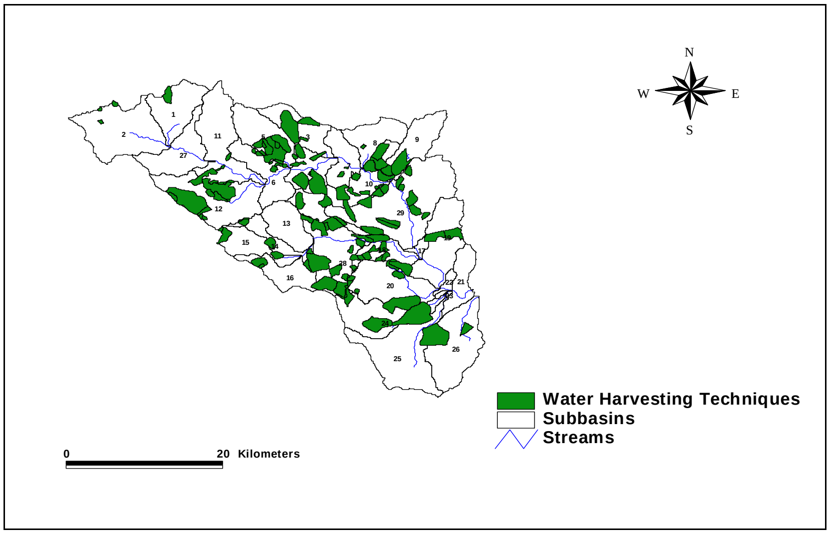


Figure 56 overlaid Water harvesting maps (MERGUSIE PROJECT-CRDA) and subbasin discretisation map generated by SWAT model

Description of data gauging stations used during calibration is shown in the previous chapter; the total number of descritized sub-basin is 29. We keep on mind that the outlets of subbasins n°27, 28 and 29, respectively represent the points of measurement of hydrometric stations Skhira-Kef-Labiodh, Zebbess and Haffouz. The sub basin outlets n°21 and 26 jointly correspond to the outlet of the watershed where volume inflowing the Dam El Houareb can be measured.

6.1.6.1 ANNUAL SIMULATION RESULTS

The Table 25 reports the results of the annual calibration of the SWAT model in the basin outlet. For each subbasin, the mean, max and min annual stream-flow values, and the standard deviation, and the two coefficients and R2 statistics Nash are calculated. Figure 58 presents the results of simulation SWAT for the stream flow before and after calibration.

Table 25 Statistical coefficients calculated for annual calibration of the SWAT model

	Outlet	Mean m^3/s	Max m^3/s	Min m^3/s	Standard Deviation	Nash	R2
Without Calibration	Skhira	0.41	0.64	0.23	0.14	0.20	0.81
	Zebess	0.15	0.32	0.04	0.10	0.07	0.65
	Haffouz	0.40	0.70	0.13	0.18	0.06	0.51
	Watershed	27.41	42.00	15.60	9.50	0.35	0.75
After Calibration	Skhira	0.43	0.67	0.19	0.16	0.53	0.86
	Zebess	0.12	0.35	0.03	0.12	0.49	0.71
	Haffouz	0.32	0.64	0.06	0.20	0.41	0.66
	Watershed	20.73 Mm3	36.30 Mm3	7.50 Mm3	10.49	0.71	0.89

The SWAT model overestimates the annual stream flow at the Skhira subbasin this implies a divergence between simulated and measured values, in particular in 1997; the simulated flow is 4 times larger than value of observed one. The Nash coefficient is improved during the calibration from 0.20 to 0.53. The coefficient of determination increases to 0.86 and can be considered as an improvement.

• In the Zebbess sub-basin, there is a reduced model performance for the streamflow production. The Nash coefficient before the calibration is 0.07 and the coefficient of determination is 0.65, after calibration, an improvement is obtained respectively in 0.49 and 0.71, note a simultaneous decrease in the average simulated series. This result can be explain by the fact that the sub-basin Zebbess has a good distribution of rainfall stations selected for the study and therefore represents heterogeneity spatial precipitation less important compared to other sub-basins during the simulation. In addition to the accuracy of flow measurements done on the hydrometric station because it dates from 1996 and because the hydrometric section is therefore more stable and represent less error.

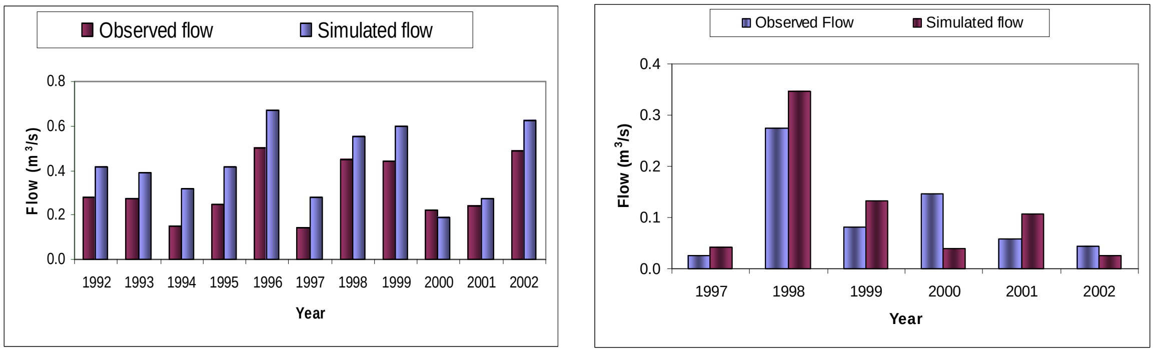


Figure 57: Observed and simulated yearly flow for the Skhira (left) and Zebbess (right) gauging station

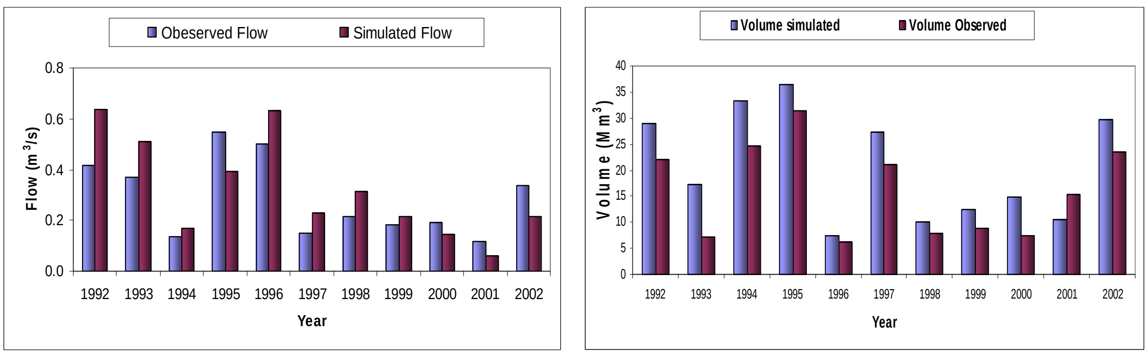


Figure 58: observed and simulated yearly flow for the Haffouz gauging station and the Merguellil watershed

For the Merguellil watershed outlet, the Nash coefficient is improved from the value 0.35 to the value of 0.71, and coefficient of determination of the value 0.75 to the value of 0.89 which attribute a good efficiency of the model after annual calibration. The Figure 58 illustrate a good concordance of the both measured and the simulated values. However, an overestimation of measured values is observed throughout the simulation period. This overestimation is not uniform over all period observed. The difference between the value of the mean flow measured with the simulated one is more important in 1996 and 1998 than for the other years. Moreover, this same type of observation can be confirmed by Arnold et al (2002) explains this by the fact that the runoff is highly overestimated in the SWAT model.

The calibration of model parameters for each of the three main subbasins was advantageous for the calibration for model parameters the entire watershed. In fact, the outflow drained from Skhira sub-basin located at the upstream is considered the inflow for Haffouz sub-basin.this implies that adjusting the flow from upstream to downstream can reduce simulation errors and can refine the calibration, in this way, the outflow of the Zebess and Haffouz sub basins constitute a major portion of the flow discharged to the outlet of the watershed. This justifies the approach to perform calibration in the way from upstream to downstream i.e. from the sub-basin Skhira through Zebess then ingoing to Haffouz and arriving to the Merguellil watershed outlet.

6.1.6.2 WATER BALANCE

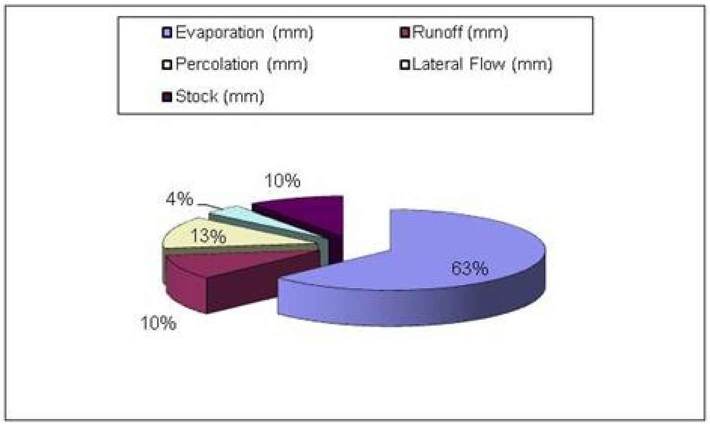


Figure 59 The water balance of the watershed Merguellil for an annual simulation

The water balance of the watershed was estimated over the period 1992-2002 (Figure 59). Runoff is evaluated at 40.5 mm which allows a runoff coefficient of 14%. In percentage terms, the rainfall is lost through evapotranspiration (63%).

6.1.7 MONTHLY SIMULATION RESULTS

- **At the Skhira gauging station**

The Figure 60 shows the variation of monthly streamflow measured and simulated by SWAT model at the gauging station Skhira. The Nash coefficient for this simulation before calibration was 0.12. The solutions proposed for the calibration of the model are: the reduction parameters CN2 and SOL_AWC respectively 8% and 5% in the subbasin n° 1, 2 and 27. Moreover the contribution of the water to supply the river system has been reduced by decreasing the parameter drain ALPHA_BF to 19% and also compensation factor of soil evaporation is increased by 15%. The result of the calibration at the gauging station Skhira is acceptable since the Nash coefficient obtained is then equal to 0.29, the improvement can be noted in the Figure 64

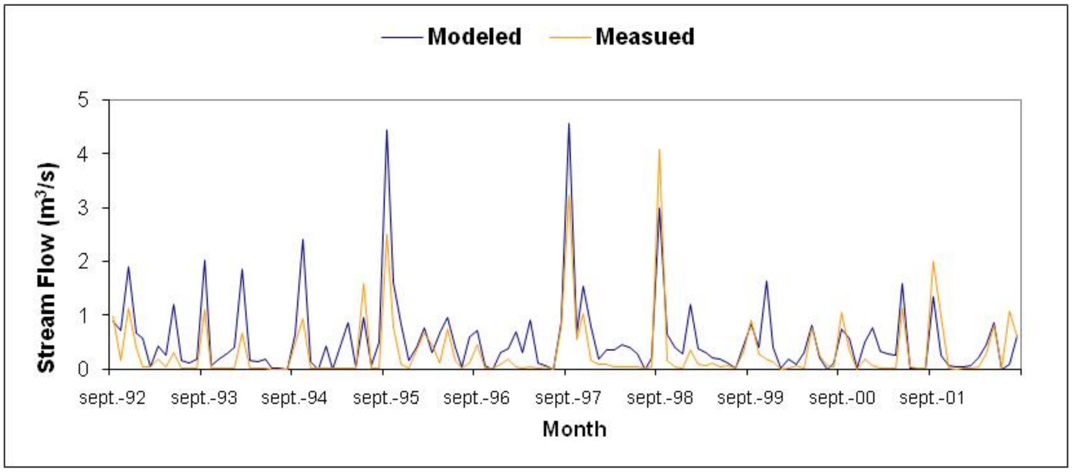


Figure 60 Variation of monthly measured and simulated stream flows by SWAT at the gauging station Skhira before calibration.

Before the calibration, the Nash coefficient and the coefficient of determination R2 were calculated respectively 0.62 and 0.69. it can be shown from figure that simulation with SWAT model can reproduces the hydrograph peak, however, it overestimates the measured values. After the calibration phase, a further improvement of efficiency and determination coefficients is seen, respectively, calculated to 0.75 and 0.81, which represents a good performance, however, there are still occurrence of overestimation stream flow especially during low flow . It should be noted that the measurement errors (human and technical error) and the existence of unrepresentative rainfall stations have an important role in assessing the results of simulation.

- **At the Zebbess gauging station**

The monthly stream-flow measured for this station are available from July 1996 until August 2002. The calibration process has led to improved values Nash coefficient and coefficient of determination values respectively from 0.64 and 0.79 before calibration to 0.85 and 0.88 after calibration. It can deduced from results that the simulation with SWAT before and after calibration allow to highlight the performance of the model to reproduce the flow in this sub basin. The model generates good peak stream flow of the two flood events that occurred in September 1997 and May 2000 according to the hydrographs (Figure 61), however we note that during the months of May and November 1999, the model generates more stream flow in the despite the measured stream flow on the field is insignificant.

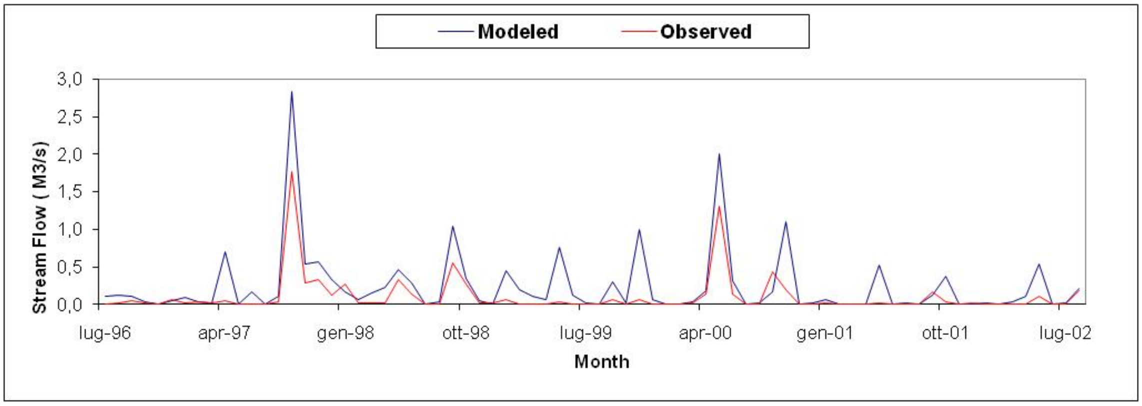


Figure 61 Variation of monthly measured and simulated stream flows by SWAT at the gauging station Zebbess before calibration

Calibration of hydrological and hydrogeological parameters (CN SOL_AWC, SLSUBSN, soil depth, Alpha_BF and GW_revap.) was performed only on sub-basin (n°13, 14, 15, 16 and 28) that are located upstream of Zebbess. Figure 65 shows the variation of monthly flows measured and simulated by the SWAT model at this sub-basin. The simulated average monthly flow at the outlet of sub-basin would be 0.15 m^3/s with a standard deviation of $0.32 m^3/s$.

- **At the Haffouz gauging station**

The Nash coefficients calculated respectively before and after calibration are 0.52 and 0.71 . The Adjustment of the model parameters has improved the coefficient of determination from 0.77 to 0.81. The simulation results of SWAT model before and after calibration are shown in Figure 62 and Figure 66. As observed in hydrograph, the SWAT model can well generate the flow especially during major flood in September 1997.

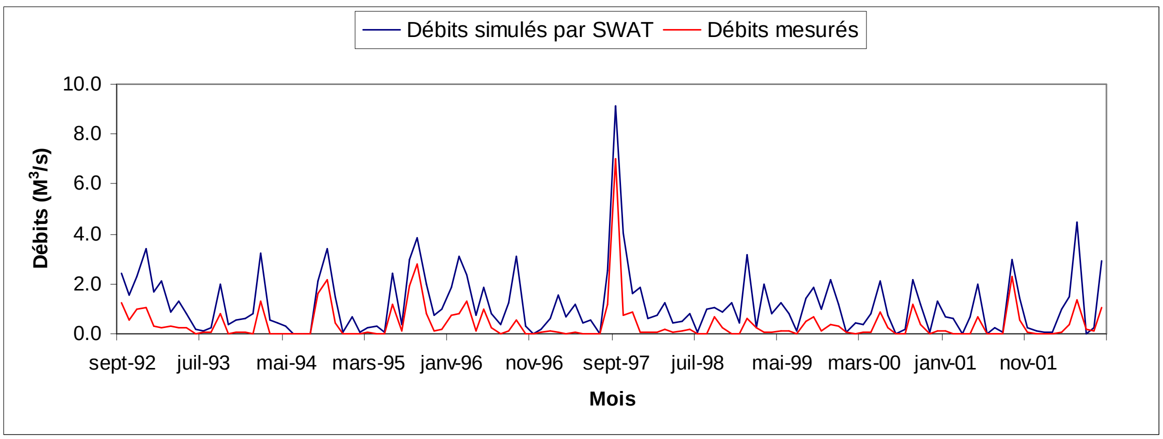


Figure 62 Variation of monthly measured and simulated stream flows by SWAT at the gauging station Haffouz before calibration

The solutions selected for adjusting the parameters include the reduction parameters and CN2 SOL_AWC respectively to 7% and 10%. In the same way, the parameter ALPHA_BF which reflect the contribution of groundwater to supply the hydrographical network was reduced by decreasing to 12%. Some efforts were done in this study to adjust effectively the parameters to decrease difference between simulated and measured data during the low flood, this unsuccessful task is related to the impact of WWSC on the hydrological system of the watershed. These works slowing the runoff and can store surface water. whereas the swat model is well appropriate to reproduce the stream-flow in the monthly Haffouz.

- **At the watershed Outlet**

Graphically we describe the variation of monthly inflow simulated and measured expressed in million cubic meters before calibration (Figure 63). During the whole period of simulation, we can observe that the SWAT model overestimates the outflow in the basin outlet. At the same time, we note a correlation between the modelled and observed volume for large floods during the months of October 1994, September 1995 and September 1997,

Particularly, for October 1994, if we compare the measured inflow 18Mm^3 to the simulated one 26 Mm^3. we confirm that the model overestimates the contribution. it is also noticeable through the same figure that there is a failure to reproduce the low and the null inflow event, the Nash coefficient calculated for this simulation is 0.60.

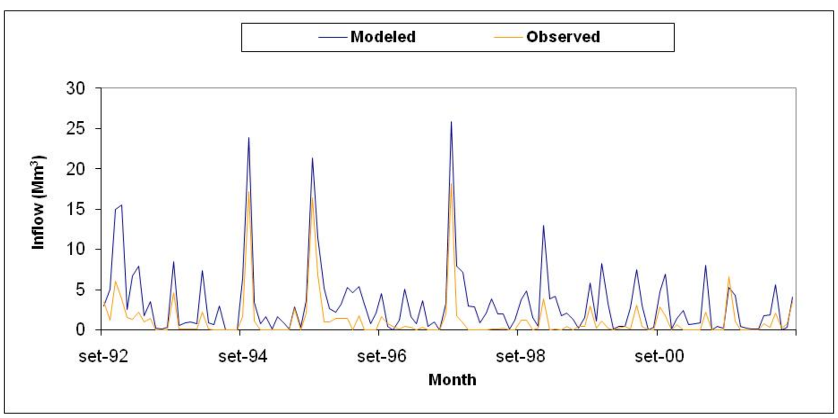


Figure 63 Variation of monthly measured and simulated stream flows by SWAT at the Merguellil watershed outlet before calibration

The adjustment of model parameters for the calibration procedure allowed a slight improvement in this coefficient to 0.64 while, the coefficient of determination R2 has undergone a slight reduction from 0.80 to 0.78. On the Figure 67, we plot the variation of inflow at the El Houereb dam after the simulated and measured calibration tests; we can see graphically the performance of the simulation results after calibration tests.

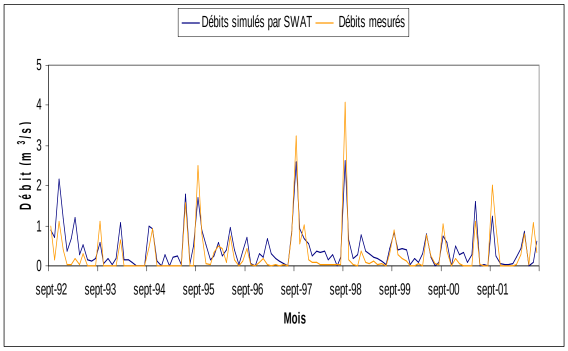


Figure 64: Observed and predicted monthly streamflow at Skhira after calibration

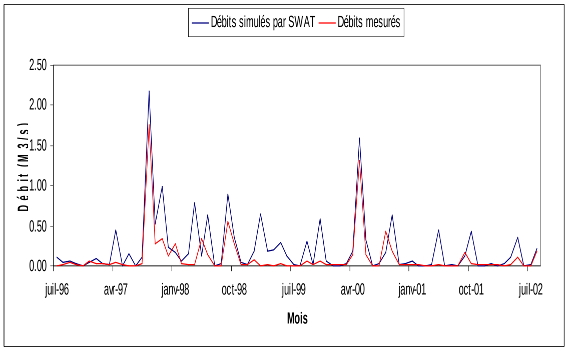


Figure 65: Observed and predicted monthly streamflow at Zebbess statio after

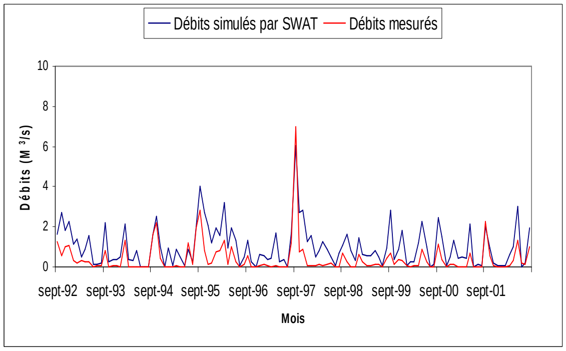


Figure 66: Observed and predicted monthly streamflow at Haffouz station after calibration

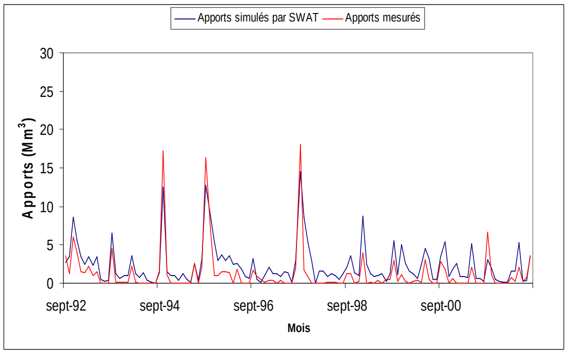


Figure 67: Observed and predicted monthly streamflow at watershed outlet after calibration

The solutions proposed during the process of calibration of parameters consist of reducing CN2 and SOL_AWC respectively to 9% and 9%. Similarly the contribution of groundwater to supply the hydrographic network was reduced by decreasing the parameter ALPHA_BF to 10%. After calibration test, we obtain a Nash coefficient of 0.64 implying an improvement in the efficiency of the model.

In conclusion, we can perceive that at the monthly scale, the simulation results of SWAT model were more satisfactory. The performance of the model to reproduce the flows at Skhira Zebbess and Haffouz as well as the inflow in the watershed outlet shows that the model is adequate for the Merguellil study area., all the statistical coefficients calculated before and after calibration tests are reported In

Table 26. The simulation results at the Zebess sub-basin are the most perform with the higher coefficient of efficiency.

Table 26 : statistics coefficients calculated for the monthly calibration of the SWAT model

	Outlet	Average	max	Min	Standard Deviation	Nash	R^2
Without Calibration	Skhira	0.55	4.57	0.00	0.74	0.62	0.69
	Zebess	0.2	2.83	0.00	0.45	0.64	0.79
	Haffouz	1.18	9.10	0.00	1.26	0.52	0.77
	Watershed	3.34	4.49	0.00	4.49	0.60	0.80
With calibration	Skhira	0.4	3.6	0.00	0.60	0.75	0.81
	Zebess	0.2	2.15	0.00	0.32	0.85	0.88
	Haffouz	0.65	5.93	0.00	0.76	0.71	0.81
	Watershed	2.29	2.64	0.00	2.64	0.64	0.78

6.1.8 MONTHLY WATER BALANCE OF THE WATERSHED

The Figure 68 and Figure 69 show the water balance of the month of September and of March Watershed Merguellil, balance are represented in terms of percentage. It is noted that during the month of September, most precipitation is lost through evapotranspiration (63%). runoff depth calculated to 29 mm which implies a runoff coefficient of 10%. During the month of March, we have less evaporation 55%, and runoff coefficient is about 11%, with more percolated water (15%). The water that flows laterally increases in March of 3% compared to September.

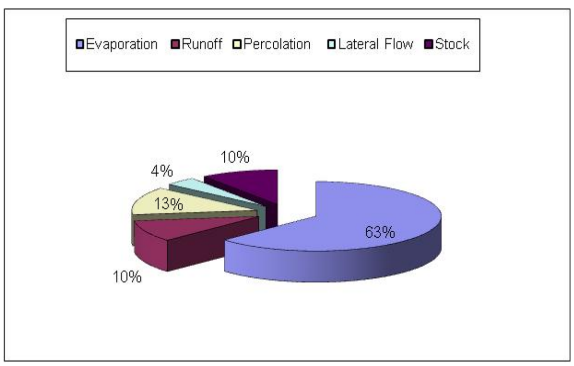


Figure 68 The water balance of the watershed Merguellil for an monthly simulation (September)

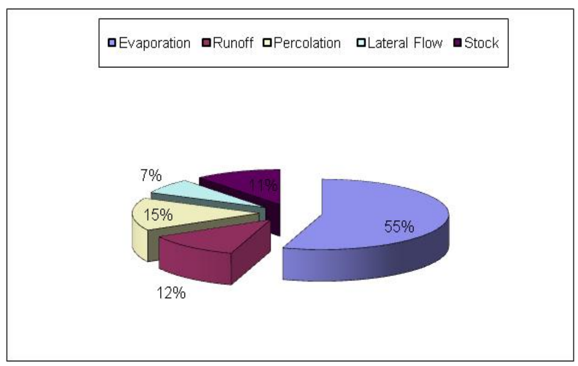


Figure 69 The water balance of the watershed Merguellil for an monthly simulation (March)

6.1.9 DAILY SIMULATION RESULTS

In the daily simulation, some Parameters "key" of the model are modified to adjust the simulation: the Curve Number, the Alpha Base Flow and the Ground Water Delay coefficients, soil depth parameter was changed to 1500 mm in the sub-basin sited in downstream of the watershed. The Sub basins affected by the calibration are: Skhira Haffouz and Zebbess, daily measurements at the dam were not available, we will only explain the simulated results.

- **At the Skhira gauging station**

The results presented in the graphs and table show a fairly good fit of the model to measured data. Indeed, the index of Nash (Nash and Suttcliffe, 1970) as the coefficient of determination R^2 is satisfactory for the calibration period (Table 27). Note that compared to the R^2, the Nash index provides a more accurate assessment of the effectiveness regarding compliance with the volume up, the absolute differences and representation of floods. The flood peak as recession phases also appear relatively well reproduced on the graphs (and Figure 74).

Table 27 : statistics coefficients calculated for the daily calibration of the SWAT model

	Outlet	Average	max	Min	Standard Deviation	Nash	R^2
Without Calibration	Skhira	0.50	41.9	0.00	2.46	0.68	0.71
	Zebess	0.16	12.47	0.00	0.76	0.75	0.76
	Haffouz	1.27	76.00	0.00	4.32	0.20	0.22
With calibration	Skhira	0.36	29.9	0.00	1.76	0.72	0.73
	Zebess	0.15	10.80	0.00	0.69	0.78	0.79
	Haffouz	0.82	67.40	0.00	3.11	0.59	0.60

Before calibration, the coefficient of Nash-Sutccliffe calculated for flow simulation in the Skhira subbasin is 0.68, which indicate a good prediction. The coefficient of determination R2 is 0.71. The test of calibration done consisted to reduce the parameter CN2 to 6% and to increase both parameters and SOL_AWC ALPHA_BF respectively 5% and 4%.

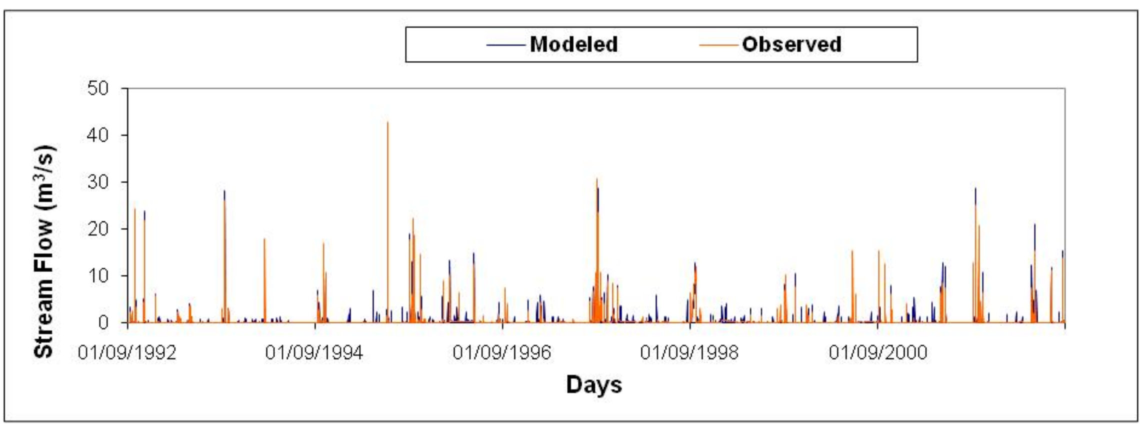


Figure 70 Variation of daily measured and simulated stream flows by SWAT at the gauging station Skhira before calibration

The coefficient Nash Sutccliffe was improved and there is a slight improvement for the coefficient of efficiency calculated after calibration (0.72). While coefficient of determination R2 obtained was 0.73. Figure 74 shows the variation of measured and simulated daily flow after calibration. Comparing the Figure 70 Variation of daily measured and simulated stream flows by SWAT at the gauging station Skhira before calibration and Figure 74) we can note a distinct improvement in the simulation of three major floods taking place on 14/09/1993, 07/09/1997 and 18/09/2001. However, we note a low flow simulated in particular dates in which no flow was recorded at the Skhira station, for example days of April 1995. The Stream flows generated by the SWAT models for this period are very high compared to which that are measured with insignificants values. According to Rabhi (1998), flow data recorded from the gauging station Skhira (B 16) are well reliably. The daily mean simulated flow in sub-basin Skhira throughout the simulation period is 0.36 m^3/s with a standard deviation of 2.46 m^3/ s, the mean measured daily flow at the gauging station is 0, 31 m^3/s with a standard deviation of 1.89 m^3/s.

- **At the Zebbes gauging station**

The daily flow measured for the gauging station Zebess are available from the date of startup of the station 08/06/1996, we calibrated the model and calculated the coefficients of Nash and determination R2 for the data set from 1992-2002. Before model calibration, the coefficient of Nash-Sutccliffe for this simulation was 0,75, involving a good prediction of simulated streamflow. The coefficient of determination R2 is calculated 0.71.

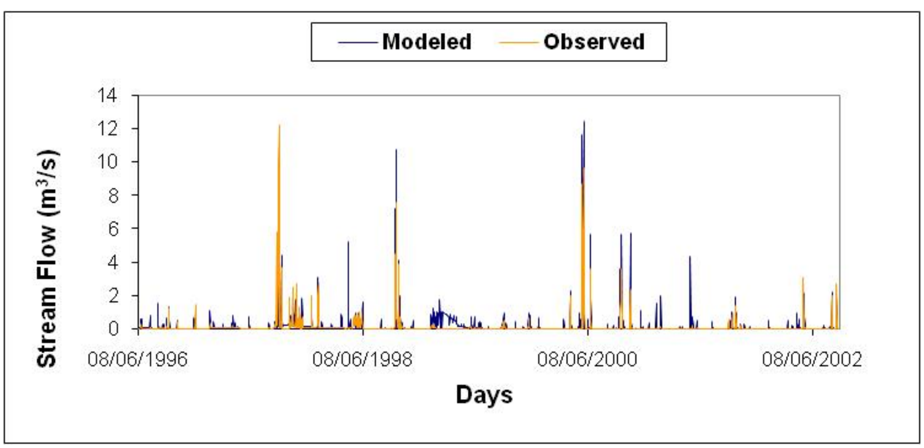


Figure 71 Variation of daily measured and simulated stream flows by SWAT at the gauging station Zebbess before calibration

The calibration approach consisted to reduce the parameter CN2 to 7% and increasing both SOL_AWC and ALPHA_BF parameters respectively to 6% and 7% of the average value predefined by the model, too. However, we reevaluated the SLSBSN parameter of the beginning of the simulation, because it was inadequate for daily simulation since the statistical results and graphics obtained did not allow the performance issued after monthly calibration , the values of the coefficient of Nash-Sutccliffe are in fact very low during the initial simulation. This setting as we have explained before refers to the slope in the sub basins so we have adjusted this parameter before model calibration. After calibration of the model, the coefficient of determination R2 obtained was 0,79 and the efficiency factor reached was 0.78. We can see the improvement of results through the Figure 71 and *Figure 75* which refer to the variation of measured and simulated daily flow before and after calibration. The mean daily stream flow modeled in sub-basin Zebbess throughout the simulation period 1996-2002 is 0.15 m^3/s with a standard deviation of $0.97 m^3/s$, while the mean daily stream flow measured is 0, 10 m^3/s with a standard deviation of 0.67 m^3/s.

- **At the Haffouz gauging station**

In the case of the Haffouz station, flow measurement is from the mean velocity derived from the measurement of velocity at the surface (which is not always the case, because of the stone can damage the meter flow), the bed of the river is very wide 200 m (El Euch, 2000).

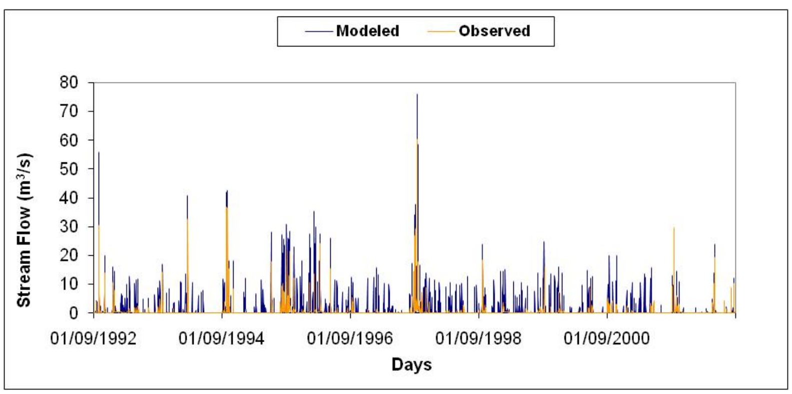


Figure 72 Variation of daily measured and simulated stream flows by SWAT at the gauging station Haffouz before calibration

The *Figure 72* represents variation of daily flow measured and simulated by SWAT before calibration for the Haffouz gauging station, we can assume that the SWAT model failed to simulate the measured values particularly for low flows. As approach considered, we have calibrated the model for the upstream of sub-basin and in particular Skhira and Zebbess subbasin (as indicated in the last paragraph) and then adjusted the internal parameters for Haffouz the sub-basin, keeping always in mind the distribution of WSCW. The coefficient of Nash-Sutccliffe for this simulation is calculated 0.19. The coefficient of determination R2 is calculated 0.20. The calibration approach consisted to reduce the CN2 parameter of 4% and to increase both parameters SOL_AWC and ALPHA_BF respectively 3% and 10%. In addition the parameter set (GW_DELAY and RCHRG_DP) were modified. The coefficient Nash-Sutccliffe was enhanced to 0.58. The coefficient of determination R2 was improved to 0.59. The Figure 76 illustrate the result after calibration for the Haffouz gauging station.

- **At the Mergullil watershed outlet**

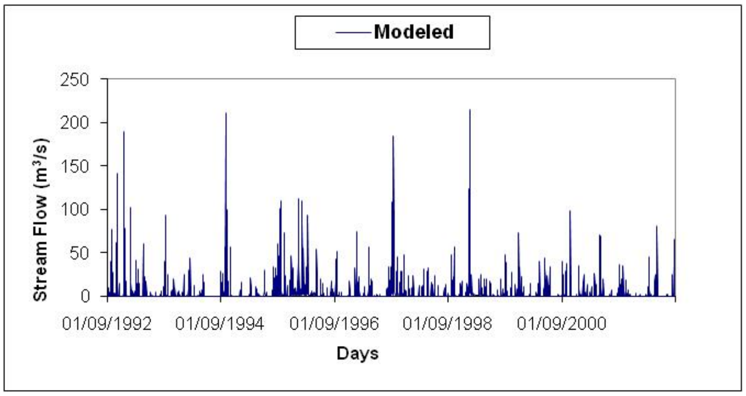


Figure 73 Variation of daily simulated stream flows by SWAT at the Outlet Merguellil watershed

The mean daily stream flow simulated at the Outlet Merguellil watershed through the period 1992-2002 is estimated to 3.31m^3/s, with a standard deviation of 12.49 m^3/s and a maximum value of 214.54 m^3/s calculated at 19/01/1999.

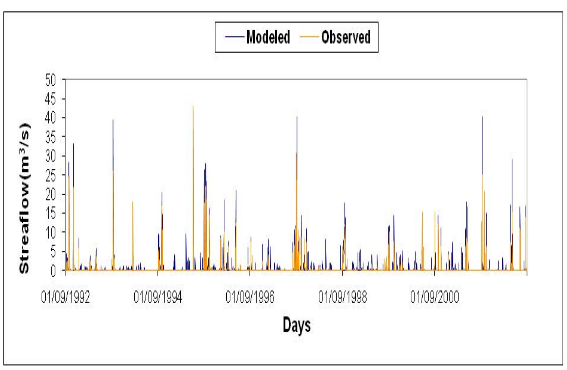


Figure 74: Observed and predicted daily streamflow at Skhira gauging station after calibration

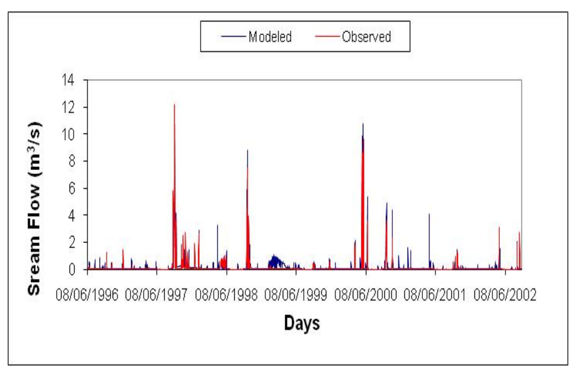


Figure 75: Observed and predicted daily streamflow at Zebbess gauging station *after calibration*

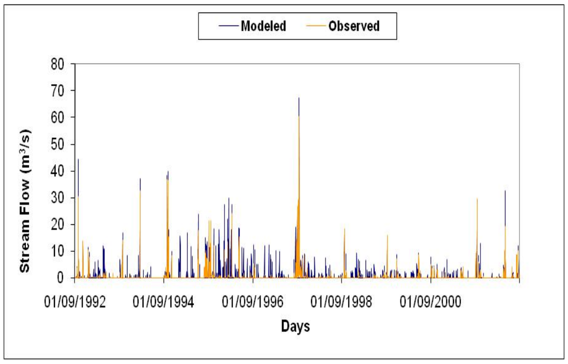


Figure 76: Observed and predicted daily streamflow at Haffouz gauging station after calibration

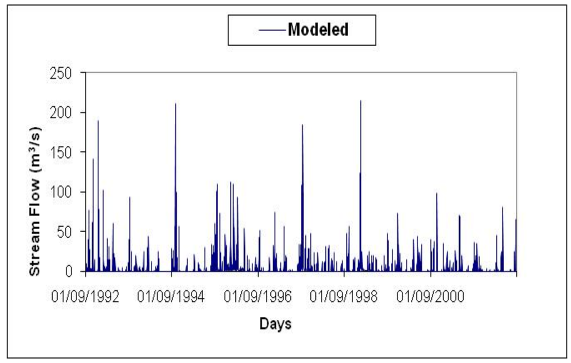


Figure 77: predicted monthly streamflow at daily watershed outlet after calibration

6.1.10 WATER QUALITY SIMULATION

The sediment and nutrient of surface water were simulated form 1992 to 2002 with the SWAT model taking into consideration actual land-use and management practices (fertilizer application tillage operations,)

6.1.10.1 EVALUATION OF ANNUAL SEDIMENT

Figure 78, Figure 79 and Figure 80 show respectively the simulation of annual variation of sediment load and sediment concentration at the outlet of sub-watershed, Skhira and Haffouz Subbasin.

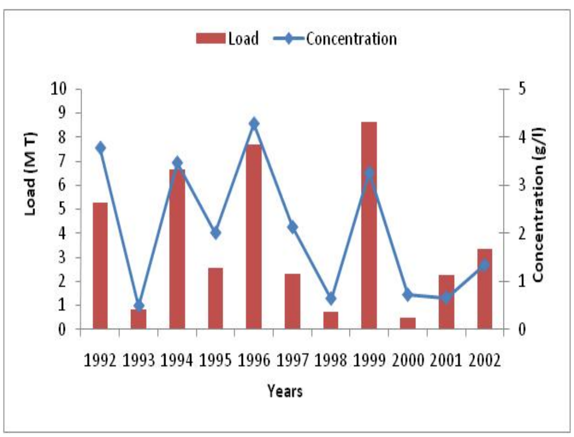


Figure 78 Sediments Concentration and Sediments Average yearly loads simulated at the watershed outlet. 1992-2002

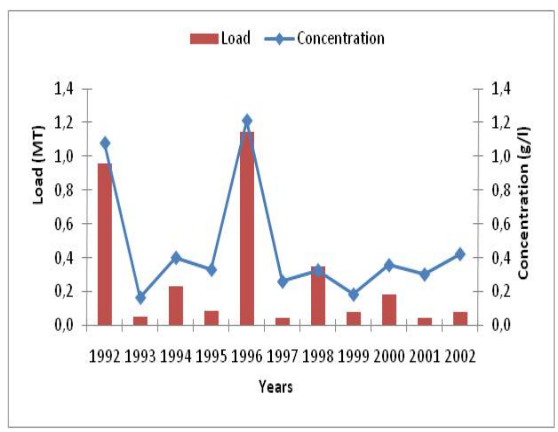


Figure 79 Sediments Concentration and Sediments Average yearly loads, simulated at the Skhira subbbasin 1992-2002

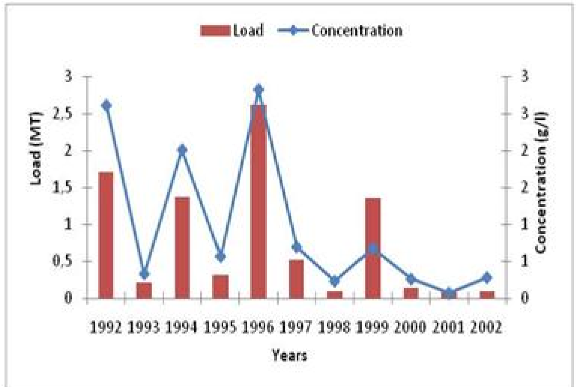


Figure 80 Sediments Concentration and Sediments Average yearly loads simulated at the Haffouz subbbasin 1992-2002

Table 28 Masses and concentrations of sediment load in the watershed outlet and Skhira subbasin

	Sediment Load (T/km/Y)		Concentration (mg/l)	
	Watershed	Skhira	Watershed	Skhira
Average	2988	1574	2.2	0.5
Standard deviation	2694	2059	2.0	0
Max value	7543	6098	6.4	1.2

The average annual of loaded suspended solids produced by the watershed Merguellil is estimated about 318400 T with a standard deviation value of 326900 T. The fluctuation of the sediment load from one year to another is directly related to the volume of water flow. The largest mass produced (862,500 T) was simulated in 1999 , corresponding to the same date in which highest flow rate (0.45 m^3/s) is observed, while the lowest sediment load (7548 T) was simulated in 2000, which corresponds to low flow (0.133 m^3/s). These average values found at the outlet are not in conformity with results of previous studies, in fact, from leveling measurements made by the IRD and the EGTH (Garetta and Our Ghem, 1999), the sediment input was estimated from the impoundment of the dam until 1997.

The total sediment load from the 1989 until 1997 is approximately 13 million m^3 of sediment. Given an average density of sediment equal to 1.3 (Garetta and Our Ghem, 1999), the estimated weight of sediment is estimated to 2,112,500 T per year. (Raspic, 1999). The results found by simulation of the SWAT model are the order of 3184300 T/yr, so the specific erosion determined by SWAT model is 2784 T/km^2/year. The mass of transported sediment from Skhira and Haffouz subasin are calculated from SWAT model respectively 218 000 and 903,000 T per year.

The sub-basin Skhira represents about 10% of total inputs water yield. The Haffouz subasin represent the half of the total area of watershed Merguellil and it provides about 43% of total loaded sediments. In fact, the rest of the sediments (57%) 1211500 T per year are loaded by the Zebbess Al Hammam, Az Zbar and Ben Zitoune subbasins. Raspic (1999) indicates that the specific erosion in the whole watershed and the Haffouz subasin are respectively estimated to 1760 T/km^2/year and 1580 T/km^2/year. The specific erosion on the Zebbess Al Hammam, Az Zbara and Ben Zitoune which the area is 525 km^2 on the Merguellil watershed would be 2300 T/km^2/year , explaining that this high value is principally due to the diverse cultures present in this part of the basin.

Table 29: Comparison of specific erosion result in Skhira subbasin

	Specific Erosion (T/km^2/Year)	**Sources**
Bouzaiane and Lafforgue (1986)	1207	Measured
Raspic (1999)	1170	Williams Formula
Swat model	1213	SWAT Model

However, if we compare the specific erosion of the Skhira subbasin, calculated by the SWAT model, with preceding studies, we can note that the simulated results agree well with the observed values (Table 29). While for Haffouz Substation, the results of previous literature studies varied much from one author to others (Table 30). In fact, specific erosion simulated by SWAT is in accordance with results of Bouzaiane and Lafforgue (1986), Saad (1995) and Tchatagba (1998). Whereas, Ben Sassi (1990) estimated the specific erosion the USLE method and by a digital model but the results have no concordance with reality according to Raspic (1999), since estimation with digital model, significantly overestimates observed solid transport. considering that the specific erosion at the dam is only 1760 T/km^2/y of, specific erosion could be Haffouz maximum of 3130 T/km^2/year if there was no erosion in the downstream part of 'Haffouz to the dam, which is not possible. The value of 5130 is impossible T/km^2/year.

Table 30 Comparison of specific erosion result in Haffouz subbasin

	Specific Erosion ($T/km^2/an$)	Method
Bouzaiane S. & Lafforgue A. (1986)	1215	Observations
Ben Sassi(1990)	1750	U.S.L.E. Method
Ben Sassi (1990)	5130	Digital model
Saadaoui (1995)	1244	Regression of observations
Tchatagba (1998)	1355	Williams formulate
Raspic (2000)	1580	Williams formulate
Actuel study	1250	SWAT model

On the watershed outlet, the concentration of the suspended matter varies from 4,16 g/l in 1999 to 0,3g/l in 2001. The average value of concentration is estimated to 2,4 g/l with a standard deviation of 2 g/l.

6.1.10.2 EVALUATION OF MONTHLY SEDIMENT YIELD

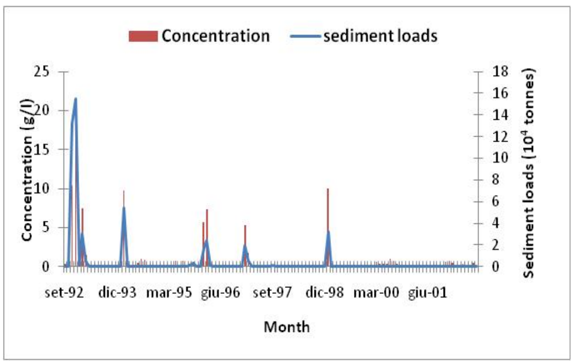


Figure 81 Sediments Concentration and Sediments average monthly load simulated at Skhira for the period (1992-2002)

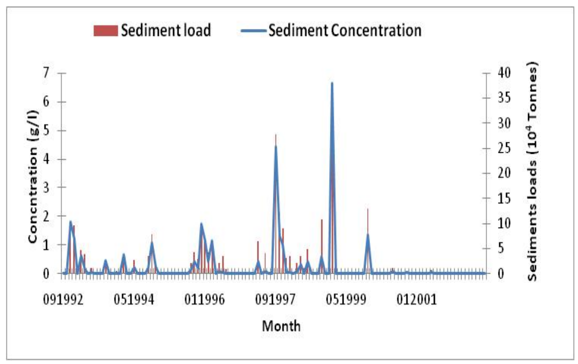


Figure 82 Sediments Concentration and Sediments average monthly load, simulated at the Zebbess subbbasin (1992-2002)

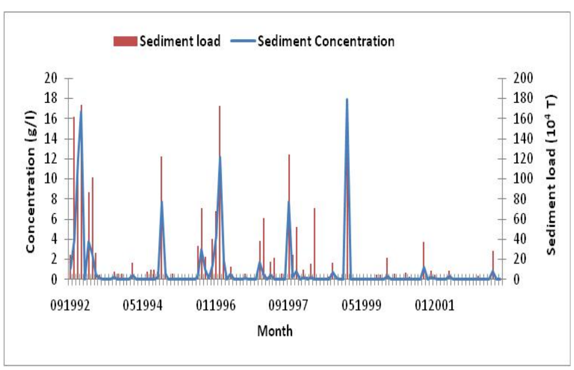


Figure 83 Sediments Concentration and Sediments average monthly load, simulated at the Haffouz subbasin for the (1992-2002)

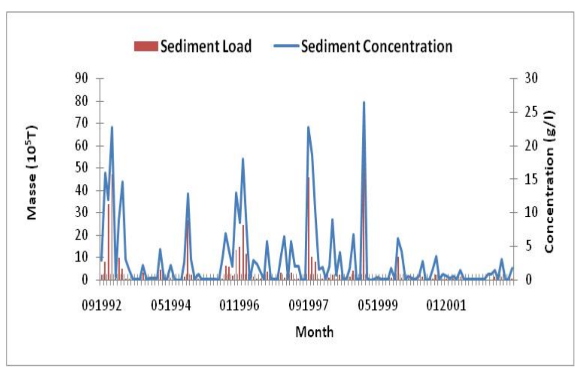


Figure 84 Sediments Concentration and Sediments average monthly load, simulated at the outlet for the period (1992-2002)

The list of figure (Figure 81, ***Figure 82***, Figure 83 and Figure 84) shows respectively the monthly variation of the sediment load and sediment concentration at Skhira, Zebbess, Haffouz subbasin and the watershed outlet. The sediments average monthly load for the entire simulation period is calculated respectively to 4000T, 13,800T, 91140T and 342480T, with a respectively standard deviation of 19500T, 45,560 T, 290800 T and 1023600 T. The annual average concentrations determined are 1 g/l ,0.35 g/l, 1,8 g/l and 2,9 g/l with a respectively standard deviation of 3g/l - 0.86 g/l.

6.1.10.3 EVALUATION OF DAILY SEDIMENT YIELD

The Figure 85 and Figure 86 show respectively the daily variation of the sediment load and concentration at the watershed outlet. The sediments average monthly load for the entire simulation period is calculated to 318T, , with a standard deviation of 26,7 T. The annual average concentration would be 2,4 g/l with a standard deviation of 13 g/l . The maximum value of sediment concentration is 157 g / l simulated on 25/10/1997 but it does not correspond to the date of maximum stream-flow.

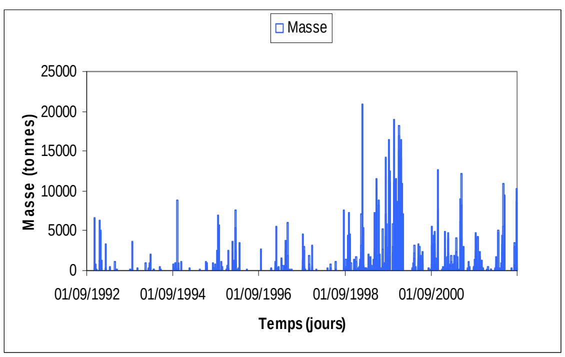


Figure 85 Sediments average daily load simulated at the Haffouz subbbasin for the period (1992-2002)

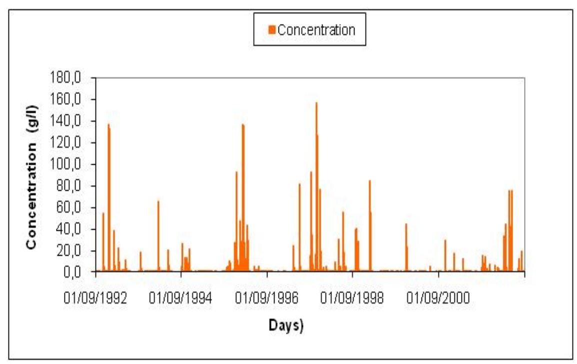


Figure 86 Sediments Concentration simulated at the outlet for the period (1992-2002)

6.1.11 EVALUATION OF NITROGEN AND PHOSPHORUS LOAD

6.1.11.1 EVALUATION OF ANNUAL NITRATE LOAD

Since no water quality data were available during the simulation period (1986-2005), the model was not calibrated. Figure 87 shows the annual variation of the nitrate load (as nitrate, ammonium and nitrite) simulated at the watershed outlet. The mean annual load of nitrate loaded from the entire watershed is evaluated by the swat model to 1276 kg with a standard deviation of 1170 kg. Annual nitrate load fluctuate with a minimum value of 93 kg recorded in 1998 and a maximum value of 3423 kg recorded in 1999. The variation of annual loaded nitrate into the watershed, show a high inter-annual variability that can be due to the by variation of the inter-annual flow.

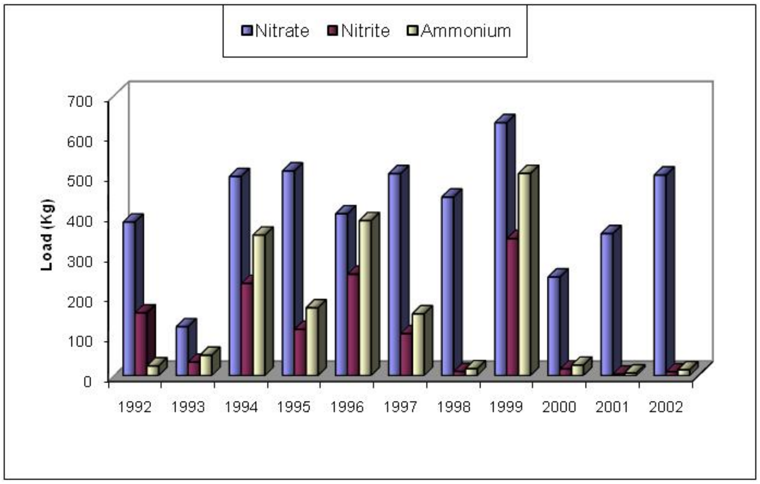


Figure 87 Annual variation of the of nitrate load at Merguellil watershed outlet

6.1.11.2 EVALUATION OF ANNUAL MINERAL PHOSPHORUS LOAD

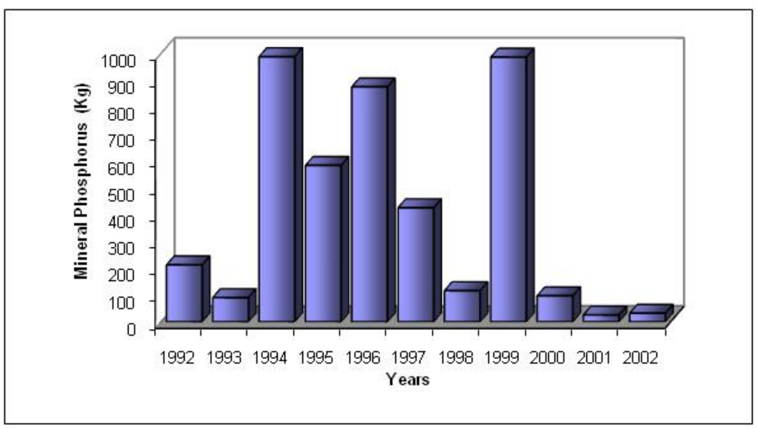


Figure 88 Annual variation of the of nitrate load at Merguellil watershed outlet

Figure 88 shows the annual variation of the phosphorus load simulated of the watershed outlet. The average annual mineral phosphorus load is estimated by SWAT model to 443 kg with a standard deviation of 391 kg while the average annual organic phosphorus load is estimated to 1923 kg with a standard deviation of 1170 kg. These values highlight the importance of mineral phosphorus produced by the Merguellil basin from organic phosphorus. The maximum value of mineral phosphorus simulated in 1994 was 990 kg and the minimum value modeled in 2001 was 25 kg. The variation of annual loaded phosphorus into the watershed, show a high inter-annual variability that can be due to the by variation of the inter-annual flow.

6.1.11.3 EVALUATION OF DAILY NITRATE LOAD

Figure 89, Figure 90 and Figure 91 show respectively the daily variation of the nitrate, ammonium and nitrite load simulated by SWAT model at the watershed outlet. The daily average concentration of loaded nitrate the Merguellil watershed is estimated to 12.8 µg/l, with a standard deviation 51.5µg/l. The maximum value of 1080 kg was simulated on 26/10/1997 related to measured high flow rate (Table 31).

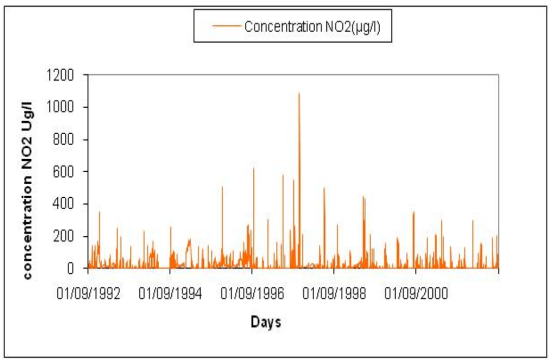


Figure 89 Daily variation of the of NO2 load at the Merguellil watershed outlet for the period (1992-2002)

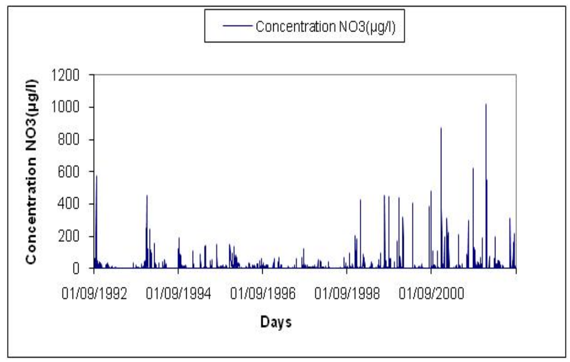


Figure 90 Daily variation of the of NO3 load at the Merguellil watershed outlet for the period (1992-2002)

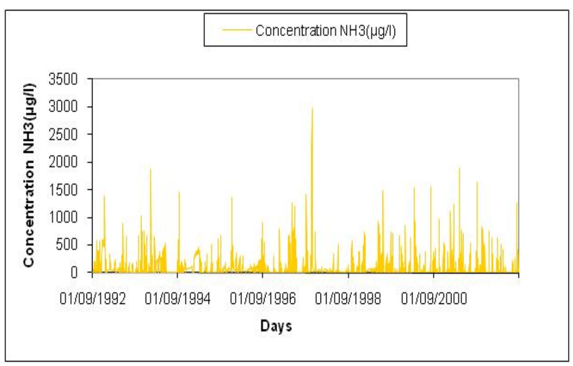


Figure 91 Daily variation of the of NH3 load at the Merguellil watershed outlet for the period (1992-2002)

Table 31: Concentration of NO2, NO3 and NH at the Merguellil watershed

	Concentration NO2(µg/l)	**Concentration NO3(µg/l)**	**Concentration NH3(µg/l)**
Average	21,6	12,8	73,8
Standard Deviation	41,0	46,6	170,0
Valeurs maximales	1080	1020	2980

6.1.11.4 EVALUATION OF DAILY MINERAL PHOSPHORUS LOAD

Figure 92 shows the daily variation of mineral phosphorus concentration, simulated at the outlet of the watershed. The daily average concentration of mineral phosphorus is about 3380 µg/l with a standard deviation of 7184 µg/l. By examining these values we can deduce the importance of the quantity of mineral phosphorus produced by the basin relatively to the mineral nitrate in its various forms (nitrate, nitrite and ammonium). We also note that the daily concentration produced is very irregular and the maximum value of 103,000 µg/l was observed on 26/10/1997.

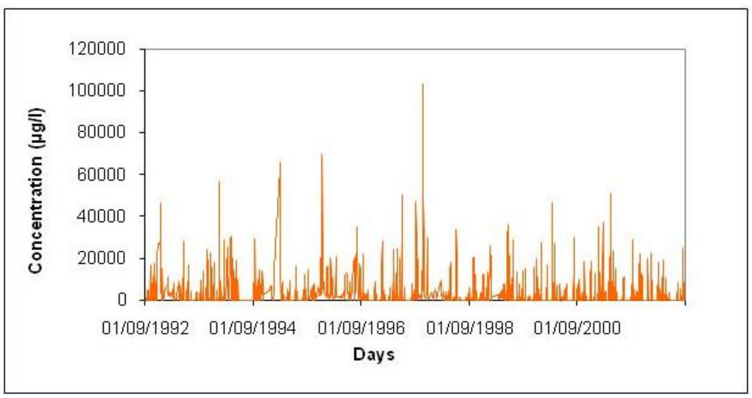


Figure 92 Daily variation of the mineral phosphorus loaded at Merguellil watershed.

6.1.12 SPATIAL DISTRIBUTION OF PHOSPHATE AND NITRATE LOADS

SWAT model through its interface (GIS AVSWAT) is able to visualize the results of spatial simulation. we can observe from the Figure 93 and Figure 94, the spatial distribution load of nitrate and phosphorus in the watershed Merguellil. From Figure 93 we can observe that the worst areas affected by diffuse pollution of nitrates in the Merguellil watershed are the sub-basin 16 and 21 which correspond respectively to the upstream o Zebbess sub-basin and the region Houereb, with an average daily loss of between 4 and 5 kg / ha. The areas least affected by the losses of nitrate are the subbasin 1, 2, 6, 12, 27 and the region of Skhira with a load between 0 and 0.5 kg / ha. Regions and Haffouz and Chrichira are moderately involved in the load of nitrates because the sub-basin 10, 9 and 29 have a loss of nitrogen between 1 and 3 kg/ha.

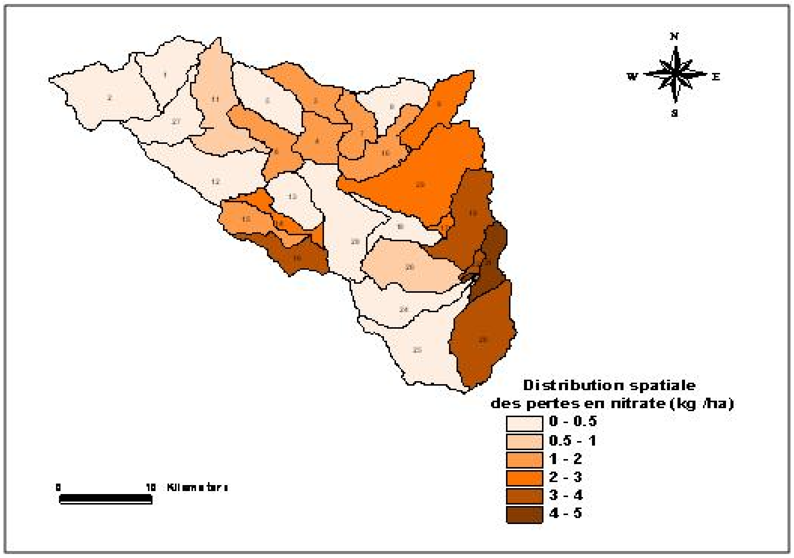


Figure 93 : Spatial distribution of nitrate losses in the watershed Merguellil

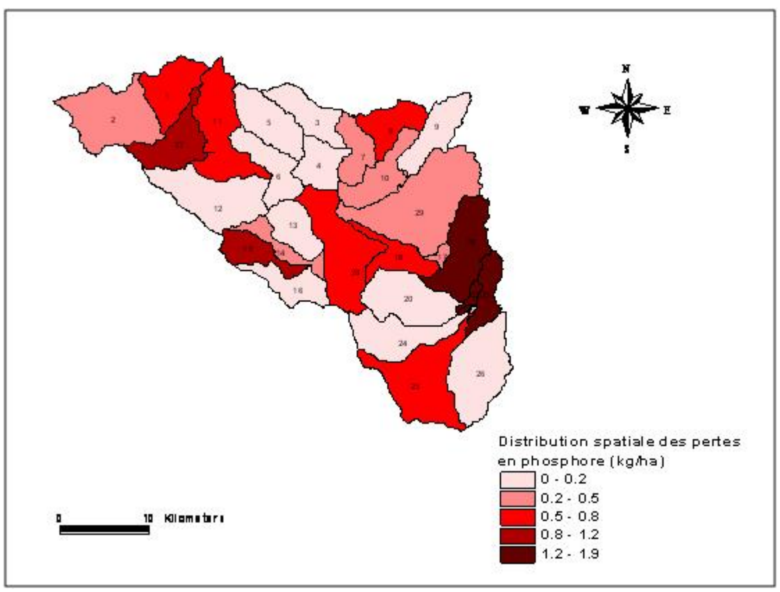


Figure 94 : Spatial distribution of nitrate losses in the watershed Merguellil

The spatial distribution map of phosphorus load (Figure 94) shows that the area's most affected by the diffuse pollution in the Merguellil watershed are the sub catchments 19, 21, 15 and 22 which correspond to the area neighboring to the dam El Houereb. The Subbasins least affected by the phosphorus pollution, are extended over the entire watershed.

6.1.13 ALTERNATIVE SCENARIOS

In the SWAT model, multiple scenarios can be generated by changing land management by varying crops and cultivation methods and by using crop rotations and pattern; in the current case, we will try to study four scenarios that will be tested to assess the impact of these changes on diffuse pollution and the relative impact of water balance.

In the first scenario, we assume that all agricultural area was converted to irrigate wheat (WWHT) with an application rate of nitrate and phosphorus and water quantities of 60 mm for irrigation are applied, and divided into two quantities of 30 mm each during the months of April and May. The quantities of nitrate and phosphorus are respectively 100 kg / ha and 10kg/ha. Two sub-scenarios were studied for irrigation. In a first, all the water quantity required is provided from the river, in the second sub-scenario, irrigation water is provided by the river with rate of 50% while the other 50% of quantity is provided from the aquifer. The results concerning the evolution of volumes at the outlet are shown in Figure 95. We note that monthly flows down following the pumping of water while impact are more pronounced when the pumping is done from the river (scenario 1) than in the water (scenario 2). We also note that actual evapotranspiration is also increased in both scenarios as indicating an increase in crop production. This increase in crop production is also due to increased intake of nutrients. This increase in production simulated by SWAT model is about 35% while fertilization increased by only 20%.

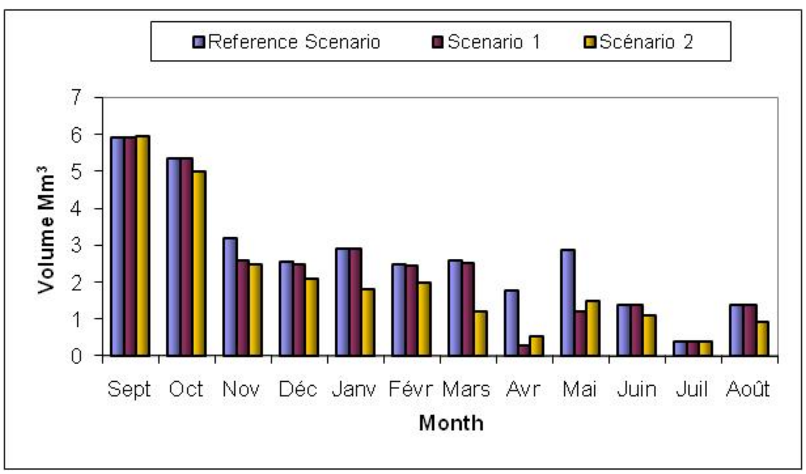


Figure 95 Impact of irrigation scenario (April and May) on monthly water volume in the outlet - Scenario 1: provide 60 mm of irrigation from rivers - Scenario 2 provide 30 mm irrigation from river and 30 mm from aquifer.

However, the increase of fertilization also resulted in increased diffused pollution from agriculture and especially an increase of 22% of nitrate concentrations in the River. It is interesting to note that the two scenarios lead to different variations of nitrate concentration from the fact that the water of aquifers is less charged than the River. This result is illustrated in Figure 96.

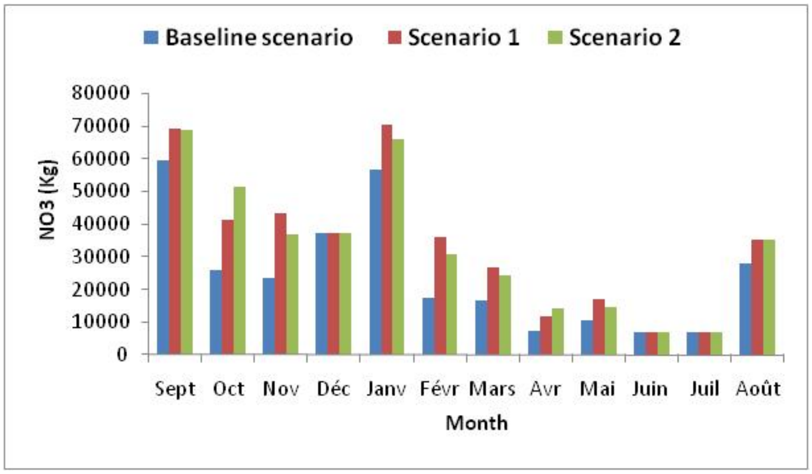


Figure 96 Variation of nitrate concentration in the river for the 2 scenarios

The second type of analysis of scenario done in this study deals about the ponds, as previously mentioned these structure constructed within the watershed contribute to the storage of big volume of water (about 6.43 million cubic meters per year (Mm^3/year), from 1996 to 2005 (Le Goulven and al, 2009). The first scenario selected predict to increase the percentage of managed area by small dams from 30% to 40% over the entire basin. This scenario was designed to investigate the impact of changing land management on flow rates and erosion. Some of parameters relative to the modeling of the pond in SWAT must be modified. The PND_FR parameter which represent the fraction of subbasin area that drains into ponds are increased, this parameter should be between 0 and 1. This last is increased from the initial value fixed during the calibration phase (6.1.5) to 0,3, we decide to increased it to 0,5 in the subbasins n° (1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18). The surface area of ponds when filled to principal spillway and volume of water stored in ponds when filled to the principal spillway were increased also. The volume of water stored in ponds when filled to the emergency spillway is kept constant. However the number of days needed to reach target storage from current pond storage was selected 30 because the storage period of the small dams in the Merguellil does not exceed one day since all the water entering to the pothole is loosed either by evaporation or by infiltration to the aquifer. The streamflow simulated with the new scenario in the sub basin Skhira Zebess and Haffouz was compared to the baseline scenario. The results of these simulations are presented in Figure 97, Figure 98 and Figure 99.

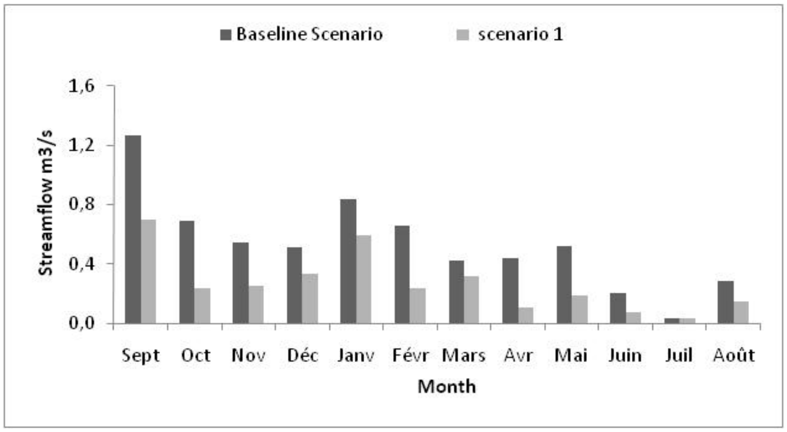


Figure 97 Impact of the intensification of water harvesting systems "ponds" on the average monthly stream flow in the Skhira subbasin

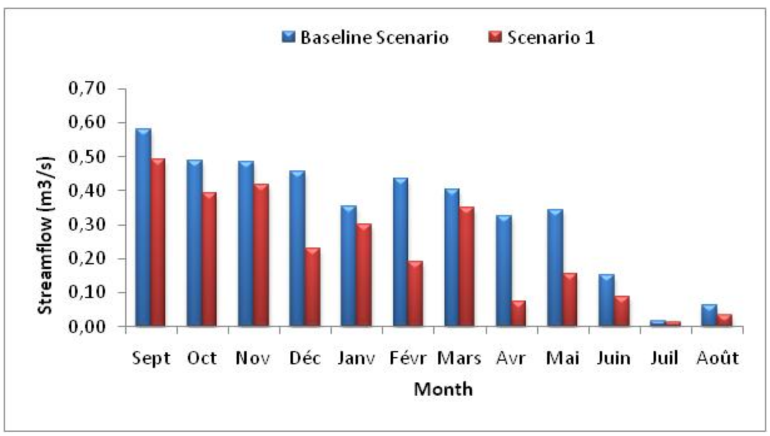


Figure 98 Impact of the intensification of water harvesting systems "ponds" on the average monthly stream flow in the Zebbess subbasin

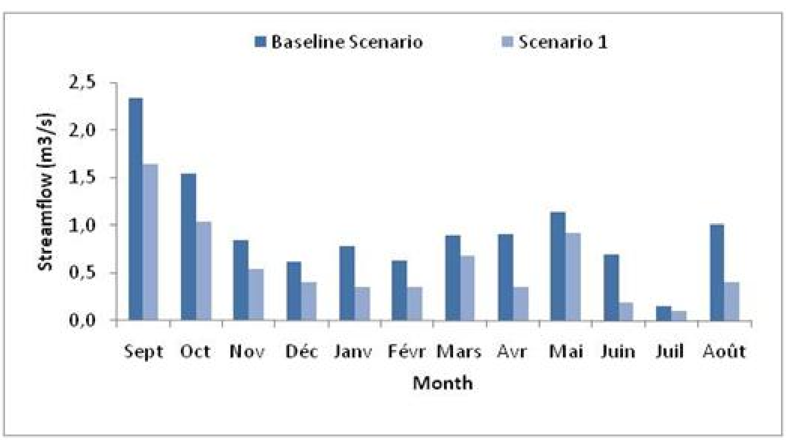


Figure 99 impact of the intensification of water harvesting systems "ponds" on the average monthly stream flow in the Haffouz subbasin.

According to those results, there is a significant rate reduction at the sub basins Skhira Zebbess and Haffouz. and as expected, a significant reductions in stream-flow especially during the months September is observed. The Table 32 reports the result of this scenario.

Table 32 Impact of the intensification of water harvesting systems "ponds" on streamflow in the Merguellil watershed management

Subbasin	Average reduction of flow rate %	Maximal reduction of flow rate %		Minimal reduction of flow rate %	
Skhira	50%	76%	April	24%	March
Zebbess	38%	77%	April	13%	March
Haffouz.T	40%	73%	June	24%	March

6.2 WEAP SIMULATION

6.2.1 SENSITIVITY ANALYSIS

In order to assess the sensitivity of the model to the different parameters used for calibration, a sensitivity analysis was undertaken. Sensitivity of the model to parameters was assessed by estimating effects of changes in parameters on the Least squares objective function in the Merguellil Watershed. This function was selected because it varies the same way as the Efficiency criterion but it is much more sensitive and it was easier to assess changes in the efficiency of the model. Mean monthly flow was also plotted and compared to the mean monthly flow corresponding to the best set of parameters. Table 33, Figure 100, Figure 101, Figure 102and Figure 103 illustrate the results of the sensitivity analysis.

Table 33 Variations of the Least Squares Objective function and of the mean annual simulated flow due to changes in the parameter values.

Parameters	Value	Least squares	Mean annual flow (Mm3)
Effective precipitation	90	340.7	378,2
	89	302.7	343,1
	93	375.6	410,0
Runoff/infiltration ratio	35/65		358,9
	40/60	313.5	378,2
	45/55	334.3	398,6
Hydraulic conductivity (m/day)	0,9		362,5
	0,7	328.9	380,6
	0,1	306.8	369,0
Crop coefficients	+10%	400,12	438,3
	-10%	298,23	332,4

The sensitivity analysis shows that only effective precipitation and crop coefficients have an impact on the mean annual flow. Compared to the other parameters, Effective precipitation has a relatively low impact on the quality of the simulation (lowest variation of the Least squares objective function). In contrast hydraulic conductivity and crop coefficients variations seem to have the greatest impact on the model efficiency. Figure 100 and Figure 101 (monthly average stream-flow variations) shows that hydraulic conductivity and runoff/infiltration ratio affect the balance in the quantity of water all the months, however effective precipitation and crop coefficients not affect the mean monthly flow curve.

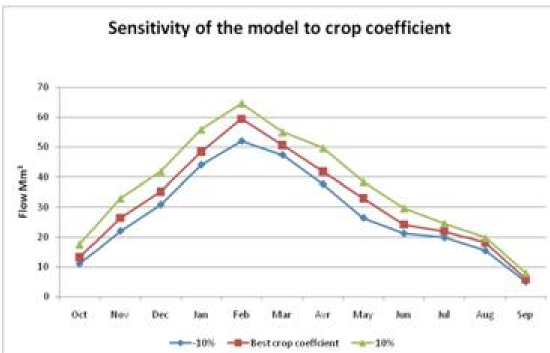


Figure 100 : Sensitivity of the model to crop coefficient

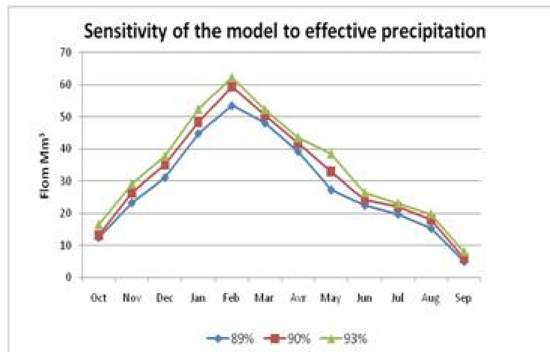


Figure 101 Sensitivity of the model to effective precipitation

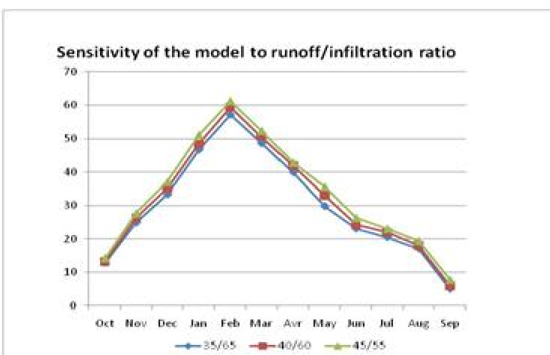


Figure 102 Sensitivity of the model to runoff/infiltration ratio

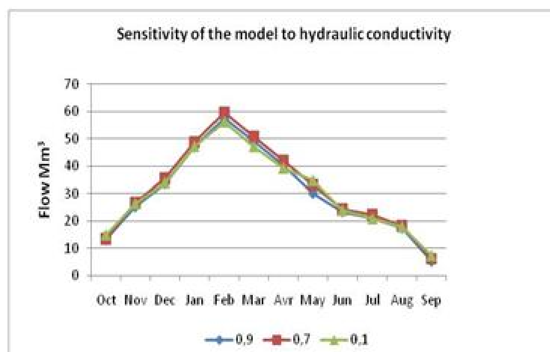


Figure 103 Sensitivity of the model to hydraulic conductivity

6.2.2 SIMULATION OF STREAMFLOW

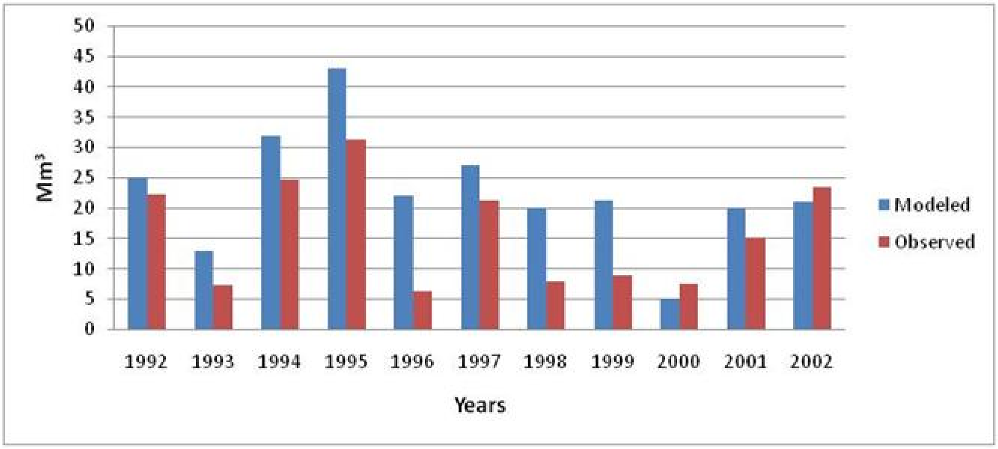


Figure 104 Comparison of simulated and observed yearly flow (1992-2002).

Figure 104 represent a comparison of observed and simulated flows at the outlet of Merguellil watershed for the period 1992-2002. Comparison of monthly observed and simulated flow for the entire period of simulation (1992-2002) is also presented in Figure 105. It seems to be a good agreement between observed and simulated flow. the Nash coefficient was calculated for the yearly simulation is 0.65 and for the monthly simulation 0,41, Simulated yearly flow seems to agree the least with observed data . In this catchment the model is systematically overestimating values of flows, but this could not be resolved during the optimization routine. The fact that Merguellil catchment encompasses a large zone with WSCW area (i.e. an area with zero runoff) could be an explanation for the difficulty of calibration. However important note about the efficiency of the model are that the model is generally either overestimating the flow but there is a good agreement in time concordance of peak flows. According to this result we note that the return to low flow after a peak flow follow the same pattern in simulated and observed-plots which means that groundwater modeling gives an acceptable view of the slow response of the catchment.

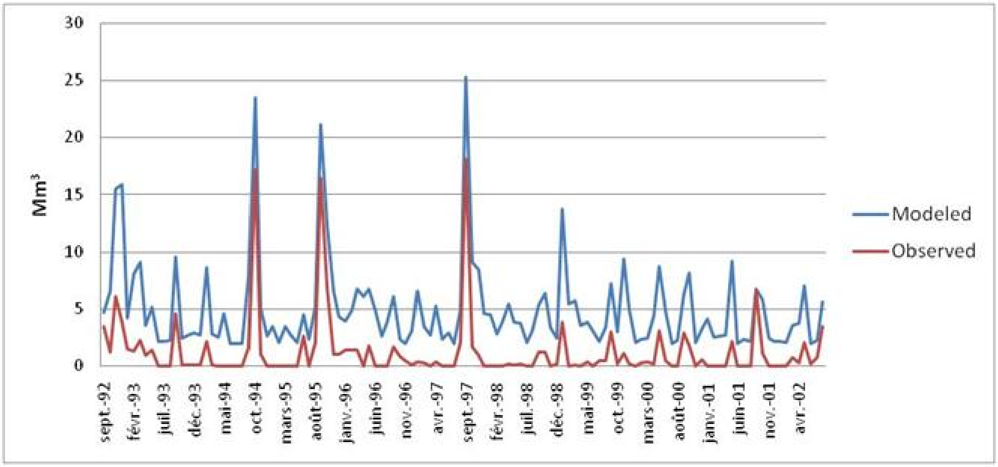


Figure 105 Comparison of simulated and observed monthly flow (1992-2002).

6.2.3 ANNUAL DEMAND

Figure 106 shows the annual water demand for the agricultural and domestic sites in the Merguellil watershed. as a result, it is shown that main source of consuming water is the urban. From the land use map,. That means urban has a great effect on the water consumption and this is what exactly shown in this figure since urban utilizes the noticeable amounts compared with the agriculture ones. The water demand, of Haffouz, sahel and Kairouan cities are respectively 4,4Mm^3, 55 Mm^3 and 60 Mm^3 while upstream irrigated and Downstram irrigated areas required respectively 24,5 Mm^3 and 38,5 Mm^3.

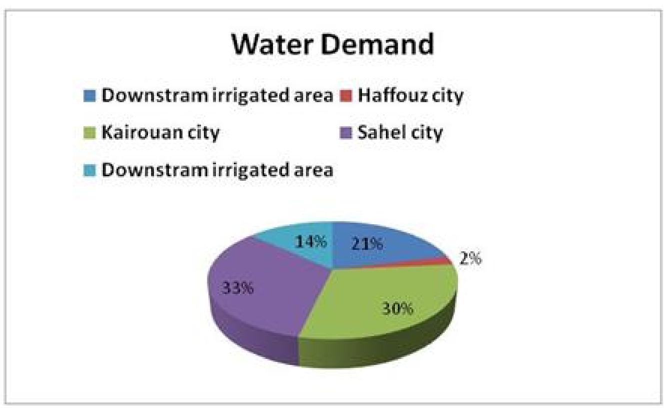


Figure 106 Water demand for agricultural and domestic sites in the Merguellil watershed

Figure 107 illustrates the annual water demand for agricultural and urban sites, we can note that urban demand is constant this because the growth rate is considered constant between 1992 and 2002, While water demand for irrigated area fluctuates.

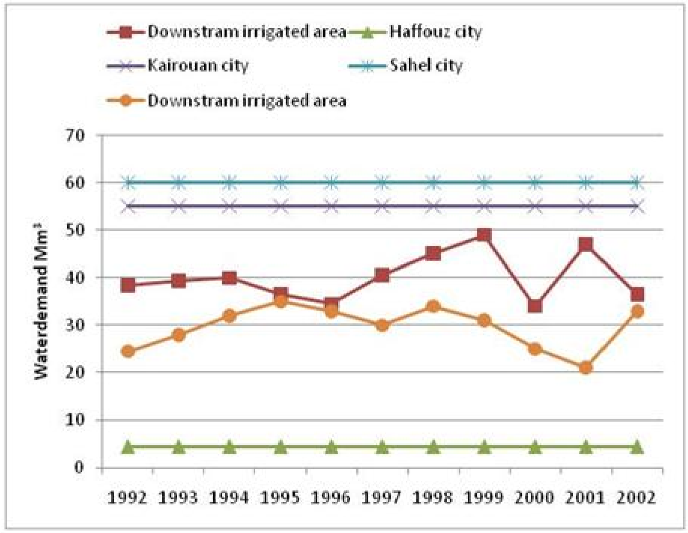


Figure 107 Annual water demand for agricultural and urban sites.

6.2.4 ANNUAL GROUNDWATER INFLOWS AND OUTFLOWS

Figure 108 shows the annual groundwater inflows and outflows. It could be noticed that there are a lot of hydrologic processes occur within the aquifer; inflow, outflow, recharge which cause changes in storage as the time pass. Positive sign in WEAP charts shows the inflows while the negative sign shows the outflows).

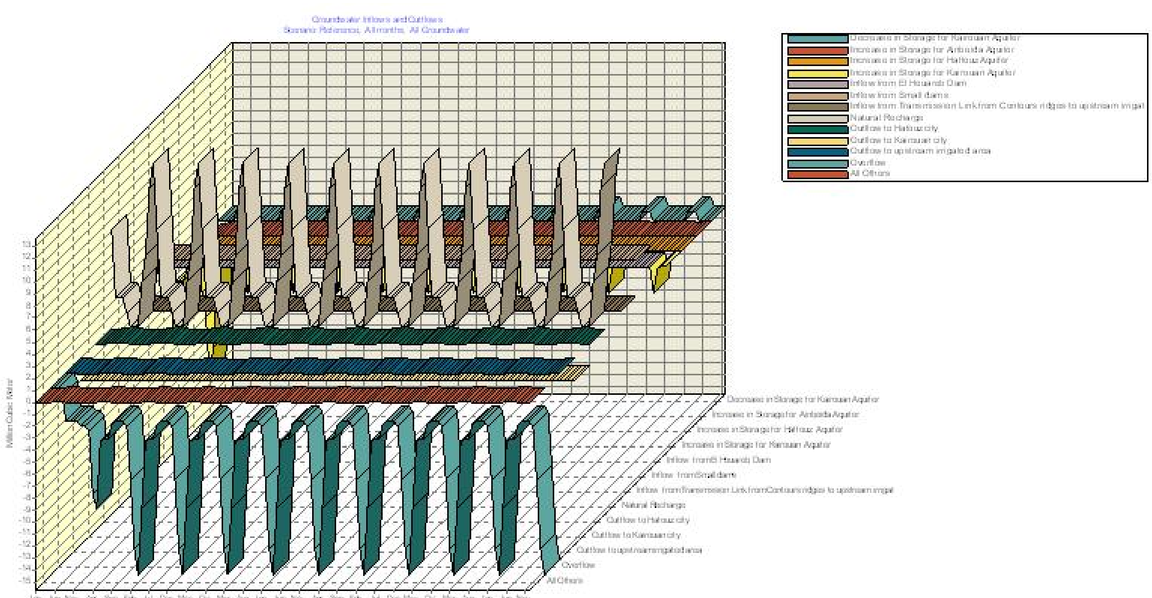


Figure 108 Annual Groundwater Inflows and Outflows in the Merguellil watershed

From the Figure 109 we can observe oscillation trend of 13 variables in the period 1992 - 2002 (as order listed in the figure): the Decrease in Storage for Kairouan Aquifer, the Increase in Storage for Ainbeida Aquifer, the Increase in Storage for Haffouz Aquifer, the the Increase in Storage for Kairouan Aquifer, the Inflow from El Houareb Dam, the Inflow from Small dams, the Inflow from Transmission Link from Contours ridges to upstream irrigation, the Natural Recharge, the Outflow to Hafouz city, Outflow to Kairouan city, the Outflow to upstream irrigated area, and the Overflow. We can observe the overflow oscillation from can reach minimal value -10,11 Mm^3. The Figure 109 shows the annual groundwater inflows and outflows for Ainbidha

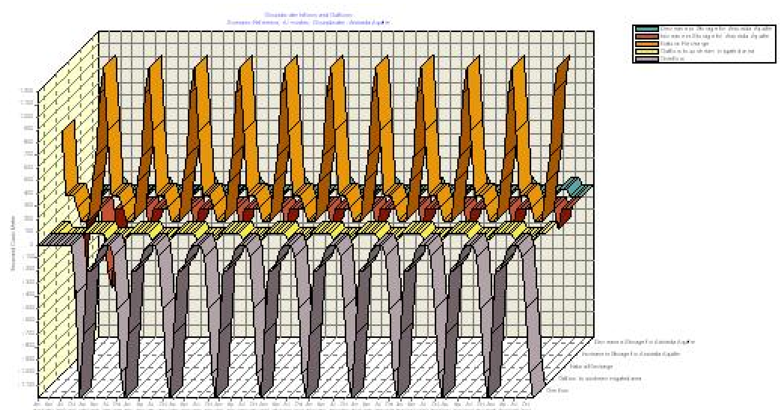


Figure 109 Ainbidha aquifer inflow- out flow in period 1992-2002

6.2.5 CREATION OF SCENARIOS

The following scenarios were created in order to ascertain the impact of these small reservoirs on the streamflow in the study area. In creating these scenarios the water year method was used to specify different climate conditions in the given period of the scenario analysis. This is shown in table 5.3 and was used to represent all the three scenarios created. The values were chosen based on an assumption. The model gives the values for the water year as Normal = 1, Wet =1.3, Very wet = 1.45, Dry =0.8, Very Dry = 0.7 (figure). This means that the discharge values are multiplied by these factors. The purpose of this method is to assess the impact of climate change on water resources (precipitation, runoff, groundwater recharge).

Year	Water
2002	Wet
2003	Very wet
2004	Wet
2005	Normal
2006	Normal
2007	Dry
2008	Dry
2009	Dry
2010	Normal
2011	Normal
2012	Normal
2013	Dry
2014	Dry
2015	wet
2016	wet
2017	Very wet
2018	Normal
2019	Dry
2020	Very Dry

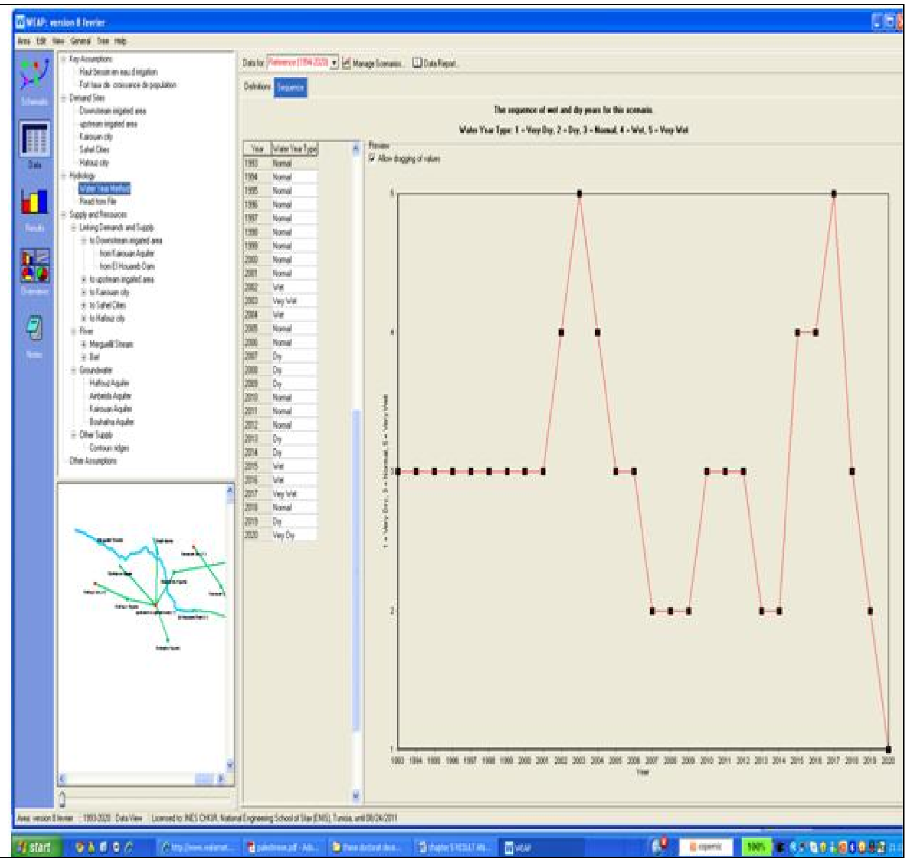


Figure 110 Climate change scenario in the Merguellil watershed 2002-2020

Figure 111 shows the result related to the impact of climate change on Haffouz aquifer inflow-outflow for the period 1992-2020. This figure reveals the variation of the overflow which decreases highly. The inflow of small dam increase more than 3000 thousand cubic meter, the nature recharge of the Haffouz aquifer and the outflow to upstream irrigated area seem to oscillate regularly without being affected by the climate change. The Figure 112 illustrates the average monthly demand site coverage for the period 1992-2020. We can observe through the figure that Kairouan city water demand is not affected by climate change while the irrigated area (upstream and downstream) and Haffouz city suffer more specially between December and April where the water demand is uncovered at 100%. Under the same scenario of climate change we have introduced a new scenario that we called in which we increase the unit of activity (consummation) from 3500m^3/ha to 4000 m^3/ha. The result of simulation is illustrated in the Figure 113. We can see that the difference between the water demand of both scenarios, increase particularly during November-April period and remains constant the rest of the year.

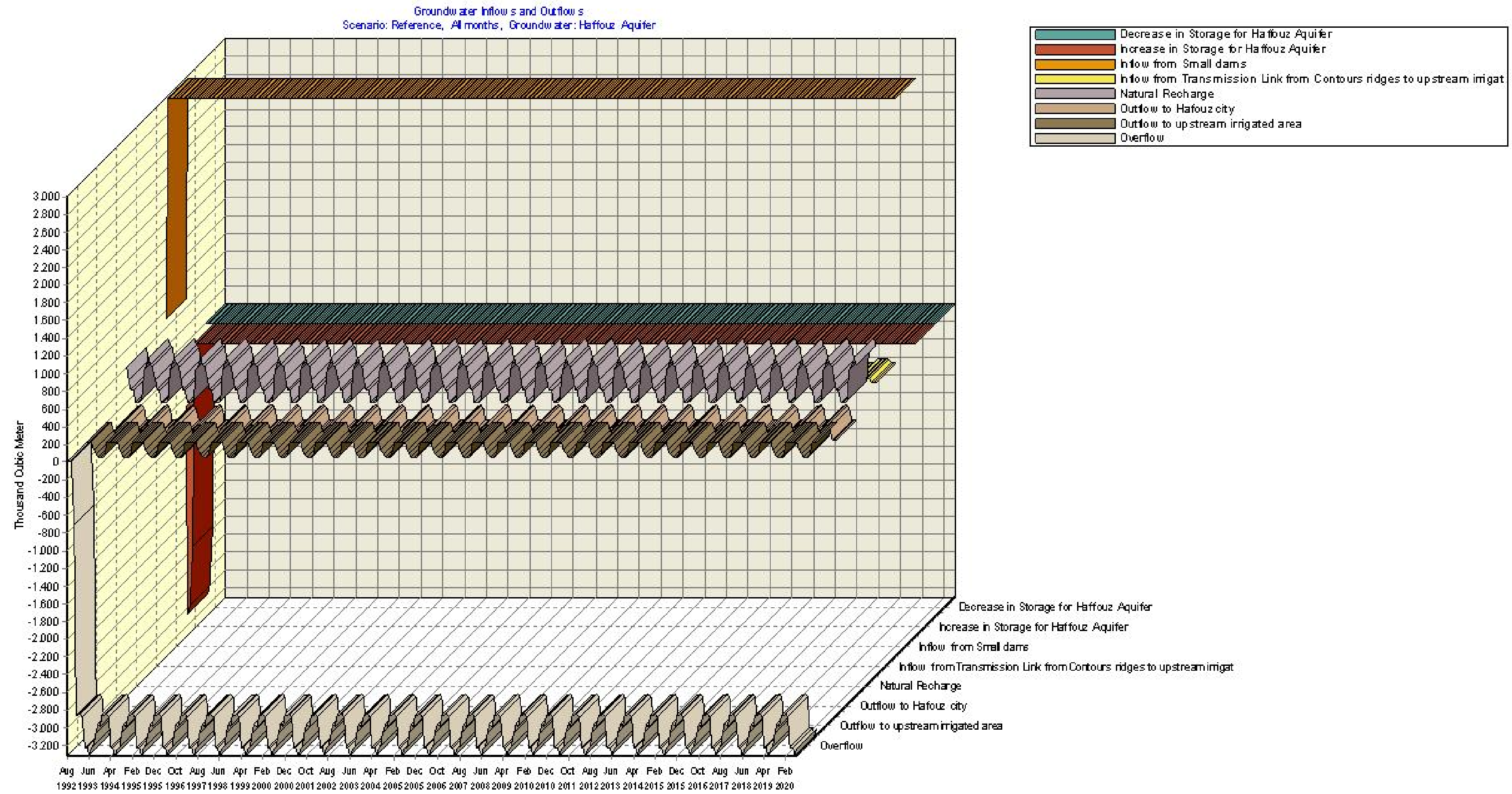


Figure 111 Impact of climate change on Haffouz aquifer inflow-outflow

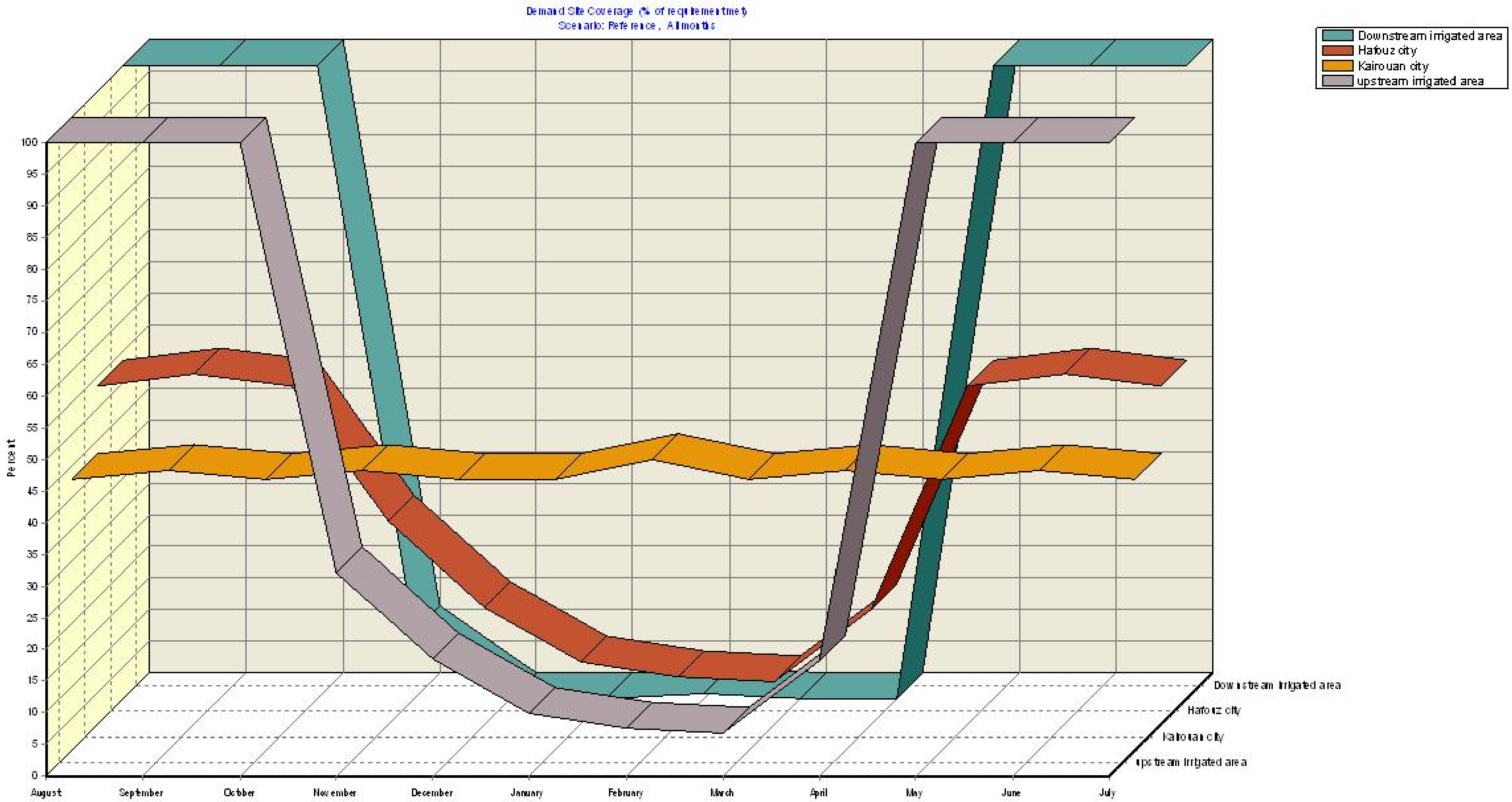


Figure 112 Average monthly Demand site coverage 1992-2020

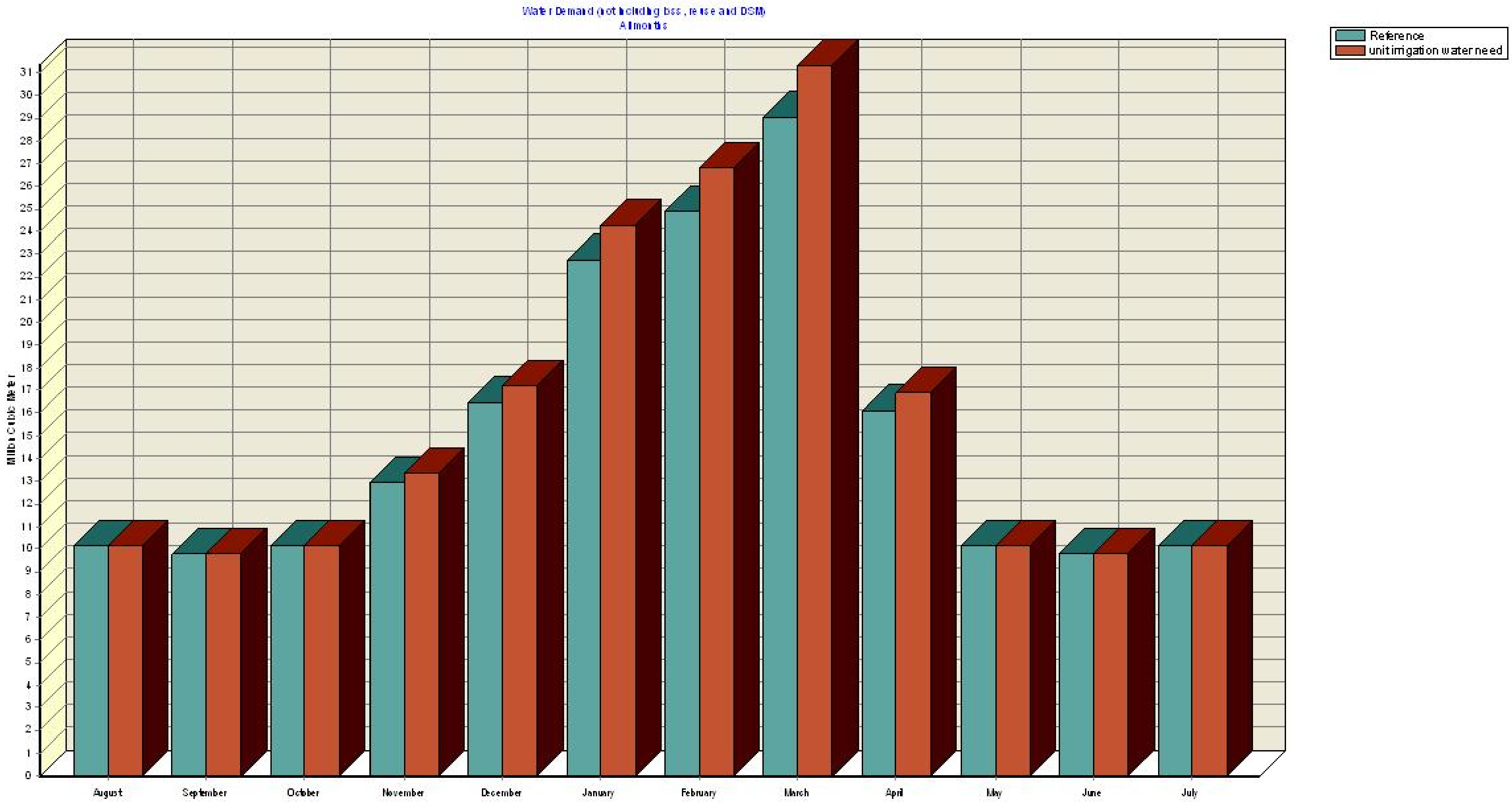


Figure 113 Monthly average water demand for all the site (agriculture and urban) 1992-2020

CONCLUSION

This study investigates the use of hydrological model to assess the hydrological responses to changes in land use, land cover and management practices. These models address methods that are required to better characterize impacts of land use and cover and climate change scenarios and understand the upstream-downstream linkages with respect to irrigation water allocation. Understanding how the changes in land use and cover influence stream-flow and subsequently optimization of available water resources utilization can enhance the ability of planners, practitioners, researchers and farmers to formulate and implement sound policies to minimize undesirable future impacts and devise management alternatives.

Two tools, a physically-based spatially distributed hydrological model SWAT (Soil Water Assessment Tool) and IWRM integrated water resources management lumped model WEAP (Water Evaluation And Planning) were utilized to simulate hydrological responses to land use and climatic changes. The SWAT is considered to be good for making predictions in ungauged catchments. It also has strengths that enable to carry out scientific researches on soil erosion and hydrological impacts of land use and climate changes.

The Merguellil basin is typical of the problems faced in Tunisia and in the Mediterranean basin in general: limited water resources; intermittent flows; strong increase in, and diversification of, demand; strong human-induced hydrological changes; competition between declining upstream rural societies and a more dynamic urban/tourist downstream or coastal, zone; and very localized uses of overexploited aquifers.

The hydrological model SWAT was applied to the Merguellil river basin, which area is widely occupied by WSCW (25% of watershed surface). The hydrologic regime is controlled by groundwater flow which disturbed by overexploitation of the aquifer by the agriculture. This study has shown that SWAT model was partially successful to generate annual and monthly water flow but does not properly represent all the fine details of the daily stream-flow. The model was able to predict the peak flow in monthly and annually simulation.

The sensitivity analysis of hydrology, soil and vegetation parameters of SWAT and WEAP was conduct to identify influential parameters and this could serve as a guide in calibrating the models. These important parameters for the SWAT model included ALPHA_BF, GW_REVAP, CN2 and SOL_AWC model and for the WEAP model included the crop coefficient and the effective precipitation.

SWAT Model evaluation was performed based on daily runoff events recorded at the Skhira and Haffouz Zebbess and the watershed outlet gauging station, between 1992 and 2002. For the WEAP model only the stream flow data at the outlet of the watershed was utilized to analyze streamflow variability, caused by to land use and land cover changes. The SWAT model predicted that the average annual watershed rainfall of the 11-year valuation period (295,5 mm) was split into ET (63%), groundwater recharge (10%), runoff (10%) percolation (13%) and lateral flow (3%). The evaluation coefficients for calibration were, respectively, R2 (coefficient of determination) 0.78; Esn (Nash- Sutcliffe coefficient) 0.64; indicating that the model could reproduce the observed events reasonably acceptable. Intended for WEAP model, the efficiency coefficient Ens values were 0,41 for the runoff in the calibration period. So SWAT simulation was better than WEAP in most case and could be used with reasonable confidence for runoff quantification in the Merguellil watershed. An estimation of the suspended sediment and nutrients loads in the watershed was performed with SWAT model without calibration with presence of data lack.

Two principal's scenarios were generated by the SWAT model. The first one consists in the increasing of the repartition ponds area in some subbsasins. The second scenario converts the non agricultural land to irrigated crop. The results of the first scenario illustrate a decrease in the surface runoff whereas in the second scenario, it is shown an increase.

The WEAP Model was a very good tool for this thesis. It is easy to use and offers a wide range of possibilities to be analyzed under the scenario creation. the WEAP model was reconfigured to simulate the impact of climate change on water resources and the Results of these different simulations provide insight into: - availability of water resources in the catchment, - impact of hydrological structures on water resources in the catchment.- water demand development for the period 2002-2020.

Finally taking into consideration that there is a lot of uncertainty in the input data (e.g. rainfall data and discharge measurements), the results obtained with the SWAT model are satisfactory.

This work could be very helpful for planners and decision maker of water resources management and crop production for the future years. They have to consider a number of management alternatives in order to improve the climate change impact on this catchment.

The result will contribute to the scientific community‘s understanding of climate change impact on water resources and provide information to support future water resources planning and management in the Merguellil and other catchments with the same climatic conditions.

Recommendations for future research include the installation of additional rainfall and runoff gauges with continuous data logging and the collection of more field data to represent the soils and land use. In addition, crop growth and yield monitoring is needed for a proper evaluation of crop production, to allow an economic assessment of the different water uses in the watershed

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APPENDICES

APPENDIX 1 : SOIL PROFILES (DIRECTION DES SOLS 1963-1982)

12
15

SOL PEU EVOLUE NON CLIMATIQUE D'APPORT MODAL (CALCIMORPHE)

SOGETHA - (A. CALO) - Profil 407 dans étude N. 305

Situation morphologique :
Topographie :
Végétation :
Matériau originel : Colluvions de sol calcimorphe descendues du Djebel Rebia.

Description du profil :

0 - 25 cm : Limon argileux, poreux, frais, calcaire-brun foncé, polyédrique moyen, à fin bien développé plus ou moins émoussé quelques petits cailloux calcaires, racines.

25 - 65 cm : Argilo-limoneux, poreux, frais, calcaire, brun, polyédrique moyen très bien développé, racines, vague tendance à une structure prismatique grossière.

65 - 115 cm : Humide nette, argilo-limoneux, peu poreux, frais, calcaire plus ou moins, brun gris sombre, structure prismatique moyenne se débitant en prismatico-cubique fine, racines.

115 - 150 cm : Argilo-limoneux, peu poreux, frais, calcaire, brun gris plus clair que le précédent, lissage des agrégats, cubique à prismatique moyen bien développé, nombreux pseudomycéliums calcaires, quelques amas.

Résultats d'analyses

Profondeur	Granulométrie %					pH	Calcaire	Matière Organique
	A	L	STF	SF	SG			
0 - 25	26	32	11	19	11	8,1	18 %	2,28 %
25 - 65	34	30	11	19	6	8,4	27	1,34
65 - 115	41	27	7	13	9	8,1	14	1,66
115 - 150	36	32	4	15	10	8,3	10	1,48

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RENDZINE HUMIFERE DE MONTAGNE

P. DIMANCHE - Etude d'Oum Djeddour N. 302

Situation morphologique : glacis
Topographie : Pente moyenne
Végétation naturelle . Chêne vert - Erinacéa anthyllis

Description du profil :

0 - 15 cm : Brun foncé, texture équilibrée, structure finement granulaire (micropolyèdres accolés), calcaire, abondants fragments d'encroûtement calcaire, racines et radicelles très abondantes.

15 - 45 cm : Blanc, encroûtement calcaire à très abondants cailloux, très calcaire, sans structure, consistant.

45 - 85 cm : Brun pâle, encroûtement calcaire à cailloutis et pseudomycélium calcaire, très calcaire.

85 - 125 cm : Marnes en voie d'encroûtement par larges plages de torba, sans structure, très consistant.

125 cm et plus Marnes altérées se divisant en plaquettes ou en boules.

Résultats d'analyse

Profondeur	Ganulométrie %						CO3Ca total %	CO3Ca actif	Mat. Org. %	C/N
	A	L	STF	SF	SG	pH				
0 - 15	16	14	14,5	14,1	21,4	8,5	77,8	27	4,8	16
15 - 45	14	18	19	25,5	15,5	8,8	85,2	20,5	0,82	12,3
45 - 85	18	21	14	25,5	12	8,8	82,3	17,5	—	—

Humus %

MHT	HA	AF	MHT/HT	HA/THM
8,28	4,35	3,93	10,6	52,3

10

RENDZINE SUR CROUTE

A. FOURNET - Profil S-8 - Oussoltia

Situation morphologique : Glacis sur cône alluvial ancien
Topographie : Pente faible à moyenne régulière
Régime agronomique : Culture en sec des céréales
Matériau originel : Limon quaternaire.

Description du profil :

) - 30 cm : Brun foncé, texture équilibrée, structure nuciforme à grumeleuse, sans cohésion, calcaire, bonne porosité, bien colonisé par les radicelles.

0 - 60 cm : Beige rosé, texture sablo-limoneuse, structure polyédrique fine émoussée, calcaire, bien colonisé par les racines, emballe une croûte calcaire beige rosée à pellicule zonaire disloquée en miches soulevées.

) cm et plus Encroûtement calcaire feuilleté au sommet, diffus à la base, beige rosé, texture sablo-limoneuse.

Résultats d'analyses

Profondeur	Granulométrie %					CO3Ca total %	M. O. %
	A	L	STF	SF	SG		
0 - 30	23	19	13	28	13	48	3,6
30 - 60	10	9	12	30	35	72,8	3,5
60 et plus	7	8	7	41	34	86,4	1,0

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SOL BRUN CALCAIRE ENCROUTE

A. FOURNET - Profil N. 58 - Oued Zit

Situation morphologique : glacis
Topographie : Pente régulière, faible
Régime agronomique . Céréales
Matériau originel : Limon quaternaire.

Description du profil :

- 30 cm : Brun (10 YR 5/3), texture équilibrée, structure polyédrique émoussée dans une surstructure en grands éléments peu développés de 10 cm de diamètre, calcaire fort, meuble, poreux.

- 70 cm : Jaune brun (10 YR 7/6), limoneux, structure prismatique se défaisant en plaquettes cubiques de 1 cm d'épaisseur, très calcaire, bonne macroporosité.

- 120 cm : Jaune brun (10 YR 5/6), argilo-limoneux, structure prismatique cubique fine, agrégats revêtus d'argile, taches calcaires blanches de 1 cm de diamètre, piquetures ferro-manganiques, calcaire, compact, très peu poreux.

cm et plus Jaune-rouge, argileux, structure en gros prismes cubiques déformés, faces horizontales des agrégats lisses, brillantes à slikensides, revêtement en nappe de calcaire sur les faces verticales des agrégats, calcaire.

Résultats d'analyses

Profondeur	Granulométrie					CO3Ca %	pH	M. O. %	Conductivité mmhos/cm
	A	L	STF	SF	SG				
0 - 30	23,5	11	9	35	19	18,8	8,4	1,19	0,82
30 - 70	34,5	29	8	19	7	34,8	8,3	1,03	2,13
70 - 120	37	30	22	16	4	40,9	8,5	0,21	—
120 et plus	46	15	15	21	3	48,8	8,7	0,21	

SOL PEU EVOLUE NON CLIMATIQUE D'APPORT MODAL (STEPPIQUE)

J. LE FLOCH - Profil N. 29 étude N. 253

Situation géomorphologique : glacis quaternaire
Topographie : Mi-pente
Cultures . Céréales - localement plantations arbustives - oliviers
Matériau originel : Alluvions colluvions remaniant des apports éoliens, gypseux.

Description du profil :

- 40 cm : Texture équilibrée, couleur brun-jaune, structure à tendance polyédrique moyenne, horizon humifère, calcaire, 20 % CO_3Ca, pH 8,5.
- 60 cm : Argilo-limoneux, couleur brun jaune, structure à tendance cubique, cohésion moyenne à forte, quelques taches plus calcaires humifères, calcaire.
- 200 cm : Sablo-argileux, couleur beige jaune, structure massive-fentes de retrait étroites profondes délimitant de grands prismes, compacité moyenne à forte.

s d'analyses

deur	Granulométrie A	L	STF	SF	SG	pH	CO_3Ca %	Mat Org. %	Sel p %	Cl mmhos	CL me/L
40	30	11	18,0	38,5	3,0	8,5	20,0	0,88	—	—	—
0	42	11	13,0	26,5	4,5	8,5	30,4	0,83	42	1,5	3

SOL CALCAIRE HYDROMORPHE CULTIVE

A. FOURNET - Etude pédologique de l'U.R.D. de Béja

Situation morphologique : versant marneux colluvionné
Topographie : Pente moyenne à forte
Régime agronomique : Céréales
Matériau originel : Grès argileux du miocène inférieur

Description du Profil N. 16 :

0 - 35 cm : Brun foncé, argilo-sableux, à sable fin, structure motteuse, grossièrement nuciforme, calcaire, compacité moyenne, bonne porosité radiculaire.

35 - 95 cm : Brun jaune à beige jaune, argilo-sableux à sable fin, surstructure en prismes de 5 à 10 cm de diamètre tendant à se pulvériser au sommet et à la base de l'horizon sous forme de petits prismes irréguliers, structure en petits polyèdres, calcaire, compacité moyenne, bonne porosité. Présence de taches calcaires à partir de 35 cm, groupées en essaims nombreux à partir de 65 cm.

95 - 135 cm : Ocre jaune, sableux à sable grossier, sans structure, quelques blocs de grès argileux burdigalien.

135 - 200 cm : Substrat jaune grise de gley, marne vindobonienne altérée et remaniée à surstructure prismatique et structure en éclats à cassure conchoïdale. Accumulation d'amas calcaires pulvérulents au sommet de la couche.

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SOL BRUN CALCAIRE ENCROUTE

A. FOURNET - Profil N. 75 bis - Oued Zarga

Situation morphologique : Glacis résiduel ancien
Topographie : Pente forte .
égétation naturelle : Association végétale à Pinus halépensis et Rosmarinus officinalis, forme dégradée à Stipa tenacissima.
Matériau originel : Limon quaternaire.

Description du profil :

0 - 20 cm : Couleur brune 7,5 YR 5 4, texture équilibrée, structure nuciforme moyenne à fine, faiblement calcaire (horizon A1).

20 - 50 cm : Couleur brun 7,5 YR 5/4, texture équilibrée structure nuciforme moyenne à fine, calcaire, pseudomycélium calcaire tubulaire et sur les faces d'agrégats.

50 - 90 cm : Couleur brun très pâle 10 YR 7/4, texture équilibrée, structure polyédrique émoussée au sommet en éclats à la base, fortement calcaire, (horizon B.).

90 cm et plus Couleur brun très pâle 10 YR 7/4, texture limono-sableuse, structure en éclats, fortement calcaire, (horizon C).

Résultats d'analyses

Profondeur	Granulométrie % A	L	STF	SF	SG	pH	CO_3Ca total %	M. O. %	C/N
0 - 20	18,5	17,5	12,0	23,0	27	7,9	27,5	3,56	11,1
20 - 50	22,0	19,5	13,0	22,0	23	8,05	37,5	1,08	10,0
50 - 50	20,0	20,5	14,0	20,0	23	8,10	48,0	—	—
90 et plus	14,5	24,5	13,0	19,0	29	8,15	50,0		

RENDZINE SUR CROUTE

A. FOURNET - Profil 75 a - Béja

Situation morphologique : Glacis de piedmont ancien
Topographie : Zone plane à pente moyenne
Végétation naturelle : Absente
Régime agronomique : Culture de céréales
Matériau originel, grès oligocène

Description du profil :

0 - 30 cm : Couleur brun rouge foncé 5 YR 3/3, texture équilibrée, structure motteuse, sous structure finement nuciforme, calcaire (horizon A1).

30 - 50 cm : Couleur blanc jaunâtre 5 YR 8/2, texture sablo-argileuse, structure fondue, encroûtement calcaire (Horizon B).

50 cm et plus Couleur blanc jaunâtre 5 YR 8/2, texture sablo argileuse, structure feuilletée, encroûtement calcaire (horizon Cca).

Résultats d'analyses

Profondeur	Granulométrie % A	L	STF	SF	SG	pH	CO_3Ca Total %	M.O. %	C/N
0 - 30 cm	29	15	12	16	25	8,0	26,4	3,05	9
30 - 50 cm	19	8	9	18	42	—	87,3	—	—
50 et plus	13	11	10	17	44	—	89,3	—	—

SOL PEU EVOLUE NON CLIMATIQUE D'APPORT VERTIQUE

L. GUYOT - Profil N. 123 dans étude N. 173

Coordonnées : 39G64 9G32

Topographie : Pente faible et régulière

Régime agronomique : Quelques oliviers médiocres isolés et cé-réales

Description du profil :

0 - 50 cm : Marron-limono-argileux à argilo-limoneux sur structure prismatique très grossière à très larges fentes. La structure est cubique moyenne (4 cm) - très cohérent, non poreux. Lissage de quelques faces horizontales. Un léger gauchissement, peu calcaire.

50 - 100 cm : Idem, mais plus massif - le lissage est plus important, le gauchissement un peu plus accentué. Aucune porosité-calcaire.

00 - 160 cm : Marron sombre - limono-argileux - la structure prismatique moyenne se défait en polyèdres moyens bien développés - très cohérent.

60 - 180 cm : Brun sombre - argilo-sableux - peu calcaire.

SOL BRUN CALCAIRE SUR LIMON A NODULES CALCAIRES

A. FOURNET - Ousseltia

Situation morphologique : Ravinement de glacis remblayé

Topographie : Pente faible autour d'une petite dépression

Régime agronomique : Céréales

Matériau originel : Limon quaternaire

Description du profil S-17 :

0 - 35 cm : Brun foncé limono-argileux, structure nuciforme à granulaire, calcaire, cohérent, porosité moyenne radiculaire.

35 - 70 cm : Ocre-rosé, limono-argileux, structure polyèdrique émoussée à faible tendance prismatique, calcaire, compacité moyenne, porosité faible.

70 - 135 cm : Ocre-rosé, limono-argileux, structure polyédrique émossee, calcaire, présence croissante en profondeur de nodules bosselés, indurés de couleur rosé, très compact porosité nulle.

Résultats d'analyses

Profondeur	Granulométrie %					CO3Ca total %	Mat. Org. %
	A	L	STF	SF	SG		
0 - 35	25	27	12,5	23,5	9	19	1,84
85 - 70	23	30	13	23	8,5	34,7	0,62
70 - 135	24	29	10	24	11	26	—

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SOL BRUN CALCAIRE A ACCUMULATION CALCAIRE

A. FOURNET - Profil - P 11 - Ousseltia

(Non publié)

Situation morphologique : Vallon alluvial ancien

Topographie : Plane régulière à pente faible

Régime agronomique : Céréales

Matériau originel : Limon quaternaire

Description du profil :

- 35 cm : Couleur brun foncé, texture limono-argileuse, structure nuciforme à faible cohésion, calcaire, porosité radiculaire, bien colonisé par les radicelles.

- 55 cm : Couleur brune, texture limon-argileuse, structure polyédrique émoussée à faible cohésion, compacité nette, calcaire avec léger pseudomycélium calcaire, porosité radiculaire, bien colonisé par les radicelles.

- 100 cm : Couleur beige rosée, texture équilibrée, structure polyédrique émoussée fine à cohésion moyenne, encroûtement calcaire.

- 200 cm : Couleur rosée beige, texture limono-sableuse, structure polyédrique émoussée fine à cohésion moyenne avec agrégats enrobés de calcaire.

Résultats d'analyses

Profondeur	Granulométrie %					CO3Ca total %	CO3Ca actif %	M. O. %
	A	L	STF	SF	SG			
0 - 35	30	28	8,5	22,5	9,5	34,2	20,0	2,24
35 - 55	32	33	3,5	20,0	9,0	46,2	35,5	1,29
55 - 100	27	20	13,5	28,5	10,0	65,8	48,5	0,65
100 - 200	14	22	10,5	34,0	20,5	59,6	33,5	—

SOL ISOHUMIQUE

Sol isohumique subtropical chatain modal

R. GADDAS - Profil 493 - Etude 245

Topographie : Pente comprise entre 3 et 7 =

Végétation : Hypéricum crispum - Carlina corymbosa - Cichorium Mentibus - Asteriscus aquaticus - Linaria Longera - Rhapuncticum Acaule - Convolvulus althaeoides.

Description du profil :

0 - 30 cm : Brun-rouge, texture limoneuse, structure nuciforme, friable, effervescence forte, riche en matière organique. Racines nombreuses, pH : 8,3.

0 - 70 cm : Rouge-brun, texture limono-argileuse, structure nuciforme à polyèdrique. Effervescence forte. Faces lissées, quelques petits grains de silice.

70 cm : Rouge-brun, texture argilo-limoneuse, structure polyèdrique à prismatique, porosité faible, très compact, très riche en nodules et taches calcaires friables.

ses :

fondeur	Granulométrie %					CO3 Ca %	Mat. Org. %	pH	Fer libre %	Fer total %	Fer L Fer L
	A	L	STF	SF	SG						
– 30 cm	18	31	11	26	14	10	2,9	8,3	0,42	3,5	0,12
– 70 cm	29	28	8	22	14	12	1,1	8,5	0,34	3,5	0,09
– 70 cm	41	23	8	16	14	27	0,6	8,9	0,56	3,5	0,16

SOL ISOHUMIQUE

Sol isohumique subtropical chatain modal

R. GADDAS - Profil 493 - Etude 245

Topographie : Pente comprise entre 3 et 7 =
Végétation : Hypéricum crispum - Carlina corymbosa - Cichorium Mentibus - Asteriscus aquaticus - Linaria Langera - Rhapunticum Acaule - Convolvulus althaeoides.

Description du profil :

0 - 30 cm : Brun-rouge, texture limoneuse, structure nuciforme, friable, effervescence forte, riche en matière organique. Racines nombreuses, pH : 8,3.

0 - 70 cm : Rouge-brun, texture limono-argileuse, structure nuciforme à polyèdrique. Effervescence forte. Faces lissées, quelques petits grains de silice.

70 cm : Rouge-brun, texture argilo-limoneuse, structure polyèdrique à prismatique, porosité faible, très compact, très riche en nodules et taches calcaires friables.

ses :

fondeur	Granulométrie %					CO3 Ca %	Mat. Org. %	pH	Fer libre %	Fer total %	Fer L / Fer t
	A	L	STF	SF	SG						
– 30 cm	18	31	11	26	14	10	2,9	8,3	0,42	3,5	0,12
– 70 cm	29	28	8	22	14	12	1,1	8,5	0,34	3,5	0,09
– 70 cm	41	23	8	16	14	27	0,6	8,9	0,56	3,5	0,16

37-39-40

SOL ISOHUMIQUE

Sol isohumique subtropical brun modal ✓

K. BELKHODJA - Profil 44 - Etude N. 272

Situation géomorphologique : En bas d'une colline dont le sommet est encroûté.
Matériau originel : Sable et argiles du Miopliocène
Régime agronomique : Non cultivé.

Description du profil :

0 - 25 cm : Frais brun, limono-sableux, structure nuciforme, friable, nombreux pores, racines et radicelles, petits granules calcaires.

25 - 70 cm : Brun beige clair, limono-sableux, structure massive se débite en éclats polyèdriques, porosité moyenne, nombreux nodules calcaires de diamètre variable, certains friables crayeux d'autres durcis. Consistance et cohésion moyenne.

70 - 160 cm : Beige jaune, limono-sableux, structure massive se débite en éclats polyèdriques, porosité moyenne, nombreux mycéliums calcaires et nodules blancs friables de 0,5 à 2 cm de diamètre, certains arrondis d'autres allongés avec des apophyses.

Résultats d'analyses

Profondeur	Granulométrie %					CO3 Ca %	M.O. %
	A	L	STF	SF	SG		
0 — 25 cm	19	11	8	43	19	12	1,2
25 — 50 cm	15	10	7	44	23	15	0,8
50 — 70 cm	19	7	5	46	22	10	0,5
70 — 100 cm	16	11	5	45	22	21,6	0,05

SOL ISOHUMIQUE

Sol isohumique subtropical chatain-rouge

P. MARTINI - Ph. GRAFFIN - Profil N. - Cheylus

(Non publié)

Situation géomorphologique : Glacis aux pieds d'une barre calcaire
Topographie : Pente faible
Matériau originel : Marnes grises du crétacé inférieur
Végétation :
Régime agronomique : Céréales.

Description du profil :

0 - 15 cm : Brun 7,5 YR 4/4 argilo-limoneux, structure grumeleuse à nuciforme, porosité moyenne, consistance et cohésion faible, calcaire faible, quelques petits cailloux calcaires, assez nombreuses racines.

15 - 40 cm : Brun 7,5 YR 4/4, argilo-limoneux, structure nuciforme porosité moyenne à assez forte, cohésion et consistance moyenne, quelques petits cailloux (plus rares que dans l'horizon précédent), calcaire moyen, bon enracinement.

40 - 65 cm : Brun rouge, 5 YR 4/4, argileux, structure polyédrique grossière (5 cm) se défaisant en polyèdres fins, quelques faces luisantes, porosité tubulaire moyenne à faible, cohésion moyenne à forte, consistance forte, quelques petites taches calcaires arrondies (0,5 cm), calcaire, racines.

65 - 95 cm : Brun rouge, 5 YR 4/4, argileux, structure prismatique moyenne (10 cm) se défaisant en cube à faces subhorizontales lissées puis en polyèdres fins, porosité tubulaire moyenne à faible, cohésion et consistance fortes, quelques petits granules et taches calcaires, calcaire, racines peu nombreuses.

95 - 115 cm : Brun rouge, 5 YR 4/4, argileux, structure cubique, quelques plaquettes à faces lissées, miroirs de glissement, petits granules et taches calcaires, calcaire moyen à fort, quelques racines.

115 - 150 cm : Brun rouge 5 YR 4/4 panachures grises et plages blanches (calcaire), argilo-limoneux, structure polyédrique moyenne bien individualisée, porosité faible, consistance et cohésion forte, amas calcaires pulvérulents plus ou moins consolidés concrétions moyennes (1 à 2 cm) très peu de racines, calcaire fort.

150 - 175 cm : Gris à taches brun rougeâtre et quelques taches bleutées (couleur de l'altération de la marne), limono-argileux, structure polyédrique mal définie, on retrouve le litage de la marne, filons de calcite, petites taches noires ferro-manganeuses, calcaire fort, peu de racines.

175 et plus : Gris, horizon d'altération de la marne, fragmentation en éléments de forme polyédrique vaguement arrondie par pellicules de desquamation, cassure plus ou moins conchoïdale.

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APPENDIX 2 LANDUSE/SOIL DISTRIBUTION CLASS IN THE MERGUELLIL CATCHMENT WITH SWAT MODEL

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Detailed LANDUSE/SOIL  distribution    SWAT model class

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                                                          Area [ha]
Area [acres]

Watershed                                               114349.8996
282564.3194

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                                                          Area [ha]
Area [acres] %Wat.Area

LANDUSE
                               Pasture --> PAST         30772.8001
76041.1276     26.91
                  Southwestern US (Arid) Range --> SWRN    1949.5123
4817.3424      1.70
                          Forest-Mixed --> FRST         19525.9695
48249.6469     17.08
                     Residential-Low Density --> URLD     288.1929
712.1391      0.25
                        Summer Pasture --> SPAS          2467.6230
6097.6198      2.16
                          Winter Wheat --> WWHT         59345.8018
146646.4437     51.90

SOIL
                                    D'erosion           42010.3367
103809.6426     36.74
                                   D'apport PE           1765.9521
4363.7558      1.54
                                  Brun_calcaire         10937.9671
27028.2635      9.57
                                     Rendzine           51847.0948
128116.7636     45.34
                                  Brun_subaride          7788.5489
19245.8938      6.81

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                                                                  Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                              1          3774.5660
9327.1413      3.30

LANDUSE:
                Southwestern US (Arid) Range --> SWRN               9.0037
22.2487      0.01      0.24
                                Forest-Mixed --> FRST           2820.1700
6968.7812      2.47     74.72
                     Residential-Low Density --> URLD               4.0017
9.8883      0.00      0.11
                              Summer Pasture --> SPAS               4.0017
9.8883      0.00      0.11
                                Winter Wheat --> WWHT            937.3889
2316.3349      0.82     24.83

SOIL:
                                        Brun_calcaire           1239.5143
3062.9017      1.08     32.84
                                            D'erosion            936.3885
2313.8628      0.82     24.81
                                             Rendzine           1598.6633
3950.3768      1.40     42.35
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                                                                  Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                              2          6702.4724
16562.1444      5.86

LANDUSE:
                                     Pasture --> PAST               9.9739
24.6460      0.01      0.15
                Southwestern US (Arid) Range --> SWRN              44.8826
110.9072      0.04      0.67
                                Forest-Mixed --> FRST           3145.7735
7773.3636      2.75     46.93
                     Residential-Low Density --> URLD              14.9609
36.9691      0.01      0.22
                              Summer Pasture --> SPAS              33.9113
83.7966      0.03      0.51
                                Winter Wheat --> WWHT           3452.9702
8532.4619      3.02     51.52

SOIL:
                                             Rendzine           3788.0938
9360.5691      3.31     56.52
                                        Brun_calcaire           2310.9566
5710.4894      2.02     34.48
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                                          D'erosion            603.4220
1491.0859      0.53      9.00
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                                                               Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                        3            3184.1978
7868.3120      2.78

LANDUSE:
                                   Pasture --> PAST            1077.1113
2661.5959      0.94     33.83
                Southwestern US (Arid) Range --> SWRN            84.2433
208.1695      0.07      2.65
                              Forest-Mixed --> FRST              97.2810
240.3862      0.09      3.06
                     Residential-Low Density --> URLD             1.0029
2.4782      0.00      0.03
                              Winter Wheat --> WWHT            1924.5592
4755.6821      1.68     60.44

SOIL:
                                      Brun_calcaire             406.1733
1003.6744      0.36     12.76
                                          D'erosion             670.9381
1657.9215      0.59     21.07
                                           Rendzine            1940.6056
4795.3334      1.70     60.94
                                      Brun_subaride             166.4809
411.3826      0.15      5.23
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                                                               Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                        4            2729.4550
6744.6198      2.39

LANDUSE:
                                   Pasture --> PAST             984.2792
2432.2030      0.86     36.06
                              Winter Wheat --> WWHT            1745.1758
4312.4167      1.53     63.94

SOIL:
                                      Brun_calcaire             584.3846
1444.0435      0.51     21.41
                                          D'erosion            1014.1965
2506.1302      0.89     37.16
                                           Rendzine             879.5686
2173.4580      0.77     32.23
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                                       Brun_subaride            251.3053
620.9880      0.22      9.21
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                                                               Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                          5          4004.9292
9896.3803      3.50

LANDUSE:
                                    Pasture --> PAST            791.1836
1955.0542      0.69     19.76
                Southwestern US (Arid) Range --> SWRN            14.0032
34.6027      0.01      0.35
                               Forest-Mixed --> FRST           1170.2715
2891.7994      1.02     29.22
                     Residential-Low Density --> URLD            43.0100
106.2798      0.04      1.07
                               Winter Wheat --> WWHT           1986.4609
4908.6442      1.74     49.60

SOIL:
                                       Brun_calcaire            390.0905
963.9331      0.34      9.74
                                           D'erosion           1462.3393
3613.5135      1.28     36.51
                                            Rendzine           2152.4994
5318.9337      1.88     53.75
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                                                               Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                          6          3367.6908
8321.7324      2.95

LANDUSE:
                                    Pasture --> PAST           1692.3421
4181.8619      1.48     50.25
                Southwestern US (Arid) Range --> SWRN            79.9689
197.6072      0.07      2.37
                               Forest-Mixed --> FRST            100.9608
249.4791      0.09      3.00
                               Winter Wheat --> WWHT           1494.4190
3692.7842      1.31     44.38

SOIL:
                                           D'erosion           1446.4377
3574.2199      1.26     42.95
                                            Rendzine           1785.3060
4411.5803      1.56     53.01
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                                        Brun_subaride           135.9472
335.9322      0.12      4.04
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                7          2514.0504
6212.3442      2.20

LANDUSE:
                                     Pasture --> PAST           1096.9676
2710.6619      0.96     43.63
                Southwestern US (Arid) Range --> SWRN              1.9945
4.9285      0.00      0.08
                                Winter Wheat --> WWHT           1415.0883
3496.7539      1.24     56.29

SOIL:
                                        Brun_calcaire             47.8677
118.2834      0.04      1.90
                                            D'erosion           1312.3722
3242.9373      1.15     52.20
                                             Rendzine           1153.8105
2851.1235      1.01     45.89
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------------------------------------------
                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                8          2911.9504
7195.5750      2.55

LANDUSE:
                                     Pasture --> PAST           2070.6758
5116.7435      1.81     71.11
                Southwestern US (Arid) Range --> SWRN            116.0379
286.7354      0.10      3.98
                                Winter Wheat --> WWHT            725.2367
1792.0962      0.63     24.91

SOIL:
                                            D'erosion           1260.4114
3114.5395      1.10     43.28
                                             Rendzine           1651.5390
4081.0355      1.44     56.72
------------------------------------------------------------------------------
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------------------------------------------
                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area
```

```
SUBBASIN #                                             9           3406.5832
8417.8374      2.98

LANDUSE:
                                      Pasture --> PAST              515.1467
1272.9533      0.45     15.12
                Southwestern US (Arid) Range --> SWRN              354.7898
876.7033      0.31     10.41
                                 Forest-Mixed --> FRST              822.8317
2033.2582      0.72     24.15
                               Summer Pasture --> SPAS                2.0045
4.9531      0.00      0.06
                                 Winter Wheat --> WWHT             1711.8106
4229.9695      1.50     50.25

SOIL:
                                           D'apport PE               43.0959
106.4922      0.04      1.27
                                             D'erosion              721.6063
1783.1253      0.63     21.18
                                              Rendzine             2641.8809
6528.2199      2.31     77.55
------------------------------------------------------------------------------
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------------------------------------------------------------------------------
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                                                                 Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                            10           3421.5416
8454.8004      2.99

LANDUSE:
                                      Pasture --> PAST             1722.2391
4255.7389      1.51     50.34
                Southwestern US (Arid) Range --> SWRN              180.5010
446.0271      0.16      5.28
                               Summer Pasture --> SPAS               12.9642
32.0351      0.01      0.38
                                 Winter Wheat --> WWHT             1505.8373
3720.9993      1.32     44.01

SOIL:
                                           D'apport PE               18.9476
46.8205      0.02      0.55
                                             D'erosion             1655.4238
4090.6350      1.45     48.38
                                              Rendzine             1725.2308
4263.1316      1.51     50.42
                                         Brun_subaride               21.9394
54.2132      0.02      0.64
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                      11              6193.8780
15305.3822      5.42

LANDUSE:
                                   Pasture --> PAST              548.1397
1354.4805      0.48      8.85
              Southwestern US (Arid) Range --> SWRN               31.0646
76.7622      0.03      0.50
                              Forest-Mixed --> FRST             3678.6485
9090.1243      3.22     59.39
                   Residential-Low Density --> URLD               12.0250
29.7144      0.01      0.19
                            Summer Pasture --> SPAS               84.1750
208.0007      0.07      1.36
                              Winter Wheat --> WWHT             1839.8253
4546.3002      1.61     29.70

SOIL:
                                         D'erosion               158.3292
391.2393      0.14      2.56
                                          Rendzine              6035.5488
14914.1429      5.28     97.44
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                      12              6533.9380
16145.6875      5.71

LANDUSE:
                                   Pasture --> PAST             1247.7418
3083.2323      1.09     19.10
              Southwestern US (Arid) Range --> SWRN               90.7630
224.2799      0.08      1.39
                              Forest-Mixed --> FRST             1077.1872
2661.7833      0.94     16.49
                   Residential-Low Density --> URLD                1.9948
4.9292      0.00      0.03
                            Summer Pasture --> SPAS              221.4218
547.1443      0.19      3.39
                              Winter Wheat --> WWHT             3894.8295
9624.3184      3.41     59.61

SOIL:
                                     Brun_calcaire                88.7682
219.3507      0.08      1.36
                                         D'erosion              1711.5307
4229.2779      1.50     26.19
                                          Rendzine              4733.6391
11697.0589      4.14     72.45
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                               13          2902.9752
7173.3969      2.54

LANDUSE:
                                     Pasture --> PAST               519.2476
1283.0869      0.45     17.89
                Southwestern US (Arid) Range --> SWRN                10.0241
24.7700      0.01      0.35
                              Summer Pasture --> SPAS                36.0867
89.1721      0.03      1.24
                                Winter Wheat --> WWHT              2337.6168
5776.3679      2.04     80.52

SOIL:
                                        Brun_calcaire               828.9919
2048.4804      0.72     28.56
                                            D'erosion              1998.8027
4939.1414      1.75     68.85
                                        Brun_subaride                75.1806
185.7751      0.07      2.59
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                               14          1793.0434
4430.6999      1.57

LANDUSE:
                                     Pasture --> PAST                37.1044
91.6867      0.03      2.07
                Southwestern US (Arid) Range --> SWRN                 2.0056
4.9560      0.00      0.11
                              Summer Pasture --> SPAS                83.2341
205.6757      0.07      4.64
                                Winter Wheat --> WWHT              1670.6993
4128.3814      1.46     93.18

SOIL:
                                        Brun_calcaire               316.8913
783.0543      0.28     17.67
                                            D'erosion              1299.6556
3211.5140      1.14     72.48
                                             Rendzine                55.1551
136.2911      0.05      3.08
                                        Brun_subaride               121.3413
299.8404      0.11      6.77
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                         15           2550.9484
6303.5210      2.23

LANDUSE:
                                     Pasture --> PAST            249.1671
615.7043      0.22      9.77
                Southwestern US (Arid) Range --> SWRN            350.6424
866.4548      0.31     13.75
                              Summer Pasture --> SPAS            106.4988
263.1639      0.09      4.17
                                Winter Wheat --> WWHT           1844.6401
4558.1980      1.61     72.31

SOIL:
                                        Brun_calcaire            449.1036
1109.7573      0.39     17.61
                                            D'erosion           1533.1813
3788.5676      1.34     60.10
                                             Rendzine            568.6636
1405.1961      0.50     22.29
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                         16           2742.4190
6776.6545      2.40

LANDUSE:
                                     Pasture --> PAST            111.8539
276.3967      0.10      4.08
                Southwestern US (Arid) Range --> SWRN              0.9987
2.4678      0.00      0.04
                                Winter Wheat --> WWHT           2629.5664
6497.7900      2.30     95.88

SOIL:
                                            D'erosion           2556.6616
6317.6385      2.24     93.23
                                        Brun_subaride            185.7574
459.0159      0.16      6.77
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                                                                Area [ha]
Area [acres] %Wat.Area %Sub.Area
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SUBBASIN #                                              17            396.9028
980.7667      0.35

LANDUSE:
                                              Pasture --> PAST            32.9090
81.3198      0.03      8.29
                     Residential-Low Density --> URLD            71.8015
177.4251      0.06      18.09
                                       Summer Pasture --> SPAS            61.8291
152.7827      0.05      15.58
                                         Winter Wheat --> WWHT           230.3632
569.2389      0.20      58.04

SOIL:
                                                   D'apport PE           140.6113
347.4575      0.12      35.43
                                                 Brun_calcaire           182.4955
450.9555      0.16      45.98
                                                      Rendzine            73.7960
182.3536      0.06      18.59
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                                                                      Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                              18           2572.8878
6357.7344      2.25

LANDUSE:
                                              Pasture --> PAST          1009.2103
2493.8090      0.88      39.22
                                       Summer Pasture --> SPAS           194.4625
480.5264      0.17      7.56
                                         Winter Wheat --> WWHT          1369.2151
3383.3990      1.20      53.22

SOIL:
                                                   D'apport PE           115.6802
285.8516      0.10      4.50
                                                    D'erosion          1264.5045
3124.6540      1.11      49.15
                                                      Rendzine          1007.2158
2488.8805      0.88      39.15
                                                 Brun_subaride           185.4873
458.3483      0.16      7.21
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                                                                      Area [ha]
Area [acres] %Wat.Area %Sub.Area
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SUBBASIN #                                               19          5212.5908
12880.5725     4.56

LANDUSE:
                                           Pasture --> PAST          1248.5787
3085.3004     1.09     23.95
                Southwestern US (Arid) Range --> SWRN                  19.0241
47.0094      0.02      0.36
                                      Forest-Mixed --> FRST           602.7621
1489.4554     0.53     11.56
                     Residential-Low Density --> URLD                  34.0430
84.1221      0.03      0.65
                                    Summer Pasture --> SPAS           289.3659
715.0375     0.25      5.55
                                      Winter Wheat --> WWHT          3018.8170
7459.6477     2.64     57.91

SOIL:
                                                D'apport PE           264.3342
653.1831     0.23      5.07
                                              Brun_calcaire          2325.9409
5747.5163     2.03     44.62
                                                  D'erosion          1518.9205
3753.3286     1.33     29.14
                                                   Rendzine           834.0546
2060.9906     0.73     16.00
                                              Brun_subaride           269.3406
665.5540     0.24      5.17
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                                                                   Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                               20          5362.1772
13250.2080     4.69

LANDUSE:
                                           Pasture --> PAST          4404.3191
10883.2926     3.85     82.14
                     Residential-Low Density --> URLD                   7.1103
17.5699      0.01      0.13
                                    Summer Pasture --> SPAS           178.7731
441.7573     0.16      3.33
                                      Winter Wheat --> WWHT           771.9747
1907.5882     0.68     14.40

SOIL:
                                              Brun_calcaire           285.4275
705.3056     0.25      5.32
                                                  D'erosion          1198.5924
2961.7817     1.05     22.35
                                                   Rendzine          3671.9588
9073.5938     3.21     68.48
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                                         Brun_subaride            206.1985
509.5268      0.18      3.85
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                                                                 Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                 21          2235.8194
5524.8215      1.96

LANDUSE:
                                      Pasture --> PAST            1142.0807
2822.1386      1.00     51.08
                      Residential-Low Density --> URLD              27.1924
67.1938      0.02      1.22
                               Summer Pasture --> SPAS             392.7791
970.5768      0.34     17.57
                                 Winter Wheat --> WWHT             673.7672
1664.9124      0.59     30.14

SOIL:
                                           D'apport PE             277.9667
686.8697      0.24     12.43
                                             D'erosion            1403.9334
3469.1897      1.23     62.79
                                         Brun_subaride             553.9192
1368.7621      0.48     24.77
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                                                                 Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                 22           402.8863
995.5522      0.35

LANDUSE:
                                      Pasture --> PAST             302.1647
746.6641      0.26     75.00
                      Residential-Low Density --> URLD               1.9945
4.9285      0.00      0.50
                               Summer Pasture --> SPAS              98.7271
243.9596      0.09     24.50

SOIL:
                                           D'apport PE             141.6086
349.9218      0.12     35.15
                                             D'erosion             186.4845
460.8125      0.16     46.29
                                         Brun_subaride              74.7932
184.8179      0.07     18.56
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                                                                  Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                          23              38.8925
96.1053      0.03

LANDUSE:
                                      Pasture --> PAST              19.9449
49.2848      0.02     51.28
                               Summer Pasture --> SPAS              14.9587
36.9636      0.01     38.46
                                 Winter Wheat --> WWHT               3.9890
9.8570      0.00     10.26

SOIL:
                                           D'apport PE               8.9752
22.1781      0.01     23.08
                                             D'erosion              29.9173
73.9272      0.03     76.92
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                                                                  Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                          24            4570.3660
11293.6029      4.00

LANDUSE:
                                      Pasture --> PAST            4361.6689
10777.9020      3.81     95.43
                Southwestern US (Arid) Range --> SWRN               7.9884
19.7397      0.01      0.17
                               Summer Pasture --> SPAS              13.9797
34.5446      0.01      0.31
                                 Winter Wheat --> WWHT             186.7290
461.4166      0.16      4.09

SOIL:
                                           D'apport PE               0.9986
2.4675      0.00      0.02
                                         Brun_calcaire             616.1057
1522.4280      0.54     13.48
                                             D'erosion            1319.0853
3259.5258      1.15     28.86
                                              Rendzine            2415.4939
5968.8061      2.11     52.85
                                         Brun_subaride             218.6826
540.3756      0.19      4.78
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                                                             Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                        25         7120.3168
17594.6588      6.23

LANDUSE:
                                   Pasture --> PAST          2522.3815
6232.9307      2.21     35.43
                Southwestern US (Arid) Range --> SWRN          16.9555
41.8979      0.01      0.24
                     Residential-Low Density --> URLD          15.9581
39.4333      0.01      0.22
                            Summer Pasture --> SPAS             0.9974
2.4646      0.00      0.01
                              Winter Wheat --> WWHT          4564.0243
11277.9323      3.99     64.10

SOIL:
                                      Brun_calcaire           129.6598
320.3958      0.11      1.82
                                          D'erosion          2926.3215
7231.0868      2.56     41.10
                                           Rendzine          1861.1166
4598.9121      1.63     26.14
                                      Brun_subaride          2203.2189
5444.2641      1.93     30.94
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                                                             Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                        26         6367.3984
15734.1598      5.57

LANDUSE:
                                   Pasture --> PAST           658.6964
1627.6717      0.58     10.34
                            Summer Pasture --> SPAS           167.6682
414.3164      0.15      2.63
                              Winter Wheat --> WWHT          5541.0338
13692.1717      4.85     87.02

SOIL:
                                          D'erosion          2570.9120
6352.8520      2.25     40.38
                                           Rendzine          2422.2063
5985.3928      2.12     38.04
                                      Brun_subaride          1374.2802
3395.9151      1.20     21.58
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                                                                   Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                27         3906.2020
9652.4205      3.42

LANDUSE:
               Southwestern US (Arid) Range --> SWRN                    1.0114
2.4993      0.00      0.03
                               Forest-Mixed --> FRST             3333.7239
8237.7985      2.92     85.34
                             Summer Pasture --> SPAS               46.5265
114.9693      0.04      1.19
                               Winter Wheat --> WWHT              524.9401
1297.1533      0.46     13.44

SOIL:
                                           D'erosion              168.9114
417.3885      0.15      4.32
                                            Rendzine             3737.2906
9235.0320      3.27     95.68
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                                                                   Area [ha]
Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                28         7015.6064
17335.9142      6.14

LANDUSE:
                                    Pasture --> PAST              411.5635
1016.9941      0.36      5.87
               Southwestern US (Arid) Range --> SWRN               72.0987
178.1596      0.06      1.03
                    Residential-Low Density --> URLD               49.0672
121.2475      0.04      0.70
                             Summer Pasture --> SPAS              154.2112
381.0635      0.13      2.20
                               Winter Wheat --> WWHT             6328.6658
15638.4496      5.53     90.21

SOIL:
                                           D'erosion             5614.6881
13874.1751      4.91     80.03
                                            Rendzine              183.2509
452.8222      0.16      2.61
                                        Brun_subaride            1217.6673
3008.9169      1.06     17.36
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                                                                   Area [ha]
Area [acres] %Wat.Area %Sub.Area
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SUBBASIN #                                                   29         10413.2144
25731.5734      9.11

LANDUSE:
                                            Pasture --> PAST            1986.1085
4907.7735      1.74     19.07
                Southwestern US (Arid) Range --> SWRN             461.5108
1140.4162      0.40      4.43
                                       Forest-Mixed --> FRST            2676.3593
6613.4178      2.34     25.70
                     Residential-Low Density --> URLD               4.0307
9.9600      0.00      0.04
                                     Summer Pasture --> SPAS             269.0467
664.8278      0.24      2.58
                                       Winter Wheat --> WWHT            5016.1584
12395.1783      4.39     48.17

SOIL:
                                                 D'apport PE             753.7337
1862.5137      0.66      7.24
                                                Brun_calcaire             735.5958
1817.6939      0.64      7.06
                                                  D'erosion            3466.3690
8565.5712      3.03     33.29
                                                   Rendzine            4930.5069
12183.5290      4.31     47.35
                                                Brun_subaride             527.0090
1302.2656      0.46      5.06
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