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Modelling the Hydrologic Behavior of the Upper Tiber River Basin under Climate Change Scenarios

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Modelling the Hydrologic Behavior of the Upper Tiber River Basin under Climate Change Scenarios

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Dedicated to:

my mother, Aberash Belayneh;
the departed soul of my father Behulu Muluneh;
my brothers and sisters;
my wife Bizunesh Wodajo;
and my son Yeabsira Fiseha.

Abstract

Quantification of the various components of hydrological processes in a watershed remains a challenging topic as the hydrological system is altered by internal and external drivers. This study investigates hydrological behavior of the Upper Tiber River Basin (UTRB) in central Italy under climate change scenarios. It addresses the response of the watershed by evaluating the relative changes in magnitudes of various hydrological processes using downscaled climate data in a watershed model. The observed data from regional concerned offices of the basin and the readily available global and regional climate model data were collected for analysis.

First, the reliability of the precipitation and temperature data through two statistical downscaling methods are evaluated. The Statistical Downscaling Model (SDSM) and the Long Ashton Research Station Weather Generator (LARSWG) are used to downscale the HadCM3 GCM predictions of the A2 and B2 scenarios for the Chiascio sub-basin in the UTRB. The results show that the downscaling methods used have different performance to reproduce the precipitation patter but they agree on both minimum and maximum temperature. However it is difficult to choose which method is of downscaling as both have their own limitations and associated uncertainties

Second, a physically-based watershed simulation model called Soil Water Assessment Tool (SWAT) is used to understand the hydrologic behavior of the basin. The model is successfully calibrated for the period of 1963-1970 and validated for the period of 1971-1978 using observed weather and flow data. A total of eighteen hydrologic parameters are evaluated and the model showed high relative sensitivity to groundwater flow driven parameters than the surface

flow driven parameters. The objective function for model evaluation statistics showed coefficient of determination (R^2) from 0.68 to 0.81 and Nash Sutcliffe Efficiency (E_{NS}) between 0.51 and 0.8 for the validation period. Based on the calibrated parameters the model is proved to be capable of predicting impact of climate changes in water resources planning and management.

Third, the calibrated watershed model is used to evaluate the response of the basin under different climate change scenarios. Bias correction to three regional climate model (RCM) from the PRUDENCE including RegCM, RCAO, and PROMES outputs are applied. The current (1961-1990) and future (2071-2100) time periods were considered for the analysis. The result indicated that there will be significant decrease in the hydrologic components and water yields of the basin which resembles some previous findings in the basin. The result of the present study is different from the others in that most of them used indices based on observation. However, future work on the uncertainty issues related to projected climate variables is highly recommended. Despite some common limitations, this study is relevant to assist the development of climate change adaptation in the study.

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Acronyms and Abbreviations

FAO	***F**ood and **A**griculture **O**rganization of the United Nations*
a. m.s.l	***a**bove **m**ean **s**ea **l**evel*
CMIP3	***C**limate **M**odel **I**ntercomparison **P**roject (third)*
CORDEX	***C**oordinated **R**egional **C**limate **D**ownscaling **E**xperiment*
DEM	***D**igital **E**levation **M**odel*
FAR	***F**irst **A**ssessment **R**eport of the IPCC*
GCM	***G**lobal **C**limate **M**odel*
GHGs	***G**reen**h**ouse **G**ases*
GIS	***G**eographic **I**nformation **S**ystems*
HadCM3	***Had**ley **C**entre for Climate Prediction and Research **C**oupled **M**odel, version **3***
HC	*The **H**adley **C**entre*
IPCC	***I**ntergovernmental **P**anel on **C**limate **C**hange*
IRPI	***I**stituto di **R**icerca per la **P**rotezione **I**drogeologica*
ITCP	***I**nternational **C**enter for **T**heoretical **P**hysics*
LH-OAT	*Latin Hypercube sampling-One-Factor-At-a-Time*
PRUDENCE	***P**rediction of **R**egional scenarios and **U**ncertainties for **D**efining EuropeaN **C**limate change risks and **E**ffects*
RCM	*Regional Climate Model*
SMHI	***S**wedish **M**eteorological and **H**ydrological **I**nstitute*
SWAT	***S**oil and **W**ater **A**ssessment **T**ool*
TRB	***T**iber **R**iver **B**asin*
UCM	***U**niversidad **C**omplutense de **M**adrid*
UTRB	***U**pper **T**iber **R**iver **B**asin*

Chapter 1

This chapter is an overall preface to the research undertaken in this doctoral thesis. It provides a general background to the research with some issues related to climate change on water resources. The water resources problem in the Italian context with the motivation of the research was also provided un this background section. The objectives of the study are presented in section 1.2. Section 1.3, provides the overall framework of the research and finally, the structure of the present thesis is presented in section 1.4.

1. Introduction

1.1. General background

One of the challenge in water resources planning and management is to estimate future availability of water and to develop management strategies in the face of climate change. It is expected that global climate change will have a strong impact on water resources in many regions of the world (Bates et al., 2008). One of the most important impacts of future climatic changes on society will be the changes in regional water availability (Xu and Singh, 2004). In view of sustainable development, man has always remained very conscious of the requirements of water towards meeting the mandatory needs for food production, public health, energy needs, industrial development and production and other important aspects of quality of life. Due to ever increasing demands for water in the recent times following the population growth and variations in the hydrological inputs, the problem of water management (i.e. the control of water in quantity and quality) as it passes through natural hydrological cycle with attention to maximizing economic, social and environmental goals, has become crucial. In water management planning, the basic complexity arises from conflicts among different objectives and various beneficiary groups of the society and their organizational structure. Thus planning for water resources must take into account the integration of these different objectives and interests for effective implementation.

As part of water resources planning objectives and potential assessment, small scale studies at watershed level now a days are getting due attention. In a watershed, numerous internal and external drivers act on the natural ecosystem regardless of their geographic locations. These effects of the drivers on the system understanding create a twofold problem. On one hand, the quantification of the hydrological processes (precipitation, evaporation, recharge, runoff, etc.) and storages taking place within the system is a scientific challenge. On the other hand, quantification of the drivers such as land cover change due to human interaction with the natural environment and real determination of climate change impact on the hydrologic processes is difficult. Also, studies revealed that over next few years an increasing population and increasing use of water will put high pressure on global water resources (Arnell, 1999). The aggregate impacts of both the internal and external drivers determine the amount and quality of water available in long run.

The development of hydrologic and watershed models has been the direct outcome of the need to integrate our knowledge on existing theories on real world flow behaviour with all physical and measured data. However, large-scale and complex environmental systems such as the global hydrological cycle or basin pollutant loading cannot be investigated directly through experimentation, but instead must be generalized into their component processes through modelling (Praskievicz and Chang, 2009). The key factor in model development has been and still is the on-going breakthrough in computation technologies particularly the introduction of the digital computer that is capable to store, manipulate data and to execute complex calculations beyond the physical ability of man, yet within his mental capacity.

The hydrologic cycle plays a key role in the energy balance of the earth's surface-atmosphere system. The world's water resources are impacted by global warming in complex manner associated with the changes in storage and fluxes in the general water balance equation of the hydrologic cycle. Moreover, different catchments respond differently to the same change in climate drivers, depending largely on watershed physiogeographical and hydrogeological characteristics and the amount of lake or groundwater storage in the catchment (IPCC, 2007). Climate changes are undergoing globally, however, mitigation policies are expected at local scale.

Italy, is endowed with quite substantial amounts of surface and subsurface water resources that have been used for agricultural production, local scale hydropower, industrial activities and domestic uses. Agriculture is perhaps the main water using sector with a share around 50% of total water use, mainly due to irrigation (Bartolini et al., 2010). For example in 2003, 30% of the total agricultural area was irrigated with significant growth in the last decades. However, the irrigated area is very heterogeneous between regions, ranging from 9% in Marche, to 67% in Lombardia (ISTAT, 2007). At regional scale, the heavy and uncontrolled exploitation of surface water and groundwater resources has had a negative impact on water quality in the Tiber River Basin. Also use of fertilizers in agriculture along with municipal and industrial pollution have all added to environmental degradation (Cesari, 2010). In addition to the above issues, there is high variability of climate characteristics over the entire Italian territory due to its north south extension, mountain chains and its location in the Mediterranean region. Hence watershed scale studies are important to evaluate such local level problems. The present study is therefore initiated to evaluate main issues related to water resources as it is impacted by climate change under various scenarios.

1.2. Objective of the research

The Tiber River Basin (TRB) in the central Italy is one of the significant basins in the Mediterranean region related to its water resources and ecological balances. In addition to the known climate change issues in the region, over exploitation of water resources for domestic and agricultural purpose imposes high pressure in the basin. More importantly, the activities on the upstream part are expected to have lots of impact on the downstream part of the basin. The present study is thus undertaken to analyse the hydrologic behaviour of a catchment using observed data and selected climate models outputs. Under the umbrella of this general objective, the sensitivity of the hydrologic regime to climate change through integration of bias-corrected precipitation and temperature data into watershed model will be assessed.

The specific objectives are therefore; to:

- analyse the hydrological characteristics of the study area through analysis of observed weather and river flow data.
- calibrate and validate watershed model (SWAT) based on the observed dataset and identify the most significant hydrologic behaviour of the basin from the parameters used in the model.
- evaluate the reliability of precipitation and temperature data as obtained from single GCM but downscaled with different statistical methods.
- analyse bias correction of precipitation and temperature data as obtained from RCM
- evaluate the response of the basin to climate model outputs at watershed scale using the calibrated watershed model and evaluate the response of various hydrologic processes to climate change.

1.3. Overall framework of the research

The present research is conducted following some framework of methodologies. It comprises early stage literature review to the presentation of findings based on the defined objectives . Through detailed literature review, the available theoretical background on climate change and its impact on water resources is thoroughly reviewed. Gaps, drawbacks and limitations of existing methodologies were identified. Based on the review of existing methods of climate change impact studies on hydrology, one of the methods is adopted to evaluate the hydrological behaviour of the Upper Tiber River Basin (i.e. the basin used as a study area).

Thus the study has three major parts. In the first part, two statistical downscaling of precipitation and temperature were used to downscaled climate outputs from the single GCM; the results of two downscaling methods were compared whether or not they are reliable to use in the hydrological model. Again, in the same part of the research the precipitation and temperature data from selected RCM were bias corrected and their performance is evaluated under different emission scenario. The available observed weather, river flow, soil and land cover data for the study area are also analysed in the first part. In the second part of the research, two separate activities were performed: first the selected hydrological model is calibrated and validated using observed data sets, second, the bias-corrected climate data are further used to force hydrologic model. Finally, in the third part of the research the hydrological behaviour of the basin is evaluated to understand. Discussion of main issues in the face climate change were performed for the study area. The overall research framework is summarized in figure 1.1.

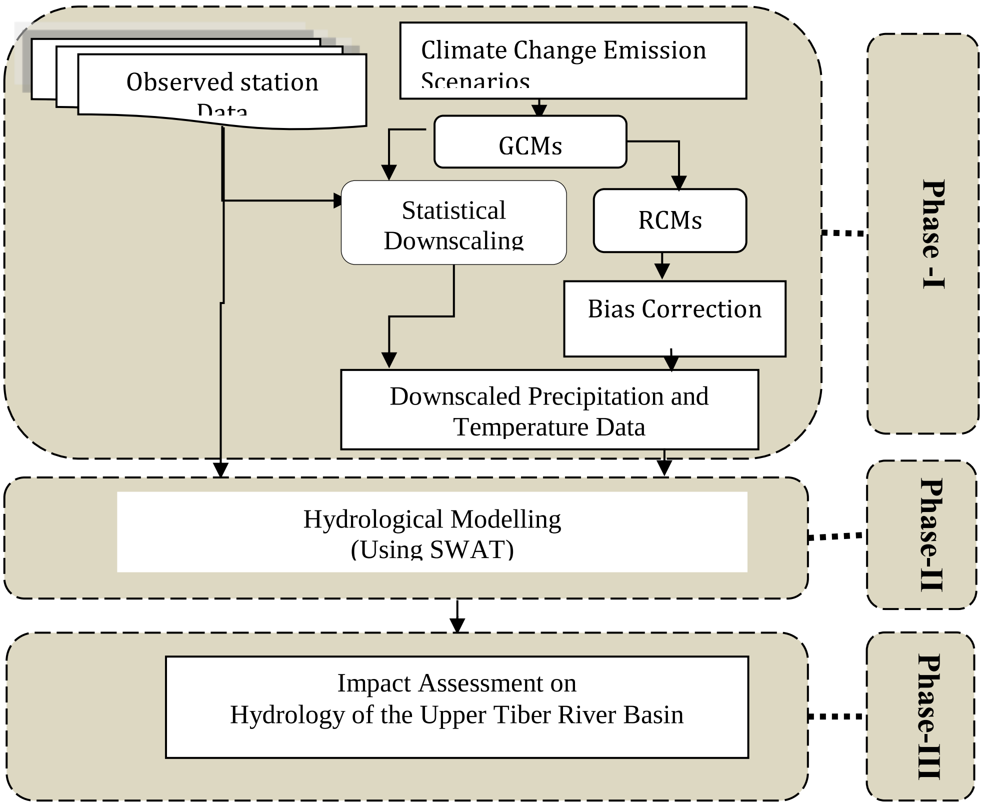

Figure 1.1. General flow of the research

1.4. Structure of the thesis

The thesis is structured in seven chapters. In **Chapter 1** the overall background of the research is presented. The study objective s and the general flow of the research is also presented in this chapter.

In **Chapter 2**, the detailed literature review on the-state-of-the-art climate change and water resource is presented. The use of climate models with the most widely used methodologies were explained. Climate change issues in the context of Italy is also presented in this chapter.

In **Chapter 3**, the study area which is the Upper Tiber River Basin is described with regard to its geographic and climatic settings. The available datasets including: rainfall, precipitation, temperature, river flow and other dataset that are useful for watershed simulation are also presented.

In **Chapter 4**, application of the statistical downscaling methods from general circulation model (GCM) is presented. The performance of two different statistical downscaling approaches over the Chiascio sub-basin is explained with the result obtained .Finally some remarks were pointed out on the reliability issues of the downscaled data.

In **Chapter 5**,the analysis of hydrologic behavior of the basin using the Soil and Water Assessment Tool (SWAT) is presented. Basic theoretical description for different classes of watershed model and the SWAT model with respect to its ability to simulate hydrologic processes is summarized. Finally, based on the calibration and validation results the parameters that govern the basin characteristics are presented.

In **Chapter 6**, the response of the watershed to climate change scenario derived from three regional climate models (RCMs) are analyzed. The bias correction procedures applied in the climate change assessment is used and the effects on the river flow, recharge and baseflow are evaluated.

In **Chapter 7**,the overall summary of the research with some concluding remarks are given. The limitations and some assumptions made during the research are presented in this chapter.

Note that each chapter of the thesis was thought to be independent, however in some sections overlapping was unavoidable as the results of one chapter is dependent on the proceeding chapter.

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Chapter 2

This chapter provides a short review on the state-of-the-art, climate change impact assessment on water resources. The growing interests of climate change impact studies with respect to water resources were reviewed. The use of both global and regional climate model outputs for water resources impact assessment were explained. The most widely used methods of climate model downscaling were summarised and the impact studies in surface water and groundwater are given in detail. Finally issues related to uncertainties and climate change studies in Italy were summarised.

2. Climate Change and Water Resources :A Short Review

2.1. General

The terms climate change and global warming are quite often misused. In the most general sense, climate change is the long-term change in the statistical distribution of weather patterns over periods ranging from decades to millions of years (IPCC, 2007). Whereas, global warming is the name given to the increase in the average temperature or the Earth's near-surface air and oceans that has been observed since the mid-20th century and is projected to continue. It is well documented and widely accepted that the Earth's climate has fluctuated and changed throughout history. The fluctuation in earth's climate imposes pressure on the water cycle mainly by changing the precipitation and temperature characteristics (Loaiciga et al., 1996).

The studies related to water resources assessment in the face of climate change generally evaluate the impacts from both the supply and the demand side. The supply-side impacts include among others the climate change (or variability) and environmental degradation; and demand-side impacts include population growth and increased environmental requirement. Climate change, however, is just one of the pressures that affect hydrological systems and water resources management over next few years (Xu, 1999a; Varis et al., 2004). Despite this it is reported by (Loaiciga, 2009), that few topics attract as much attention today as global warming (climate change). Its impact on hydrologic regime will affect nearly every aspect of human well-being, from agricultural productivity and energy use to flood control, municipal and industrial water supply, and fish and wildlife management.

The global atmospheric General Circulation Models (GCMs) have been developed to simulate the present climate and they were implemented to predict future climatic change under various GHG concentrations (Xu, 1999). These models are also regarded as principal tools for accounting the complex set of processes which will produce future climate change (Karl and Trenberth, 2003). Based on the simulation results of GCMs there is already evidence that anthropogenic emissions of GHGs have altered the large-scale patterns of temperature over the twentieth century (Cubasch et al., 2001). Therefore it is not surprising that there are wide ranges of such GCM identified by the IPCC (2001) for impact assessment studies. Among these, HadCM3 (Hadley Centre for Climate Prediction and Research Coupled Model, UK), ECHAM (Climate Research Centre, European Centre/Hamburg Model, Germany), CGCM (Canadian Centre for Climate Modeling and Analysis), GFDL_R30 (Geophysical Fluid Dynamics Laboratory & NOAA), and CCSR/NIES (Centre for Climate Systems Research & Japanese National Institute for Environmental Studies) are the commonly used ones. However, the uncertainties related with such models are not yet well studied. Consequently, the Special Report on Emission Scenarios (SRES) of the IPCC describes six different scenario groups drawn from a four different story lines. Each story line represents different demographic, social, economic, technological, and environmental developments (IPCC, 2001).While GCMs demonstrate significant skill at the continental and hemispheric spatial scales and incorporate a large proportion of the complexity of the global system, they are inherently unable to represent local sub grid-scale features and dynamics (Wigley et al., 1990; Carter et al., 1994). This mismatch in system representation is due to the difference in resolution and referred to as the scale issue discussed in section 2.3.3. The conflict between GCM performance at regional spatial scales and the needs of regional-scale impact assessment is largely related to model resolution in such a way that, the GCM accuracy decreases at increasingly finer spatial scales, and the needs of impact researchers conversely increase with higher resolution (Hostetler,1994; Schulze, 1997). Therefore there is high interest by researchers to bridge the gaps between the resolution of climate models and regional and local-scale processes to deal with the impact of climate change and the application of climate change scenarios to hydrological models.

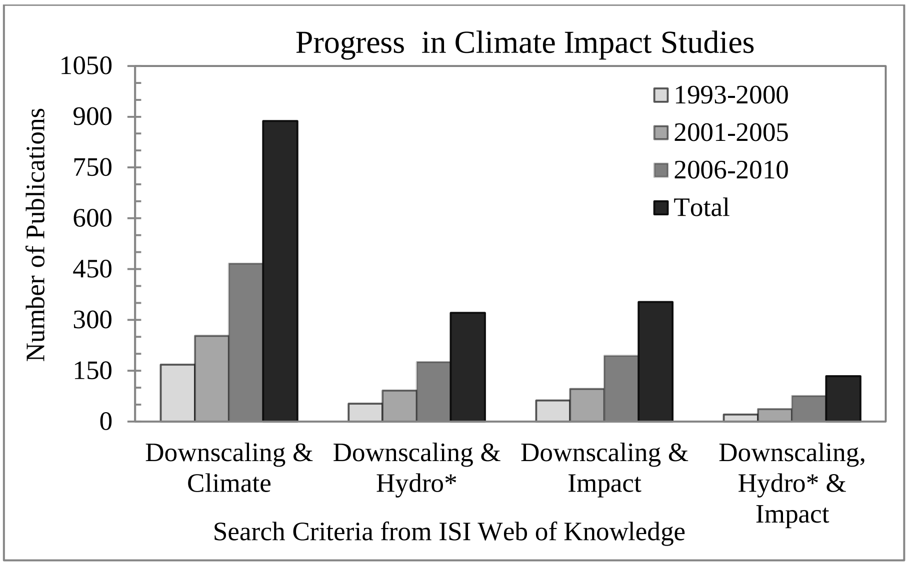

Figure 2.1. Progress in application of downscaling for hydrological impact studies (last accessed Dec 28/2010)

The scientific literatures over the past decade contain large number of reports and reviews detailing the application of hydrologic models to the assessment of the potential effects of climate change on a variety of water resource issues. The intention of this section is thus not to bring all the findings of the researches; rather, to show the attention given to this research area and mapping of the available methodology related to hydrology and water resources. One of the interesting ways to look at the attention given to this area of research is the intense number of progressive articles emerging on downscaling GCMs and RCMs for hydrological impact studies. Figure 2.1 shows publications on the use of downscaling in climate change impact in hydrology. All of these literatures emerged after the IPCC's First Assessment Report (FAR) of 1991. In all the search criteria used in ISI Web of Knowledge, the last five years (2006-2010) shows huge number of publications than the first ten years (1991-2000) which indicates that there is high attention given to impact studies. When the search criterion "Downscaling, Hydrol* & Impact" is used, comparatively less number of publications were found. This could indicate that the need of impact studies associated to hydrology is still limited and an ongoing interest among scientific societies. Despite this fact, there were different reviews provided by different authors on the available methodologies since establishment of FAR and new developments. The following consecutive sub-sections will provide a review of some of such literatures.

2.2. Climate Models in Water Resources Studies

2.2.1. GCM for Water Resources Studies

Global Atmospheric General Circulation Models (GCMs) have been developed to simulate the present climate and used to predict future climatic changes. In water resources impact assessment there are varieties of such GCMs' and RCMs' outputs at different spatial and temporal resolutions. It is also obvious that GCMs are the only tools that are now days providing dataset in water resources impact studies. Among the total number of available literatures presented in section 2.1 above majority of the research works focused on the use of GCMs through downscaling and only few studies have focused on the use of the RCMs through a technique called "Model Output Statistics" –MOS, (Maraun et al., 2010). The one that uses RCMs will be discussed in the later section, whereas those based on GCMs will be reviewed in this section.

Before exploring some examples that use GCMs that are used in water resources impact study, we will see some drawbacks. Variables such as runoff, soil moisture, and evapotranspiration are not well represented by GCMs (Loaiciga et al., 1996). The GCMs simulation skills decreases from climate variables to hydrological variables while the hydrological importance increases along the same direction (Xu, 1999a). Further, Xu (1999a) has identified three different gaps in using the GCMs for water resources studies. These are: (i) The spatial and temporal scale mismatches, (ii) The vertical level mismatches, and (iii) The accuracy mismatch. As an additional gap (Loaiciga et al., 1996) has mentioned the issue of feedbacks as hydrologic models are used in offline process modelling and GCMs do not consider lateral transfer of water within the land phase.

Despite all the above drawbacks, there are numerous studies conducted using the available GCMs in different part of the world. For example, to relate GCM hydrologic output to river hydrographs, Liston *et al.* (1994)

developed a runoff routing model that routes GCM-computed runoff through regional- or continental-scale river drainage networks. By following the basin overland flow paths, the routing model generates river discharge hydrographs that can be compared to observed river discharges, thus allowing an analysis of the GCM representation of monthly, seasonal and annual water balances over large regions. Later, Bergstrom et al. (2001) have used two GCMs: UKMO HadCM2 of the Hadley Centre in Reading and the ECHAM4/OPYC3 of the Max Planck Institute for Meteorology in Hamburg to show the impact of climate change on runoff in Sweden. They analysed changes in runoff totals, runoff regimes and extreme values for six selected basins. Their result shows change in extreme values of runoff can be more critical than mean values. More recently, Lotsari et al.(2010) have used two GCMs (HadCM3 and ECHAM5) to evaluate the impact of climate change on future discharges and flow characteristics of the Tana river in sub-arctic northern Fennoscandia under three different emission scenarios: A1B, A2 and B1. They found projected future increase in both temperature and precipitation which are critical parameters governing future floods and flow characteristics as they control the timing and intensity of flood events in the region. Gao *et al.*, (2010) has also used the same emission scenario to evaluate projected stream flow in the Huaihe River Basin (2010-2100) in china by downscaling ECHAM5 using artificial neural network. There is very few applications of GCMs in impact assessment related water quality; however, Mimikou *et al.*(2000) have shown that there will be significant water quality impairments because of decreased stream flows using two GCM based climate change scenarios of transient (HadCM2) and equilibrium (UKHI) conditions in central Greece.

2.2.2. RCM for Water resources Studies

Regional Climate Models (RCMs) are developed based on the same representations of atmospheric dynamical and physical processes as GCMs. They have higher spatial resolution in the order of 10-50km that can cover a sub-global domain. As a result of the higher spatial domain, RCMs provide a better description of orographic effects, land-sea surface contrast and land-surface characteristics (Christensen and Christensen, 2007a). Moreover, they enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales which shows their improved ability to reproduce present day climate (Xu, 2000). However, there is still some limitations (Xu, 2000; Hay and McCabe, 2002; Varis et al., 2004) such as: (i) the inheritance of systematic errors in the driving fields provided by global models, (ii) lack of two-way interactions between regional and global climate (iii) the algorithmic limitations of the lateral boundary interface (iv) computationally demanding, and (v) further downscaling requirement for impact studies.

There are many different RCMs currently available, for various regions, developed at different modelling centres of the world. However, the uncertainty issues remains another drawback in use of RCM. Due to this fact, several international efforts have been taken to quantify uncertainties through model intercomparison. Some of these include the project work in European region: PRUDENCE [Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects] (Christensen and Christensen, 2007a) and ENSEMBLES; and in North America the NARCCAP (North American Regional Climate Change Assessment Program). More recently, a new project called CORDEX (Coordinated Regional Climate Downscaling Experiment) has been initiated by the world climate research program simulations at 50km resolution for multiple regions.

Due to the availability of numerous numbers of such RCMs a number of studies have been conducted in the past. Teutschbein and Seibert (2010), Teutschbein et al., (2011), and Teutschbein and Seibert, (2012) provided a recent review on the use of RCMs for hydrological models. They recommend that a bias correction is necessary for using the outputs in any hydrological models as RCMs are susceptible to systematic model errors caused by imperfect conceptualization, discretization and spatial averaging within grid cells. These biases are typically due to the occurrence of too many wet days with low-intensity rain or incorrect estimation of extreme temperature in RCM simulations. Bias correction is also recommended by Wilby *et al.*(2000) and Wood *et al.*, (2004) as a minimum requirement when using RCM outputs in hydrological impact studies. However, (Ehret et al., 2012) have the opinion not to misuse the . available methods which may add up the uncertainties in impact assessment.

The uses of RCMs are most often applied in European river basins. Some of the examples are the studies of the effects of climate change on groundwater assessment (Roosmalen et al., 2007), run-off estimation (Rigon et al., 2007), flood risk assessment (Fowler and Wilby, 2010), precipitation, potential evapotransipiration estimation (Baguis et al., 2010), overall catchment scale hydrologic processes (Senatore et al., 2011) . All these assessments are conducted through further downscaling (bias correction) of RCMs. Wood *et al.*(2004), have applied six approaches for downscaling climate model outputs for use in hydrologic simulation with particular emphasis on each method's ability to produce precipitation and other variables used to drive hydrologic model. Of the six approaches the Linear Interpolation (LI), Spatial Disaggregation (SD), and Bias Corrected Spatial Disaggregation (BCSD) were applied to RCM to evaluate the climate impact on British Colombia River Basin. Their result showed the BCSD method yielded the only consistently plausible stream flow simulations, whether or not dynamical downscaling was used. Graham *et al.*(2007a) has also used two bias correction methods (i.e. delta approach and scaling approach) to evaluate the impact of climate change on the hydrology of northern Europe using seven ensembles of RCMs and two GCM scenarios, The two methods gave a similar mean results, but considerably different seasonal dynamics. Hence it can be concluded that the problem of stationarity remains unsolved where extreme conditions are not taken into account. As a means to overcome such error, Seguí *et al.*(2010) have used the quantile-mapping method to evaluate the uncertainty related to the downscaling and bias-correction. In order to provide optimized climate scenarios for climate change impact research, Themeßl *et al.* (2010) have proposed merging of linear and nonlinear empirical-statistical techniques with bias correction methods and investigated their ability for reducing RCM error characteristics. They also found that quantile mapping shows the best performance, particularly at high quantiles, which is advantageous for applications related to extreme precipitation events.

2.2.3. Scale issues in water resources modelling and climate change impact studies

In dealing with processes in a given watershed, conditions are often different in their space or time scale. As stated by Bloschl and Sivapalan, (1995); and Skøien *et al.*,(2003), hydrological processes occur at a wide range of scales, from unsaturated flow in a 1 m soil profile to floods in river systems of a million square kilometres; from flash floods of several minutes duration to flow in aquifers over hundreds of years. These processes may take place over a shorter time span whereas their estimates may be needed for very long times (eg. the impact of climate change on a water resource of a watershed in the next 100 years). Conversely, the large-scale models and data are used for small-scale predictions (eg. Climate model outputs for event studies). Such differences in time scale involve some sort of extrapolation, or transfer of information across scales. This transfer of information is called scaling and the problems associates with it are scale issues (Bloschl and Sivapalan, 1995). Both the spatial and temporal scale dilemma in applying hydrological models in impact studies is described in (Schulze, 1997). They are grouped under any of the four categories: *(i)* The spatial and temporal scale mismatches between GCMs and Catchment models, *(ii)* The precipitation response mismatch between GCM output and its hydrological importance, *(iii)* The means vs. variability paradox, and *(iv)* The transient/invariate climate control paradox.

The scale issue is not only limited to the characteristic time length as spatial variability are also one of the issues in hydrological processes. For example in using climate data for hydrological study bridging the gap between the resolution of climate models and regional and local scale processes represent a considerable problem for the impact assessment. The technique to bridge this gap is known to be downscaling. Overviews of downscaling methods are well summarized in Fowler *et al.* (2007) including their advantages and disadvantages (refer section 2). As means of scientific approach to overcome the scale issue, it has been discussed in many studies through up-scaling (distributing and aggregating) or downscaling (disaggregation and singling out) processes. The reviews of some of these studies were given in (Rigon et al., 2007; Loaiciga, 2009).

2.3. Known Methodologies for Climate Change Impact Assessment

One of the earliest review of techniques used for assessing the effect of climate change on water resources is provided by Leavesley (1994). Their review showed a clear image of types of models used in impact studies and problem areas related to number of modelling issues. The issues could be parameter estimation, temporal and spatial scale of application, validation, climate scenario generation, data and modelling tools. Future solutions to such issues are recommended to bring a way for quantitative determination of climate impacts.

The methodologies and major steps for assessing hydrological response to global climate change were explained in detail in (Schulze, 1997; Xu, 1999a; Xu and Singh, 2004; Xu et al., 2005) and their summary is given in the following section. Clear diagrammatic representations of the methodologies were described by different authors (e.g.Loaiciga et al., 1996; Xu and Singh, 2004) and the one by Xu and Singh, (2004) is used for detailed explanation in this short review.

2.3.1 The direct use of GCM outputs in hydrological models

The approach is to directly use the GCM-derived hydrological output since the GCM is the only available tool for detailed modeling of a future climate (Xu et al., 2005). A GCM has four interactive models:

atmospheric, land surface, ocean and sea ice that are expected to produce all the processes to represent the water cycle.

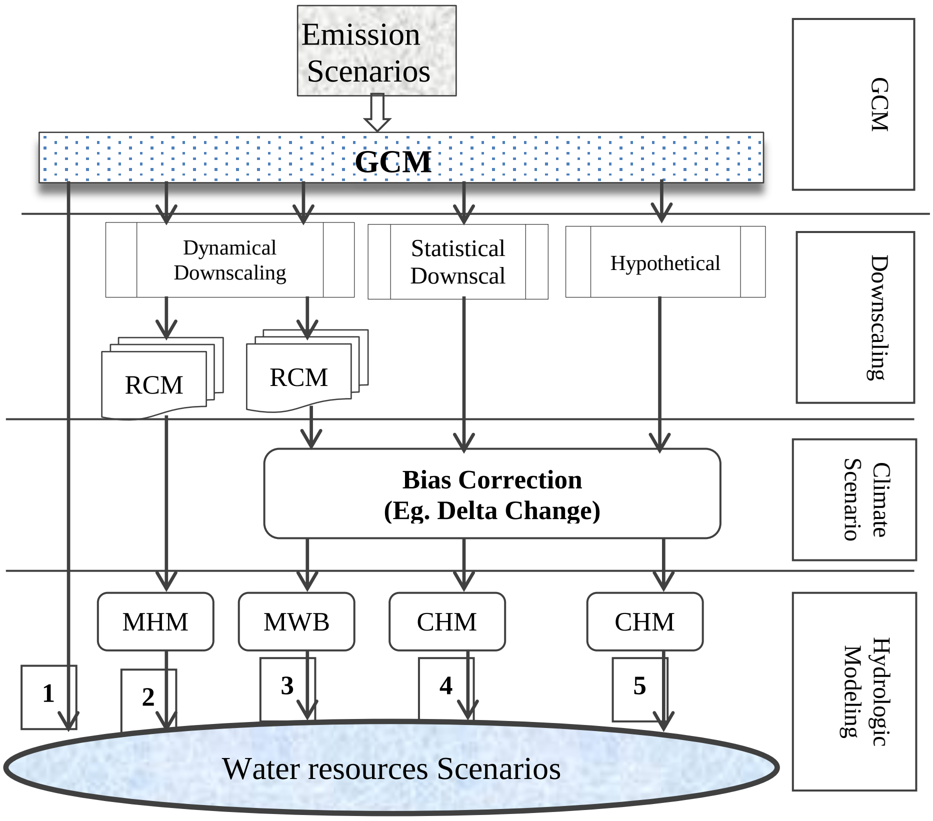

Figure 2.2. Schematic representation of the methods for assessing water resources under changing climate (Source:- Xu and Singh, 2004). *In the figure, GCM is the Global Circulation Model, RCM is the regional climate model, MHM is the macro scale land-surface hydrological model, MWB is the macro scale water balance model, and CHM is the catchment-scale hydrological model. The numbers in circle indicate the individual methods.*

However, direct representations of hydrological quantities are highly simplified large- scale averages with little spatial reliability or relevance to specific regions as GCMs were not originally designed for climate change impact studies in hydrology. They thus reflect inherent GCM shortcomings such as runoff being calculated as a secondary variable and not a first-order GCM variable such as P, T, wind or vapor pressure. This process is explained in the diagram (figure-2.2) with the first step labelled with number 1.

2.3.2. Coupling GCMs and Macro-Scale Hydrologic Models

As stated in method i), the GCM does not give a good estimates of hydrologic responses of climate changes. Hence there is a need to couple hydrological models with GCM. Some of the research work done in different part of the world were reviewed by Xu, C.(1999) and Xu et. al., (2005). The results of the studies showed that coupling the hydrological model (macroscale or global) with GCM produces a better representation of the recorded flow regime than GCM predictions of runoff for very large river basin. The examples of such models are: MacPDM (Arnell, 2004), WBM (Vorosmarty et al., 2000) and WaterGAP(Alcamo and Henrichs, 2002). The main theoretical limitations of this method are given in (Hay and McCabe, 2002; Varis et al., 2004) and they are summarized in Xu et al., (2005) as listed below.

i) The inheritance of systematic errors in the driving fields provided by global models (Loaiciga et al., 1996).

ii) Lack of two-way interactions between regional and global climate. This limitation is considered as a problem associated with feedbacks by Loaiciga, H. et al., (1996).

iii) Algorithmic limitations of the lateral boundary interfaces

iv) RCM simulations can be computationally demanding depending on the domain size and resolution (however in recent days this effects are better understood)

v) The need of downscaling (will be explained later) will remain for individual site impact studies (Wilby and Wigley, 1997; Xu, 1999a)

This method explicitly indicates that simulation of water resources response to climate change is carried out based on hydro-climatic data from GCMs or RCMs and the study focuses more on the world's largest water bodies. However, Arnell (2004) stated that the macro-scale models are characterized by: their transferability from one geographical location to another, they should be applied either to every sub-basin in the spatial domain or on a regular grid, and runoff must be routed from the point of generation through the spatial domain along the river network. According to the review by Xu et al (2005), the coupled modeling of the atmospheric and hydrological processes is proved to be a powerful tool to study the spatial and temporal evolution of the water and energy budgets of a basin. However, the main problem in using such methods is that the models need large amount of hydroclimatic and topographic data for calibration that may not available everywhere. The methods of coupling GCM (RCM) with macro-scale hydrologic models are shown in the diagram, (see figure-2.2) with the label numbers 2 and 3.

2.3.3. Downscaling GCM to Force Hydrological Models

Hydrological models require input data (such as precipitation and temperature) at smaller sub-grid scale, which has to be provided by converting the GCM outputs into a reliable time scale for the study area under consideration. However, due to the limitations of GCMs related to the scale issue, an alternate way of using direct GCM-derived hydrological outputs is to downscale the GCM climate outputs for use in hydrological models.

To date, there are different techniques for downscaling large-scale GCM outputs to small-scale resolutions in order to use in impact models. All the available techniques and rationale of downscaling are categorized under two broad groups namely: ***dynamic downscaling*** and ***statistical downscaling*** techniques (Wilby and Wigley, 1997; Xu, 1999 ; Fowler et al., 2007 are among other reviews).Common to all downscaling methods, Maraun *et al.*, (2010), has provided the most recent review on the application of downscaling techniques for precipitation considering the interest of end users. The most widely used and available techniques under each category are summarized in the literatures stated above and the relevant information are extracted in the following section.

Dynamic Downscaling

It refers to the use and extraction of local scale information from large scale GCM data using regional climate model (RCM) or limited-area models (LAMs) at $0.5^o \times 0.5^o$ or even higher resolutions that parameterizes the atmospheric processes. They utilize large-scale and lateral boundary conditions from GCMs to produce higher resolution outputs required by hydrologic models. However, the computationally expensiveness of the dynamical downscaling method limits its applicability to smaller time slices; normally ~30 years (eg. from 1961-1990 for control or 'baseline' climate and from 2070-2100 for a changed climate used in PRUDENCE) which in turn brought difficulty to assess climate change impacts for other periods (Fowler et.al., 2007).

Statistical Downscaling

In this method, the large-scale atmospheric variables eg. Sea-level pressure and geopotential heights) are empirically related to the local or station-scale atmospheric variables (eg. average precipitation or temperature). The large-scale atmospheric variable are commonly referred to as the predictors whereas the local scale climate variables are the predictands. According to this method, the predicatnd-predictor relationship can be given using equation-1 below which could be a stochastic or deterministic representation of their relation.

$$R = F(X) \qquad (1)$$

Where:

R=Predictand (local climate variable that is being downscaled).

F= A deterministic or stochastic function that relates the two and is typically established by training and validating historical point observation or reanalysis data.

X= Predictors (Set of large-scale climate variables)

From equation-1 above the success of the downscaling method is dependent on the relationship used and choice of predictor variables and their performance can be evaluated through quantification of error in mean and explained variances (Khan et al., 2006). The underlying principle of all the statistical downscaling methods is that regional (local scale) climates are however largely a function of the large-scale atmospheric state. The key assumptions (von Storch et al., 2000; Fowler et al., 2007; Maraun et al., 2010) of this method include: (a) the predictors are variables of relevance and are realistically modeled by the GCM, (b) the transfer function is valid also under changing climate conditions (may not be provable) and, (c) the predictors employed fully represent the climate change signal.

All the statistical downscaling methods are categorized under the following three sub group. The description of each method is given in numerous reviews and project papers (Xu, 1999; Fowler et al., 2007; Rigon et al., 2007). where the summary of them are explained as follows.

a. **Transfer Functions:** in this method, a direct quantitative relationship between predictand and set of predictors are derived using a linear or nonlinear formulation. Some of the methods that are included under this category are: multiple linear regression methods (eg. Wilby et al., 2002), Canonical Correlation Analysis – CCA (eg. Zorita and von Storch, 1999), Artificial Neural Network – ANN (eg. Coulibaly et al., 2005) and Principal Component Analysis – PCA approaches (eg. Palatella et al., 2010). Among others, the multiple linear regression method, is used to establish regression equation through calibration and validation of local scale climate variables and observed atmospheric predictors for the current climate. For downscaling purpose, the change factors (commonly called as 'delta changes') (Prudhomme et al., 2002) calculated based on the GCM outputs are applied to the established regression models. However, it has to be noted that the change factors used in the regression model disregards variability and regression models are only able to capture part of this variability. As a means to overcome such problems, Prudhomme et al. (2002) proposed that any increase in precipitation is distributed evenly among existing rain days that could make each third dry day wet or distributed on only the three wettest days to simulate an increase in extremes. Other approaches to account variability in regression based downscaling are (i) variable inflation (Karl et al., 1990) that increases variability by multiplying by a suitable factor, (ii) randomization (von Storch et al., 2000) where additional variability is added in the form of white noise, and (iii) expanded downscaling like that of CCA.

b. Stochastic Weather generators (WGs): Stochastic weather generators like WGEN (Richardson, 1981), LARS-WG (Semenov and Barrow, 1997), GiST (Baigorria and Jones, 2010) are numerical models that generate random numbers realistically looking at sequences conditioned upon the large-scale weather of dry or wet states. These random numbers are expected to have identical statistical properties to that of observed weather. The fundamental principles of weather generators are either based on the Markov chain approach (Hughes et al., 1999; Bellone et al., 2000) or spell-length approach (Wilks and Wilby, 1999b). In Markov chain approach, a random process is constructed which determines a day at a station as rainy or dry, conditioned upon the state of the previous day, following given probabilities. If a day is rainy, then the amount of rainfall is drawn from yet another probability distribution (e.g., Gamma distribution). One of the drawbacks of this method (eg. First order Markov) is that the probability of precipitation depends only on whether precipitation occurred on the previous days that may produce synthetic series exhibiting very long dry spells too frequently (Wilks, 1999). However, in case of spell-length approach, instead of simulating precipitation occurrences day by day, the models operate by fitting probability distribution to observed relative frequencies of wet and dry spell lengths.

Weather Generators are originally developed to serve for two main purposes (Semenov et al., 1998). The first one is the provision of weather data time series long enough to be used in an assessment of risk in hydrological or agricultural applications. The second purpose is to provide the means for extending the simulation of weather to locations where observed data is not available. In addition to these purposes, weather generators have got due attention in climate change studies as they can serve as a computationally inexpensive tool to produce site-specific climate change scenarios at the daily time-step. For the latter purpose, the changes in the simulated results of GCM scenarios can be applied to the parameters of the weather generators that are derived using observed data (mainly precipitation, maximum temperature, minimum temperature and radiation). The Long Ashton Research Station Weather Generator (LARS-WG) is among the types of weather generators widely applied in downscaling climate GCM datasets for impact studies.

Table 2.1: Comparative summary of the relative advantages and disadvantages of dynamical and statistical downscaling method (*adapted from Fowler, 2007*)

	Statistical Downscaling	**Dynamical Downscaling**
Advantages	• Computationally inexpensive • Can provide point-scale climatic variables from GCM. • Easily transferable to other regions • Based on standard and accepted statistical procedures • Able to directly incorporate observations into methods	• Produces responses based on physically consistent processes • Produces finer resolution information from GCM output that can resolve atmospheric processes on a smaller scale.
Disadvantages	• Assumes that predictor-predictand relationships will be unchanged • Requires long/reliable observed historical data for calibration • Affected by biases in underlying GCM: dependent on GCM boundary forcing • Climate system feedbacks are not included • Climate region, domain size and season affect downscaling skill	• Computationally intensive • Limited number of Scenario ensembles available • Strongly dependent on GCM boundary forcing

c. **Weather Typing:** is based on the more traditional synoptic climatology concept (including analogs and phase space partitioning) and which relate a particular atmospheric state to a set of local climate variables. This scheme define empirically weather classes (synoptically or by constructing indices of airflow) related to regional climate variations. This includes analog method and classification tree analysis and it assumes that the weather classes will not change.

Given the range of downscaling techniques and the fact that each approach has its own merits and demerits, there exists no universal method which works for all situations to date. However, it is recommended that rigorous testing and model inter-comparison will have paramount benefit for the reliability of the final results of climate change impact assessments.

2.3.4. Using hypothetical scenarios in Hydrological Models

This method is also known as the delta change or simple alteration method and widely used in almost all part of the world (e.g., Loaiciga, 2009; Xu, 2000; Roosmalen et al., 2010, are few among the know research works).

The general procedure for estimating the impacts of hypothetical climate change on hydrological behavior has the following stages (Loaiciga et al., 1996; Xu, 1999): (i) Determination of parameter values of a hydrological model in the study catchment using current climatic inputs and observed river flows for model validation; (ii) Perturb the historical time series of climatic data according to some climate change scenarios; (iii) Simulate the hydrological characteristics of the catchment under the perturbed climate using the calibrated hydrological model; and (iv) Compare the model simulations of the current and possible future hydrological characteristics.

The simple alteration method consists of two steps:

i) *Estimate the annual changes (absolute and relative) in precipitation and temperature using either GCM/RCM results or historical measurements of change, or personal estimates (typically, ΔT= +1, +2 and +4^{o}C and ΔP= 0, ±10%, ±20%).*

ii) *Adjust the historic data using the following relationship. For temperature series the absolute changes are used because temperature is a state variable and not a flux, whereas for precipitation relative change factors are applied.*

Numerous works have been conducted based on the hypothetical scenarios and some them are reviewed in Xu et. al. (2005). This approach provides a useful sensitivity study of hydrological regimes to global climate change. Moreover the advantage of using delta change or simple alteration method is that the bias correction of the RCM data is not necessary as the change in variables between the scenario and the control period is used and the bias is assumed equal for both the control and scenario simulation (Roosmalen et al., 2010). However, the use of an observed database has a drawback in that the information on the changes in variability and extremes in the future climate as simulated by the model is lost; hence the method is suggested to be more applicable for impact studies on groundwater and mean stream discharges. Because groundwater system are generally more sensitive to changes in mean precipitation amounts than to change in extremes.

2.4. Review of Climate Change Impact on Water Resources

A changing climate and its possible impacts on water resources have become a priority area of research and currently are intensely discussed issues among researchers (e.g., Lettenmaier et al., 1999). The most recent report of Intergovernmental Panel on Climate Change (IPCC- Fourth Assessment Report-AR4) provides detail information on the possible future impacts of climate change on water resources. More specifically, the findings indicated in chapter three of IPCC-AR4 (Kundzewicz et al., 2007), summarized the main issues related to water resources as: (i) the impacts of climate change, and the most effective ways of adapting to change, depend on local conditions; (ii) climate change is superimposed onto other pressures on water resources; and (iii) little can be said about the implications of climate change for the availability of safe water for the most vulnerable.

Later, Bates *et al.*, (2008) provided a technical report for the IPCC with specific investigations related to water resources. The report investigated that warming of the climate system in recent decades is unequivocal, as it is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. The impact of climate change on water resources depends on system characteristics, changing pressures on the system, how the management of the system evolves, and what adaptations to climate change are implemented (IPCC, 2001). The assessment of impact studies on water resources related issues are also affected by the selection of possible emission scenarios and Green House Gas (GHG) concentration effects including Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O) and halocarbons. The possible impacts of such GHG concentrations on the water resources availability has been given in detail on the IPCC's fourth assessment report (IPCC, 2007). Consequently, it has been reported by Loaciga et al.,(1996) and Xu,(1999a) that assessments of consequences of a possible climate change for double CO_2 conditions have become standard practices and the present research in this thesis followed the same assumption.

The changes in global climate appear to affect most of the world's water resources potential by altering the processes taking place in the natural ecosystem. However, these effects could be positive or negative within a given system. The IPCC report states with high confidence that the negative impacts of climate change on freshwater system outweighs its benefits (Kundzewicz et al., 2007). Accordingly, global mean surface temperatures have reported to be risen by 0.74 ^{o}C ± 0.18 ^{o}C over the last 100 years (1906-2005) and recently the year 2010 is reported to be the warmest year[1] since 1850. Changes in river flows as well as lake and wetland levels due to climate change depend on changes in the volume, timing and intensity of precipitation (Chiew, 2007). Groundwater systems generally respond more slowly to climate change than surface water systems and groundwater levels correlate more strongly with precipitation than with temperature, but temperature becomes more important for shallow aquifers and in warm periods (Bates et al., 2008). Hence the research into the water–climate interface is required to improve understanding and estimation, in quantitative terms, of climate change impacts on freshwater resources and their management, to fulfill the pragmatic information needs of water managers and stakeholders who are responsible for adaptation.

2.4.1. Impact Studies on Surface Water Resources

Global changes are undergoing at larger scale, however mitigation policies are expected to be applied locally. The impact studies related to surface water resources could be assessed through river flow and environmental requirement (Gul et al., 2010), water supply availability (Frederick and Major, 1997; Bekele and Knapp, 2010) regional water

[1] http://www.wmo.int/pages/mediacentre/press_releases/pr_904_en.html

management (Cashman et al., 2010), or flood frequency analysis (Prudhomme et al., 2002). Moreover, it was reported that the changes are variable from one geographic location to another (Kulshreshtha, 1998). As such this effect could be pronounced through alteration of regional precipitation and evapotranspiration that have direct consequences on hydrologic processes and water resources (rivers, lakes, aquifers, and springs) through their possible shifts of basin-wide water balances (Loaiciga, 2009). For example, in Europe, climate change will pose two major water management challenges: increasing water stress mainly in south eastern part and increasing risk of floods throughout most of the continent (Alcamo et al., 2007). The mean annual temperatures are likely to increase more than the global mean, with the largest warming in summer for the Mediterranean area, and in particular the highest summer temperatures are expected to increase more than the average for central and southern Europe (Christensen et al., 2007). In the Mediterranean area, annual precipitation and annual number of precipitation days are very likely to decrease. Consequently, significant hydrological changes are expected for southern Europe. In this region, there is a likely decrease in annual runoff, by 0 to 23% up to 2020s and by 6 to 36% up to 2070s; accompanied with a decrease by up to 80% of low summer flows, making the risk of drought particularly important. Projected increase of water withdrawals in Southern Europe would amplify the risks associated to climate change, being the Mediterranean region more exposed to drought risk (Alcamo and Henrichs, 2002). This global climatic changes caused by increases in the atmospheric concentration of carbon dioxide and other trace gases may continue to appear in the next few decades where it is expected to change future regional water availability (Xu, 1999a).

The impact studies related to surface water resources are more concentrated to the regions in Europe, North America and Australia (Kundzewicz et al., 2007), and majority of these use hydrological model driven by scenarios based on climate model simulations (Lettenmaier et al., 1999; Xu, 2000; Middelkoop et al., 2001; Cashman et al., 2010). However, only few studies focused on African and Asian regions (Kundzewicz et al., 2009). In surface water the impact studies related to inland reservoirs are limited in number where the priority is given to the stream flow river runoff. After IPCC's third assessment report, studies at basin scale are also becoming common practice. Nohara *et.al* (2006) investigated the projections of river discharges for 24 major rivers in the world during the 21st century simulated by 19 coupled AOGCMs based on SRES A1B scenario. Using weighted ensemble mean, they have shown that at the end of the 21st century the annual mean precipitation, evapotranspiration and runoff increase in high latitudes of the northern hemisphere, southern to eastern Asia and central Africa. In contrast, these variables decrease in the Mediterranean region, southern Africa, southern North America, and Central America. In the same study they have also shown that for rivers in high-latitude (Amur, Lena, MacKenzie, Ob, Yenisei, and Yukon), the discharge increases, and the peak timing shifts earlier because of an earlier snowmelt caused by global warming. And discharge tends to decrease for the rivers in Europe to the Mediterranean region (Danube, Euphrates, and Rhine), and southern United Sates (Rio Grande). Elshamy *et al.*, (2009) have used 17 GCMs from the IPCCs AR4 to evaluate the upper Nile flow at Diem. Their assessment showed that there is poor agreement between the different GCMs used in terms of evaluating change in precipitation. However, their overall result showed that water balance of the upper Blue Nile basin may become more moisture constrained for moderate change in precipitation in the future. A more comprehensive study for the same basin by Kim and Kaluarachchi, (2009) showed that there will be a mild increases in hydrologic variables (precipitation, temperature, potential evapotranspiration and runoff) over the entire area for a weighted scenarios from six GCMs. Their finding also indicated low-flow statistics and reliability of stream flows are increased and severe drought events are decreased due to the increment of precipitation.

In fact, the studies focusing on the components like precipitation and temperature take the first priority as they are the most dominant climatic drivers for water availability and thus used in assessing quantity and quality of water resources in a given area. The IPCC (2007) has reported with a very high confidence that the impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level and precipitation variability. Temperature is particularly important in snow-dominated basins and in coastal areas (due to the impact of temperature on sea level).

Mean annual global surface temperature is expected to increase between 1.4 and 5.8^{o}C by year 2100 relative to 1990 for the range of scenarios described in the IPCC Special Report on Emission Scenarios (IPCC, 2000, 2001). According to IPCC (2007), global average temperature would rise by 1.1-6.4°C by the end of the 21st century, relative to 1980-1990, with a best estimate of 1.8-4.0°C. While temperatures are expected to increase everywhere over land and during all seasons of the year, although by different increments, precipitation is expected to increase globally and in many river basins, but to decrease in many others.

2.4.2. Impact Studies on Groundwater Resources

In the last three decades, numerous studies have been conducted focusing on the investigation of regional climate change or variability impacts on surface water, ground water or on individual components of the hydrologic cycle. Majority of those studies focus more on surface water resources (few of the examples include: Graham et al., 2007a, b; Fujihara et al., 2008; Abdo et al., 2009). There have been few studies conducted on the future impact of climate change on groundwater because of the visibility, accessibility, and more obvious recognition of climate effects on surface water than on groundwater. However, in recent years there are numbers of studies emerging focusing on aquifer recharge and groundwater storage using climate change predictions from GCMs or RCMs. The studies conducted by Loaiciga, (2003); Allen et. al.,(2004; 2010), Chen *et al.*,(2002; 2004), Scibek and Allen, (2006), Toews and

Allen (2009) and Roosmalen et al.,(2007, 2009, 2010) are among few of the comprehensive works related to climate change and groundwater.

Almost all the studies have used the outputs from GCMs through statistical downscaling except the work of Roosmalen et. al(2007) who have used the outputs of RCM through bias correction in European region. Moreover, all the studies have used the estimation of recharge using surface hydrologic model and further applied for simulation of transient or steady state groundwater conditions. The recent work by Allen et al., (2010), have used four GCMs (namely: CGCM3.1, ECHAM5, PCM1, and CM2.1) to compare their recharge simulation with the historical time period. They have shown that there is both relative increase and decreases, where by in the 2080s the range of model prediction spans -10.5% to +23.2% relative to historical recharge. Scibek and Allen (2006) developed a methodology for linking climate models and groundwater models to investigate future impacts of climate change on groundwater resources in an unconfined aquifer, situated near Grand Forks in south central British Columbia, Canada. They found that the effect of spatial distribution of recharge on groundwater levels, compared to that of a single uniform recharge zone, is much larger than that of temporal variation in recharge, compared to a mean annual recharge representation. Similarly, Woldeamlak et al.(2007) modeled the effects of climate change on the groundwater systems in the Grote-Nete catchment in Belgium using a physically distributed water balance model and a finite difference groundwater model for different scenarios (wet, cold and dry).

Their result showed that the wet and dry scenario is more representative for the study area. They also recommended that concrete conclusion about the impact of climate change on groundwater can be made if their interaction in the hydrologic cycle is considered as there is no clear demarcation line between groundwater and surface water in the system.

The consideration of different scenarios has also an impact on the future groundwater availability in a given region. Loaiciga *et al.* (2000) observed that the effect of climate change on a groundwater system in Texas resulted in a reduction of the aquifer's groundwater resources under climate scenarios with a doubling of the atmospheric CO_2 concentration. They pointed out that the assumption of double CO_2 is found to be a common practice in such impact studies. Under the same condition, Roosmalen *et al.*(2007) compared the effects of future climate change on groundwater recharge, storage, and discharge to streams for two regions in Denmark. They demonstrated the importance of using site-specific models that capture the physical characteristics of the area by applying the same climate change scenarios at two hydrologically and geologically different areas. Later, Roosmalen *et al.*(2009) investigated the sensitivity of the groundwater system to different climate change scenarios showing 2.2^o and 3.2 ^oC increases in temperature for B2 and A2 scenarios, respectively as compared to the base period (1961-1990). Their comparative assessment shows that groundwater systems tend to respond more slowly to variability in climatic conditions than do surface water systems. Due to this fact, assessments and models of groundwater resources are commonly based on long-term average climatic conditions (eg. average annual recharge) and potentially underestimate the importance of variations from the norm (Alley, 2001). Further the IPCC (2007) report states that Climate change affects groundwater recharge rates (i.e., the renewable groundwater resources) and depths of groundwater tables. However, knowledge of current recharge and levels in both developed and developing countries is poor; and there has been still very little research on the future impact of climate change on groundwater, or groundwater–surface water interactions.

2.5. Climate Change in Italy

Italy lies at the center of the Mediterranean region, which has been identified as one of the most sensitive areas to GHG-induced global warming (Giorgi, 2006; IPCC, 2007). Consequently, it can be expected that the Italian territory is susceptible to climate change. Like any other part of the world, this in turn will have considerable impacts on various sectors including: water resources, agriculture, tourism, etc.

Despite its importance, studies related to projected impacts of climate change in Italy are limited in number. This is due to the reason that Italy is characterized by complex and fine-scale variability in topography, coastlines and vegetation cover. The north-south elongated shape of the country also experiences different climatic behavior. The northernmost region that consists the Alps are characterized by cold climate, the central part of the territory experiences temperate condition; and the southernmost part (eg. Sardinia and Sicily) are known by their semi-arid and hot climate. The major mountain systems, such as the Alpine chains in the north and the Appenines extending from north to south direction along the entire Italian Peninsula also modulates the climate conditions of the entire nation. Hence, accurate characterization and its representation in climate models is reported to be very difficult (Coppola and Giorgi, 2010).

Majority of the studies in the face of climate change issues focused more on the precipitation and temperature characteristics as they determine the hydrologic cycle and other natural phenomena. These studies pointed out significant variations exist in the climate of Italy since early 20th till the end of 21st century. Coppula et. al.(2010) has conducted a comprehensive assessment of precipitation and temperature projections over Italy using 19 recent GCMs from CMIP3 and 10 RCMs from PRUDENCE simulations. They indicated that both precipitation and temperature have seasonally varying signals. Precipitation is found to be substantially decreasing over the entire peninsula in summer as low as -40% and to the lesser extent in spring and fall seasons. Their result also indicates, summer precipitation will tend to increase in the north, whereas it shows transitional signal over the central Italy and decreases over the southern Italy. Inter-annual variability of precipitation is tend to increase in all seasons and for temperature in summer. Both minimum and maximum temperatures are expected to show a warming up to several degrees in all the seasons (however, maximum in summer and minimum in winter). Through analysis of different types of extremes, Beniston et al., (2007), have reported three main results for the Italian peninsula: (i) an increase in frequency, intensity and duration of heat waves; (2) an increase in drought occurrence as measured by the maximum length of dry spells; (3) an increase of intense precipitation events over northern Italy in winter and a decrease over central and southern Italy in summer. Kjellstrom,. et al.,(2007) analysed daily maximum and minimum temperature extremes under warmer scenario conditions and found an increase of extremes greater than the increase in mean temperature. Similarly, Vergni and Todisco,(2011) have used observed dataset in central Italy and found the rate of change in the minimum temperature is greater than the maximum that will be resulted in reduction of daily temperature range.

As the global and/or regional scale assessment based on climate models are not enough to understand the extent of change at local scale, various authors have explored trends of precipitation and temperature in Italy based on indices derived from observation of long time series data. Few among others are, Moonen et.al.,(2002), Brunetti et.al, (2001; 2002; 2004; 2006), Di Matteo and Dragoni, (2006), Colombo et al.,(2007), Todisco and Vergni (2008), Fatichi et.al., (2009), Matzneller et al.(2010), D'Agostino et al., (2010), Vergni and Todisco, (2011), Romano and Preziosi, (2012). Compared to precipitation, most of the studies agree on the general increase in trends of temperature (depending on the site and data treatment). However, some authors reported different results on the precipitation patterns of Italy as summarized by (Romano and Preziosi, 2012). For example, temperatures in the annual series have a positive trend of 1^{o}C per century at national level with a systematic increase in winter droughts (Brunetti et al., 2006); an increasing trend from 0.4 ^{o}C/100 years for northern Italy and of 0.7 ^{o}C /100 years in southern Italy (Brunetti et al., 2004); Colombo et al.(2007) divided the available ground observation stations into mountain, continental and coastal areas and described a positive trend in 1980–2000 (mainly for the mountain stations). According to Brunetti et al.(2006) precipitation shows a decreasing tendency in the whole of Italy over the last two centuries. On a yearly basis a negative trend is evident for northern and southern Italy, with -47 mm/100 years and -104 mm/ 100 years respectively (Brunetti et al., 2004). Colombo et al.(2007) found that stations in the mountains of Italy has been affected by significant increase of precipitation events during autumn and winter but for the rest of the Italian territory a precipitation is reduced during early springs.

The high spatio-temporal variability of climate over the entire Peninsula, has triggered site specific studies to evaluate the local scale climate variability on the hydrologic behaviour. For example, the Tiber River Basin Authority has reported that most severe climate change scenarios for central Italy (where a 6°C to 8°C increase in temperature) is forecast by 2080 – foresee a decreasing trend in rainfall throughout the year, most notably between October and April where precipitation could drop by as much as 50%. These predictions are partially confirmed by measurements and summarized as (i) from 1920 to 1938 there has been a modest increase in mean annual precipitation (from 914.2 mm to 923.3 mm) with an average increase of about 0.48 mm per year; (ii). From 1938 to 2003 there has been a decrease (from 923.3 mm to 806.9 mm) with an average decrease of 1.79 mm per year and (iii) from 2003 onwards, the rate of decrease amounts to 3.65 mm per year. Later, the authority has reported based on data collected between 1952 and 2007 that there is a consistent trend of gradually decreasing annual precipitation (mainly in winter that falls up to 30%) and rising surface temperature.

Romano and Preziosi,.(2012), have analysed daily time series data of rainfall over the period of 1920-2010 in the Tiber River Basin (central Italy). They analysed the precipitation patterns through standardized indices, which shows significant decrease in annual precipitation over the entire Tiber River Basin nearly -8 %. and decrease in winter precipitation around -16% . They argued that such reduction is related to decrease in the number of rainy days. The reduction in annual river discharge that amounts to 1.27 m^3s^{-1} was also reported to be related with the reduction in precipitation (Romano et al., 2011). In the same basin, Brocca et al., (2011), have shown preliminary investigation on the climate change effects on the flood frequency in selected sub-basins of the UTRB. They used HadCM3 and their result showed different responses to climate change for the selected sub-basins. The A2 emission scenario is more critical in short term (2020s) than the B2 scenario for which an increase in maximum discharge reaches up to 78%. Another comprehensive work on the analysis of change in precipitation regime in central Italy was the work of Fatichi and Caporali,(2009). They used forty indices to evaluate change in the precipitation patterns and trend detection. Contrary to other studies in the area, they presented that there is no evidence for non-stationary. They presumed that the complexity of the climate in central Italy, i.e. the presence of numerous feedbacks might distort or remove the consequences of global warming on the precipitation regime. Bartolini et al.,(2012), argued that Mediterranean warming is especially due to summer season. They supported their findings by using observed data from Tuscany (central Italy). Their result highlighted a positive trend for mean temperature of about 0.9 ^{o}C per 50 years with a slightly more pronounced increase in maximum temperature.

Some authors have also made a thorough analysis based on single station using various indices and comparison of results with different sites. For example, in Bologna-Cadriano area, the analysis during the second half of the 20th century (1952-2007) showed an increase in mean annual temperature of 1.2 ^{o}C; significant increasing trend in reference evapotranspiration; no clear signs of a decrease in precipitation, but maximum groundwater table level deepened by 42cm (Matzneller et al., 2010). In order to evaluate climate change risk on agriculture, Moonen et al.,(2002), have used a station from Pisa having time series data of 122 years. Their results indicate that there is a shift towards more extremely low rainfall events but negligible effect on agriculture and drought risk. From trend analysis over the same period, they indicated that no significant changes in soil water surplus or deficit on annual basis.

From hydrological study point of view, Burlando and Rosso (2002) evaluated effects of transient climate change impacts on runoff variability in the Arno River, central Italy. They showed that a reduction of the annual maxima of daily flows is expected for the Arno basin. For all the scenarios used in their analysis, a general reduction of water availability was also expected but it does not necessarily mean a reduction in total discharge in the river rather a different distribution in time and space that could substantially constrain the effective availability of water for exploitation purposes. D'Agostino et al.,(2010) have used distributed catchment scale model to study the impact of land use and climate change in Apulia region (Candelaro catchment), southern Italy. They forced the hydrologic model by climate scenario that showed rainfall reduction 5-10% during winter and 15-20% during summer while temperatures are expected to increase between 1.25 – 1.5 ^{o}C during winter and 1.5 – 1.75 ^{o}C during summer. Their result showed that by 2050, groundwater recharge in the catchment would decrease by 21-31% and stream flows by 16-23%. Di Matteo and Dragoni,(2006), have also evaluated the effect climate change on the water resources of Firenzuola Lake in Umbria region (central Italy). Their result indicated that the yield of the basin is likely to decrease.

Chapter 3

This chapter provides the description of the study area selected in this PhD research work. The general physiographic characteristics of the area with the summary of the dataset used are explained. Basic information related to the hydrologic, soil and geologic behaviour of the study are also explained in the following subsections.

3. Study Area Description

3.1. Location and General Characteristics

Tiber River Basin (TRB) is the largest river basin in central Apennines District in Italy. Geographically, the basin is located between 40.5^o N to 43^o N latitudes and 10.5^o E to 13^o E longitudes covering an area of about 17,500 km^2, that occupies roughly 5% of the Italian territory. The basin crosses six administrative regions and twelve provinces. Almost 90% of the basin lies in the regions of Umbria and Lazio, and the remaining 10% falls within the regions of Emilia–Romagna,Tuscany, Marche and Abruzzo. The area covered under each region is shown in parentheses in the legend of Figure 3.1. Including the oldest city of Rome, major cities such as Perugia, Terni and Rieti are located within the basin (http://www.abtevere.it/node/379). The total population of the basin is reported as 4.7 million inhabitants (census report of 2009). Of the total population in the basin, nearly 70% of the population lives in urban area of Rome, about 10% in five of the main cities (Rieti, Perugia, Terni, Tivoli and Spoleto), and the rest in the other small municipalities. The population densities are high in the flood plains and the lower part of the Tiber River.

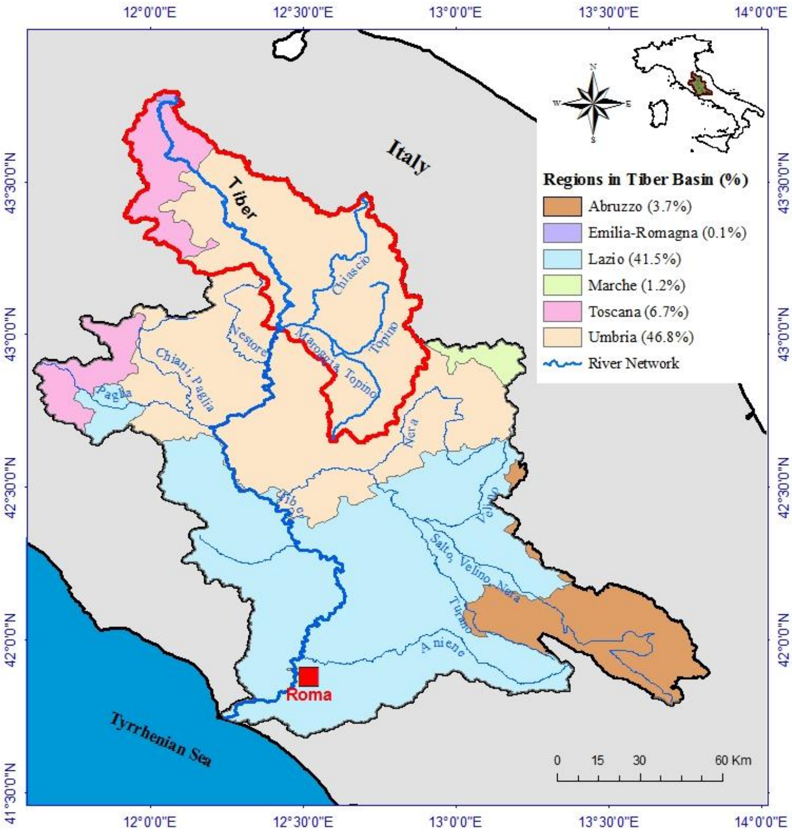

Figure 3.1. The Tiber River Basin and the regions it crosses in central Italy. The red boundary shows the area used for hydrological simulation and analysis.

The basin is mainly drained by the Tiber River which originates at an elevation of about 1268m a.m.s.l near Mount Fumaiolo (about 1407 m high a. m.s.l.) in the Emilia-Romagna region. The river flows towards the south until it reaches the Tyrrhenian Sea at south of Rome. On its north-south course of about 405km, the Tiber River collects flows from different tributaries consist of small to medium river systems. The main contributing river systems include the Chiani-Paglia and Nestore River systems from west; the Chiascio-Topino, Salto-Turano-Velino-Nera and Aniene river systems from east side. In addition to the river systems, there are small natural lakes exist in the basin; including lake Trasimeno (area 122.7 km^2), lake Piediluco (area 1.7 km^2), lake Vico (area 12.3 km^2) and lake Albano (area 6.0 km^2).

Figure 3.1. shows the location of the TRB and the case study area selected for the hydrological simulation. The Upper Tiber River Basin (UTRB) is part of the TRB that covers an area of 4145 km^2 (~ 20% of the TRB) with its outlet at Ponte Nuovo. The elevation of the catchment ranges from 145 to 1560 m above sea level.

In addition to the main Tiber River, the Chiascio and Topino are the main tributaries that drain the UTRB. Most of the results and analysis in this PhD work focuses on this basin. Major hydrological characteristics and analysis related to water resources in the sub-basin are provided by Fiseha et al. (2012)

3.2. Topography, Geology, Land use and Soils

A Digital Elevation Model (DEM) which has 30m resolution obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was used to extract the watershed and topographic characteristics of the basin. The DEM is depicted in Figure 3.2. and used in chapter three for derivation of spatial parameters required by the hydrological models. The topography of the TRB varies from lowlands to highlands that reaches elevation peaks above 2500m. Naturally, the basin is limited to the east by the ridge of Umbria-Marche Apennines, while to the west, it is bound by the slopes of Tuscany and Lazio regions. Specific to the UTRB, the topography is mainly hilly or mountainous with open valleys and large intra-mountain basins. The terrain gradient ranges from almost zero along the plain of the Tiber Rivera and of its major tributaries, to more than 63 degree in the mountains and the steepest hills. Due to the regional structural setting, slopes facing East are, on average, slightly steeper than those facing West.

The geological setting of the basin is the result of the evolution of the Apennines, whose construction began in the late Miocene to early Pliocene, and is extended until present. As a result of which six major lithological groups or complexes of rock units were identified in the catchment (Cardinali et al., 2001), namely: (i) the Umbria–Marche sedimentary sequence, Lias to lower Miocene in age, (ii) the Tuscany turbidites sequence, Eocene to Miocene, (iii) the Umbria turbidites sequence, Miocene, (iv) the Ligurian allochthonous sequence, lower to middle Miocene, (v) the continental, post-orogenic sequence, Pliocene to Pleistocene; and (vi) the Recent alluvial deposits. Each lithological complex comprises different rock types varying in strength from hard to weak and soft rocks. The hard rocks include layered and massive limestones, cherty limestone, sandstones, pyroclastic deposits, travertine and conglomerates. Weak rocks include marls, shales, sands, silty clays, and over consolidated clays. Soft rocks are marine and continental clays, silty clays, and shales. The UTRB is mainly underlain by clays, limestone and sandstones in alternation and association. As a result of which, the area is characterized with a very low permeability. However, in the lower part of the TRB calcareous and carbonaceous rocks are prevalent that favors high permeability due to the fractures in the rock masses.

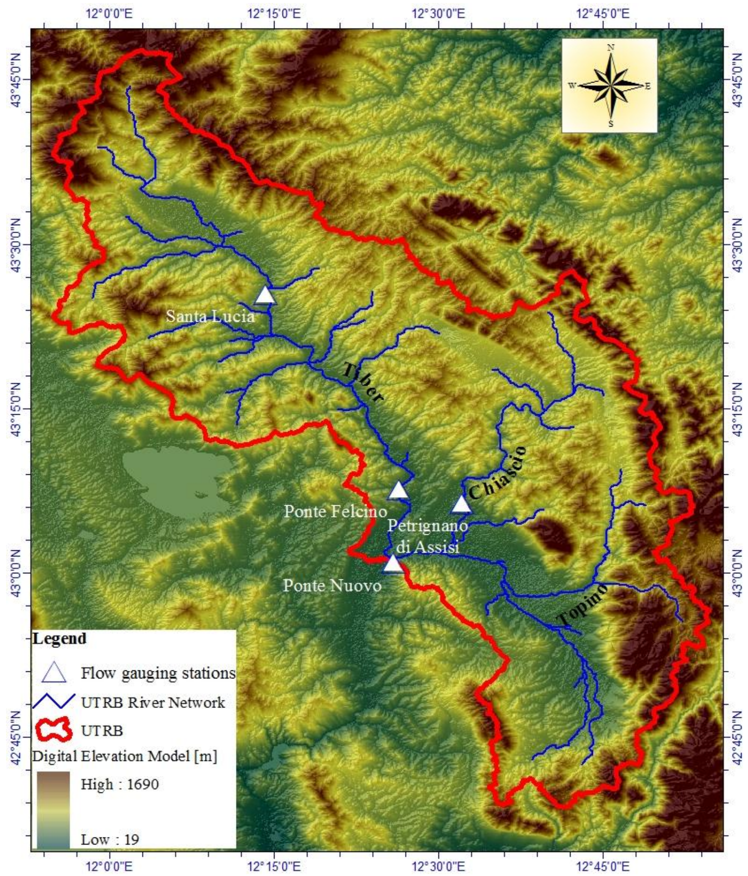

Figure 3.2. Digital Elevation Model (DEM) and River Networks in the UTRB

The soil in the area reflects the lithological types overlying practically impervious rocks. The thickness ranges from less than 20cm where limestone and sandstone crop out along steep slopes to more than 1.5m in karst depressions and in large open valleys. The soil data used in this research was obtained from Food and Agricultural Organization data base (FAO, 2009) and from Institute for Environment and Sustainability of European commission Joint Research Center (Panagos et al., 2011). The study area is covered by four dominant soil types that are mainly categorized under the hydrologic soil group C and D.

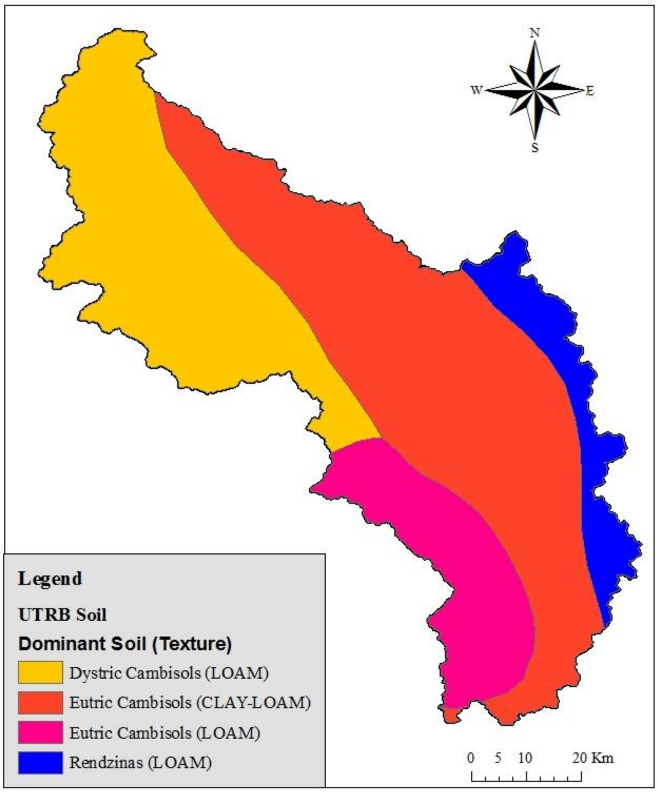

Figure 3.3. Dominant Soil classes in the Upper Tiber River Basin

The land use of the basin is mainly composed of agricultural and forested areas. Recently, the Tiber River Basin Authority and Regional Services has reported that the land use along the main river course and its tributaries is potentially related with the socio-economic developments within the basin. For example, the settlement processes and the infrastructure system consists of central railroad in the region will have a paramount impact on the land use and land cover characteristics which in turn changes the geomorphological characteristics of the river systems. In the UTRB, where the main river course is composed of narrow valleys, there exists riparian vegetation and wooden areas. Whereas, in areas near cities large plots of irrigated crops occupy most part of the Tiber flood plain.

In the present research work land used data set having 300 × 300m spatial resolution were obtained from Medium Resolution Imaging Spectrometer (MERIS) and some further reclassification was performed in the model used for simulation of hydrological processes. The land cover in the sub-basin is predominated by agricultural land (~40%), forested areas (~ 50%) and the remaining mixed land cover including urban land use areas account about 10%. The forested area consists of deciduous forests, evergreen forest land, shrubs and rangelands distributed over the sub-basin.

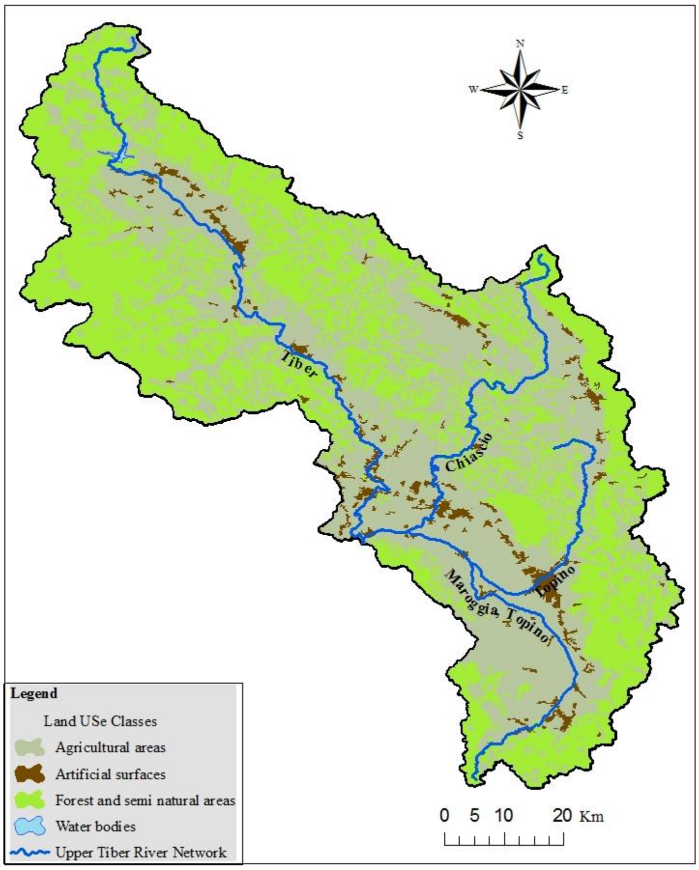

Figure 3.4. Land uses in the Upper Tiber River Basin

3.3. Hydro-Meteorological Setting

Majority of the river courses in Italy are short in length and almost all of them drain towards the Adriatic or Mediterranean Seas. Among the known river systems, the Po (652 km) and Adige (410 Km) in the north; and Tiber (405 Km) and Arno (241 Km) in the central part are the major ones. The river in the southern part are short in length as compared to the those in the north and central part. The hydrological regime of the river systems in the northern part of the nation commonly receives their maximum inflow from extended snowy seasons, whereas those in the central part depends on the rainfall which characterize spring (March - May) and autumn (September - November) floods. The annual average discharge of the Tiber River into the Tyrrhanian Sea is 225 m^3s^{-1} approximately 7 billion m^3 (calculated on a long-term average) (Cesari, 2010). In the context of the European Union's Water Framework Directive, the TRB belongs to ecoregion 3 for rivers and lakes and ecoregion 6 for transitional and coastal waters - Annex XI Directive 2000/60/CE (European Union, 2000).

The hydrological behavior of the TRB is studied by various authors (eg. Corradini et al., 1995; Calenda et al., 2000; Melone et al., 2002; Di Lazzaro, 2009). The studies undertaken so far were conducted considering the individual hydrologic processes taking place in the entire (or part of) river system. Among others: *flood forecasting* (eg. Calenda et al., 2000; Calvo and Savi, 2009; Napolitano et al., 2010), *flood routing* (Franchini et al., 2011), *soil moisture assessment* (Brocca et al., 2009a; Brocca et al., 2009b), *spatial trends of rainfall,*(Romano et al., 2011). However, much attention is given to the issues in flood risks as the Tiber River passes through many historical places in the regions' urban areas including the old city of Rome (Calenda et al., 2005). More specifically, Calenda *et al.*,(2000), have mentioned that the upper sub-basin with an outlet at Ponte Nuovo (*see Figure 2.2*) is characterized by basin lag-time of 18-22 hours and impermeable layer assumed to be 84% of the total area (4145 Km^2). The basin is characterized by a marked rainfall reduction in the dry season (from June to September). In this period runoff is marginal, evapotranspiration reaches maximum levels and surface water circulation is almost exclusively sustained by groundwater discharge.

In the upper part of the basin, small scale case studies explains more about the hydrological characteristics of the basin. For example, at the confluence of Chiascio and Topino rivers, closer to Ponte Nuovo at Torgiano flow outlet, there is known aquifer zone called Petrignano d'Assisi (covering 75 km2) which was studied in detail by Romano and Preziosi (2010). This aquifer is reported to be fed by both effective infiltration and loss from the Chiascio River in the upstream part of its course and in the downstream the aquifer tends to discharge to the river. In the central part of the plain, there is a groundwater well-constructed at the end of the 1970s for municipal drinking water supply and as a result of this a wide cone of depression since the beginning of the 1980s is observed. Brocca et al.(2009b) investigated the use of observed soil moisture data into rainfall-runoff model by conducting experiment on a plot (ranging from 13 to 137 km2) in the sub-basin that can be up-scaled to catchment level. They found that high variability in soil maximum retention which plays a significant role of antecedent wetness condition for the hydrological response assessment. However, up-scaling of such variability to a watershed level still remains a challenging research topic.

The precipitation of the area is highly predominated by frontal processes coming from the Thyrrhenian Sea and orographic effect resulting from the high elevation ranges (nearly 165-1600 m.a.s.l). The precipitation and temperature characteristics of the region (Umbria) that consists the sub-basin was studied by Todisco and Vergni,(2008) and Vergni and Todisco,(2011) with due emphasis on the extreme events and their impacts on crop production. The precipitation is reported to be decreasing with increment of duration of dry period. The temperature is however reported to increase due to the fact that the minimum temperature is increasing at a faster rate as compared to the maximum temperature in the region. The rate of change difference in the minimum temperature than the maximum will then resulted in reduction in daily temperature range (DTR). Such changes are found to be determinant factors in the study of potential effect of climate change on water resources and evapotranspiration processes (Karl et al., 1993).

Summary of the main characteristics of the UTRB and its sub-basins at selected outlets is shown in Table 3.1. The basin is mainly characterized by longest river flow path of 136.2 Km, and main channel slope ranging from 0.23%-2.85%. The basin lag associated with the available rainfall and runoff events for each sub-basins were also summarized as obtained from different authors' report. The mean annual flow based on long record dataset at the Ponte Nuovo outlet is 350mm with maximum observed discharge about 1350 m3s-1.

Table 3.1: Summary of major physiographic characteristics of the UTRB

Sub-Basins	Outlet Elevation (m a.s.l.)	Drainage area (Km^2)	Main river length (Km)	Main River Slope (%)	Basin lag (hr.)*
Upper Tiber River Basin (UTRB) at Ponte Nuovo	165.0	4145.0	136.0	0.23	18-22
Tiber at Ponte Felcino	197.0	2033.0	109.6	0.27	14-17
Tiber at Santa Lucia	265.0	932.0	63.9	0.52	10-13
Chiascio at Rosciano	171.0	1956.0	89.6	0.32	13-15

* Information obtained from literature review

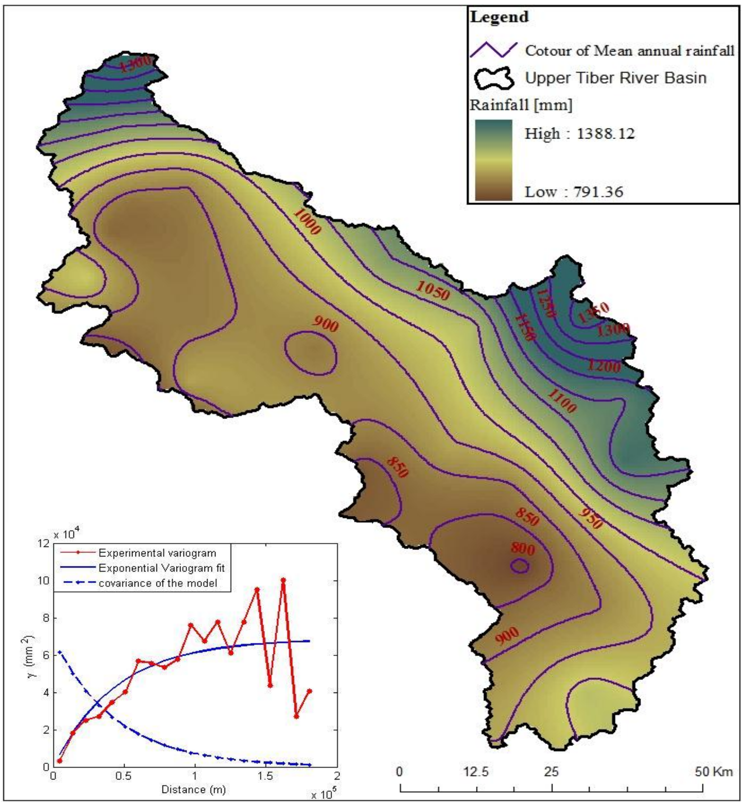

Figure 3.5. Mean annual rainfall variation in the Upper Tiber Basin (The Variogram model used in the Ordinary Kriking shown in the lower left corner).

3.3.1. Rainfall data

Time series and spatial daily rainfall data were obtained from Regional Hydrographic Services Umbria. More than 80 rainfall observation stations were available in the basin; however there were many missing values. In the time window of 01/Jan/1961 to 31/Dec/1990, rainfall stations with a long data record, i.e. an amount of daily data above 70% were selected. Out of the available stations, only 52 stations satisfied this criterion. The selected stations with their mean annual value and corresponding daily missing percentage out of the 30 years of record were summarised in Table 3.2. In terms of special coverage, some of the stations are located out of the boundary of the study area selected for the hydrological simulation. However, as the area is located within the same hydro-meteorological setting, all the stations that satisfy the required criterion were used to fill the missing data through interpolation mechanism. The available stations and their geographic location are shown in Figure 3.7.

Rainfall in the UTRB shows high temporal and spatial variability. An example for illustration of spatial variation in annual precipitation is shown in Figure 3.5. The mean annual rainfall at the stations with complete record were summarized and then spatial interpolation is performed over the entire basin. Ordinary kriging interpolation with exponential variogram is used to show the spatial variation of rainfall for the period of 1961-1990 based on the selected gauging stations of Table 3.2. The mean annual rainfall in the UTRB ranges between 790-1338 mm which shows large spatial variability with a maximum rainfall as large as

1.8 times the minimum rainfall. Areas with higher elevation shows higher rainfall on annual basis. Based on the interpolation method used, the mean annual rainfall in the period of 1961 - 1990 is estimated to be 980 mm.

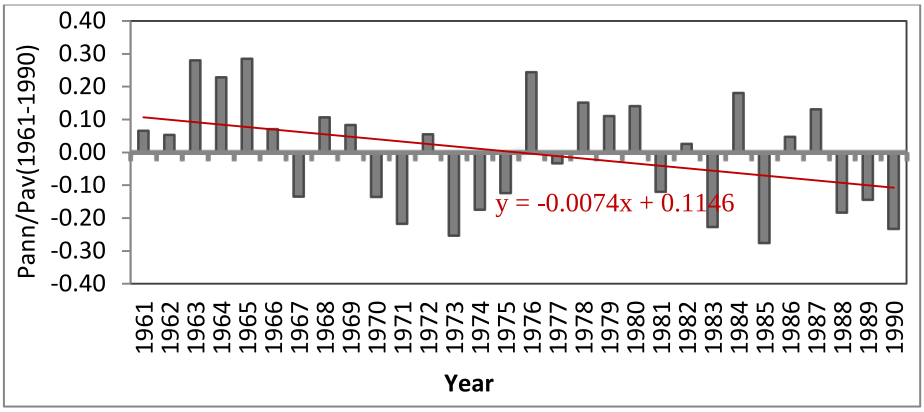

Figure 3.6: Mean annual precipitation anomaly for the study area (1961-1990)

In terms of temporal variation, a comparison of annual rainfall anomalies from selected stations with the 30 year mean annual rainfall over the area is shown in Figure 3.6. The mean annual rainfall showed a decreasing trend in the basin.

Table 3.2. Selected rainfall stations in the Tiber River Basin (TRB).

S.N.	Station Name	Easting (m)	Northing (m)	Altitude (m)	Missing daily (%)	Mean Annual Rainfall (mm)
1	Acquapendente	243825	4737890	425	10.00	962
2	Anghiari	261936	4825285	429	30.00	887
3	Arrone	316749	4717103	285	0.00	1045
4	Assisi	305791	4771528	424	3.33	877
5	Attigliano	277476	4710705	95	0.00	952
6	Balze di Santa Lucia	336731	4682847	540	0.00	1240
7	Bevagna	307346	4757302	211	3.33	791
8	Calvi dell'Umbria	299598	4697364	401	0.00	972
9	Capezzine	251058	4783839	327	3.33	723
10	Casalina	288203	4758396	168	0.00	892
11	Casalini	267394	4772110	333	3.33	736
12	Castel Rigone	272258	4787770	653	0.00	918
13	Castelluccio di Norcia	353500	4743540	1453	10.00	1005
14	Castiglione del Lago	260460	4779303	304	26.67	719
15	Ceraso	258882	4774240	280	0.00	734
16	Città della Pieve	255660	4759514	500	0.00	824
17	Compignano	278389	4758636	269	20.00	698
18	Corciano	279181	4778518	408	20.00	946
19	Cortona	255535	4796792	393	0.00	779
20	Ficulle	260354	4746941	437	16.67	909
21	Fratta Todina	285097	4747599	214	10.00	784
22	Gualdo Tadino	319935	4787521	612	13.33	1148
23	Gubbio	302461	4801637	529	10.00	1028
24	Leonessa	333446	4714507	945	10.00	1448
25	Lisciano Niccone	268097	4792471	313	23.33	932
26	Monte del Lago	269235	4781085	295	0.00	732
27	Montecoronaro	261505	4852079	800	0.00	1388
28	Montefalco	308613	4751969	473	13.33	861
29	Monteleone di Spoleto	332937	4724387	990	6.67	1057
30	Narni Scalo	298409	4713949	109	20.00	1001
31	Nocera Umbra	320276	4776417	535	10.00	1188
32	Orvieto	262590	4733451	315	13.33	811
33	Palazzo del Pero	256320	4811946	406	16.67	960
34	Panicale	262695	4768521	404	6.67	742
35	Perugia (ISA)	288073	4775452	417	0.00	823
36	Petrelle	269903	4803374	340	0.00	887
37	Pianello	298764	4779063	235	13.33	932
38	Piedipaterno	325796	4736902	333	3.33	966
39	Pietralunga	292607	4813514	607	0.00	1092
40	Pieve Santo Stefano	261588	4839552	431	30.00	1114
41	Prodo	273899	4738390	404	6.67	899
42	Sansepolcro	269190	4828509	265	26.67	915
43	Sorgenti Scirca	315208	4802294	750	3.45	1358
44	Spoleto	314422	4734026	357	0.00	1027
45	Terni	307128	4714604	130	3.33	910
46	Todi	288157	4740450	411	0.00	852
47	Toppole	259581	4820209	453	3.33	866
48	Torgiano	290077	4768110	219	0.00	840
49	Trevi Umbro	316143	4750075	425	26.67	891
50	Tuoro sul Trasimeno	262017	4789501	309	10.00	791
51	Umbertide	283569	4798107	322	23.33	893
52	Villastrada	256759	4770652	370	10.00	693

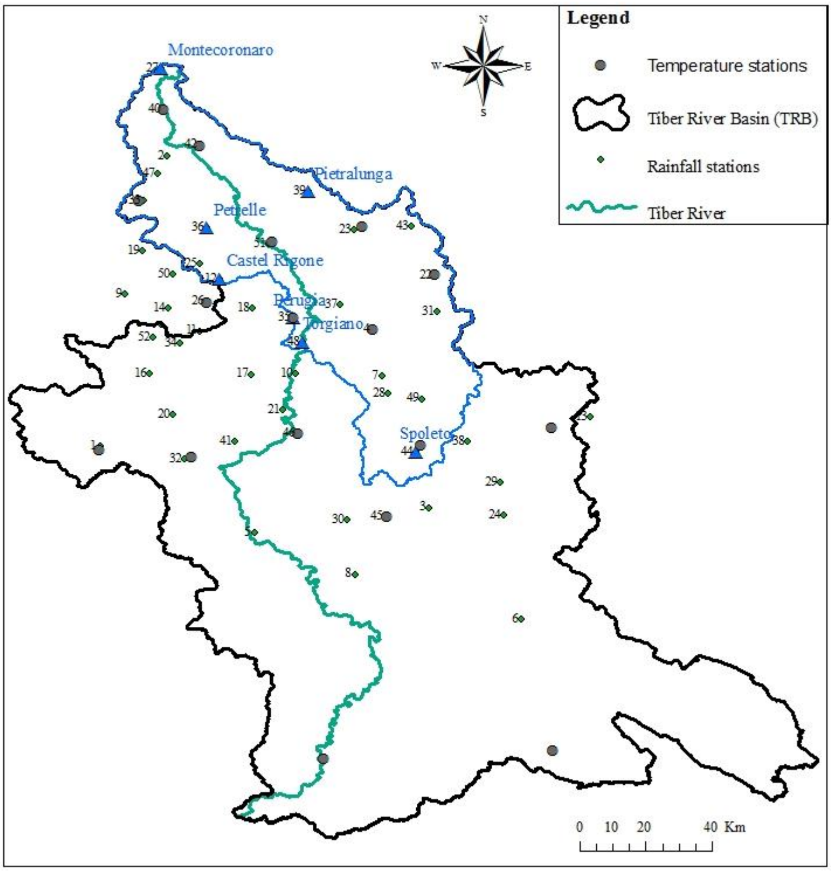

Figure 3.7: Location of rainfall and temperature gauging stations in TRB (the numbered labels show the corresponding station name in Table 32).

Some features of the observed daily rainfall at seven selected stations in the UTRB were shown in Figure 3.8. The location and name of the stations are separately labeled in Figure 3.7. These stations were chosen based on their completeness, all of which have continuous time series data between January 1961 to December 1990 and they are located within the study area (UTRB). Montecoronaro is located in the most northern part of the basin; Spoleto is located in the southern part and Torgiano is located at the outlet of the basin. The other five stations are located along the north south elongated areas between the Torgiano and Montecoronaro stations.

The box plots shown in Figure 3.8 were built only for the rainy days of the corresponding months; which considers only days with rainfall amount greater than zero. This was necessary because if zero rainfall values are included, almost all the quartiles of the box plot are zero except for the higher quartiles. The top and bottom horizontal lines of the box plot indicate the 90% quartile and the 10% quartile respectively. The inter quartile range (IQR) which is the difference between the 75% quartile and the 25% quartile is represented by the top and bottom edge of the box. The median values are represented by the horizontal line in the box. The legend for the box plot quartiles are shown in the most right-bottom panel of Figure 3.8.

In all box plots, the horizontal line that represents the median value is closer to the 25% quartile than to the 75% quartile, which indicates a skewed distribution of the rainfall. The median values for the autumn season (wet months) are shown in Table 3.3. As compared to the wet months (September to December), the dry months (June to August) are largely skewed since the median value is closer to the 25% quartile.

Table 3.3. The median values of the daily rainfall of the wet (SON) and dry (JJA) months at seven selected stations in the upper Tiber River Basin (UTRB).

Stations	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Castel Rigone	5.50	5.85	6.20	7.9	8.6	10.5	7.5
Monte Coronaro	5.40	6.40	7.00	10.0	10.3	12.0	10.0
Perugia	3.20	3.70	4.60	5.4	4.4	6.0	3.4
Petrelle	6.00	6.25	7.40	8.1	10.1	10.4	9.4
Pietralunga	4.05	5.00	6.80	7.2	7.2	7.3	5.0
Spoleto	4.00	2.70	5.10	6.4	5.6	6.2	4.0
Torgiano	5.20	7.25	6.70	9.1	8.5	8.7	6.3

Compared to the other stations, Montecoronaro has recorded high daily rainfall as it can be seen from the longer values of the IQR in the figure. In all the wet months, the median value showed that Montecoronaro receives the largest daily rainfall while Perugia receives the smallest daily rainfall, see Table 3.3. This can be due to the fact that, Montecoronaro is located at the highest altitude. Also, during the dry season, the daily rainfall in June and July are approximately half of the daily rainfall in October and November.

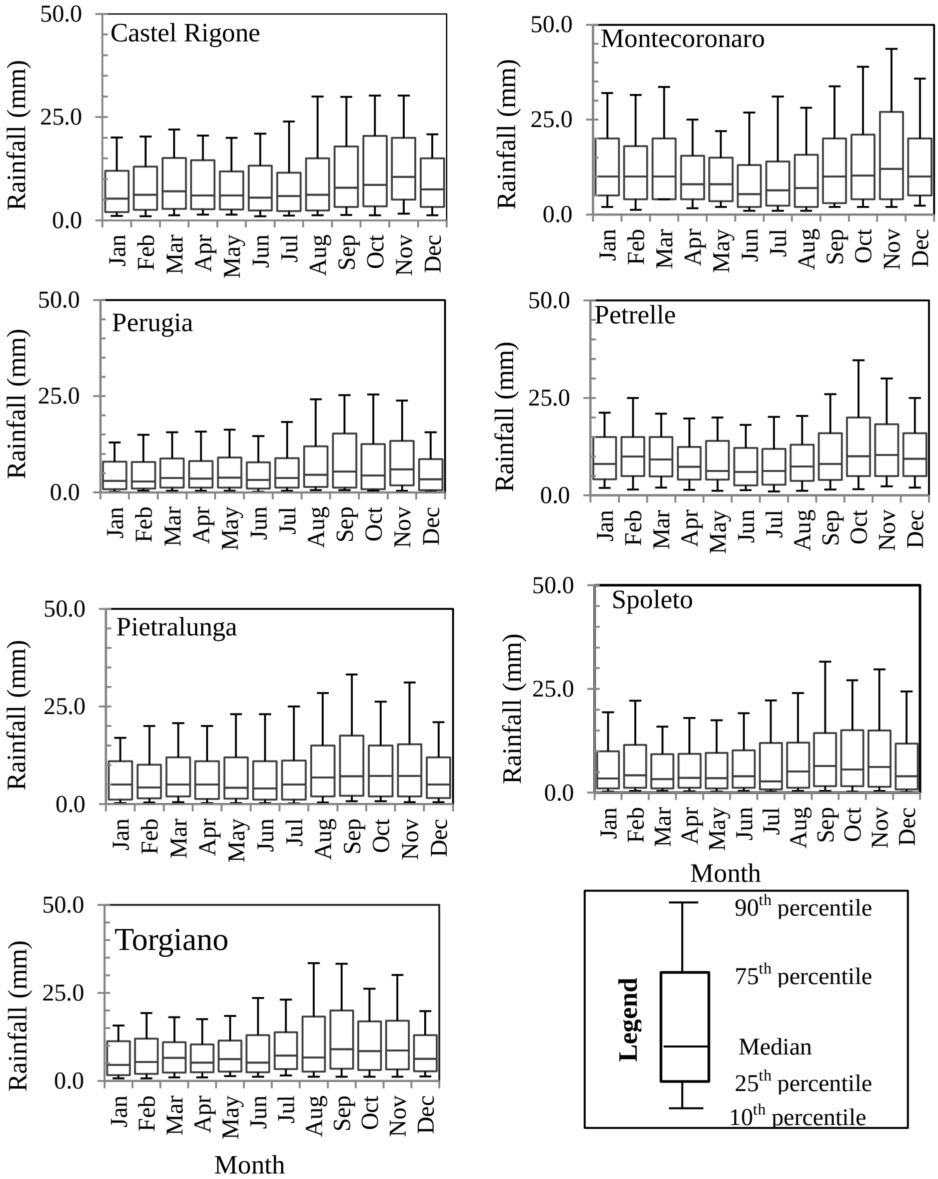

Figure 3.8: Box plots of the daily rainfall at seven selected stations in the UTRB.

3.3.2. Temperature Data

Relatively, small amount of time series data for minimum and maximum temperatures (T_{min} and T_{max}) exists in the basin with many missing values and unevenly distributed in space and time. 78 gauging station were provided by the Hydrographic Services Umbria and Lazio regions. However, only few stations have complete record of time series data for minimum and maximum daily temperature. Out of the 78 gauging stations only 17 of them have reported to have recorded data above 60%. The summary of the stations and their data availability is shown in Table 3.4. and the spatial distribution over the area is shown in Figure 2.7 with a gray colour dot representation.

Table 3.4. Selected daily temperature (Tmin and Tmax) observation station in the TRB

S.No	Station Name	Easting (m)	Northing (m)	Altitude (m)	Missing daily (%)
1	Acquapendente	243575	4737134	425	23.3
2	Assisi	305790	4771527	424	0.3
3	Gualdo Tadino	319999	4787699	612	20.1
4	Gubbio	304266	4802602	529	14.2
5	Monte del Lago	269119	4780869	295	3.8
6	Norcia	344901	4740693	700	40.0
7	Orvieto	264158	4734165	315	9.8
8	Palazzo del Pero	255091	4812269	406	7.2
9	Perugia	288073	4775451	417	0.0
10	Pieve Santo Stefano	261645	4839386	431	26.7
11	Roma Collegio Romano	290905	4641778	49	36.7
12	Sansepolcro	269156	4828311	265	21.3
13	Spoleto	315504	4736219	357	0.3
14	Subiaco	342995	4642863	952	33.4
15	Terni	307216	4714779	130	0.0
16	Todi	288080	4740465	411	0.0
17	Umbertide	284268	4798825	322	10.4

The analysis of inter-annual surface temperature in the UTRB is performed using time series data from four weather stations in the period of 01/Jan/1961 to 31/Dec/1990. The four stations were selected based on their location and completeness of time series data. These stations are Assisi, Gubbio, Perugia and Spoleto, see figure 3.7.

The inter-annual variability of daily maximum temperature is shown in figure 3.9 with the 95% confidence of the mean values. The patterns of both daily minimum and daily maximum temperature are similar, see figure 3.9 and figure 3.10. From figure 3.9, it is clear that the highest daily maximum temperature is observed in July and August which are the dry period of the region. The lowest value of maximum temperature is recorded in the months of January and February.

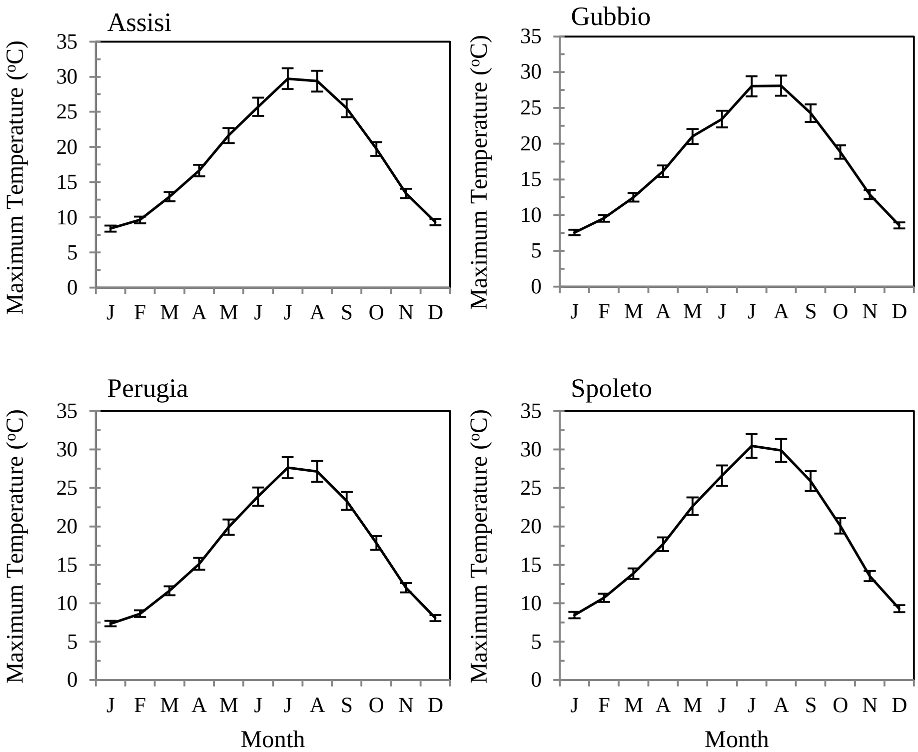

Figure 3.9: Inter-annual variability of daily maximum temperature at selected stations in the UTRB (January 1, 1961- December 31, 1990). The 95% confidence intervals of the mean values are also shown.

Figure 3.10 shows the inter-annual variability of the daily minimum temperature averaged over each month. Like that of the daily maximum temperature, higher values of daily minimum temperatures are recorded in July and August at all the stations. The lowest value is observed in the month of January. Relatively Gubbio station shows the smallest minimum temperature value on average, whereas Perugia shows the highest value. Such kind of variation calls for the dependences of temperature on elevation as the two stations are at the highest and lowest level respectively.

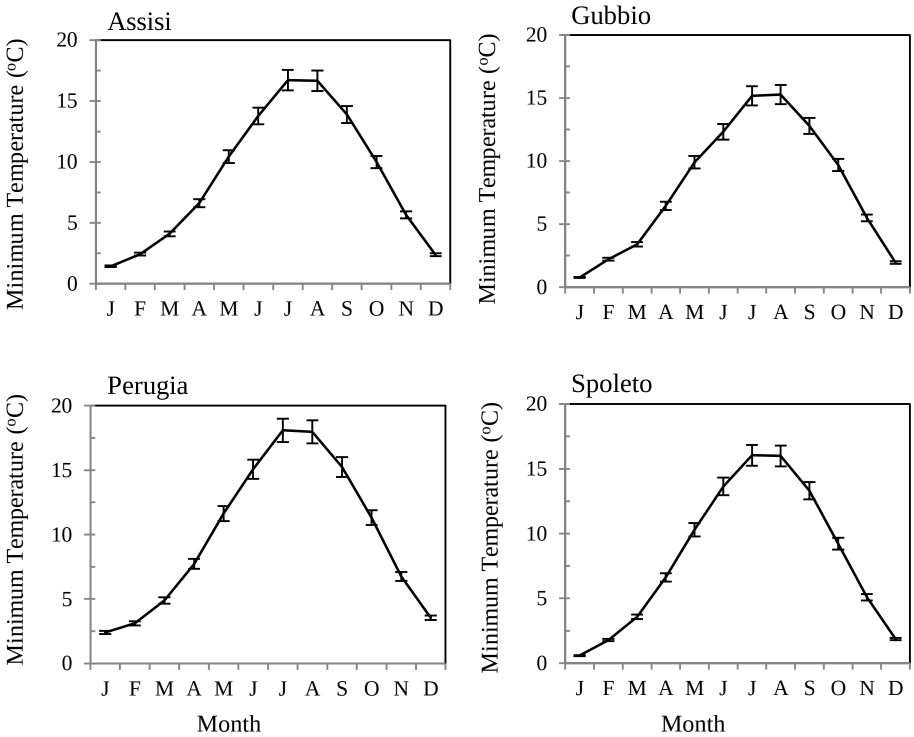

Figure 3.10: Inter-annual variability of daily minimum temperature at selected stations in the UTRB (January 1, 1961- December 31, 1990). The 95% confidence intervals of the mean values are also shown.

The dependence of both daily minimum and daily maximum temperature on elevation of the dry season (JJA) is shown in figure 3.11. The upper panel shows the variation of daily maximum temperature with elevation that shows a decrease 5 oC per 100m elevation. The variation of daily minimum temperature with elevation is shown in the lower panel of figure 2.11 that indicate change of 8 oC every 100m of elevation.

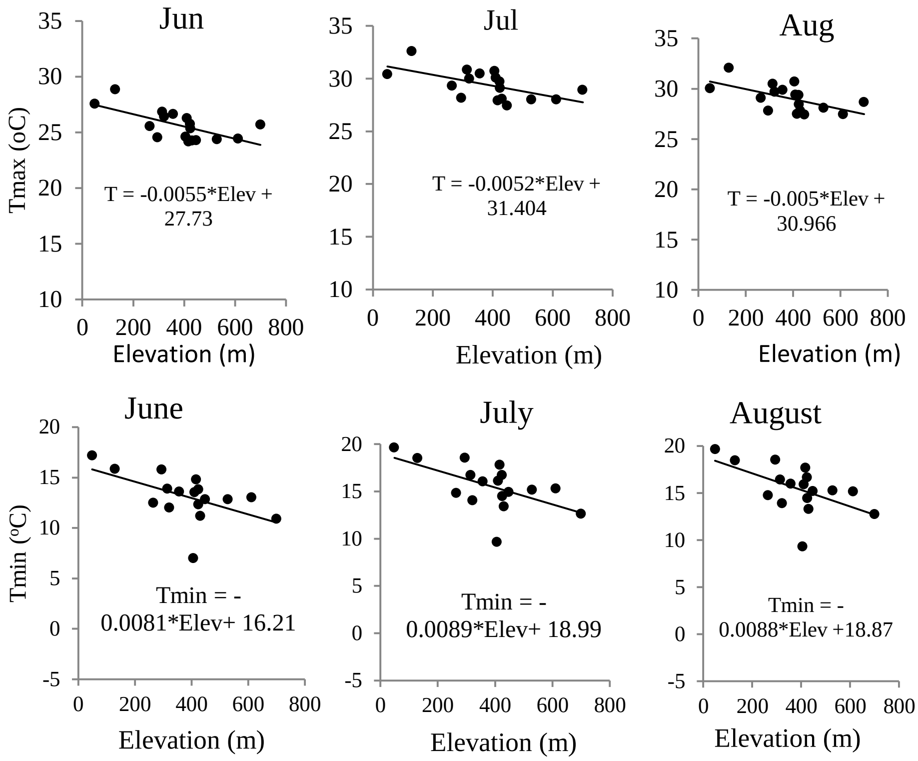

Figure 3.11: Variation of daily maximum temperature (upper panel) and daily minimum temperature (lower panel) with elevation for the dry months (JJA) in the TRB.

3.3.3. River Flow Data

Observed river flow data from Santa Lucia, Ponte Felcino, Ponte Nuovo and Petrignano di Assisi were used. The first three gauging stations are located along the Tiber river and only the station at Petrignano di Assisi is along Chiascio river which is one of the tributaries of the upper Tiber river, see figure 3.12. Relatively, the Ponte Nuovo station which is the basin outlet, has long record of time series of data as compared to the other three gauging stations. For the calibration of hydrologic model used in this study, the flow data at Ponte Nuovo is used and the other stations which are located in the upstream are used for validation.

Figure 3.12 shows the frequency of flow based on the average daily flow recorded at the four gauging stations along the Tiber River and its tributary in the UTRB. Notwithstanding the length of the time series data figure 3.12 shows that the maximum daily flow at all the recorded station is above 100 m^3s^{-1} and the minimum daily flow varies depending on the location of the station. The minimum daily flow at Ponte Nuovo is above 1m^3s^{-1}, as the frequency curve ends at the 100% probability of axceedance. However, 10% of the flows at the other upstream stations show the daily flow less than 1 m^3s^{-1}. Likewise, 50% of the flow at Ponte Nuovo shows daily average flow larger than 20 m^3s^{-1}; whereas the other three stations show the corresponding value of 10 m^3s^{-1}.

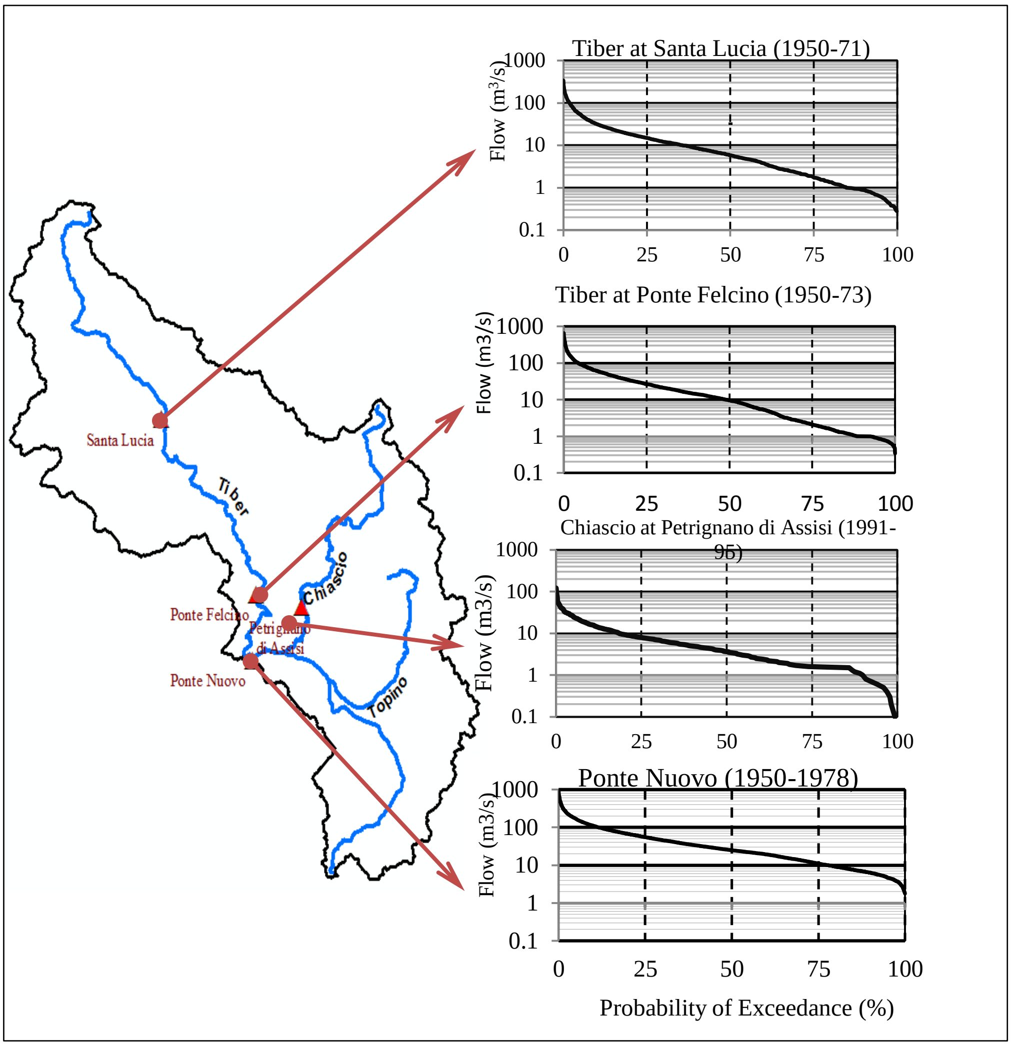

Figure 3.12. Flow gauging stations and their corresponding frequency of flow.

The daily maximum, average and minimum flow at Ponte Nuovo is shown in figure 3.13. The maximum flow in the wet season indicates that there is a decrease in flow at a rate of 5.735 $m^3 s^{-1}$ whereas the minimum flow shows an increasing trend of 0.17 m^3s^{-1}. The trend in the maximum flow has a similarity with the rainfall characteristics in the UTRB which have shown a decreasing trend over the time period of 1961 – 1990.

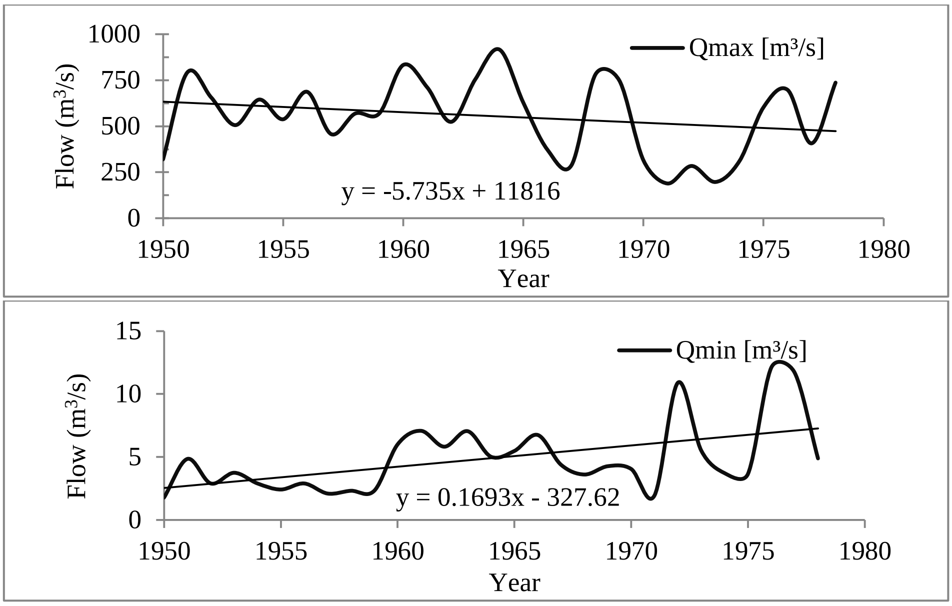

Figure 3.13. Daily maximum and minimum flows in the dry and wet seasons at Ponte Nuovo gauging station.

3.4. Summary

The location and main physiographic characteristics of the Tiber River Basin (TRB) in general and the upper Tiber Basin (UTRB) in particular is explained. The main Tiber River and other medium to small sized river systems drain the basin with the existence of small inland lakes ranging from 1.7 km^2 to 122.7 km^2.

The topography, geology, land use and soils of the UTRB is explained in detail with the major properties obtained from different data sources. The DEM from ASTER is used to derive the drainage characteristics. The geologic setting of the basin is reported to be the result of evolution of the Appennines, whose construction began in the late Miocene to early Pliocene that extended until recent year. Land use from MERIS showed the basin is covered by 40% agricultural land and 50% forested areas with the remaining 10% accounting for mixed land cover and urban areas. Based on the FAO soil data, the UTRB is covered by four dominant soil types that are mainly categorized under the hydrologic soil group C and D. The basin is mainly characterized by 84% impermeable area and estimated lag time of 18 to 22 hours.

The hydro-meteorological setting of basin with respect to the Italian rivers and the European Union’s water framework directive is explained. A short review on the hydrologic studies in the basin is made. Previous studies show that there is a major effort taken on the flood issues in the basin and few studies analyzed the precipitation and temperature characteristics. The precipitation is highly predominated by frontal processes coming from the Thyrrhenian Sea and orographic effect resulting from the high elevation ranges. Both minimum and maximum daily temperature was reported to increase over the time window with a faster rate of increase in daily minimum temperature.

Time series data for rainfall at 52 stations that have missing data less than 30% in the time window of 01/Jan/1961 to 31/Dec/1990 were analyzed in the UTRB. Based on the kriging interpolation used with exponential variogram, the mean annual rainfall is estimated to range between 790-1338 mm with a maximum annual rainfall as large as 1.8 times the minimum rainfall. Areas with higher elevation show higher rainfall on annual basis and the mean annual rainfall is estimated to be 980mm. The annual rainfall anomalies showed a decreasing trend at the rate of 0.007mm per year. Seven stations were selected to further analysis on the temporal variation of rainfall. Box plot for rainfall amount greater than zero is built for all the seven stations showing the 25%, 75%, the median value and the IQR. In all the plots, the median value is closer to the 25% which indicates skewed distribution in rainfall. The wet months (September to December), are largely skewed as compared to the dry months (June to August).

The inter-annual variability of temperature in the UTRB is analyzed based on the time series data obtained from seventeen gauging stations. Four stations, namely: Assisi, Gubbio, Perugia and Spoleto with complete time series data in the period of 01/Jan/1961 to 31/Dec/1990 are used for the analysis. Highest values of both daily maximum temperature and minimum temperature are observed in July and August; whereas, the lowest values of maximum temperature and minimum temperature are recorded in months January and February. Variation of temperature with elevation for the dry months indicates that there is decrease of 5 ^{o}C per 100m for T_{max} and 8 ^{o}C per 100m elevation for T_{min}.

Daily river flow data four gauging station; three of which are along the Tiber River and one on the Chiascio River are used to analyze characteristics of the discharge in the UTRB. Flow duration curves are established based on the available dataset. From the Ponte Nuovo gauging station, 50% of the average daily flow is larger than 20 m^3s^{-1} and the minimum daily flow is greater than 1 m^3s^{-1}. In the other three upstream stations, 50% of the data are larger than 10 m^3s^{-1} and 10% the data are below 1 m^3s^{-1}. The maximum flow in the wet season at the basin outlet shows a decreasing trend at the rate of 5.735 m^3s^{-1} and the minimum flow shows an increasing trend of 0.17 m^3s^{-1}.

[2] Chapter 4

4. Downscaling Climate Model Outputs from Single GCM

Abstract

Precipitation and temperature data are the most frequently used forcing terms in hydrological models. However, the available General Circulation Models (GCMs), which are widely used nowadays to simulate future climate scenarios, do not provide those variables to the need of the models. The purpose of this study is therefore, to apply a statistical downscaling method and assess its strength in reproducing current climate. Two statistical downscaling techniques, namely regression based downscaling and the stochastic weather generator, were used to downscale the HadCM3 GCM predictions of the A2 and B2 scenarios for the Upper Tiber River basin located in central Italy. Four scenario periods, including the current climate (19611990), the 2020s, the 2050s and the 2080s, were considered. The Statistical Downscaling Model (SDSM)based downscaling shows an increasing trend in both minimum and maximum temperature as well as precipitation in the study area until the end of the 2080s. Long Ashton Research Station Weather Generator (LARSWG) shows an agreement with SDSM for temperature, however, the precipitation shows a decreasing trend with a pronounced decrease of summer season that goes up to60% in the time window of the 2080s as compared to the current (19611990) climate. Even though the two downscaling models do not provide the same result, both methods reveal that there will be an impact of climate on the selected basin as observed through the time series analysis of precipitation and temperature. The overall result also shows that the performance of the LARSWG resembled the results of previousstudiesandtheIPCCsAR4projections.

Keywords Downscaling, SDSM, LARSWG, Climate Change, Central Italy

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[2] This chapter is based on : Fiseha, B.M.,Melesse, A.M., Romano, E., Volpi, E., Fiori, A., (2012). **Statistical Downscaling of Precipitation and Temperature for the Upper Tiber Basin in Central Italy**. *International Journal of Water Sciences 1*.

4.1. Background

The issue of climate change is among the hot topics getting the attention of almost every media since the last few decades. The discussions are more or less supported by the outputs from Global Climate Models (GCMs) under different emission scenarios that are usually used in impact assessments. Among other outputs from GCMs, precipitation and temperature data are the most frequently used variables to force impact models (e.g., hydrological models). Beside this, both are the most dynamic atmospheric characteristics affected by the GHG emissions. For instance, the Fourth Assessment Report of Intergovernmental Panel on Climate Change: IPCC-AR4, (Parry et al., 2007) has reported with a very high confidence that the impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level and precipitation variability. Accordingly, global mean surface temperatures have reported to be increased by 0.74 ^{o}C ± 0.18 ^{o}C over the last 100 years (1906-2005) and recently the year 2010 is reported as one of the top three warmest years[3] since 1850. While temperatures are expected to increase everywhere over land and during all seasons of the year, although by different increments, precipitation is expected to increase globally and in many river basins, but to decrease in many others (Kundzewicz et al., 2007). Mediterranean is among those regions where mean annual temperatures are likely to increase more than the global mean, with the largest warming in summer

[3] http://www.wmo.int/pages/mediacentre/press_releases/pr_904_en.html

and annual precipitation as well as annual number of precipitation days are very likely to decrease (Alcamo et al., 2007; Christensen et al., 2007).

While GCMs demonstrate significant skill at the continental and hemispheric spatial scales and incorporate a large proportion of the complexity of the global system, they are inherently unable to represent local sub-grid scale features and dynamics (Wigley et al., 1990; Carter et al., 1994). This mismatch in system representation is due to the difference in resolution and referred to as the scale issues. The conflict between GCM performance at regional spatial scales and the needs of regional-scale impact assessment is largely related to model resolution in such a way that, the GCM accuracy decreases at increasingly finer spatial scales, and the needs of impact researchers conversely increase with higher resolution (Hostetler,1994; Schulze, 1997). As a means of bridging this gap, downscaling is commonly used to assess the impact of climate change on water resources at basin scale. The basic assumption of downscaling is thus the large scale atmospheric characteristics highly influence the local scale weather but in general, it disregards any reverse effects from local scales upon global scales (Maraun et al., 2010).

4.2. Study Area and Data Used

4.2.1. Study Area

The study area selected for this research is the sub-basin of Chiascio River in the UTRB. The sub-basin is located between 42.6^o-43.5^{o}N and 12.4^o-12.92^o E in the Umbria region of central Italy. It covers an area of 1955 km^2 (10.5% of the Tiber Basin) with an elevation ranging from 160 to 1685 m. a. s. l (Figure.4.1) and includes Chiascio and Topino rivers, that drains to the main Tiber River. Tiber River is the largest river basin in central Italy (third largest river in Italy) with the main river course (405 km in length) draining towards the Mediterranean Sea near the southern part of the city of Rome at Ostia.

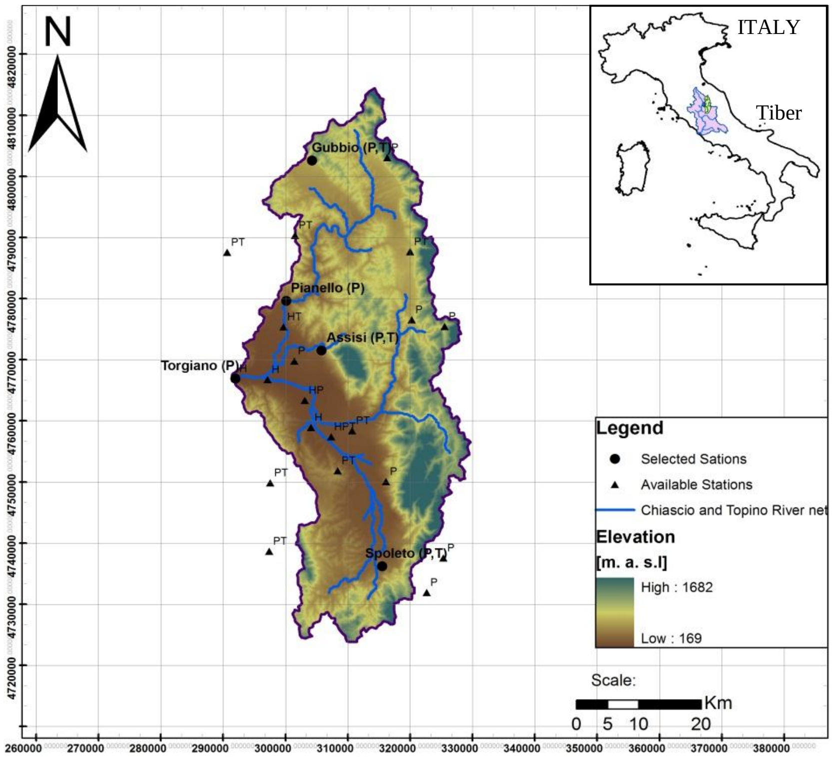

Figure 4.1. Location map of the Upper-Tiber River basin and the gauging stations

At the confluence of Chiascio and Topino rivers, closer to Torgiano and Assisi stations, there is known aquifer zone called Petrignano d'Assisi (75 km^2) which is studied in detail by Romano and Preziosi (2010). This aquifer is fed by both effective infiltration and loss from the Chiascio River in the upstream part of its course and in the downstream the aquifer tends to discharge to the river. In the central part of the plain, there is a groundwater well constructed at the end of the 1970s for municipal drinking water supply and as a result of this a wide cone of depression since the beginning of the 1980s is observed. A reservoir built in upstream part of the sub-basin alters the natural system of recharge to the groundwater zone. The effect of climate change in addition to those observed challenges could presumably aggravate the pressure on the available water resources of the basin. Due to such aggregate impacts, there will be a shift from surface water utilization to groundwater.

4.2.2. The Datasets

The historical precipitation and temperature data for the study area were collected from the National Research Council (CNR) and further analyzed for quality control. For the sake of data management and analysis, comparison was carried out among selected meteorological stations (Table 4.1). Only few meteorological stations have continuous datasets.

Moreover, some of those stations with complete datasets are located outside the selected sub-basin boundary. Therefore, the missing values are calculated using inverse distance weighted (IDW) and simple regression methods between existing and nearby stations at comparable altitude and distances. Thus, the stations in the basin (Figure 4.1) were used for the downscaling experiment and other surrounding stations were used for calculating the missing values.

Table 4.1: Summary of selected meteorological stations

Station Name	Code	Northing (m)	Esting (m)	Altitude [m.a.s.l]	Data Availability	% Missing
Maximum and Minimum Temperature						
Assisi	12918	4771527	305790	424	1951-2000	10.0
Gubbio	12901	4802602	304266	529	1951-1997	13.0
Spoleto	15195	4736219	315504	357	1951-1996	0.0
Precipitation						
Assisi	12918	4771527	305790	424	1951-2000	2.0
Pianello	19687	4779635	300099	235	1951-2000	12.0
Spoleto	15195	4736219	315504	357	1951-1996	0.0
Torgiano	12778	4766910	291977	219	1954-2000	2.0

In addition to the historical datasets observed, large-scale predictor variables representing the current climate condition (1960-2000) are also taken from the National Center for Environmental Prediction (NCEP). These large scale datasets are re-gridded (Kalnay et al., 1996) and provided by the Canadian Institute for Climate Studies (CCICS) and are used to calibrate the downscaling model. In this study, the third version of an Atmosphere-Ocean General Circulation Model (AOGCM) outputs from Hadley Center-HadCM3 (Gordon et al., 2000) *(see also* *http://www.metoffice.gov.uk/research/hadleycentre/)* were used for the generation of future climate scenarios. This model is a coupled atmospheric-ocean GCM where the atmospheric part has horizontal resolution of 2.5 degrees of latitude by 3.75 degrees of longitude and 19 vertical levels while the ocean component has horizontal resolution of 1.25^0 latitude and 1.25^0 longitude and 20 vertical levels. The predictor datasets from NCEP and HadCM3 having a resolution of 2.5^o latitude $\times$ 3.75^o longitude have been archived by the Canadian Center for Climate Modeling and Analysis (CCCma).

Table 4.2: Lists of large scale predictor variables from NECP and HadCM3

No.	Daily predictor variable description	Code
1	Mean sea level pressure	mslp
2	Mean temperature at 2m	temp
3	Near surface specific humidity	shum
4	Near surface relative humidity	rhum
5	500 hPa geopotential height	p500
6	850 hPa geopotential height	p850
7	Relative humidity at 500 hPa	r500
8	Relative humidity at 850 hPa	r850
9	Airflow strength	**_f
10	Zonal velocity component	**_u
11	Meridional velocity component	**_v
12	Vorticity	**_z
13	Wind direction	**th
14	Divergence	**zh
	** represents variable values derived from pressure fields near the surface, at 500 hPa or 850 hPa heights (i.e. P_, P5 or P8) respectively.	

These lists of large scale predictor variables are used in the downscaling process and are provided in Table.2. The candidate predictor set contained 25 normalized daily predictors (describing atmospheric circulation, thickness, and moisture content at the surface, geopotential heights at 850 and 500 hPa).

4.3. Downscaling Daily Precipitation and Temperature Time Series

4.3.1. Downscaling Model Description and Setup

Two of the statistical downscaling tools described in section 2.3.3 were selected namely: Statistical Down-Scaling Model (SDSM) Version 4.2. (Wilby et al., 2002) and Long Ashton Research Station Weather Generator (LARS-WG) Version 5 developed by Semenov *et al.*, (1998). Both tools were used in various regions of the world and found to be widely accepted in climate change impact studies (eg. hydrological modeling).

The SDSM is best described as a hybrid of stochastic weather generator and regression- based in the family of transfer function methods. It permits the spatial downscaling through daily predictor-predictand relationships using multiple linear regressions and generates predictand that represents the local weather. There are seven major steps to be followed in developing best performing multiple linear regression equation for the downscaling processes including: quality control and data transformation, screening of predictor variables, model calibration, weather generation (using observed predictors); statistical analyses, graphing model output and finally scenario generation (using climate model predictors). A detailed discussion of the steps are shown in (Wilby et al., 2002; Wilby and Dawson, 2007).

After performing the quality control, the daily precipitation and temperature (T_{min} and T_{max}) are considered as predictand variables of interests. For precipitation, four stations and for temperature, three stations were selected. All the stations lies within the basin and based on the availability of continuous time series data, only the period from 1961-1990 are considered for downscaling purpose. Thus, the corresponding 30 years observed daily reanalysis of NCEP dataset for the current climate (1961-1990) for the study area are extracted from a closest grid box Y=18 Latitude: 42.5^{o}N, X=04 Longitude:11.25^{o}E from the European window. For the same grid box, the HadCM3 dataset for the period of 1960-2099 for the A2 and B2 emission scenarios are also extracted. The A2 (medium-high) scenario describes a very heterogeneous world and B2 (medium-low) scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. The selection of these scenarios has been made based on the IPCCs fourth assessment guidelines (see also http://www.ipcc-data.org/guidelines/TGICA_guidance_sdciaa_v2_final.pdf) but also the downscaling method selected requires the use of predictor variables from these scenarios.

The LARS-WG however uses semi-empirical distributions to simulate weather data based on the observed statistical characteristics of daily weather variables at a site both under current and future climatic conditions (refer section 2.3.3). There are two major stages in this method: the first is the site analysis (calibration) stage and the second is scenario generation, which includes the downscaling processes. The inputs to the weather generator are therefore the series of daily observed data (precipitation, minimum and maximum temperature) of the base period in days (1961-1990) and site information (latitude, longitude, and altitude). In the LARS-WG, the quality check is performed by the model itself (for example some stations show T_{min} is greater than T_{max}) and corrected through site analysis. After the input data preparation and quality control, the observed daily weather at a given site were used to determine a set of parameters for probability distributions of weather variables. These parameters are used to generate a synthetic weather time series of arbitrary length by randomly selecting values from the appropriate distributions. However, the LARS-WG distinguishes wet days from dry days based on whether the precipitation is greater than zero. Then the occurrence of precipitation is modelled by alternating wet and dry series approximated by semi-empirical probability distributions. The detailed model setup and working principle are explained in Semenov and Barrow (1997) and Semenov (2007).

4.3.2. Calibration and Validation of SDSM

Selection of predictor variables

The success of the SDSM-based downscaling is highly dependent on the selection of predictor variables while developing predictand-predictor relationship. The first step to calibrate the model is thus starts from the selection of the predictor variables. From the 30 years observed historical datasets of 1961-1990, the first 20 years (1961-1980) are used for calibration and the remaining 10 years (1981-1990) are used for validation purpose. Before performing the calibration process, predictor variables from NCEP data were selected through screening process in SDSM using the values of explained variances and scatter plots in the predictor-predictand relationship. Through screening predictor variables, some important settings of the SDSM model were considered like 'variance inflation', 'bias correction' and transformation functions. The adjustment of the variance inflation is performed in order to account for the variance of downscaled daily weather variables by adding or reducing the amount of 'white noise' applied to regression model. This is also used to enable the SDSM regression model to produce multiple ensembles of downscaled weather variables for the considered area. For precipitation, the selections of predictor variables are performed by transforming to the fourth root without any lag time. However, for the case of maximum and minimum temperature, normal distribution was considered hence no transformation function is applied. After routine screening procedures, the predictor variables that provide physically sensible meaning in terms of

Table 4.3: Summary of selected predictor variables with their respective predictands

Station	Predictors	code	Station	Predictors	Code
	Precipitation		***Maximum Temperature***		
Assisi	Mean sea level pressure	mslp	Assisi	500 hPa geopotential height	p500
	500 hPa vorticity	p5_Z		Near surface specific humidity	Shum
	500 hPa geopotential height	p500		Mean temperature at 2m	Temp
	850 hPa geopotential height	p850	Spoleto	500 hPa vorticity	p5_Z
	Relative humidity at 850 hPa	r850		500 hPa geopotential height	p500
Spoleto	Mean sea level pressure	mslp		Near surface specific humidity	Shum
	500 hPa vorticity	p5_Z		Mean temperature at 2m	Temp
	500 hPa geopotential height	p500	Gubbio	500 hPa vorticity	p5_Z
	850 hPa geopotential height	p850		500 hPa geopotential height	p500
	Relative humidity at 850 hPa	r850		850 hPa geopotential height	p850
Torgiano	Mean sea level pressure	mslp		Near surface specific humidity	Shum
	500 hPa vorticity	p5_Z		Mean temperature at 2m	Temp
	850 hPa vorticity	p8_Z	***Minimum Temperature***		
	500 hPa geopotential height	p500	Assisi	Near surface specific humidity	Shum
	850 hPa geopotential height	p850		Mean temperature at 2m	Temp
	Relative humidity at 850 hPa	r850	Spoleto	Near surface specific humidity	Shum
Pianello	Mean sea level pressure	mslp		Mean temperature at 2m	Temp
	500 hPa vorticity	p5_Z	Gubbio	Near surface specific humidity	Shum
	500 hPa geopotential height	p500		Mean temperature at 2m	Temp
	850 hPa geopotential height	p850			

their correlation value and the magnitude of their probability were selected. Table 4. 3 shows the identified predictor variables for the stations and predictand under consideration. From the selected predictors, it is observed that different atmospheric variables control different local variables. For instance, precipitation is more sensitive to mean sea level pressure and pressure fields at geopotential heights of 500 and 850 hPa. Mean temperature at 2 m height and near surface specific humidity controls both the maximum and minimum temperature observed at each sites. Finally, the selected predictor variables are used to derive parameter files that can be used for downscaling purpose after validation with the independent dataset.

Validation of SDSM results

The parameters established during the calibration process that explains the statistical agreement between observed and simulated data are then used for validation purpose. The 10 years data (1981-1990) were used to validate the performance of the model. For precipitation, the mean daily precipitation, average wet and dry-spell lengths are used as statistical performance evaluation criteria. Figure 2 shows comparison of the downscaled and observed precipitation during the validation period for selected stations. As shown from the graphs, the model shows satisfactory agreement based on the mean absolute error (MAE) between the simulated and observed values of mean precipitation values (Table 4). The dry-spell length (not shown) has also revealed the good performance of the model. However, the average wet-spell lengths (not shown) were underestimated at all stations. This is one of the drawbacks of the model in simulating precipitation.

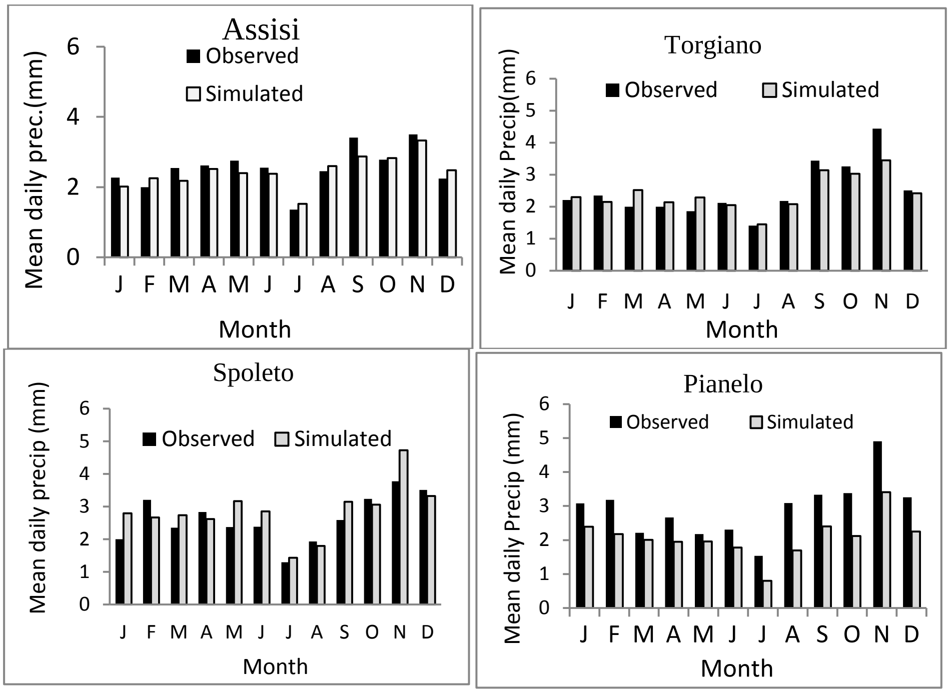

Figure 4.2. Validation results of SDSM-based downscaling for Precipitation (1981-1990)

For temperature (T_{max} and T_{min}), the mean and variances corresponding to each month are used to evaluate the performance of the model. The results are shown in Figure 4.2 which indicate a reasonable agreement between the simulated and observed results at all stations.

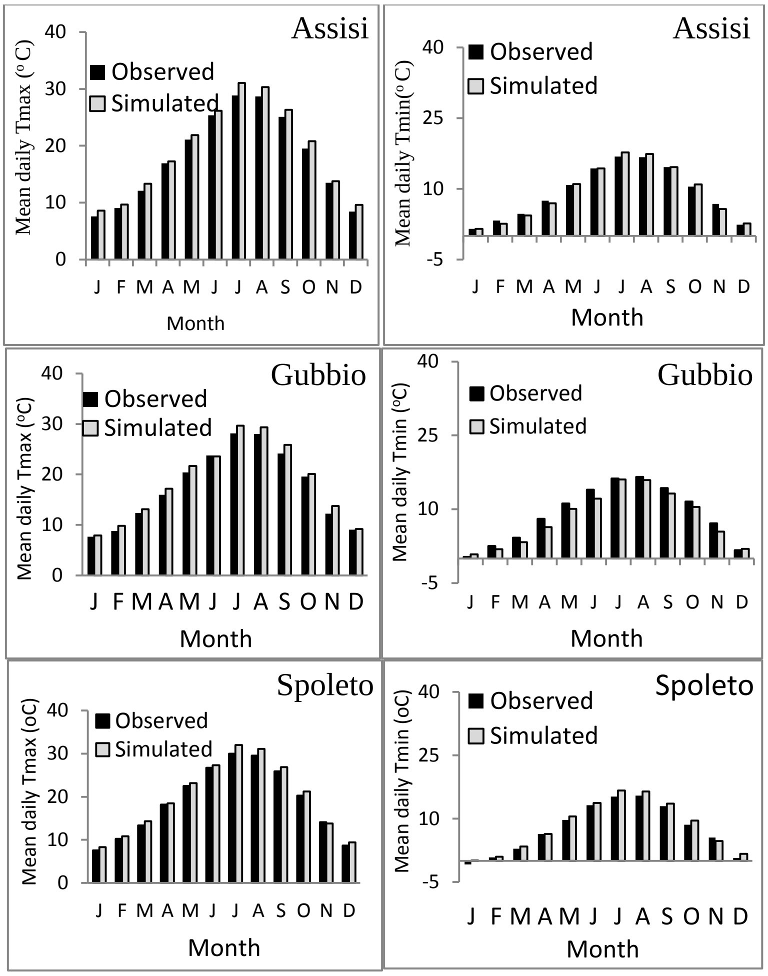

Figure 4.3: Validation results SDSM-based downscaling for T_{max} and T_{min} (1981-1990)

Through closer evaluation, there is a slight over estimation of both maximum and minimum temperature except for the station at Gubbio. This could be due to the fact that Gubbio is located at the far northern part of the basin that is closer to the Apennines along the Italian Peninsula. Table 4.4 summarizes the overall performance of the SDSM both for the calibration and validation periods.

Table 4.4: Performance of SDSM during the calibration and validation periods

		Calibration		MAE of the Validation period				
Predictand	Station	R^2	SE	Winter	Spring	Summer	Autumn	Annual
Precipitation	Assisi	0.29	0.40	0.28	0.07	0.00	0.11	0.07
	Spoleto	0.17	0.48	1.93	0.13	0.86	0.58	0.32
	Torgiano	0.13	0.42	1.04	0.86	0.28	0.34	0.34
T_{max}	Assisi	0.61	2.48	0.94	0.80	1.56	0.93	1.06
	Spoleto	0.69	2.12	0.70	0.66	1.37	0.57	0.82
	Gubbio	0.54	2.92	0.47	1.09	0.90	1.24	0.93
T_{min}	Assisi	0.57	2.02	0.13	0.22	0.52	0.18	0.00
	Spoleto	0.47	2.42	0.70	0.45	1.00	0.28	0.61
	Gubbio	0.36	2.91	0.04	1.21	0.88	1.31	0.84

R^2: *Coefficient of determination;* **SE:** *Standard Error*

4.3.3. Calibration and Validation of LARS-WG

The calibration of LARS-WG model is based on the derivation of statistical parameters using the observed historical data. The daily precipitations as well as minimum and maximum temperature for the period of 1961-1990 at the selected stations (Assisi, Gubbio and Spoleto) were used to perform the site analysis. During site analysis, LARS-WG produces monthly means and standard deviations of precipitation, minimum, and maximum temperature using semi-empirical distributions of dry and wet series. The statistical significance of the result is analyzed by forcing the model to generate synthetic series of data for 300 years. The resulting synthetic values are then compared with the observed records considering the t-test, F-test and K-S (Kolmogorov-Smirnov) tests. Figure 4 shows the performance of LARS-WG for the generation of mean precipitation at an acceptable confidence values (>90%) at all stations. The same acceptable result is achieved for temperature, which was modeled as conditional process unlike that of SDSM and the calibration result could not exactly the same.

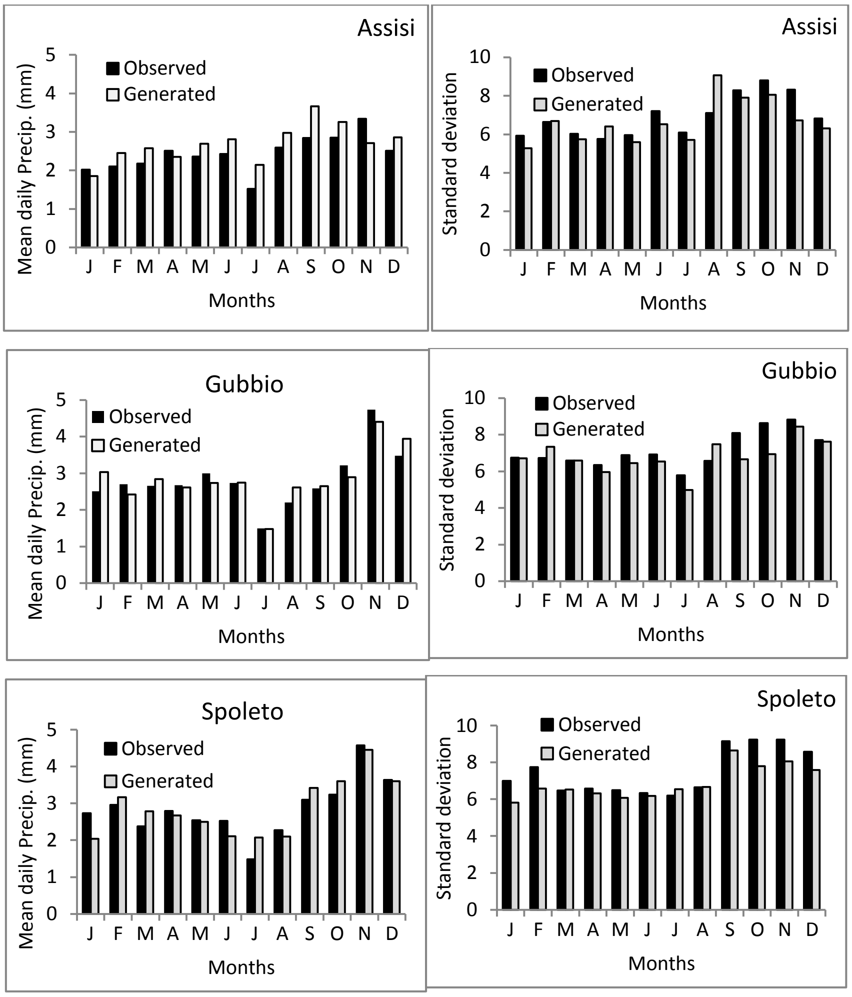

Figure 4.4: Comparison of observed and generated data with LARS-WG for precipitation.

4.4. Results and Discussions

Generation of Climate Scenario

In this study, future climate scenario is generated for maximum and minimum temperature and precipitation at the selected stations of the study area. The SDSM is calibrated and validated as explained in section 4 above. In SDSM-based statistical downscaling method, the A2 and B2 emission scenarios from HadCM3 were used whereas in LARS-WG, only the A2 emission scenario from the source was used for building future climate scenario. Hence, it has to be noted that, even though the two methods are applied at different stations; we limit ourselves to make a comparison between the two methods based on the analysis at Assisi and Spoleto stations for A2 scenario. This is because the version of LARS-WG we have used accepts only A2, A1B and B1 scenarios for HadCM3 whereas the SDSM supports A2 and B2 scenario for the same GCM model.

4.4.1. Downscaling with SDSM

In the SDSM model, the regression equations established for all the stations during the calibration process are used to build the scenario data considering four scenario periods including: the current-commonly called base period (1961-1990), the 2020s (2011-2040), the 2050s (2041-2070) and the 2080s (2071-2099). The stations considered for the SDSM-based downscaling purpose are in a distance of tens to few hundred kilometers where we found that there is no significant difference while using the GCM data at each of them. Therefore, for the sake of brevity and explanation through figures, the Assisi station is used. In Figure 4.5, the trends of daily precipitation at Assisi station is shown corresponding to the A2 and B2 scenarios. Comparatively, the A2 scenario shows a slight over estimation in mean precipitation. On the other hand, the downscaled result shows an increase in average dry-spell lengths and decrease in average wet-spell lengths in both scenarios. Similarly, the downscaled results of minimum and maximum temperature at Assisi are shown in Figure 6. Both scenarios show an increasing trend for temperature with A2 scenario showing slight over estimation compared to B2 scenario like that of precipitation. Another close evaluation based on seasonal result revealed that the average T_{min} increases by 3.5 ^oC and 2.6 ^oC for A2 and B2 scenarios respectively for summer season by the end of 2080s. From the same monthly statistics shown in the plot for data downscaled in both cases, the winter average T_{max} shows 6.45 ^oC and 5 ^oC for A2 and B2 scenarios respectively by the end of 2080s. This result for the temperature shows an agreement with the previous study conducted by Coppola and Giorgi (2010) and the IPCC's global projections, where the ensemble average of various GCMs show an increasing trend of both T_{min} and T_{max}. However, for the case of precipitation the result shows considerably different trend. This can be attributed to the uncertainty in the method of downscaling and type of GCM used over a smaller areal (Xu et al., 2005; Praskievicz and Chang, 2009).

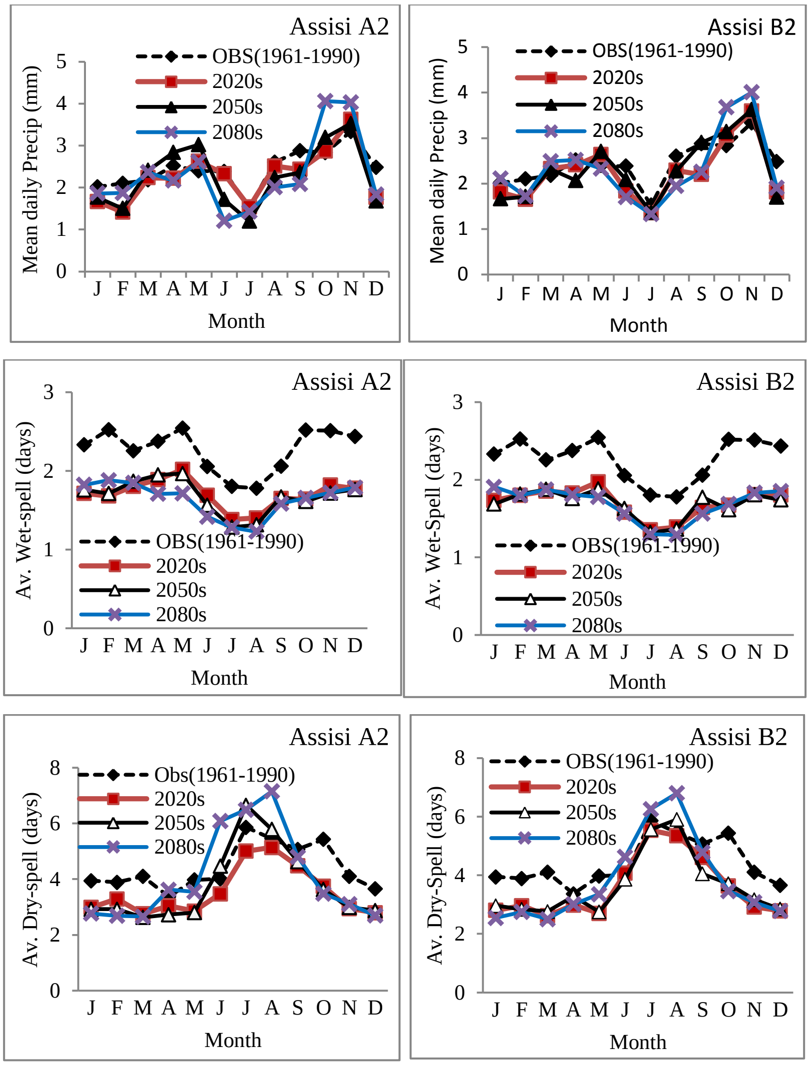

Figure 4.5: Trends of precipitation at Assisi station under A2 and B2 Scenario downscaled with SDSM.

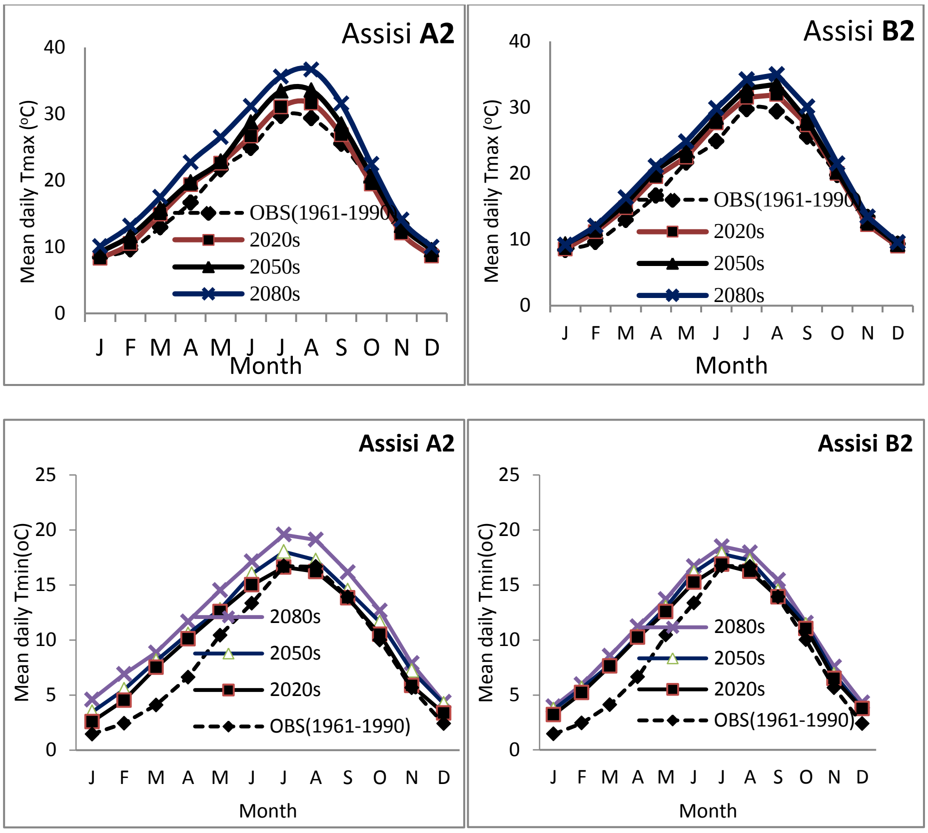

Figure 4.6: Trends of Temperature (min and max) at Assisi station under A2 and B2 Scenario downscaled with SDSM.

4.4.2. Downscaling with LARS-WG

For generation of climate scenario, the recent version (Version 5) of the LARS-WG is used. The parameter files are developed during the calibration (site analysis) of the model using the observed data. The future climate scenario corresponding to the current climate (1961-1990), the 2020s, the 2050s and the 2080s are then generated. For the purpose of climate studies, the model supports 15 GCM data (Semenov, 2007); however to make a comparison with SDSM, this analysis used the

HadCM3 A2 scenario. This is due to the fact that both the downscaling models support the HadCM3 A2 scenario in common. The building up of climate scenario in LARS-WG is performed in such a way that the relative changes of precipitation and absolute changes of temperature are first calculated through scenario generation setup in the LARS-WG. Then the calculated change factors based on the GCM data are applied to the observed data to get the corresponding future characteristics of the climate. Some of the downscaled results for precipitation and temperature data are shown in Figures 4.7 and 4.8, respectively. In the case of precipitation, the A2 scenario shows significant decreasing trend for the time window of 2080s; whereas the temperature values show more dry summer at all the stations.

Unlike the SDSM, precipitation shows decreasing trends at all the stations; which shows an agreement with the findings of Coppola and Giorgi (2010). This comparison indicates that the LARS-WG is able to capture the climate characteristics relatively in a good agreement with IPCC’s projections. The decrease in precipitation in 2020s not significant; however, there will be a pronounced decrease in summer precipitation (JJA) in 2080s. In 2050s, the trend of precipitation is expected to have an increasing pattern for the winter (DJF) and early spring (MAM) seasons at all the considered stations.

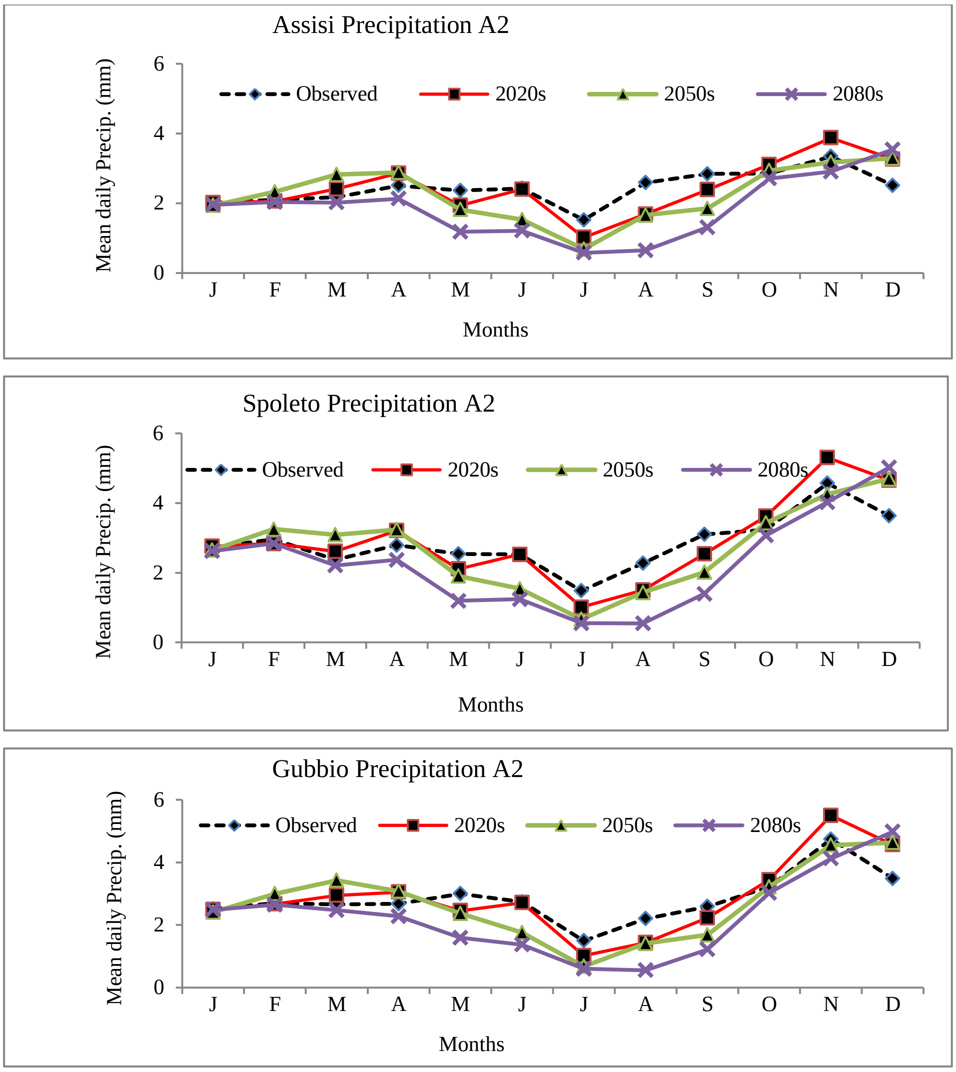

Figure 4.7: Downscaled results of Precipitation using LARS-WG.

Another comparison between the downscaled results can be seen by evaluating the difference between Figures 4.5 and 4.7 that shows the downscaled precipitation results based on SDSM and LARS-WG, respectively. However, the two models show slightly different downscaled results in terms of precipitation and able to show the same result in terms of temperature.

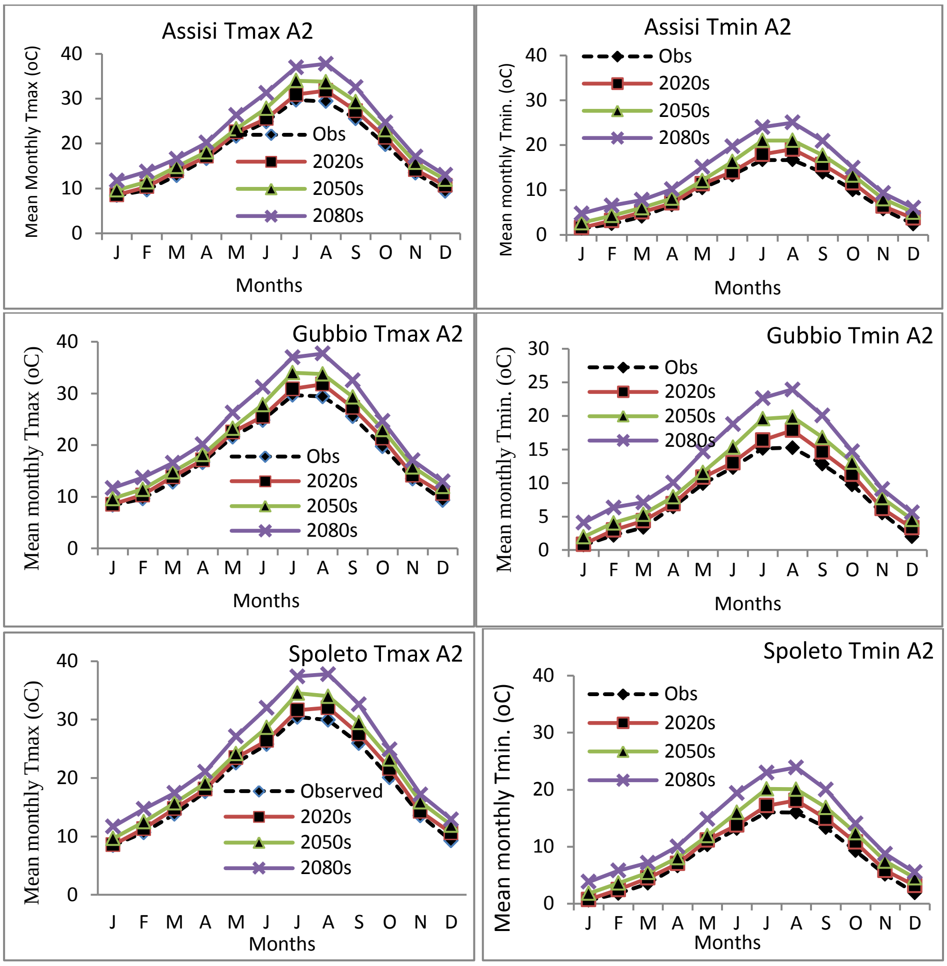

Figure 4.8: Downscaled results of Temperature (T_{min} and T_{max}) using LARS-WG

The major reasons for such difference are mentioned in section 4.4.2; where the variable of interest determines the performance of the methods used. In this case, it is impossible to decide which result of downscaling could be used as an input to models for hydrological impact studies. The presumable reason is that, in SDSM, the large scale predictor variables from GCM are used; whereas in LARS-WG the relative change factors from the GCM are applied to the observed data resulting in different performance of the methods. This could also be considered as an indication of uncertainty while using different downscaling methods for the same impact study. Further investigation could be analyzed as a continuation of the work by forcing hydrologic model for the study area. However, it is also mentioned by IPCC's fourth assessment report (Kundzewicz et al., 2007) and still worthy to note that the GCMs are susceptible to various uncertainties due to model setup in representing the climate system.

4.5. Final Remarks

Despite the progressive advances and use of GCMs to represent land-surface processes, the outputs from these GCMs are subject to various sources of uncertainties while used by end users. Among others, the choice of GCMs (i.e. uncertainty due to climate scenarios) and the one associated with transferring large-scale climatology to regional-scale climatology (i.e. uncertainty due to downscaling) play major role for end users and adaptation to local-scale impact assessments (Graham et al., 2007)

In this study, we have seen different results from the SDSM and LARS-WG though we have used the same GCM (HadCM3) and emission scenario which reveals the uncertainties due to downscaling method. In case of precipitation, the result shows significant difference where the GCMs are not reliable in simulating precipitation as the local-scale dynamics are not well represented by the governing equations used in the large-scale models. Also in the case of temperature, though both downscaling models show the same trend the SDSM shows slight over estimation as compared to LARS-WG. Hence due to such sources of uncertainities further use of the downscaled outputs (say in hydrological modles) needs to be handled with caution. Among others measures the use of ensamble GCM model outputs and the use of model intercomparisons are widely accepted and recommended by many researchers (Dibike and Coulibaly, 2005; Xu et al., 2005; Minville et al., 2008)). To date, there are no universal and quantitative answers given to questions associated with such uncertainties beyond showing the signals and mentioning the probable causes. However, since recent years lots of effort have been put to evaluate uncertainties and there is an agreement in that the choice of GCMs or emission scenarios remains as the major source (Graham et al., 2007; Minville et al., 2008; Prudhomme and Davies, 2009a; Prudhomme and Davies, 2009b). This uncertainty arises from the fact that there is imperfect representation of topography and climate processes of GCMs due to their computational limitations. Moreover, the selection of emission scenarios based on the prescribed story lines have their own limitations, as there is no exact rule to predict the global socio-economic systems in the future. In our case, we have seen for station at Assisi for example, the downscaled results from A2 and

B2 scenario used in SDSM not exactly identical where B2 scenario shows slight over estimation of summer temperature. Finaly, we also would like to note that though the achievements to capture the trends are promissing, the use of such downscaling techniques in areas with sparse data is still uncertain.

4.6. Conclusion

The performance of two statistical downscaling models based on the multiple linear regressions (i.e. SDSM) and stochastic weather generator using LARS-WG were evaluated in terms of their ability to reproduce the mean values of current climate and future precipitation and temperature data. Historical datasets from the national research center of Rome were used to perform the statistical downscaling in the Upper Tiber River basin drained by Chiascio and Topino rivers. Four sets of analysis time window were selected including: the current (1961-1990), the 2020s, the 2050s and the 2080s to evaluate the capability of both models. The results from both statistical downscaling model shows an agreement with the IPCC's prediction over the Mediterranean window. In the case of temperature (T_{min} and T_{max}), both models show identical results to capture the general trends of the mean values. For precipitation, the analysis of the results from the two models does not lead to an identical conclusion. The difference in this result is presumably due to the use of large-scale predictor variables in SDSM; whereas, the LARS-WG is analyzed by applying the change factors from the GCM to the observed climate.

Moreover, the difference in precipitation downscaling result is dependent on the inability of the GCM to capture local dynamics related to precipitation characteristics. Beside this, both statistical downscaling models used in this study are able to show an acceptable performance with LARS-WG showing better agreement with previous studies conducted for Mediterranean region and Italian peninsula. Among others, a better agreement has been observed with the local scale analysis of Todisco and Vergni (2008) who found (by analyzing long time historical series of five stations in Umbria region) that the average rainfall depths of rainy days are all decreasing.

In general, it was noted that the results show an agreement with the findings of some research works in the region in particular and global context in general. However, the authors consider the results are perhaps indicators of possible future changes rather than actual prediction and it is worthy to recommended caution for further usage. Moreover, various uncertainties are associated to the direct usage GCMs in climate impact assessment. This analysis has shown that the same scenario from the same GCM (HadCM3) sources gave different outputs of future precipitation and temperature characteristics. The scenario data are also based on sets assumptions on international geopolitics, economic and population growth rate and technical development as well. Thus these assumptions are still dependent on local dynamics of the system which cannot be provided in quantitative term.

Chapter 5[4]

Abstract

Quantification of the various components of hydrological processes in a watershed remains a challenging topic as the hydrological system is altered by internal and external drivers. Watershed models have become essential tools to understand the behavior of a catchment under dynamic processes. In this study, a physically-based watershed model called Soil Water Assessment Tool (SWAT) was used to understand the hydrologic behavior of the Upper Tiber River Basin, central Italy. The SWAT model was successfully calibrated and validated using observed weather and flow data for the period of 1963-1970 and 1971-1978 respectively. A total of eighteen parameters were evaluated and the model showed high relative sensitivity to groundwater flow parameters than the surface flow parameters. Analysis of annual hydrological water balance was performed for the entire upper Tiber watershed and selected sub-basins. The overall behavior of the watershed was represented by three categories of parameters governing surface flow, sub-surface flow and the whole basin response. The base flow contribution has shown that 60% of the stream flow is from shallow aquifer in the sub-basins. The model evaluation statistics that evaluate the agreement between the simulated and observed stream flow at the outlet of a watershed and other three different sub-basins has shown coefficient of determination (R^2) from 0.68 to 0.81 and Nash Sutcliffe Efficiency (E_{NS}) between 0.51 and 0.8 for the validation period. The components of the hydrologic cycle showed variation for dry and wet period within the watershed for the same parameter sets. Based on the calibrated parameters the model can be used for prediction of the impact of climate and land use changes and water resources planning and management.

Key Words: Hydrological modeling**;** Watershed Models; SWAT; Calibration; stream flow; Surface runoff, Groundwater flow; Water Balance, Tiber Basin; Central Italy

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[4] This chapter is based on . Fiseha, B. M., S. G. Setegn, dA. M. Melesse, E. Volpi and A. Fiori (2012). **Hydrological analysis of the Upper Tiber River Basin, Central Italy: a watershed modelling approach**. *Hydrological Processes*

5. Watershed Modelling

5.1. General background

To deal with water resources planning and management issues in a watershed, it is important to understand problems that involve complex processes and their interactions at the surface, subsurface, and their interfaces. Different watersheds respond differently to the same change in those drivers, depending on physiogeographic and hydrogeologic characteristics within the system. Such effects are known to be heterogeneous and complex over time and space that will result in scale dilemma (Bloschl and Sivapalan, 1995). One of the ways to understand such problems is through watershed hydrology which is defined as that branch of hydrology that deals with the integration of hydrologic processes at the watershed scale to determine the watershed response. In watershed hydrology, the interactions between the various processes of the hydrologic cycle are represented by watershed simulation models. These models are assemblages of mathematical descriptions of components of the hydrologic cycle (Singh and Woolhiser, 2002). They simulate hydrologic processes in a more holistic approach compared to many other models which primarily focus on individual processes or multiple processes at relatively small-or field-scale without full incorporation of a watershed area (Daniel et al., 2011). Moreover, watershed-scale simulation models are mostly employed to understand the dynamic interactions between meteorological forcing terms and land-surface hydrology Thus, the development of watershed models has been the direct outcome of the need to understand hydrologic system behavior with all physical and measured data.

5.1.1. Overview of Watershed Model Classification

To date there are broad palettes of watershed simulation models available and numerous methods of classifications also exist (Clarke, 1973; Chow et al., 1988; Todini, 1988; Dingman, 2002; Singh and Woolhiser, 2002). The complexity of such models does not only depend on the model class to which they belong, but also on the processes incorporated, the process formulations used, the different space and time scales employed and the quality of the data input. These models should be sufficiently detailed to capture the dominant processes and natural variability, but not unnecessarily refined that computation time is wasted and/ or data availability is limited. According to Grayson *et al.*, (1992), watershed models may be either predictive (to obtain a specific answer to a specific problem) or investigative (to further our understanding of hydrological processes). Whether they are predictive or investigative, they involve the following steps (O'Connell and Bowles, 1991): (a) collecting and analysing data; (b) developing a conceptual model (in modeller's mind) which describes the important hydrological characteristics of a watershed; (c) translating the conceptual model into a mathematical model; (d) calibrating the mathematical model to fit a part of the historical data by adjusting various coefficients; (e) and validating the model against the remaining historical data set.

The most common methods of classification are summarized as follows;

(i). classification ***based on the nature of algorithms employed*** that include – empirical, conceptual, or physically-based models. Empirical models are based on observation or experiments and the various functions (eg. simple egressions) are used to fit to the available data. In conceptual models relatively simple mathematical relations (eg. Unit hydrograph) are applied to simulate the observed watershed behavior Physically-based models are based on understanding of the physics of the processes involved in the watershed. Conservation equations of mass, momentum and energy are used to describe the physics of the processes and partial differential equations can be solved by various numerical methods (eg. St. Venant equation for surface flow (Chalfen and Niemiec, 1996), Richards equation for unsaturated zone flow (Richards, 1931), Penman-Monteith equation for evapotranspiration (Monteith, 1965). Unlike conceptual and physically-based models, empirical models disregard the physical laws.

(ii). classification based on ***mode parameter specifications*** – deterministic or stochastic models. In deterministic models all parameters and variables of the watershed are uniquely defined and regarded free from random variations. Whereas, in stochastic models the watershed variables or parameters are regarded as random having probability distributions in parameter space. Most watershed models are deterministic in nature; however, stochastic models have two important advantages (Daniel et al., 2011). First, their conceptually simple framework makes it possible to describe heterogeneity when there are limited spatial or temporal details. Second, they provide decision makers with the ability to determine uncertainty associated with predictions.

(iii). classification based on ***temporal representation*** – event-based, continuous-process models. Event-based models simulate individual precipitation-runoff events with a focus on infiltration and surface runoff, while continuous process models explicitly account for all runoff components while considering soil moisture redistribution between storm events. There are other types of model that falls under this category: steady state or unsteady-state watershed models. In steady state (or hydro-static) the time derivative in the model is set to infinite; whereas, in unsteady-state (hydro-dynamic) models, the time variable is calculated for each calculation time step.

(iv). classification based on ***spatial domain*** – lumped, semi-distributed, or distributed models. In lumped models spatial distribution of watershed characteristics are ignored over the entire model domain and the processes are represented by average, single values. Semi-distributed models partitions the watershed into relatively smaller sub-watershed which are treated as a single unit. Contrary to lumped and semi-distributed models, distributed models discretize the watershed into fine resolutions typically defined by the modeler.

5.1.2. Model Selection Criteria

Despite, the existences and development of numerous watershed simulation models, the choice of the most suitable model for a particular watershed to address a particular problem and find solutions is difficult. Although there are no clear rules for making a choice from the existing watershed models, some guidelines can be considered. At first the objective of the study at hand should be clearly defined (i.e. the question that the simulation model needs to answer should be defined). Secondly, the nature and type of hydrologic process need to be simulated (i.e. whether or not the model is capable of simulating single-event or continuous processes). At the third place, the availability of input data also determine the choice of the model; some models are data hungry whereas some are parsimonious. The fourth guideline may be the availability of the simulation model itself. Some models are readily available as public domain, whereas some others are costly. The fifth, guideline will be nature of data handling mechanisms by the watershed model or its embedment into other spatial and/or temporal data management system has an impact on the choice of the models. For example, physically-based distributed models require large quantities of data to consider spatial heterogeneity which can be stored, retrieved, managed and manipulated with use of Geographical Information Systems (GIS). Hence the ability of a hydrological model to integrate GIS for hydrologic data development, spatial model layers and interface may be considered as model selection criteria. Beside the above personal rule of thumbs, some other subjective guidelines can be stated. For example, preferences for Graphical User Interface (GUI), computer operation system also determine the choice of the model.

5.2. The Soil and Water Assessment Tool (SWAT)

Among the large number of watershed models (Singh and Woolhiser, 2002), the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) was selected to simulate stream flow and other hydrological components in the Upper Tiber River Basin. The model was selected due to three main reasons: (i) it is widely used in different part of the world even under scarce data condition (up-to-date publications can be explored from SWAT Literature Database[5]), (ii) it is freely available with detailed documentation and progressive review works (eg. Gassman et al., 2007; Neitsch et al., 2009), (iii) its GIS interface simplifies the spatial data handling and catchment delineation in the modeling processes.

SWAT is a physically-based, a spatially distributed, and continuous time watershed model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Arnold et al., 1998; Neitsch et al.,

[5] https://www.card.iastate.edu/swat_articles/index.aspx

2009). It is actively supported by the USDA (United States Department of Agriculture) – ARS (Agricultur-al Research Service) at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA. (Neitsch et al. 2005). As a physically based model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in land cover and soil types within a watershed. The HRU is therefore the smallest spatial unit for rainfall-runoff calculations which is a lumped land area within a sub-watershed comprised of unique land cover, soil, slope and management combinations.

SWAT has eight major components: hydrology, weather, sedimentation, soil temperature, plant growth, nutrients, pesticides, and land management. No matter what type of problem studied with SWAT, water balance is the driving force behind everything that happens in the watershed (Neitsch et al., 2009). Within the HRU, water balance is represented by four storage volumes: snow, soil profile (0–2 m), shallow aquifer (typically 2–20 m), and deep aquifer (≥20 m). The model simulates relevant hydrologic processes such as surface runoff, evapotranspiration, infiltration, percolation, shallow aquifer and deep aquifer flow/storage, and channel routing (Arnold and Allen, 1996). The simulation of the hydrologic processes within the watershed can be done in four subsystems (see, Figure 5.1.): surface soil, intermediate zone, shallow and deep aquifers, and channel flow. Stream flow in the main channel is determined by three sources: surface runoff, lateral flow and base-flow from shallow aquifers.

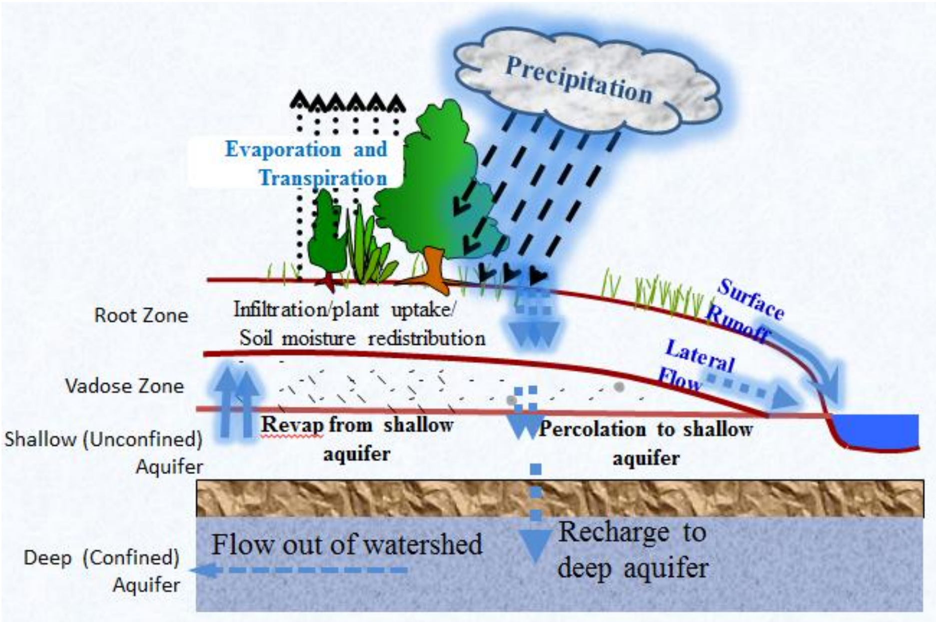

Figure 5.1. Schematic representation of the hydrologic cycle in SWAT (Source: Neitsch et al., 2009)

In general, the hydrology of a watershed can be separated into two major components as the land phase and the routing phase of the hydrologic cycle. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. The water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

$$SW_t = SW_o + \sum_{i=1}^{t} (\mathrm{R_{day}} - \mathrm{Q_{surf}} - \mathrm{E_a} - \mathrm{W_{seep}} - \mathrm{Q_{gw}}) \qquad (1)$$

where SW_t is the final soil water content (mm), SW_o is the initial soil water content on day *i* (mm), *t* is the time (days), R_{day} is the amount of precipitation on day *i* (mm), Q_{surf} is the amount of surface runoff on day *i* (mm), E_a is the amount of evapotranspiration on day *i* (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm), and Q_{gw} is the amount of return flow on day *i* (mm).

Detail description of each phase is given in the theoretical description documents of SWAT model (2009), however only a brief summary of the relevant hydrologic component in the present study are given below.

5.2.1. Surface Runoff in SWAT

Surface runoff or overland flow is a flow that occurs along a sloping surface and it occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. A simplified and conceptual representation of the hydrologic cycle in SWAT model is shown in Figure 5.2. As shown in the figure, the movement of water in the hydrologic system before it reaches the outlets of the watershed consists four components: direct surface runoff (Q_{surf}), lateral flow from unsaturated soil profiles (Q_{lt}), drainage from tiles (Q_{tl}), and baseflow from underground (Q_b).

In SWAT the surface runoff volume computation can be performed using Soil Conservation Service (SCS) Curve Number (CN) method (USDA-SCS, 1972) or the Green and Ampt infiltration method (Green and Ampt, 1911). The Green and Ampt method requires sub-daily data for simulation of flow which were not available for the present study. Hence the SCS-CN method is explained in the following section. In this method, the ratio of actual retention to maximum retention is assumed to be equal to the ratio of direct runoff to rainfall minus initial abstraction as expressed in the mathematical equation (2) below. The curve number (CN) is a function of the soil's permeability (soil group), land use and antecedent soil water conditions. SCS defines three antecedent moisture conditions; I - for dry (wilting point), II - for average moisture and III - for wet (field capacity). The standard values of the curve number that SWAT uses for various soils and land-cover conditions are based on antecedent soil moisture condition II.

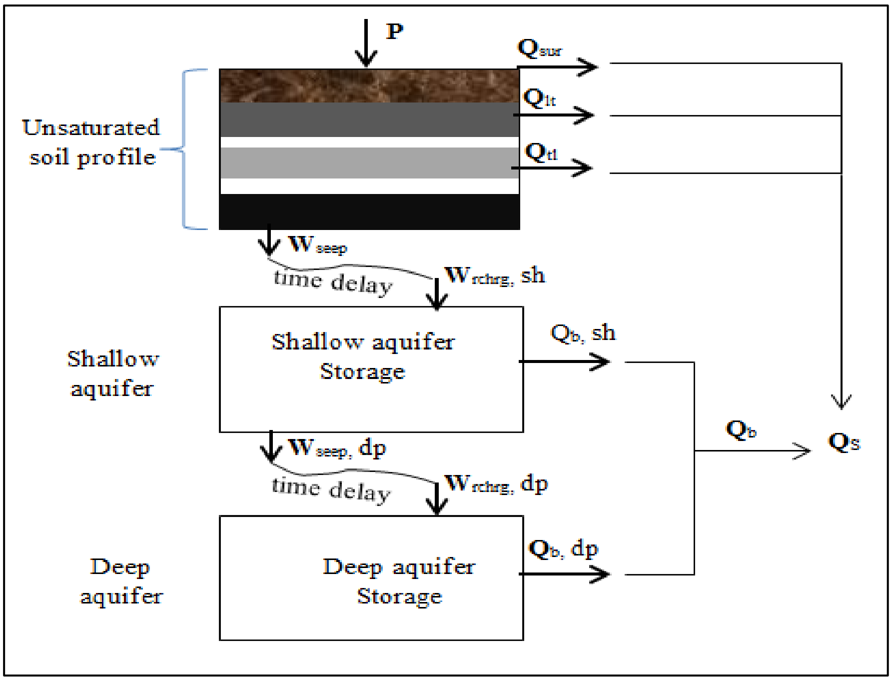

Figure 5.2. Conceptual representation of hydrologic processes in SWAT (after: Luo et al., 2012)

The SCS-CN method uses two equations for runoff, of which the first one relates runoff to rainfall and retention parameter as:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \quad (2)$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and S is the retention parameter (mm).

The second equation relates the retention parameter to the curve number as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

where *CN* is the curve number and ranges from 0 to 100 and *25.4* is a constant that gives S in mm. The higher values of CN are associated with higher runoff.

SWAT also predicts, Peak runoff rate based on a modification of the Rational Formula shown in equation (4) below. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. The rainfall intensity during the watershed time of concentration is estimated for each storm as a function of total rainfall using a stochastic technique. The watershed time of concentration is estimated using Manning's Formula considering both overland and channel flow.

$$q_{peak} = \frac{\alpha_{tc} * Q_{surf} * Area}{3.6 * t_{con}} \quad (4)$$

where q_{peak} is the runoff rate (m^3s^{-1}), α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm), *Area* is the sub-basin area (km^2), t_{conc} is the time of concentration for the sub-basin (hr) and 3.6 is a unit conversion factor.

5.2.2.. Evapotranspiration Estimation in SWAT

In the SWAT model potential evapotranspiration can be estimated using three different methods; Hargreaves method (Hargreaves, 1985) that only needs air temperature data, Priestly-Taylor method (Priestley, 1972) that needs solar radiation and relative humidity in addition to air temperature, and Penman-Monteith method (Monteith, 1965) that requires wind speed in addition to all. In this study, Hargreaves method was used as it is recommended for areas where only maximum and minimum air temperature data are available. The method has gone through various improvements since its development , whereas, SWAT uses the mathematical expression indicated in equation (5).

$$\lambda E_0 = 0.0023 * H_o * (T_{max} - T_{min})^{0.5} * (\overline{T_{av}} + 17.8) \qquad (5)$$

where λ is the latent heat of vaporization ($MJ\ kg^{-1}$), E_o is the potential evapotranspiration ($mm\ d^{-1}$), H_0 is the extraterrestrial radiation ($MJ\ m^{-2}\ d^{-1}$), T_{max} is the maximum air temperature for a given day (^oC), T_{min} is the minimum air temperature for a given day (^oC), and $T\ av$ is the mean air temperature for a given day (^oC).

5.2.2. Soil Water Estimation in SWAT

Water that enters the soil may move along one of several different pathways, see Figure 5.1 and 5.2. The water may be removed from the soil by plant uptake or evaporation. It can percolate past the bottom of the soil profile and ultimately become aquifer recharge (W_{rchg}). A final option is that water may move laterally in the profile and contribute to stream flow (Q_{lt}). Of these different pathways, plant uptake of water removes the majority of water that enters the soil profile.

SWAT uses the following equation to compute lateral flow:

$$Q_{lt} = 0.024 * \left[\frac{2. SW * K_s * sl}{\emptyset_d * L_h}\right] \quad (6)$$

Where, Q_{lt} is lateral flow (mm*day^{-1}), SW is drainable volume of soil water (mm), sl is slope (m/m), ϕ_d is drainable porosity (mm/mm), K_s is saturated hydraulic conductivity (mm*hr^{-1}) and L_h is the hill slope length (m).

Commonly, lateral flow plays significant role in areas with soils having hydraulic conductivities in surface layers and an impermeable or semi-permeable layer at a shallow depth. In such a system, rainfall will percolate vertically until it encounters the impermeable layer. The water then ponds above the impermeable layer forming a saturated zone of water and this saturated zone is then the source of water for lateral subsurface flow.

5.2.3. Groundwater in SWAT Model

SWAT differentiates the underground storage into two portions, shallow aquifer and deep aquifer. The shallow aquifer receives recharge from the unsaturated soil profile percolation. An exponential decay weighting function is utilized to account for the time delay in aquifer recharge once the water exits the soil profile (Neitsch et al., 2009). The delay function accommodates situations where the recharge from the soil zone to the aquifer is not instantaneous, i.e. 1 day or less. The recharge to aquifer on a given day is calculated as below:

$$W_{rchrg,i} = \left[1 - exp\left(-\frac{1}{\delta_{gw,\mathrm{sh}}}\right)\right] * W_{seep} + \mathrm{e}xp\left(-\frac{1}{\delta_{gw,\mathrm{sh}}}\right) * W_{rchrg,i-1} \qquad (7)$$

Where W_{rchrg} is the amount of recharge entering the aquifers (mm $*day^{-1}$), $\delta_{gw,sh}$ is the delay time of the overlying geologic formations (days), W_{seep} is the total amount of water exiting the bottom of the soil profile ($mm*day^{-1}$); subscriptions "seep" indicates seepage water exiting bottom of the unsaturated soil profile, "rchrg" indicates recharge, I is the sequential number of days, and "sh" indicates the shallow aquifer storage.

A fraction of the total daily recharge can be routed to the deep aquifer. The amount of water diverted from the shallow aquifer due to percolation to the deep aquifer on a given day is given by:

$$W_{seep,dp,i} = \beta_{dp} * W_{rchrg,i} \qquad (8)$$

Where β_{dp} is a coefficient of shallow aquifer percolation to deep aquifer, and subscription "dp" indicates deep aquifer.

The amount of recharge entering the shallow aquifer is:

$$W_{rchrg,sh,i} = W_{rchrg,i} - W_{seep,dp,i} \qquad (9)$$

Baseflow generated from the shallow aquifer on a given day i under influence of recharge is given as below (Neitsch et al.,2009):

$$Q_{b,sh,i} = Q_{b,sh,i-1} * exp(-\alpha_{gw,\text{sh}} * \Delta t) + W_{rchrg,i} * [1 - exp(-\alpha_{gw,\text{sh}} * \Delta t)] * W_{seep} \qquad (10)$$

where $Q_{b,sh,i}$ is the baseflow from the shallow aquifer on day i (mm day^{-1}), and "b" indicates baseflow, and Δt is the step time length.

When only one reservoir is used (i.e. only unconfined aquifer), the baseflow is equal to that from the shallow aquifer. However, when two reservoir (i.e. both confined and unconfined aquifer exists), baseflow from the shallow aquifer is expressed as in equation (10), and following equations. (7) and (8), the recharge to and baseflow from the deep aquifer are given by Eqs. (11) and (12), respectively. It has to be noted that SWAT assumes that water entering the deep aquifer is not considered in the future water budget calculations and can be considered lost from the system (Neitsch et al., 2009).

$$W_{rchrg,dp,i} = W_{rchrg,dp,i-1} * \left[1 - exp\left(-\frac{1}{\delta_{gw,dp}}\right)\right] + W_{seep,dp,i} * \left[1 - exp\left(-\frac{1}{\delta_{gw,dp}}\right)\right] \qquad (11)$$

$$Q_{b,dp,i} = Q_{b,dp,i-1} * exp(-\alpha_{gw,dp} * \Delta t) + W_{rchrg,i} * [1 - exp(-\alpha_{gw,dp} * \Delta t)] * W_{seep} \qquad (12)$$

where $W_{rchrg,dp}$ is the amount of recharge entering the deep aquifer (mm* day^{-1}), $\delta_{gw,dp}$ is the delay time or drainage time of the deep aquifer geologic formations (days), $W_{seep,dp}$ is the total amount of water exiting the bottom of the shallow aquifer (mm*day^{-1}), $Q_{b,dp}$ is baseflow component from deep aquifer. The total baseflow is then given as below:

$$Q_{b,i} = Q_{b,sh,i} - Q_{b,dp,i} \tag{13}$$

During the SWAT simulation process, if only the shallow reservoir, is used to generate the baseflow, the parameter for the recharge to deep aquifer will be disabled. Otherwise, the parameter β_{dp} is determined through calibration. Other parameters to be calibrated for baseflow modelling in SWAT are the delay time (δ_{gw}) and the recession constants (α_{gw}).

In addition to SWAT the use of digital filters to estimate baseflow contribution of a watershed is suggested by some authors (Arnold and Allen, 1999; Luo et al., 2012). A public domain automatic baseflow separation program(Arnold and Allen, 1999) was used in this study in order to evaluate the groundwater contribution of the watershed. The program is available at http://swatmodel.tamu.edu/software/baseflow-filter-program,2011. The filter uses the following equation

$$Q_{sf,i} = \lambda Q_{sf,i-1} + \frac{1+\lambda}{2}\left(Q_{s,i} - Q_{s,i-1}\right) \tag{14}$$

where Q_{sf} is the filtered surface runoff (quick response) at time step i and Qs the original stream flow (the surface runoff), and λ is the filter parameter. Baseflow is then calculated as below:

$$Q_{b,i} = Q_{s,i} - Q_{sf,i} \tag{15}$$

5.3. Study Area and Model Setup

5.3.1. Study Area and Data sources

The detail information and dataset about the Upper Tiber River Basin (UTRB) was presented in chapter 3. In this section, relevant information for the watershed simulation using the SWAT model is summarised. The basin is located between 42.6^{o}- 43.85^{o}N and 11.8^{o}-12.92^{o} E in the Umbria region of central Italy covering an area of 4145 km^{2} with an elevation ranging from 145 to 1560 m. above sea level (Figure.1). The area is predominantly mountainous and land locked with the Italian Apennine in the eastern part represents an important physical boundary that causes variability in precipitation and temperature. Due to the topography and intense rainfall in the upstream of the Ponte Nuovo outlet, the downstream reach experiences frequent floods. The basin is drained by main Tiber River originating near the Montecoronaro and the Chiascio and Topino rivers from the left side. Figure 1 shows the location, topographic setting and sub-basins boundaries used in the modeling process. Geologically, the catchment is predominated by low-permeability formations (flysch sandstone-clay, clay and sandstone, and limestone clay). The main data for the simulation of SWAT model are the digital elevation model (DEM), weather data (precipitation and temperature), soil of the area, land use, and observed river flow data. The sources of all these data for the UTRB were explained in chapter three.

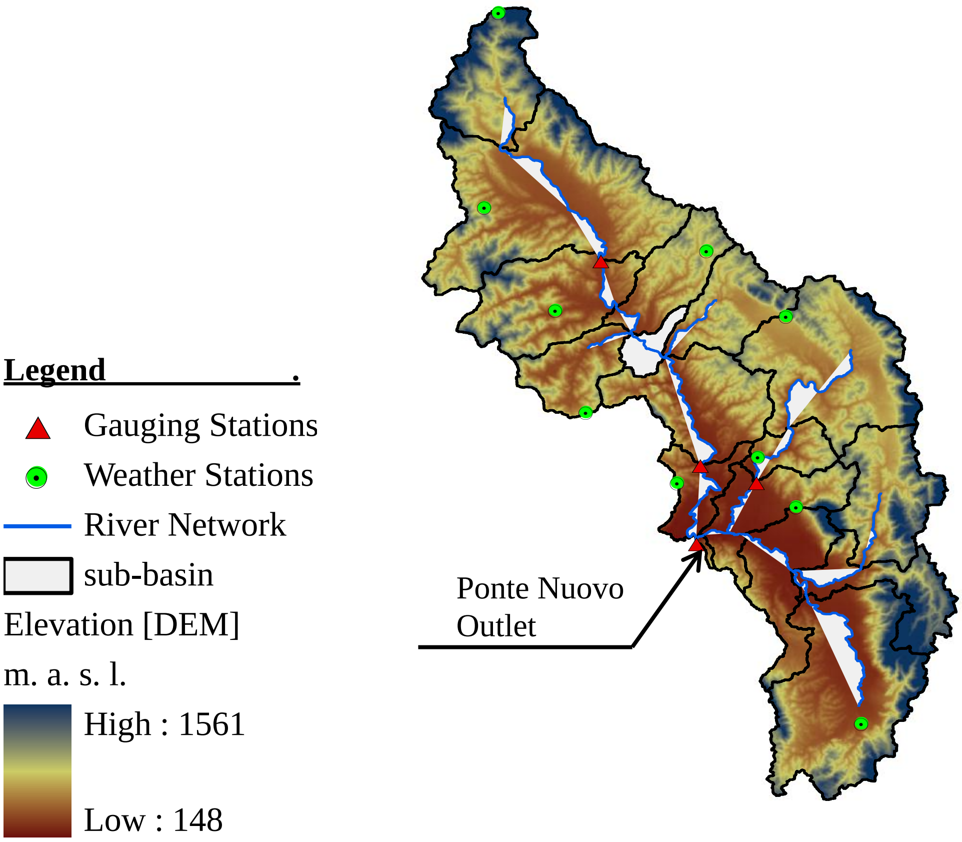

Figure 5.3. Location, DEM, and major sub-basins of the UTRB used for SWAT simulation

The DEM (30m resolution) data were collected from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) which is public data source provided by a joint program of Japan's Ministry of Economy, Trade and Industry (METI) and the National Aeronautics Space Administration (NASA). Ten tiles that cover the Tiber Basin were downloaded from the above source and imported into ArcGIS.

Catchment characteristics like slope gradient, slope length, stream network and stream characteristics (channel slope, length and width) were derived from the DEM using the automatic watershed delineation tool in ArcSWAT.

The historical weather data for the period of 1961-1995 at selected station for the study area have been provided by the hydrographic service of Umbria Region and further analyzed for simulation purpose. The area is characterized by Mediterranean climate with precipitation occurring mostly from autumn to spring seasons.

The soil data for the study area is obtained from two different sources that are publically available. The first source of data is the worldwide known FAO soil (10 km resolution), whereas the second source is from the Institute for Environment and Sustainability of the European commission Joint Research Center (JRC) (1km resolution). Using the SWAT editor module the essential soil properties like hydrologic soil group, soil available water content were incorporated during model setup. The land use land cover data with a spatial resolution of 300 m by 300m were collected from Medium Resolution Imaging Spectrometer (MERIS). Further land use classification was made in ArcSWAT model. The reclassified land cover in the watershed is predominated by agriculture and forested areas, see Table 5.1

Table 5.1: Land use and land cover classes of the sub-basin

Land use/ Land cover types	SWAT CODE	% Area
Agricultural Land (*Cropland and Pasture*)	AGRL	39.6
Rangeland (*Shrub and brush rangeland*)	RNGB	29.6
Deciduous Forest Land	FRSD	26.0
Evergreen Forested Land	FRSE	0.9
Mixed Range Land	RNGE	0.5
Mixed Urban or Built-up Land	URMD	3.2
Streams and Canals	FRST	0.1

For calibration and validation purpose, daily flow data for the period of 1961-1978 at Ponte Nuovo was considered (Figure 5.1). The average daily discharge for the calibration period of (1961-1978) was 47.93 m^3s^{-1} with a minimum value of 1.95 $m^3s^{-1}$and maximum value of 917 m^3s^{-1}.

5.3.2. Models Setup

Modeling hydrologic responses over watershed requires use of soil maps or soil survey, soil hydrologic characteristics, land use information in addition to hydrometeorological data. The input data for the basins were prepared (i.e. in the form of text or database files or grid formats). After data preparation, the model setup then performed following four major steps: (i) watershed delineation and derivation of sub-basin characteristics (ii) hydrological response unit definition (iii) model run and parameter sensitivity analysis; and (iv) calibration and validation of the model including uncertainty analysis.

The simulated flow is further divided into the corresponding surface flow and base flow for comparison with observed flow data. An automated base flow separation and recession analysis techniques (Arnold *et al.* 1999), was used for this purpose. It is developed based on the recursive digital filter techniques (Nathan and McMahon, 1990), and filters surface runoff (high frequency signals) from base flow (low frequency signals). The filter can be passed over the stream flow data three times (forward, backward, and forward). It can be downloaded from SWAT website[6] and the details of the methodology are explained in Arnold et al (1995).

During the watershed delineation, the spatial datasets that include DEM, land use, soil maps and a predefined digital stream network of the main Tiber River were projected to the same coordinate system of zone 33 in Universal Transverse Mercator (UTM 33N). The basin outlet at Ponte Nuovo was used and the delineator in the ArcSWAT follows the steepest slope paths to define the stream networks. Unlike other automated catchment delineation processes, the procedures for filling the local depressions (fill sink), flow directions and derivation of flow accumulations etc. are done using the SWAT interface. The two reservoirs in the upstream part of the study area were then added before the delineation is completed. However, it has to be noted that these reservoirs were not considered in the analysis since the calibration and validation of the model is performed before 1995 (i.e. during these periods the two reservoirs were only under construction). Finally, the

[6] http://swatmodel.tamu.edu/software/baseflow-filter-program/

basin was sub-divided into 16 sub-basins with their corresponding longest flow paths.

In the second step, the HRU definition was performed through the ‘HRU analysis’ module that requires the land use/ land cover, the soil data and slope of the basin. There are three options available in ArcSWAT for the definition of HRUs (Neitsch et al., 2005). We adopted the method that can consider spatial variability of the processes and the datasets were prepared in spatial format and linked to the ArcSWAT. Based on the soil, land cover and slope data the definition of HRU was performed that assigns a unique value for each unit in the sub-basin. The FAO soil dataset were linked to ArcSWAT and the essential soil properties were updated using the data from EU-JRC. As the area has lots of raged topography, we considered five classes of slope 0-5%, 5-10%, 10-15%, 15-20% and ≥20% in order to capture flow that occurs at the plain areas. The multiple HRU definition criteria were then performed using threshold values of 10% for land use, 20% for soil and 5% for slope of individual sub basin area. Overall there were 334 HRUs defined in the entire watershed within 16 sub- basins.

The third step is to run the model using the necessary weather data inputs and the essential information from the HRUs defined in the previous steps. Weather stations having relatively continuous daily precipitation and temperature (daily minimum and maximum) data were used in the model. In this study we have used 12 stations for precipitation and 4 for temperature. These weather stations were assigned to each sub-basin based on their proximity to centroids of the sub-basins. The simulation was run first for the calibration period of 1961 to 1970 using the first two years as a warm up period. The warm up period allowed insuring numerical stability so that the model can capture full operation of the hydrologic cycle.

The fourth step in the modeling process then rely on the outcome of the first simulation. These involve sensitivity analysis and calibration of the parameters based on selected parasol calibration algorithm. The fine tuning of the sensitive parameters then resulted in ranked outputs that show how the catchment behaves under the given conditions (see table 2).

5.3.3. Sensitivity Analysis and Calibration

After the first run (simulation) of the model, the responsiveness of different parameters was identified through sensitivity analysis. In this study two approaches were used for sensitivity analysis and calibration: the first approach is through automatic procedure and the second is manual approach. In the automatic approach we have used the Latin Hypercube (LH) One-factor-At-a-Time (OAT) (van Griensven et al., 2006) method built in the ArcSWAT. For these analyses, there are twenty six hydrological parameters in SWAT that are used to characterize the response of a catchment to the flow at the outlet. The sensitivity of such parameters are categorized into four classes according to Lenhart et al., (2002) based on their mean relative sensitivity (MRS) values. MRS is a dimensionless index calculated as the ratio between the relative change of a model output and relative change of a parameter. The variation in parameter is based on a fixed percentage of valid parameter range but not based on a fixed percentage of initial values. The mathematical explanation of this index is given in Lenhart et al., (2002) and the four classes include (i) small to negligible ($0 \leq MRS \leq 0.05$); (ii) medium ($0.05 \leq MRS \leq 0.20$); (iii) high ($0.20 \leq MRS \leq 1$); and (iv) very high ($MRS \geq 1$) sensitivities. Ranking the parameters helps to realize the dominant process governing hydrologic system characteristics and identify the influential parameters governing the processes.

Eighteen parameters were identified and some parameter value ranges for the sensitivity analysis were considered based on previous studies in the area rather than accepting the default values in the model. For example, the surface flow lag time (SURLAG) for the study area was reported to be not more than 1 day (Calenda et al., 2000); however we allowed value between 0 to 2 days during sensitivity analysis so that the algorithm can optimize over this range. The sensitivity of all parameters was analyzed using average observed flow at Ponte Nuovo outlet. The optimization procedure was then set to minimize the sum of squared error objective function. The final summary of parameters used in the sensitivity analysis and their description are given in table 2. Based on their relative indexes, the top ten most sensitive parameters were considered for further use in the model calibration and validation processes. After identifying the most sensitive parameters the model is set to run in auto-calibration processes using Parameter Solution (ParaSol) calibration algorithm (van Griensven et al., 2006) which is embedded in the ArcSWAT. The auto-calibration was run for more than one thousand simulations and the results of the best fit simulation were then compared with the observed flow at the outlet of the catchment.

The quantitative evaluation of each simulation result after parameter adjustment was performed based on the values of some selected descriptive statistics and objective functions to determine the goodness-of-fit of the selected model (Legates and McCabe, 1999). In this study we took five commonly used goodness-of-fit tests two of which have the dimension of the variables and three of which are dimensionless. These include coefficient of determination (R2), Nash and Sutcliffe efficiency (ENS) (Nash and Sutcliffe, 1970); the percent bias (PBIAS) (Yapo et al., 1996); Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE). Both the R2 and ENS ranges from 0 to 1 with higher value indicating good agreement between the model and the observation. The PBIAS measures the tendency of the simulated flows to be larger or smaller than their observed counterparts; the optimal value is 0.0, positive values indicate a tendency to overestimation, and negative values indicate a tendency to underestimation. For a perfect fit between the observed and simulated flow, the MAE and RMSE values should be 0. However due to various uncertainties even in the observation perfect fit may not be expected. Singh et al. (2005) stated that values less than standard deviation of the measured data may be considered as low and that either is appropriate for model evaluation. Following the recommendation of

Moriasi et al., (2007), we used the target objective functions: ENS > 0.5, -25%≤ PBIAS ≤+25% and R2 to be closer to 1.

$$E_{NS}=1-\frac{\sum_{i=1}^{N}(O_i-S_i)^2}{\sum_{i=1}^{N}(O_i-\bar{O})^2} \qquad (2)$$

$$R^2=\left[\frac{\sum_{i=1}^{N}(O_i-\bar{O})(S_i-\bar{S})}{\left[\sum_{i=0}^{N}(O_i-\bar{O})^2\right]^{0.5}\left[\sum_{i=0}^{N}(S_i-\bar{S})^2\right]^{0.5}}\right]^2 \qquad (3)$$

$$PBIAS=\left[\frac{\sum_{i=1}^{n}(S_i-O_i)}{\sum_{i=1}^{n}O_i}\right]*100$$
(4)

$$RMSE=\sqrt{\frac{\sum_{i=1}^{N}(O_i-S_i)^2}{N}} \qquad (5)$$

$$MAE=\frac{\sum_{i=1}^{N}|S_i-O_i|}{N} \qquad (6)$$

where: O_i and S_i represent the observed and simulated flow data respectively. $\bar{O}$ and $\bar{S}$ denotes the average values of the observed and simulated flow data respectively.

5.3.4. Validation of the Model

The validation of the model was performed using flow data at independent gauging stations and time window. The calibrated model at Ponte Nuovo is validated using mean monthly flow from 1970 to 1978. In order to test the performance of the model for the other part of the entire basin, some available flow data from other gauging stations are also compared with the output from the calibrated model. In this case, three gauging stations (namely: Santa Lucia, Ponte Felcino and Petrignano di Assisi) with observed data from 1991 to 1995 were used. The overall performance showed that the calibrated model has an acceptable agreement to simulate the flow at different sub-basins in the watershed (see table 5.3).

5.4. Results and Discussions

5.4.1. Results of Sensitivity analysis and model calibration

Flow parameters that govern the surface flow and groundwater flow have shown medium to very high relative sensitivity. Ranges of values used during the sensitivity analysis and the calibrated parameter value are shown in Table 2. The analysis was performed using observed flow data at the basin outlet. Also, the model provides sensitivity results without flow data. Some parameters show negligible responses with the later approach which is not actually the case when observed flow was used. For example ALPHA_BF showed the first rank with mean relative sensitivity of 1.09 when observed flow is used. However, without observed flow it has got sixth rank with mean relative sensitivity value of 0.062. We therefore relied on the sensitive parameters that responded well based on observed flow.

The parameters governing the hydrological processes in the entire watershed in the order of their sensitivity rank are shown in Table 2 (the first is the most sensitive). Ground water flow parameters such as base flow recession coefficient (ALPHA_BF), threshold water level in the shallow aquifer (GWQMN) and aquifer percolation coefficient (RCHRG_DP) were identified as very sensitive parameters. Also, the soil moisture condition II curve number (CN2), Manning roughness coefficient of channel flow (CH_N2), Effective hydraulic conductivity of the channel (CH_K2) and surface runoff lag coefficient (SURLAG) are found to affect the surface runoff and other basin characteristics. The soil compensation factor found to be the major determinant parameter for the evapotranspiration process in the sub-basin. More specifically, it has to be noted that the ALPHA_BF which governs the groundwater behavior and the CN2 that govern surface runoff were found to be the most sensitive parameters for the sub-basin. This is due to the higher variable nature of the soil moisture in the study area which was also reported by Brocca et al (2011). As the area is dominated by low permeable layers the sensitivity to the base recession factor was also expected. Slope of the sub-basin was also one of the geomorphologic factors found to affect the catchment response behavior as shown in Table 5.2 but has minor effect.

The sensitivity analysis was followed by calibration of the parameters. Stream flow at the outlet was calibrated by manual and auto-calibration procedures for the period of 1963-1970. Model performance was assessed using descriptive statistics and graphical representations. The auto-calibration result showed R^2 of 0.78 and E_{NS} of 0.51 at Ponte Nuovo station. Based on recommendations by Santhi *et al.*,(2001) and Moriasi *et al.*,(2007) the present result showed acceptable performance in terms of the R^2 and E_{NS} for both manual and auto-calibration. However, the auto-calibration results in terms of PBIAS (47%), MAE (27mm) and RMSE (34mm) did not satisfy the recommended limits. This difference in the result of the two calibration approach is due to the fact that R^2 and E_{NS} are over sensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999). Therefore further manual calibration was performed and the result satisfies the recommended limit as shown in table 5.4 and figure 5.5

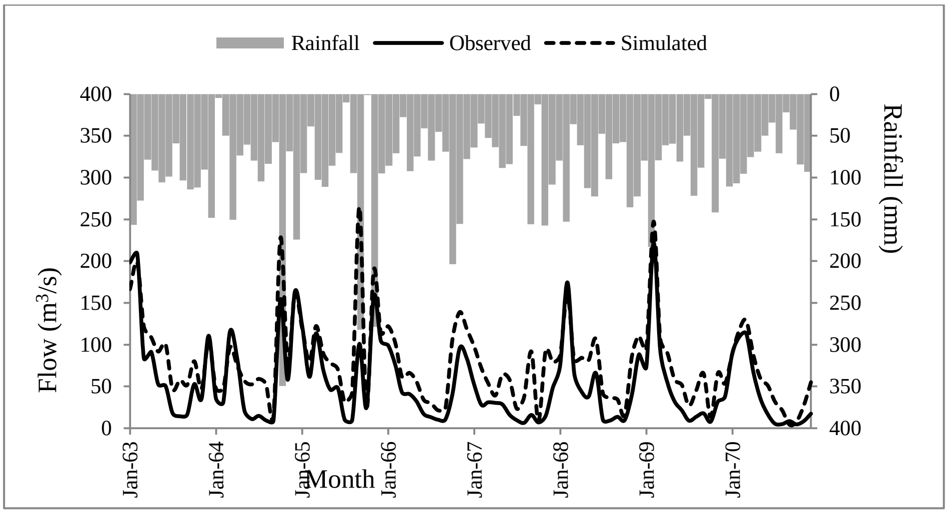

Figure 5.4. Auto-calibration results for monthly flow at Ponte Nuovo (1963-1970)

As indicated in Figure 5.4 and 5.5 the calibrated model slightly over estimate the flow in most cases which can also be revealed from the PBIAS values. Therefore in order to modify the discrepancies between the simulated and observed flow during the auto-calibration procedure, manual calibration was performed using some relative (%) and absolute (±) adjustment on the selected parameters (Table 5.2). The final fitted values were shown in Table 5.2. The calibrated model showed an acceptable agreement between the observed and simulated flow for both daily and monthly time series. The negative value of the PBIAS indicates that there is a slight under prediction over the calibration period. Both MAE and RMSE values satisfied the requirement in which both are less than half of the standard deviation of the mean observed flow (i.e., 24.75 m^3s^{-1}). The agreement between the observed and simulated mean monthly flow was also verified by analyzing the mean observed and simulated flow which resulted in 52.97 and 55.37 m^3s^{-1}, respectively. The average minimum flows also showed a good agreement with observed and simulated values of 4.64 and 5.51 m^3s^{-1} respectively. The hydrograph and rainfall time series showed the same pattern of maximum and minimum flow at the outlet (Figure 5.4 and 5.5). The calibrated model can be considered as representative tool for further application through validation using independent dataset at the main outlet of the watershed and sub-basin locations.

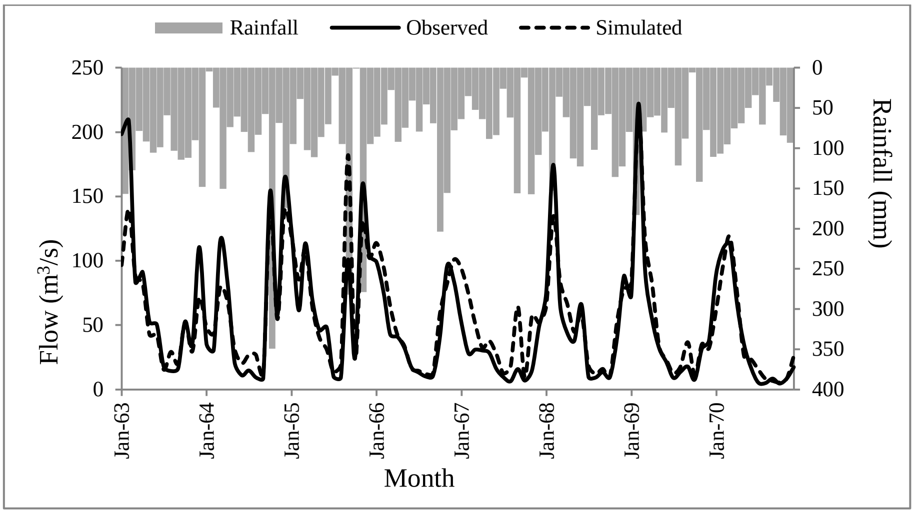

Figure 5.5. Manual calibration results for monthly flow at Ponte Nuovo (1963-1970)

For daily calibration the model shows a satisfactory agreement in terms of frequency of flows as illustrated in Figure 5.6. The figure indicated that there is slight overestimation of low flows by the model and this could presumably due to the over extraction of groundwater at the outlet during the year 1970 as studied by Romano and Preziosi (2010). However, it can be stated that the best fit during the high flow revealed the capability of the model to capture extreme events which can further be used for flood studies in the area.

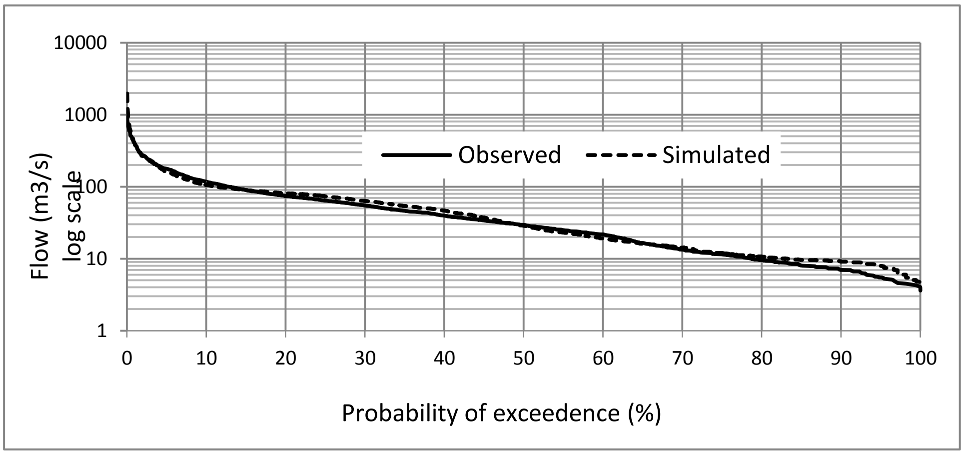

Figure 5.6:Flow duration curves for Ponte Nuovo on daily data.

Base flow separation result using a digital filter (Arnold and Allen, 1999) also showed majority of the flow contribution during the calibration period is from the shallow aquifer flow. The filter was run over both the observed and simulated flows which resulted in average monthly base flow contributions of 61.8% and 62.4% respectively during the calibration period.

Table 5.2: Selected hydrologic parameters included in SWAT sensitivity analysis for the Upper Tiber River Watershed (Central Italy)

Parameter	Description	Model Process	Rank	Variation Range	Fitted Value
ALPHA_BF	Base flow recession constant (days)	Groundwater	1	0-1	0.055[a]
CN2	SCS runoff curve number for moisture condition II	Runoff	2	±20%	-9[b]
CH_N2	Manning's roughness coefficient for main channel	Channel flow	3	0-1	-0.004[c]
CH_K2	Effective hydraulic conductivity in main channel alluvium (mmh^{-1})	Channel flow	4	0-150	15.0[a]
GWQMN	Threshold water level in the shallow aquifer for return flow to occur (mm)	Groundwater	5	0-5000	350[c]
RCHRG_DP	Aquifer percolation coefficient	Groundwater	6	0-1	0.10[a]
SURLAG	Surface runoff lag coefficient	Runoff	7	0-2	1.00[a]
ESCO	Soil evaporation compensation factor	Evaporation	8	0-1	0.85[a]
SLOPE	Average slope steepness (mm^{-1})	Geomorphology	9	±20%	---
SOL_Z	Soil depth	Soil water	10	20%	---

a=default values are replaced by this value (absolute change); b= default values are multiplied by this percentage (relative change); c=default values are increased by this value (absolute change)

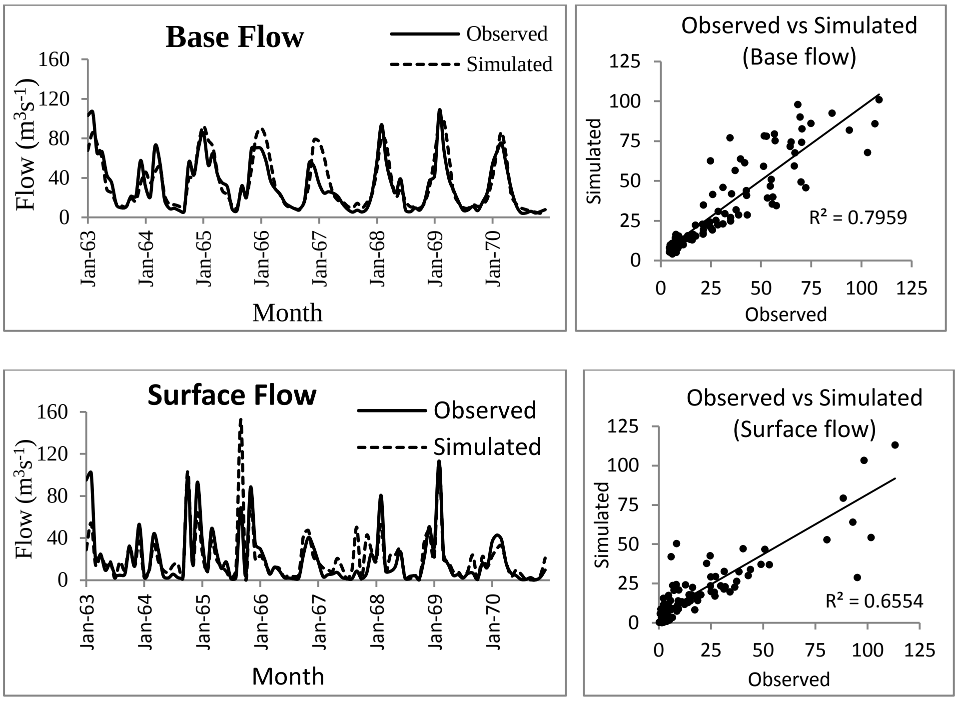

Figure 5.7: Average base flow contribution at Ponte Nuovo outlet during the calibration period (1963-1970)

The filter passed three times (forward, backward and forward) over the recorded flow; however since we have limited knowledge on the details about the groundwater condition we took the average passes of the first two as recommended by the developers. Figure 6 shows the monthly base flow variation at the outlet. The result showed that there is relatively better agreement between the observed and simulated flow in terms of base flow than the surface flow. This is also correlated to the sensitivity analysis results where the groundwater flow parameters are highly governing the catchment characteristics as compared to surface flow parameters. Moreover, we can infer that the percentage bias we have seen above (that showed underestimation) was therefore due to the surface flow than the groundwater flow.

5.4.2. Validation and Performance Evaluation of SWAT

Validation of the calibrated model was performed using independent data. The five performance indicators during the calibration were again used in the validation period to evaluate the performance of the model. First, the model is validated at the same main basin outlet where the calibration was performed and then three other gauging locations were used for the period of 1991-1995. Two of the gauging stations were selected on the same reach of the Tiber River at the upstream of sub-basin outlets (namely: Santa Lucia and Ponte Felcino) and the other station selected on the Chiascio tributary River. The summaries of model performance and validation results are shown in figure 5.8 and table 5.3. At the selected validation stations and periods, all the performance indicators fall in the acceptable limits. Except the Ponte Nuovo station, the model underestimates the flow at all the gauging stations but still within the acceptable range. This difference was actually expected since the validation period for Ponte Nuovo is different from the one for the other stations.

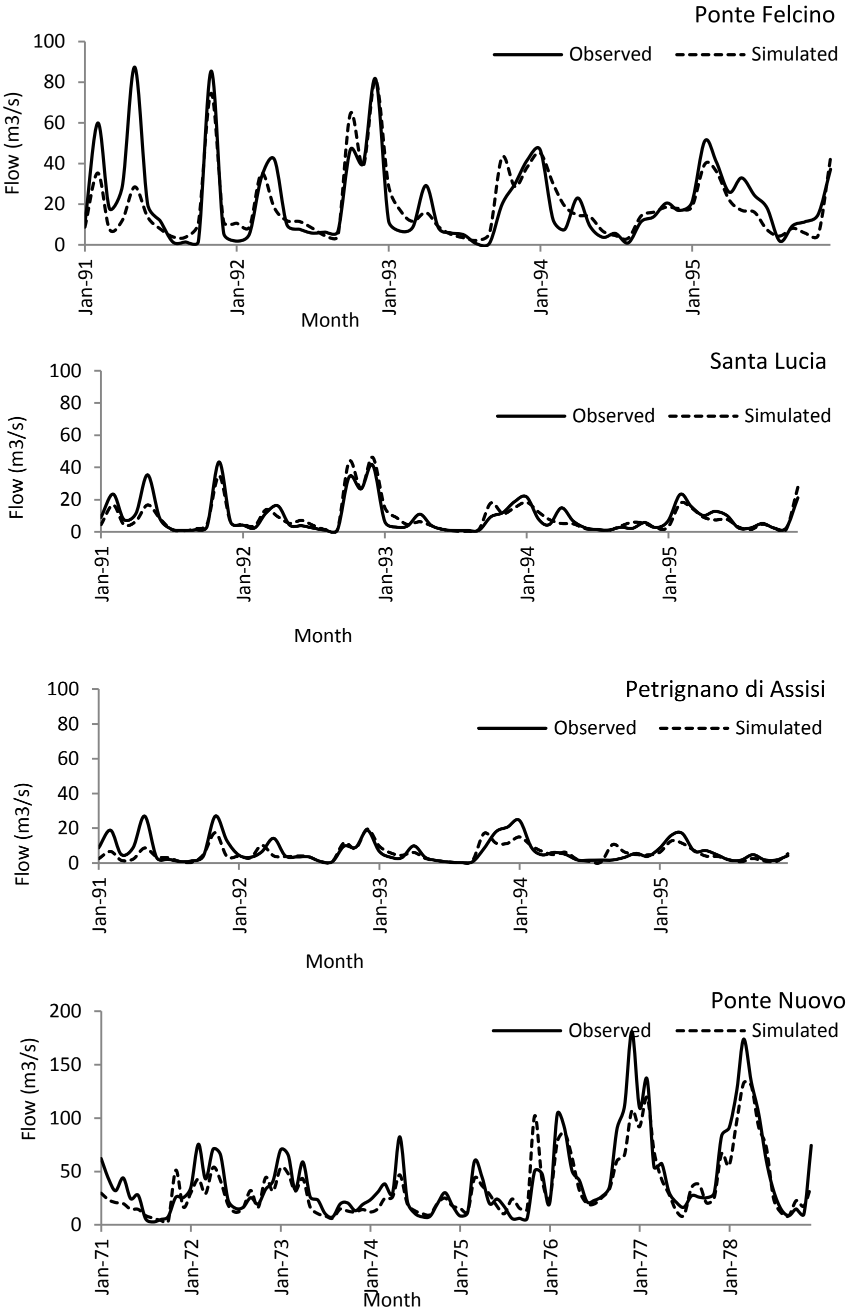

Figure 5.8: Simulated versus observed flow during validation period

Table 5.3: Performance of the model during the validation period

Performance	Calibration at Ponte Nuovo	Validation			
		Ponte Nuovo	Petrignano d'Assisi	Santa Lucia	Ponte Felcino
E_{NS}	0.85	0.8	0.5	0.81	0.68
PBIAS	-0.52	4.52	-20.88	-5.57	-7.78
RMSE	18.95	21.9	4.79	4.49	11.74
MAE	13.44	13.9	2.95	5.67	7.39
R^2	0.85	0.81	0.55	0.81	0.71

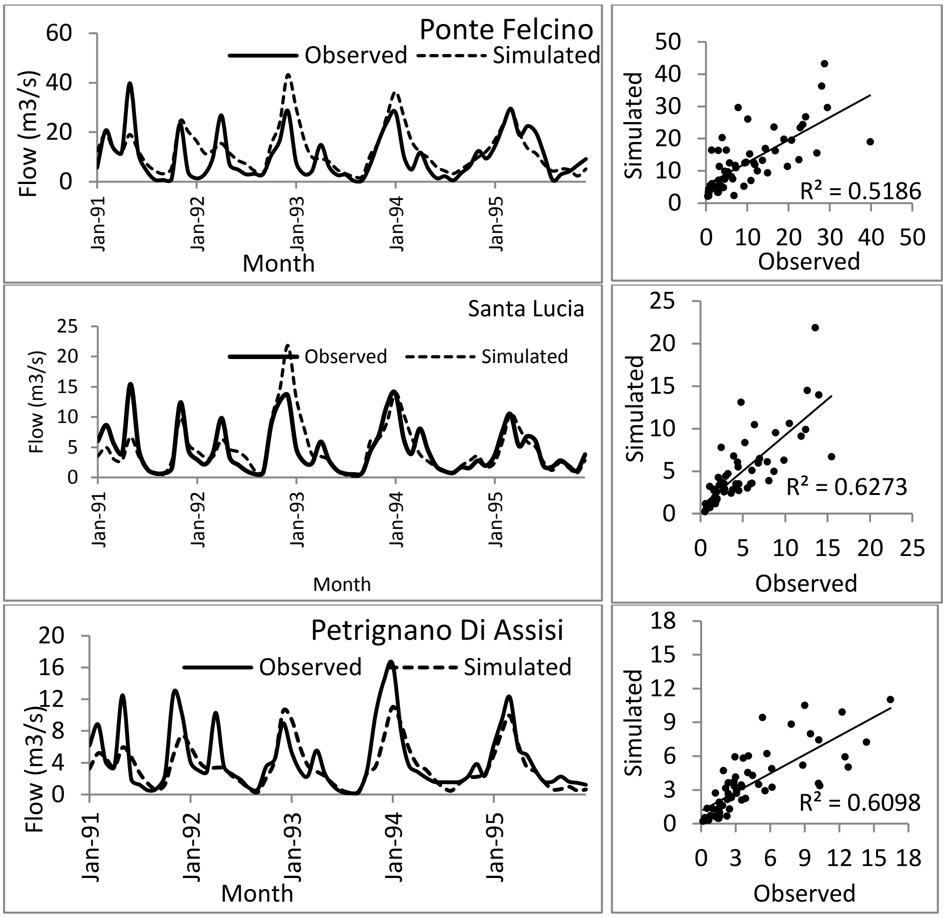

Figure 5.9: Observed and simulated base flow contribution from the three sub-basins during the validation period (1991-1995)

The base flow separation was also performed for the validation period at the three selected gauging stations. We have seen that the base flow contribution at Santa Lucia, Ponte Felcino and Petrignano di Assisi were seen to be 48 %, 49% and 62% respectively. Figure 5.9 shows the agreement between the observed and simulated base flow during the validation period on the three sub-basins. This indicates that the major groundwater contributing area is located closer to the outlet and Petrignano di Assisi sub-basin as it showed higher contribution with better agreement than the others.

5.4.3. Hydrological Water Balance of UTRB based on SWAT

Annual Water Balance Components

In order to evaluate the performance of the model for the hydrological water balance of the watershed, the major inflow and outflow components were estimated at the Ponte Nuovo outlet during calibration (1963-1970) and validation period (1971-1980). Also the water balance for the validation period (1991-1995) was done at the other selected three sub-basins.

The summary of the annual water balance for the entire watershed and the sub-basins are given in table 4 and 5. In this case, the total amount of precipitation falling on the sub-basin (PRECIP) is considered as the major inflow component. Whereas, the actual evapotranspiration (ET) and the basin water yield (WYLD) are the major outflow components from the watershed. The WYLD in SWAT model is defined as the summation of the surface water flow (Q_{surf}), the water that enters the stream from soil profile as lateral flow contribution (Q_{lat}) and the water that returns to the stream from the shallow aquifer also known as groundwater contribution (Q_{gw}) minus the total loss of water from the tributary channels as a transmission through the bed and finally reach the shallow aquifer as recharge. Another component is the percolation below the root zone commonly called as groundwater recharge (PERC) which could be an inflow for flow at downstream of the sub-basins. The water that remains in the soil profile of each sub-basin then considered as the soil water (SW) remaining at the end of the time period.

Table 5.4: Annual water balance components at Ponte Nuovo outlet (all values are in mm of water)

YEAR	PRECIP	ET	Q_{lat}	Q_{surf}	Q_{gw}	WYLD	PERC	SW
a) calibration period								
1963	963	505	51	61	246	358	345	142
1964	1138	471	59	162	242	462	438	144
1965	988	419	50	159	252	460	354	144
1966	903	419	50	77	254	382	353	144
1967	671	366	29	98	98	225	173	144
1968	874	462	44	68	179	291	297	143
1969	915	420	47	102	249	398	339	144
1970	666	386	33	33	166	232	228	127
b) validation period								
1971	581	373	26	30	0	56	130	144
1972	807	464	39	53	74	167	258	132
1973	632	383	27	52	53	132	160	137
1974	677	399	33	48	76	157	197	135
1975	842	455	38	104	83	225	234	141
1976	1016	466	52	110	201	363	379	144
1977	854	377	44	99	229	373	328	144
1978	940	432	53	71	286	409	381	142

From the result it can be inferred that the maximum water yield was found in the year 1965 and 1978 for the calibration and validation period respectively. The average simulated annual groundwater contributions were 60% and 49% for both periods respectively. This slight decrease in groundwater contribution over the validation period is due to the consecutive “dry year” occurrences as compared to the calibration period. However, the model was able to capture the effect of such frequencies which were revealed here through smaller values of groundwater contribution. In fact, when the soil is dry enough more infiltration was expected so that the water could join the stream either through lateral flow or deep aquifer recharge. However, in our case the area is highly dominated by impermeable soil characteristics as explained in previous studies (for example: Calenda et al., 2000; Di Lazzaro, 2009; Brocca et al., 2011). The dominance of such soil characteristics therefore favors surface flow than subsurface flows especially during dry period. This is also an evidence for frequent flood events along the Tiber River.

The water balance component for the validation period (1991-1995) at the three selected sub-basin are also summarized in Table 5.5 as annual average. In this case it can be seen that the rainfall is nearly the same however surface water exceeds the groundwater contribution at all the sub-basins for the following reasons: (i) the land cover characteristic was dominated by agriculture and mixed urban areas that can potentially minimize the infiltration potential of the soil and increase runoff coefficient; (ii) the shape of the catchment is also more narrowed at the upstream which favors fast occurrence of the quick flow and surface runoff to the main stream. Table 5.5 shows water balance components at the selected sub-basins.

Table 5.5: Average Annual water balance components at selected sub-basins (1991-1995)

Sub-basin	AREA (km^2)	PRECIP (mm)	ET (mm)	Q_{lat} (mm)	Q_{surf} (mm)	Q_{gw} (mm)	WYLD (mm)	PERC (mm)	SW (mm)
Santa Lucia	688	882	464	74	117	62	254	220	133
Ponte Felcino	287	883	428	73	114	96	283	263	127
Petrignano di Assisi	86	886	469	41	131	65	237	238	110

Table 5.6: Average annual water balance components for the entire watershed (all values are in mm of water)

Hydrologic Components	Calibration (1963-1970)	Validation (1971-1978)
Precipitation	1056	901
Surface Runoff	167	111
Lateral flow	80	68
Shallow groundwater flow	179	91
Groundwater re-evaporation	95	95
Deep aquifer recharge	31	23
Total aquifer recharge	309	230
Total water yield	421	267
Percolation out of soil	300	228
Evapotranspiration	510	494
Potential evapotranspiration*	953	969
Transmission losses	5	4

* Potential evapotranspiration is not part of the water balance.

For the entire watershed, summary of average annual water balance components are given in table 5.6. From these result, it is clear that the decrease in all values of hydrological component is associated with the decrease in precipitation amount. Contrary to this, the potential evapotranspiration which was estimated based on minimum and maximum temperature showed an increase. Such effects in weather variables could call for further study about impact of climate change using different climate scenarios.

Water Balance Components for Wet and Dry years

In order to understand the watershed behavior for the wet year (high rainfall) and dry year (low rainfall), we analyzed the model results by defining dry and wet years in relative terms. The dry years were defined in this study as the year when the total annual rainfall is less than the mean annual rainfall (i.e. negative deviation from the mean). The other years that have total annual rainfall greater than the mean annual rainfall (i.e. positive deviation from the mean) were then considered as wet years. The analysis is performed for the entire basin at Ponte Nuovo outlet and the three upstream sub-basins separately.

Table 5.7 shows the mean annual values of minimum and maximum flows at the basin outlets. The minimum flows were well simulated than the maximum flows at all outlets except for the calibration period of Ponte Nuovo (see also Figure 5.6). The model predicts the low flow that is supplemented more by base flow contribution to the total stream flow reasonably well.

Table 5.7: Dry and wet years during the model calibration and validation at different stations

Sub-basin	Period	Mean annual rainfall [mm]	Dry years	Wet years	Minimum Flow [m^3s^{-1}]		Maximum Flow [m^3s^{-1}]	
					Obs	Sim	Obs	Sim
Ponte Nuovo	1963-1970	890	1967, 1968, 1970	1963-1966, 1969	24.05	39.03	76.95	76.11
	1971-1978	794	1971, 1973, 1974	1972, 1975-1978	25.18	17.73	70.02	58.1
Santa Lucia	1991-1995	882	1993-1995	1991, 1992	5.98	5.76	12.52	13.99
Ponte Felcino	1991-1995	883	1991-1993	1994, 1995	14.10	16.96	27.37	18.35
Petrignano di Assisi	1991-1995	886	1991-1993	1994, 1995	5.72	4.61	9.91	6.19

[Obs= Observed; Sim= Simulated]

The big difference in extreme condition like minimum flow values at Ponte Nuovo could be the effect of rainfall data quality. In our case, we are only interested to evaluate the overall catchment response behavior than extreme conditions. The water balance components for the driest and wettest years of each basin were summarized in table 5. 8. In this case, we mainly focused on the components of groundwater recharge, surface flow, evapotranspiration and amount of water stored in the subsurface system.

In most cases of the dry year, the contribution of the groundwater flow to the total stream flow is higher than the surface flow contribution. More specifically as we move down from the upstream sub-basins to the outlet, the groundwater flow contribution show an increasing trend.

Table 5.8: Summary of water balance components for dry and wet years

Sub-basin	Year	Area [km^2]	Rainfall [mm]	ET [mm]	Soil water [mm]	Percolation [mm]	Total recharge [mm]	Shallow aquifer storage [mm]	Deep aquifer storage [mm]	Total inflow [mm]
Dry years										
Ponte Nuovo	1970	109.69	666	340	130	240	254	314	1311	267
Santa Lucia	1994	689.99	643	426	131	134	185	307	1137	194
Ponte Felcino	1992	287.96	721	361	133	184	190	299	1081	205
Petrignano di Assisi	1992	86.21	721	377	110	169	176	299	1077	188
Wet years										
Ponte Nuovo	1964	109.69	1138	441	147	406	377	367	1127	493
Santa Lucia	1991	689.99	1084	440	127	384	402	308	1063	287
Ponte Felcino	1994	287.96	1118	460	137	416	382	368	1143	439
Petrignano di Assisi	1994	86.21	1118	505	118	373	344	376	1134	381

5.5. Conclusions

Through a reasonable definition of multiple hydrological response units and use of relatively continuous time series weather as well as flow data, SWAT was successfully calibrated and validated for the study area. The model was calibrated using observed daily flow data at Ponte Nuovo outlet in the upper Tiber River Basin. Like many other river basins in different part of the world (example Bekele and Knapp, 2010; Setegn et al., 2010) the model was able to capture all the watershed responses. The calibration and validation result indicate that the model can be used for further application in the study area especially for monthly and annual time-steps. We also found that the parameter set used during calibration period at the outlet performed very well for the other sub-basins at the upstream part of the watershed. Such performance could assist the use of parameter transferability to other ungauged sub-basins in the area. In case of scarce subsurface flow observation data, the prediction capability of the model to simulate the groundwater contribution to the total stream flow at the outlet can be considered as a better alternative for the study area.

The result of the present study showed that the major contribution of flow was from the aquifer zone closer to the outlet that reaches up to 60% of the stream flow contribution. The dry and wet period catchment water balance also showed the ability of the model to simulate the pattern of flow consistent with the weather data inputs. The flow frequency analysis has also shown that there is a strong agreement between the observed and simulated flow for high and average flow than the low flow conditions. On the other hand, the calibration and validation result showed that there was a consistent pattern of flow and rainfall. Therefore it can be concluded that the model is more sensitive to weather variables than surface dynamics.

The behavior of the watershed in terms of response to stream flow at the outlet were successfully evaluated by identifying sensitive parameters. In general the identified parameters can be grouped into three based on their significance to the system. The first category is parameters that govern surface flow behavior in the system namely: antecedent moisture conditions II (CN2) and soil evaporation compensation factor (ESCO) are the dominant ones. The second category is the parameters that govern sub-surface water response including: base flow recession constant (ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) and deep aquifer percolation fraction (RCHRG_DP). The third category is however the parameters that govern the entire watershed including: the Manning's roughness coefficient of the channel (CH_N2), the effective hydraulic conductivity of channel (CH_K2), the slope of the sub-basin (SLOPE), and the surface runoff lag time (SURLAG). Through proper adjustment of these parameters, the model can be used as a decision tool in water resources planning and management for the study area

[7]Chapter Six

6. Impact of Climate change on the Hydrology of Upper Tiber River Basin Using Bias Corrected Regional Climate Model

Abstract

The use of regional climate model (RCM) outputs has been getting due attention in most European River basins because of the availability of large number of the models and modelling institutes in the continent; and the robustness the models to represent local climate. This paper presents the hydrological response to climate change in the Upper Tiber River basin (Central Italy) using bias corrected daily regional climate model outputs. The analysis include for both control (1961-1990) and future (2071-2100) climate scenarios. In this study, three RCMs (RegCM, RCAO, and PROMES) were used. These models were forced by the same lateral boundary condition under A2 and B2 emission scenarios. The projected climate variables from bias corrected models have shown that the precipitation and tempaerature tends to decrease and increase in summer season, respectively. The impact of climate change on the hydrology of the river basin was predicted using physically based Soil and Water Assessment Tool (SWAT). The SWAT model was first calibrated and validated using observed datasets at the sub-basin outlet. A total of six simulations were performed under each scenario and RCM combinations. The simulated result indicated that there is a significant annual and seasonal change in the hydrological water balance components. The annual water balance of the study area showed a decrease in surface runoff, aquifer recharge and total basin water yield under A2 scenario for RegCM and RCAO RCMs and an increase in PROMES RCM under B2 scenario. The overall hydrological behaviour of the basin indicated that there will be a reduction of water yield in the basin due to projected changes in temperature and precipitation. The changes in all other hydrological components are in agreement with the change in projected precipitation and temperature.

Key Words: RCM, Bias Correction, Climate Change, Hydrological Modeling, SWAT, Tiber River basin

[7] This chapter is based on

1. the paper- **Fiseha, B.M.,** Setegn. S.G., Melesse, A.M., Volpi, E.. and Fiori, A, Submitted to Journal of Water Resources Management (Manuscript Under Review: Number WARM-D-12-00272)
2. Conference poster at AGU- **Muluneh, F.B** ., S.G.G. Setegn, A. Melesse, A. Fiori,*Impact of climate Change on Groundwater Recharge in the Tiber River Basin (Central Italy)*

6.1. Introduction

In the last two decades, the use of watershed models for an assessment of the impact of climate change on water resources, agricultural productivity, and other environmental issues is becoming common practice (Xu et al., 2005; Fowler et al., 2007). These approaches of using watershed models in climate change studies can range from the evaluation of annual and seasonal stream flow variation using simple water-balance models (e.g., Arnell, 1992) to the evaluation of variations in surface and groundwater quantity, quality and timing using complex distributed parameter models that simulate a wide range of water, energy and biogeochemical processes (e.g.,Running and Nemani, 1991; Xu, 2000; Middelkoop et al., 2001). However, the models must be calibrated prior to application on the basis of observed (historic) data and identification of relevant parameter sets governing watershed responses so that they can closely match the reality. An ideal hydrologic calibration set would include combined climatic conditions of dry, average, and wet years. In practice, however, hydrologic models are calibrated based on average climate condition, or the best available data.

Most climate-change impact studies use an uncoupled simulation of the watershed model, requiring a method to transfer the climate-change signal from the climate model to the watershed model (Roosmalen et al., 2010). The impacts of climate change are assessed by evaluating propagation of changes in meteorological variables, such as precipitation and temperature into the various hydrologic processes like river flow, soil moisture, groundwater recharge.

Different approaches and methods are available in order to use the GCM/RCM outputs in watershed models for the possible impact studies. Detail explanation and summary of the methods are provided in chapter 2 of the thesis. Some of this methods are also applied in order to evaluate the climate change effects in different river basins of Italy. Senatore, et.al. (2011), have used the RCM outputs in a hydrological model without any correction to evaluate hydrological impact in southern Italy. However, for spatial scale consistency, they interpolated the RCM outputs to the same grid size of the hydrologic model. Aiming at the quantitative assessment of climate change impact in the Lake Como basin of northern Italy, Anghileri et al ,(2011), have used quantile mapping method of bias correction of RCM output. In central Italy, Brocca et al., (2011) have used a simple change factor from GCM to evaluate the climate change effect on flood frequency through continuous hydrological modelling. D'Agostino et al., (2010) has evaluated the hydrologic behaviour in the face of climate change in Apulia region of southern Italy. In their analysis, they used a hypothetical climate scenario that describes change in precipitation and temperature in the region. Hence, from these short review, there is no tough and hard rule to choose which method of transfer of climate change signal to watershed model. In the present study, one of the bias correction methods (refer chapter 2) called ‘delta change’ is applied to the force the calibrated watershed model calibrated and validated for the UTRB. The responses to the possible changes in temperature and precipitation is evaluated.

6.2. Materials and Methods

The study reported in this chapter used regional climate model output for the assessment of hydrologic regime in the UTRB following three major steps. First, the hydrologic model is calibrated and validated using observed climate variables; second, the RCM outputs were selected and bias correction is applied at each gauging station based on the control period (1961-1990); and third, the bias corrected RCM outputs were used to force the calibrated and validated hydrologic model in order to understand the hydrologic behavior of the basin for the scenario period.

For the hydrological analysis, the model is set to run for the period of 1961-1990 as a control period and 2071-2100 as a scenario period under two emission scenarios of the three selected RCMs. The high and low flow behavior is then evaluated by constructing the flow duration curves (FDCs) on mean monthly and seasonal base. For such analysis, the FDC was classified into different segments following the subjective classification proposed by Yilmaz et al (2008). The classification include: i) high-flow segment (0-20% flow exceedance probability) characterizing watershed response to large precipitation events; ii) mid-segment (20-70% flow exeedance probability) representing flows controlled by moderate precipitation events coupled to medium-term base flow; and iii) a low flow-segment (70-100% exceedance probability) representing a catchment response dominated by long-term base flow during the extended dry periods.

6.2.1. .Climate and Hydrology data

The dataset used in this study are explained in chapter 3. They include historical precipitation, temperature (minimum and maximum) and flow data that were obtained from the hydrographic service of Umbria Region (IRSA-CNR). Based on the observed data in the period of 1961-1995, the mean annual rainfall is nearly above 900 mm. The maximum monthly precipitation occurs in November (127 mm) and the minimum in July (44 mm). In the summer period, the average minimum and maximum temperature are 15.9 ^oC and 27.4 ^oC respectively; whereas in the winter period they are 2.3 ^oC and 8.9 ^oC respectively. The distribution of the selected weather and flow gauging stations are shown in Figure 6.1.

For calibration of the hydrologic model, daily flow data for the period of 1961-1970 at the sub-basin outlet was considered. The average daily discharge for this period was 47.93 m^3s^{-1} with a minimum value of 1.95 m^3s^{-1} and maximum value of 917 m^3s^{-1}. Observed flow at three upstream gauging stations namely: Santa Lucia, Ponte Felcino and Petrignano di Assisi were used for validation purpose.

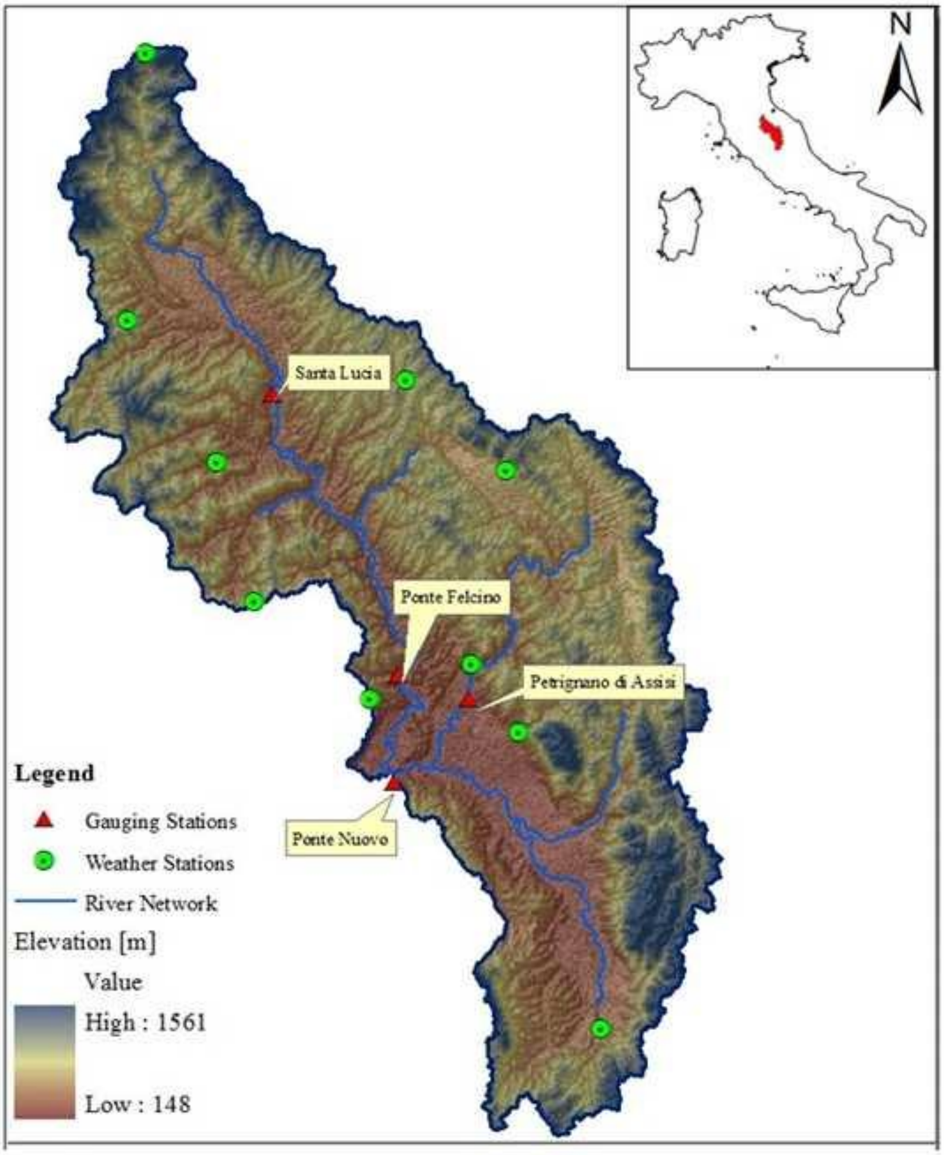

Figure 6.1. Location and DEM of the Upper Tiber River Basin

6.2.2. .Description of the Hydrological Model

In the present study, a physically based, semi distributed model, operating on daily time step called SWAT (Arnold et al., 1998) is used for simulation of watershed response in the study area. The model is capable of simulating various hydrological processes in different part of the world and intensely discussed in scientific literatures (Gassman et al., 2007).

For rainfall-runoff simulation, the model divides the main basin under consideration into sub-basins connected through stream network that allows routing of flows to the downstream sections. The sub-basins are further subdivided into homogeneous Hydrological Response Units (HRUs), which is a lumped land area within a sub-basin comprised of unique land cover, soil, slope and management combinations. In each HRU, water balance is represented by several storage volumes: canopy storage, snow, soil profile (0–2 m), shallow aquifer (typically 2–20 m), and deep aquifer (≥20 m).

The hydrologic cycle in the land phase as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad (1)$$

where SW_t is the final soil water content (mm), SW_o is the initial soil water content on day *i* (mm), *t* is the time (days), R_{day} is the amount of precipitation on day *i* (mm), Q_{surf} is the amount of surface runoff on day *i* (mm), E_a is the amount of evapotranspiration on day *i* (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm), and Q_{gw} is the amount of return flow on day *i* (mm).

The main inputs for SWAT model setup are the weather data (precipitation and temperature), Digital Elevation Model (DEM), landuse/landcover data. Observed precipitation and temperature dataset were obtained from the hydrographic service of Umbria Region. Basin characteristics such as slope gradient, slope length, stream network and stream characteristics (channel slope, length and width) were derived from the DEM using the automatic watershed delineation tool in the recent version of ArcSWAT. Land use/land cover data were obtained from the Medium Resolution Imaging Spectrometer (MERIS) public source. The soil datasets from Institute for Environment and Sustainability of the European commission Joint Research Center (JRC) were used as input to the model.

The model setup was performed following four major steps: (i) watershed delineation and derivation of sub-basin characteristics (ii) hydrological response unit definition (iii) model run and parameter sensitivity analysis; and (iv) calibration and validation of the model including uncertainty analysis. Details on the input datasets, and model setup with the calibration and validation processes were explained in Fiseha et. al,(2012).(refer, chapter 5 of the thesis).

6.3. Regional Climate Model Outputs

In this paper, we have used dynamically downscaled air temperature and precipitation datasets for the central Italy archived in PRUDENCE project. The PRUDENCE was a project in the EU 5th Framework program for Energy, environment and sustainable development which was finished in 2004 (Christensen and Christensen, 2007a). It includes ensembles of ten RCMs with sets of simulations over 30-year length for control period of 1961-1990 and future period of 2071-2100 with forcing from the A2 and B2 emission scenarios (IPCC, 2000). The set of scenario spans in the IPCC's range with the A2 being close to the high end of the range (CO_2 concentration of about 850 ppm by 2100) and B2 scenario lies towards the low end (CO_2 Concentration of about 620 ppm by 2100). All the PRUDENCE RCMs experiments are limited to the European window at a grid spacing of about 50 km and are driven by different GCMs as their lateral boundary forcing fields (Christensen and Christensen, 2007a). The Hadley Center high resolution atmospheric model, HadAM3H (Buonomo et al., 2007) is the central GCM delivering lateral boundary conditions to the RCMs used for the PRUDENCE standard ensemble (Jacob et al., 2007). This study used three regional climate models that were driven by HadAM3H for both A2 and B2 scenarios. The experimental set-up and brief description about the RCM models, participating institutes and GCM boundary forcing used in PRUDENCE are well explained in (Jacob et al., 2007; Christensen and Christensen, 2007a). The summary of models used in the present study is given in Table 1

Table 6.1: Selected Regional Climate Model for hydrological impact assessment in the Upper Tibe River Basin

Institute	**RCM (references)**	**Resolution**	**GCM**	**PRUDENCE Acronyms**	
				Control (1961-1990)	**Scenario (2071-2100)**
ITCP	RegCM (Giorgi et al., 1993a; 1993b)	50-70km	HadAM3H A2	ref	A_2
			HadAM3H B2		B_2
UCM	PROMES (Arribas et al., 2003)	0.5° (55 km)	HadAM3H A2	control	A_2
			HadAM3H B2		B_2
SMHI	RCAO (Jones et al., 2004)	0.44° (50 km)	HadAM3H A2	HCCTL	HCA2
			HadAM3H B2		HCB2

ITCP: International Center for Theoretical Physics
SMHI : Swedish Meteorological and Hydrological Institute
UCM : Universidad Complutense de Madrid

The detailed description on the experimental setup, participating institutions, and the capability of the individual RCMs to simulate the European climate were given in the summary paper by (Christensen and Christensen, 2007a). In the following section we summarized the description of RCMs chosen for our present work. As stated before, all the three RCMs were forced by the boundary condition from HadAM3H. This is an atmospheric global model developed at the Hadley Center, the resolution of which is considered high in its class and is about 150km. The HadAM3H is drived from the atmospheric component of HadCM3 which is the Hadley Centre's state of the art coupled model with horizontal resolution of 3.75° latitude and 2.5° longitude (about 417km × 278km).

RegCM is a RCM built by International Center for Theoretical Physics-ICTP (Giorgi et al., 1993a, b) The dynamical core of the RegCM is equivalent to the hydrostatic version of the mesoscale model MM5 of NCAR/Pennsylvania State University. Surface processes are handled via the Biosphere-Atmosphere Transfer Scheme (BATS), while there are special schemes for precipitation and convection. Energy transfers involving radiation are computed with the radiation package of the NCAR Community Climate Model. The model has a grid resolution of 50 km to 70 km with lambert conformal conical projection covering Europe with 119 × 98 grid boxes.

The PROMES. regional climate model is developed in Universidad Complutense de Madrid-UCM (Arribas et al., 2003) This is the climate version of the PROMES model. It is a hydrostatic and primitive equation model. Prognostic variables are potential temperature, surface pressure, horizontal wind components, specific humidity, cloud and rainwater. PROMES runs at 50 km resolution with lambert conformal conical projection covering Europe in 112 × 96 grid boxes.

RCAO is the Swedish Meteorological and Hydrological Institute (SMHI) Rossby Centre regional Atmosphere-Ocean model (Jones et al., 2004). It incorporates a regional atmospheric (RCA) and a regional ocean model (RCO), both developed in the Rossby Centre, and a river routine based on the HBV hydrological model and lakes. The RCA model has its roots to the limited area model HIRLAM and it is run in the resolution range 10-70 km and with 24-60 vertical levels. Variables are temperature, horizontal wind components, specific humidity, cloud water, turbulent kinetic energy, surface pressure, soil temperature and water content. The

RCO model is based on the OCCAM version of the Bryan-Cox-Semtner primitive equation ocean model with a free surface. The model covers the European window over 106 × 102 grid boxes with its south pole rotation of 25^{o}E and 32^{o}S.

6.4. Interfacing between RCM and Hydrological Model

The PRUDENCE-RCM outputs represent daily areal average values at the model resolution (~50 km) rather than the local values that make them not to be used directly in hydrological models. Moreover, the RCM outputs are reported to have inherent systematic biases due to their imperfect conceptualization, discretization and spatial averaging within grid cells (Graham et al., 2007); (Teutschbein and Seibert, 2010). Therefore, in order to use the RCM outputs in the SWAT model further correction was made on precipitation and temperature data. A simple bias correction method is used to prepare climate inputs to the model. This method was used in many studies (Lenderink et al., 2007; Roosmalen et al., 2007; Graham et al., 2007a; Roosmalen et al., 2010; Teutschbein and Seibert, 2010). The method is commonly applied to transfer the signal of climate change derived from a climate model simulation to an observed database. This study used the method following the work of (Graham et al., 2007a) and (Lenderink et al., 2007) as they are termed as ‘scaling’ or ‘direct forcing’ approaches respectively. The method which implicitly assumes that the future climate is a perturbed version of the present, with weather that has the variability characteristics of the baseline weather but is slightly wetter/drier and warmer/cooler in each month. In this method, the changes derived for the control simulation of a particular climate model are applied to adjust scenario simulations from the same RCM. The observed precipitation at each stations were compared with the nearest grid point of the RCM considering the grid points as a single station on the watershed. The correction procedures adopted in this study are explained in the following equations:

For temperature:

$$T_{corrected}(i,j) = T_{scen}(i,j) + \Delta T(j); \qquad (2)$$

$$\Delta T(j) = \overline{T}_{obs}(j) - \overline{T}_{ctrl}(j); \qquad (3)$$

Where: $T_{corrected}$ is the bias corrected temperature input for the hydrological model during the scenario simulation; T_{scen} is the simulated temperature in the scenario period; (i, j) is the i^{th} day of j^{th} month; $\Delta T(j)$ is the change in temperature between the observation and climate model during the reference period. $\overline{T}$ is the mean daily temperature for the month of j, which is calculated as the mean of all days in month j for all reference period (usually taken as 30 years). The indices *scen* and *ctrl* stand for the scenario period and control period (commonly taken as from 1960-1990 and 2070-2100) respectively.

For precipitation:

$$P_{corrected}(i, j) = P_{scen}(i, j) * \Delta P(j); \qquad (4)$$

$$\Delta P(j) = \frac{\overline{P}_{obs}(j)}{\overline{P}_{ctrl}(j)} \qquad (5)$$

Where: $P_{corrected}$ is precipitation input for the hydrological scenario simulation; P_{obs} is the observed precipitation in the historical period at each station; (i, j) is the ith day of jth month; $\Delta P(j)$ is the change in precipitation calculated using as a ratio. $\overline{P}(j)$ is the mean daily precipitation for the month of j, which is calculated as the mean of all days in month j for all reference period (usually taken as 30 years). The indices *obs* and *ctrl* stand for the observed and control period (1961-1990), respectively.

In both cases, the mean monthly biases correction factors for each 30-years period of climate outputs for both scenarios (A2 and B2) were calculated and applied to daily simulations. Therefore a total of six simulations were performed using three RCMs and two emission scenarios.

6.5. Results and Discussion

6.5.1. Calibration and Validation of the SWAT Model

The behavior of the basin in terms of response to stream flow at the outlet were successfully evaluated by identifying the most sensitive parameters. Before applying the climate scenario into the model, calibration and validation was performed using observed flow at the basin outlet. Out of the twenty-six available hydrological parameters in the SWAT model, eighteen relevant parameters were evaluated and the top ten parameters were used following sensitivity analysis. The calibration was performed at the basin outlet and the validation was done using independent dataset at the Ponte Nuovo station and three other upstream sub-basin outlets. All the performance indicators showed acceptable limits recommended by Moriasi *et al.*, (2007). Results of sensitivity analysis and choice of parameters was given by Fiseha et. al,(2012) in their previous work on the study area. Short summary of model calibration and validation results are shown in Table 6.2. The model performance during the calibration and validation period was shown in Figure 6. 2 and 6.3 respectively.

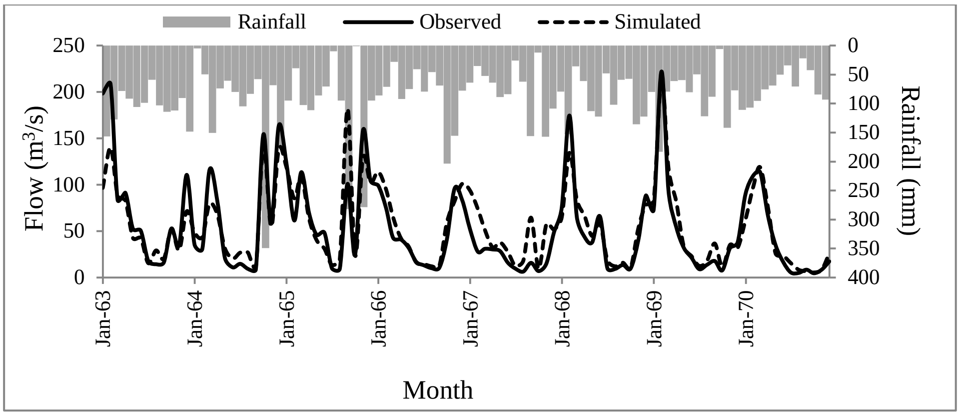

Figure 6.2. Calibration results for monthly flow at Ponte Nuovo (1963-1970)

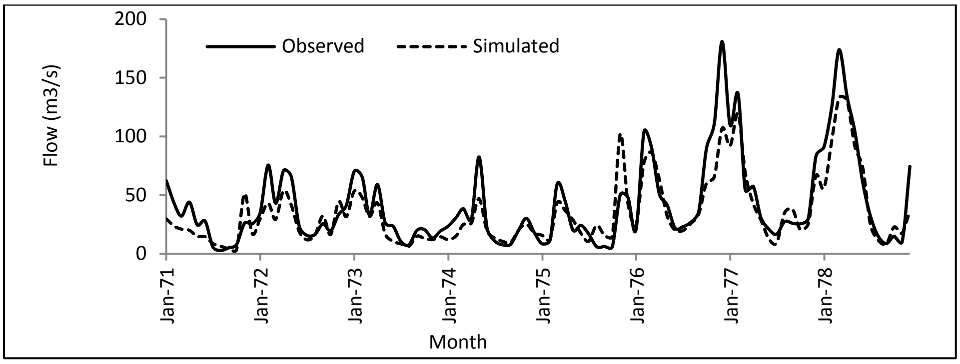

Figure 6.3. Simulated vs observed flow during validation periods at Ponte Nuovo

6.5.2. Bias Correction results of Precipitation and temperature Variables

The monthly bias corrections between the observed and simulated variables during the control period for each RCM models were applied at each rainfall and temperature stations. The methods we used is the same for all stations, hence for clarity we presented here using only one station as shown in Table 3. We also note that since the RCM simulations during the control period are the same for both A_2 and B_2 scenarios, the correction applied is also the same with their corresponding RCMs. After applying the correction, the changes due to climate scenario are evaluated. Again we used the same site for presentation purpose and the results are shown in Table 6. 4.

From Table 6. 3, it can be inferred that the regional climate model from ITCP (RegCM) showed relatively larger bias as compared to the other two models for precipitation. In case of temperature, it also shows higher warming during summer season than the others. This indicates that the difference in model parameterization and discritization produces different climate characteristics, even though they use the same lateral boundary forcing from HadAM3H. Such differences were assessed in detail by (Jacob et al., 2007) and it can be considered as one source of uncertainty.

The changes in each variable during the scenario and control period after the monthly correction is applied are shown in Table 4. The same analysis was applied to all other stations; however we have shown here the result for station at Assisi. From Table 6.3, the three models showed maximum decrease in precipitation during the summer (**JJA**) season ranging from 35% to 65%. The summer temperature however increases in all seasons and all models with temperature magnitude reaching as high as 6^{o}C on average. This result is also consistent with the work of Coppola and Giorgi, (Coppola and Giorgi, 2010).

Table 6.2. Bias correction factors used to modify the simulated climate variables for station at Assisi

RCM		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Relative correction factor for Precipitation													
RCAO		0.96	1.11	0.85	0.92	1.01	1.26	1.57	1.78	1.47	0.88	1.01	0.93
PROMES		1.87	1.84	1.25	1.28	1.14	1.48	0.75	1.19	1.4	1.08	1.58	1.32
RegCM		1.56	2.11	1.68	1.36	1.38	2.17	2.05	2.53	2.16	1.47	1.98	1.54
Absolute correction factor for Temperature													
RCAO	Tmax	1.39	0.07	0.82	1.37	1.19	0.09	0.88	0.81	2.36	3.65	2.78	1.47
	Tmin	-0.31	-0.32	0.29	0.18	0.14	-0.62	0.33	0.61	1.77	1.8	0.53	-0.82
PROMES	Tmax	4.32	4.06	5.99	7.79	7.78	4.74	6.52	7.62	8.92	8.07	5.69	3.77
	Tmin	1.13	1.63	2.37	2.6	2.6	0.93	1.82	2.44	3.49	2.73	1.36	0.49
RegCM	Tmax	3.99	3.06	3.79	3.61	1.96	-1.57	-0.57	0.92	3.64	5.36	5.11	3.94
	Tmin	1.96	2.16	2.45	2.35	1.4	-1.8	-1.8	-0.93	0.76	2.09	2.21	1.58

The changes in each variable during the scenario and control period after the monthly correction is applied are shown in Table 4. The same analysis was applied to all other stations; however we have shown here the result for station at Assisi. From Table 6.3, the three models showed maximum decrease in precipitation during the summer (**JJA**) season ranging from 35% to 65%. The summer temperature however increases in all seasons and all models with temperature magnitude reaching as high as 6^{o}C on average. This result is also consistent with the work of Coppola and Giorgi, (Coppola and Giorgi, 2010).

Table 6.3: Seasonal changes in precipitation (in %) and temperature (^{o}C **)** at Assisi station

Season		RCAO		PROMES		RegCM	
		A2	B2	A2	B2	A2	B2
				Precipitation			
DJF		4	14	8	25	-8	-3
MAM		-2	4	-3	8	0	11
JJA		-65	-35	-37	-25	-26	-31
SON		-20	6	-5	-4	-18	-15
				Temperature			
DJF	Tmax	3.5	1.87	3.37	2.2	3.69	2.16
	Tmin	3.26	1.86	3.7	2.46	3.58	1.86
MAM	Tmax	3.23	1.63	4.14	2.89	3.67	2.02
	Tmin	3.06	1.96	3.31	2.54	3.36	1.85
JJA	Tmax	6.79	5.07	6.83	6.13	5.4	3.82
	Tmin	5.65	4.18	5.66	5.05	5.44	3.83
SON	Tmax	4.45	2.99	4.27	3.77	4.7	2.91
	Tmin	4.02	2.83	4.03	3.56	4.19	2.26

6.5.3. Hydrological response to climate change

River Flow and Catchment Water Balance

The calibrated and validated SWAT model was then forced by the bias corrected RCM outputs at each stations. In order to evaluate the response of the sub-basin to the magnitude of the rainfall, monthly flow duration curves (FDC) under the three RCMs were used. The effects of the two future scenarios were evaluated by constructing FDCs for the annual and seasonal flows. Figure 5.5 show the monthly flow duration curves at the Ponte Nuovo sub-basin outlet. From all the FDCs, the monthly stream flows showed an overall decrease for both scenarios. However, in case of B2 scenario, the PROMES model showed an increase in flow while others showed the decrease in monthly flows. This is due to the winter (DJF) and Spring (MAM-*not shown*) flows over prediction of the PROMES model as shown in the left column of B2 scenario and it is also consistent with the precipitation increase for the same scenario.

During the summer (JJA) season, almost all RCMs showed a reduction in projected flow under both scenarios. The high-flow segment (i.e., 0-20% exeedance probability) showed a sharp fall in slope of the FDCs for all RCMs that indicate a characteristic signature of the sub-basin to produce quick response to the inputs. This is also due to the fact that the basin under study is dominated by soils with low infiltration capacity. Moreover, the steep slope of the mid-segment and the flatter slope of the lower segment indicate that the sub-basin has slower groundwater response. Except the PROMES_B2 scenario, the clear gap between the control and scenario period FDCs in the mid segments therefore indicate a decrease in groundwater volume of the sub-basin but not that much significant. However, it is worth to note that the land use and soil characteristics were assumed to be unchanged which may not be the case in the future. Hence, some uncertainties associated to such basin characteristics have to be considered for further usage.

Table 6.4: Comparison of mean annual water balance for the control and scenario periods

Hydrologic Components	Control (1961-1990)	RegCM		RCAO		PROMES	
		A2	**B2**	**A2**	**B2**	**A2**	**B2**
Precipitation	953	860	918	838	924	900	1099
Surface Runoff	137	97	110	79	101	105	158
Lateral flow	74	67	73	69	78	68	91
Shallow groundwater flow	149	101	137	115	160	105	220
Groundwater re-evaporation	97	112	107	113	107	115	113
Deep aquifer recharge	27	25	28	26	30	25	38
Total aquifer recharge	275	247	280	260	305	252	375
Total water yield	356	262	317	259	335	274	464
Percolation out of soil	270	244	277	257	303	249	371
Evapotranspiration	472	451	456	433	442	478	479
Transmission losses	4	4	4	4	4	3	5

(all units are in mm)

In order to understand more about the future water resources availability a basin water balance analysis was performed on annual basis using the hydrological components as simulated by the SWAT model. The result showed that there is a significant decrease in surface runoff, total aquifer recharge and the total water yield for all the RCMs under A2 scenario.

The total water yield in SWAT model is the summation of the surface water flow, the water that enters the stream from soil profile as lateral flow contribution, and the water that returns to the stream from the shallow aquifer minus the total loss of water from the tributary channels as a transmission through the bed and finally reach the shallow aquifer as recharge. It was shown that a small change in precipitation adversely affect the amount of water yield from the basin. The B2 scenario also shows a decrease in the water balance components for all RCMs except the PROMES.

The comparison between the mean annual flow under the different scenarios and the control period simulations indicated that the mean annual stream flow shows annual reduction ranging from 23 to 28 percent for A2 scenario and 6 to 11 percent for B2 scenario with the exception of PROMES model (Figure 4).

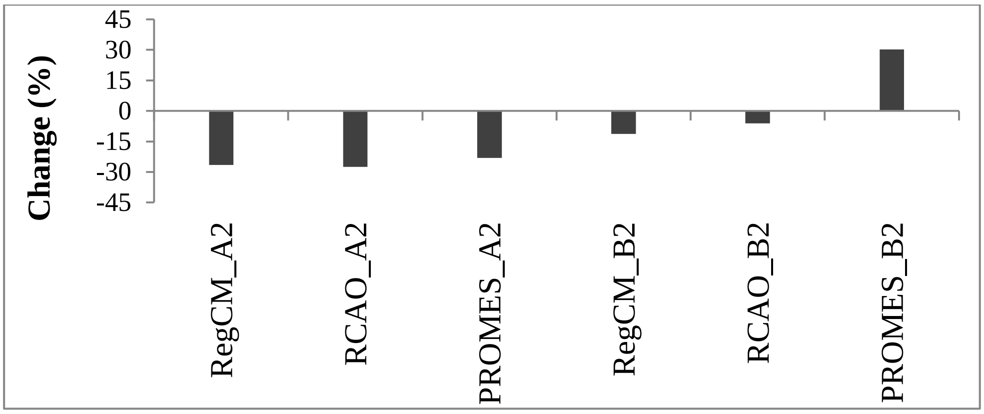

Figure 6.4. Average annual change in river flow at Ponte Nuovo under A2 and B2 Scenarios

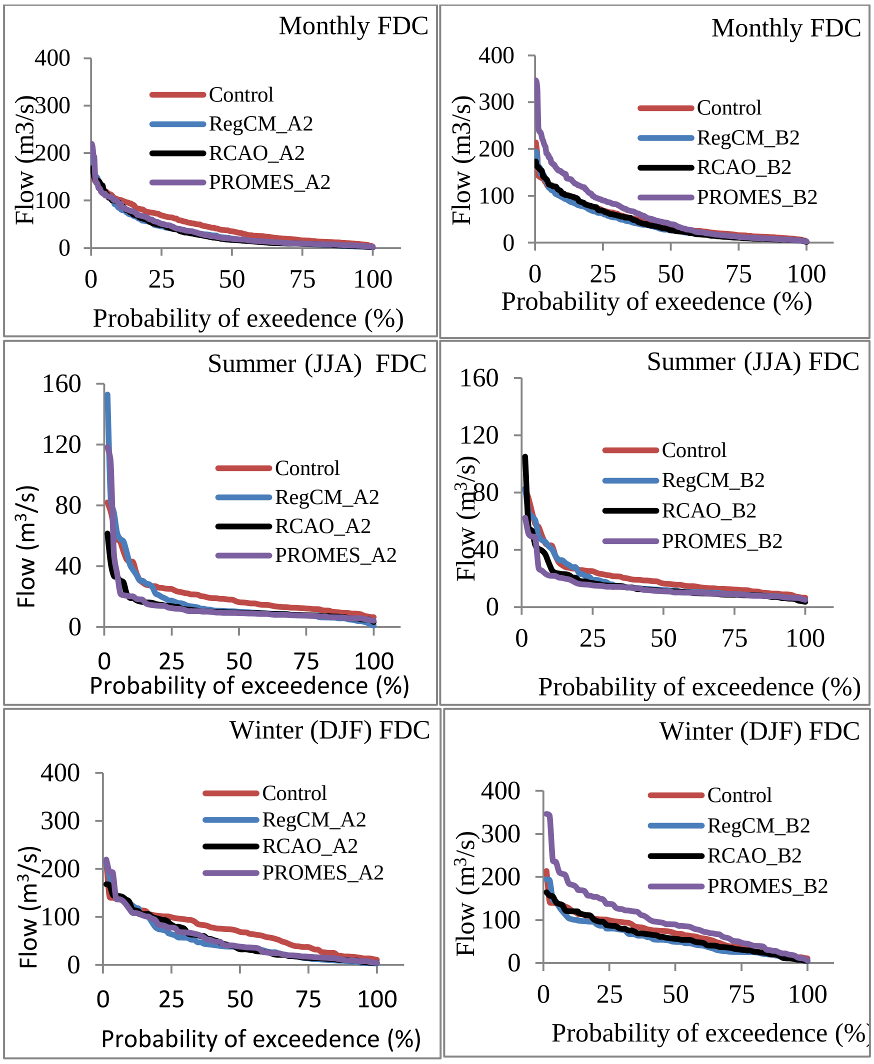

Figure 6.5. Monthly flow duration curves (FDC) for flow at the sub-basin outlet (Ponte Nuovo). The left panels show the FDC for the A2 scenario and the right panels show the FDC for B2 scenario.

Baseflow and groundwater Recharge

The change in baseflow contribution at the basin outlet was determined for both the A2 and B2 scenarios in the basin. The digital filter for baseflow separation explained by Arnold and Allen (1999) was used to determine the baseflow both from the simulated flow data during the control period (1961-1990); and the one during the scenario period (2070-2099). Assuming the simulated flow based on observed data set are "true" values, the change in the baseflow was calculated and the results were shown in Figure 6.6. In both scenarios the results show that the baseflow contribution tends to decrease. However, like we have seen for the river flow at the basin outlet and water balance analysis, the PROMES model showed different result specially in the wet seasons. On the other hand, the recharge condition in the basin showed different result for A2 and B2 scenarios, with the former showing a pronounced decrease in all the RCMs used.

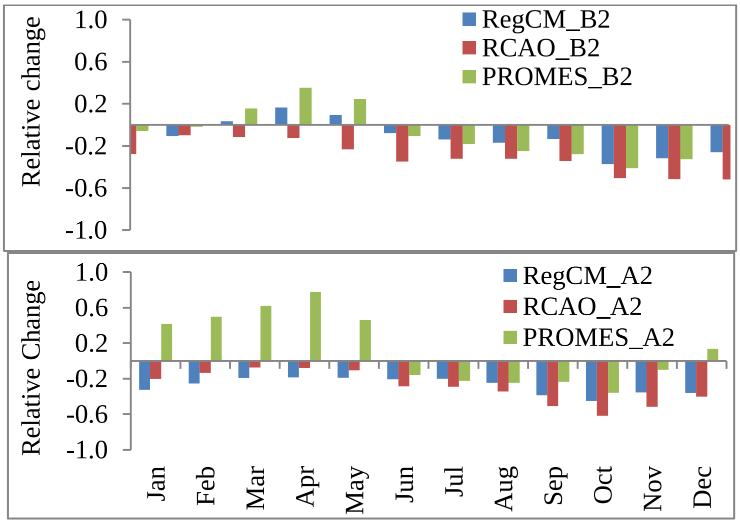

Figure 6.6. Change in baseflow contribution in the UTRB under A2 and B2 Scenarios

Table 6.5. Relative changes in groundwater recharge in the UTRB

Models	Average	Min	Max
		A2 Scenario	
RegCM	-11.4	-19	-0.3
RCAO	-10	-21	9.5
PROMES	-14.6	-43	6.9
		B2 Scenario	
RegCM	-2.7	-15	39.6
RCAO	8.5	0.8	28.5
PROMES	34.3	2.6	77.7

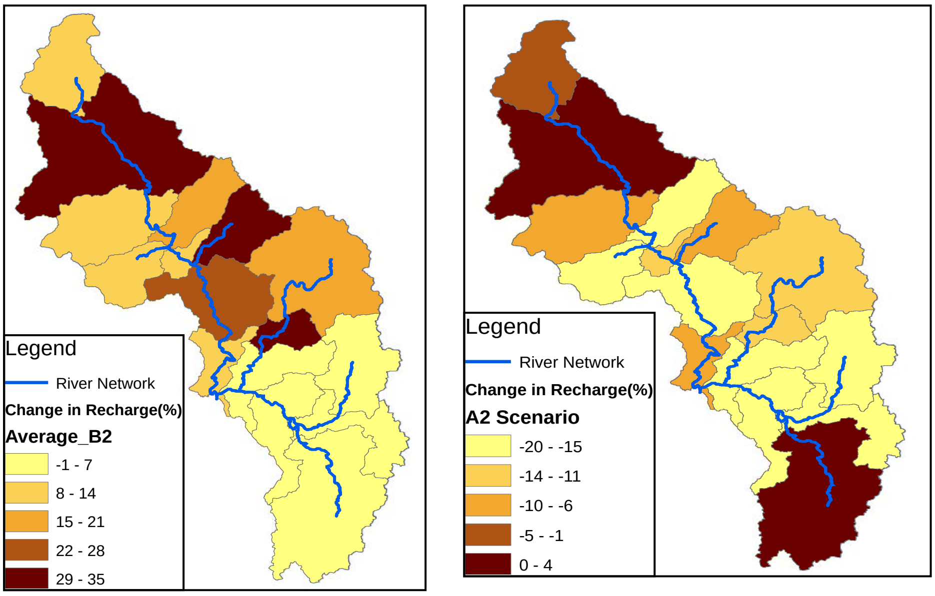

Figure 6.7. The spatial distribution on the relative changes in groundwater recharge over the UTRB.

The spatial distribution of average relative change in recharge is shown in Figure 6.7. In case of B2 scenario, the basin responded to an increase in groundwater recharge that reaches as high as 35%; whereas in case of A2 scenario the decrease could reach below to -20%. Keeping all the limitations of the methods used for bias correction and simulation capability of the watershed model; it can be inferred that choice of scenario has an impact on basin hydrology.

6.5.4. Uncertainty issues and further considerations

In the present study, we have seen different SWAT simulation results from three RCMs forced by the same GCM lateral boundary conditions from HadAM3H. Despite all the progressive uses and their added values to reproduce the forcing variables, various uncertainties still exists in using RCMs for hydrological impact assessment that require further considerations. The major sources of these uncertainties are explained in other research papers as a 'casecaded' form (Viner, 2003; Giorgi, 2005) which are inter-dependent, but not necessarily additive or multiplicative (New and Hulme, 2000). While moving from GCM outputs to basin scale hydrological impact assessment as a top-down approach, the 'casecaded uncertainty' can be grouped into four (Xu et al., 2005; Praskievicz and Chang, 2009). The first is due to the choice of GCMs (i.e. uncertainty due to climate scenarios). For example, in our case we have used the A2 and B2 emission scenarios which were resulted in different prediction of the hydrological component. The second is associated with the choice of the deriving GCM which is generally claimed as the largest sources of uncertainty by many authors (Wilby et al., 2006b; Fowler et al., 2007; Graham et al., 2007; Prudhomme and Davies, 2009a). In the present study, only single GCM was used to force the three selected RCMs; therefore it is impossible to justify the range of uncertainty under this source. The third source of uncertainty is associated to the transfer of large-scale climatology to regional-scale climatology appropriate for hydrological impact assessment, which is commonly called as downscaling. In the present study, further bias correction is applied to dynamically downscale RCM models. We found different results which are susceptible to one of these sources of biases. The fourth is related to the parameters and structures of hydrological models used for impact assessment. Finally, the uncertainty due to input variables can also affect final result. Therefore, care needs to be taken while interpreting the simulated results for further usage in impact assessment. Quantitative determination of all the uncertainties explained above is the remaining research topic in climate change and impact assessment. However, few studies have evaluated the propagation of one uncertainty to the next until it reaches the final hydrologic impact study (Graham et al., 2007a,b; Prudhomme and Davies, 2009a,b) in the top-down approach for impact study.

Beside all the uncertainties mentioned above, it is worth to note that the selection of emission scenarios based on the prescribed story lines have their own limitations, as there is no exact rule to predict the global socio-economic systems in the future. For example in the case of Upper Tiber Basin, we have seen completely different results between A2 and B2 scenarios but difficult to decide which one has correctly predicted the impact.

6.6. Conclusion

This study presents the expected changes in precipitation and air temperature for the Upper Tiber River basin by the end of this century (2071-2100) using the three different regional climate models from the PRUDENCE project. A simple bias correction method of precipitation and temperature was applied to the dynamically downscaled RCMs. The correction is applied to stations nearby to each grid cells. Observed data from twelve rainfall stations and four temperature stations over an area of 4100 Km^2 were used. From the bias corrected results it can be inferred that the decrease in precipitation can reach up to 35% and temperature changes reaches to 6 ^oC during dry summer (JJA).

The Soil and Water Assessment Tool was successfully calibrated and validated based on observed flow and weather variables. Except the PROMES model under B2 emission scenario, all RCMs have shown significant reduction in stream flow at the sub-basin outlet. The sub-basin water balance has also resulted in significant reduction of surface runoff, aquifer recharge and total water yield. This is mainly due to the reduction in precipitation over the entire basin. This study mainly focused on the use of RCM output to evaluate the possible future climate impact under two different scenarios. The limitation of this study is that the three RCMs were derived from a single GCM. According to IPCC reports high uncertainty is expected in climate change impact studies if the simulation results of a single GCM output are relied upon.

7. Conclusions and Recommendations

7.1. Conclusion

The present study the hydrologic behaviour of Upper Tiber River Basin (UTRB) based on observed weather and flow data as well as watershed hydrologic model was analysed. The Upper Tiber River Basin is characterized by Mediterranean climate and shows high rainfall variability due to topographic effects and other climatic factors. The impermeable nature of the basin in the upstream part has favoured high flows in the downstream regions specially during high rainfall seasons which in turn aggravates frequent flood effect in the lower part of the basin Annual rainfall analysis on the basin has shown high variability with higher values associated to regions mountainous regions (orographic effect).

The successful calibration and validation of SWAT model for the basin pointed that out of the eighteen parameters, ten most crucial parameters control the surface and subsurface hydrological processes of the UTRB. Like many other river basins in different part of the world, the applied SWAT model was able to capture all the watershed responses, which leads to further usage and applications in the same study area. It is also wise to note that the simulation results have shown the same pattern with the rainfall indicating that the model is more sensitive to weather variables than the other surface dynamics. The sensitivity analysis has indicated that the parameters governing groundwater system are more sensitive than the other hydrologic parameters.

In the present study evaluation of statistical downscaling method revealed that there will be significant decrease in precipitation amount and wet-spell length in the basin. This has resembled many of the past studies in the basin that are either based on derived indices from observation or climate model simulations. It was also observed that the downscaling procedures used has shown different performance due to issues like model parameterization, difference in scenario. Also, in both the GCM downscaling and RCM bias corrections used at different sites within the basin, the A2 and B2 scenarios showed different performance. For example the temperature data downscaled using SDSM showed higher warming in summer with A2 scenario than with the B2 scenario. However, in terms of precipitation both A2 and B2 scenarios shows agreement Such problems are reported to be unanswered issues of uncertainty due to downscaling. For that reason, it is difficult to rely on any single GCM simulation as well as any single downscaling method.

Keeping in mind all the limitations of downscaling, the calibrated watershed model was forced to evaluate the response of the basin. From the simulation results, (i) a significant decrease in surface runoff, and base flow contribution were seen for all the RCMs under A2 /B2 scenario, (ii) base flow in the basin during winter and summer season are expected to decrease by 40% of the control period under both scenario. (iii) the decrease in the simulated hydrologic responses are in the same pattern with the decrease in rainfall of the basin. Therefore, it can be inferred that, the effect of climate change in addition to those observed challenges could presumably aggravate the pressure on the available water resources of the basin. Due to such aggregate impacts, there will be a shift from surface water utilization to groundwater.

7.2. Recommendations

Beside the above findings of the present study; some limitations has to be considered which needs further research and investigation. The model is simulated for the period of 1961-1990, where the surface and subsurface flow control by human activities in the basin are not significant. However the reservoirs, and groundwater abstractions in the late 80s are believed to alter the hydrologic processes and system dynamics of the present study. Hence further considerations should be taken into account for the climate change and other anthropogenic study in the area.

Quantitative assessment of uncertainty in both climate model as well as watershed model is one of the future issues to be considered. From the analysis in the present study, it was difficult to choose among the available downscaling methods, GCMs and climate scenarios as most choices are subjective. For example, the scenario data are based on sets assumptions on international geopolitics, economic and population growth rate and technical development as well. These assumptions are dependent on local dynamics of the system which cannot be provided in quantitative term

Like many other climate change impact assessments, the present study has considered the land use land cover data as well as the soil characteristics remains the same in the 2070s; which is not realistic but the only way to do it. There is a hope from the IPCC's fifth assessment report to come up with some means of evaluation of such changes in impact assessment.

7.3. Future Research

In the current work, it has been reported that the single bias correction approach is applied at each for individual RCM. However, the use of ensemble models through Bayesian Averaging Method (BMA) over the entire basin is expected to give a means for quantitative assessment of uncertainties. This approach is one of the method in which most climate change impact assessment is aiming in the future. Some MATLAB code preparation and testing is underway and it will be the continuation of the present work in the same basin.

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Short Biography of the Author

Fiseha Behulu Muluneh was born on June 02, 1980 in a small village called Glando in Ilubabor zone, Ethiopia. He attended elementary school at Yanfa, Intermediate school at Gechi and finally joined his high school class at Bedele Senior Secondary school. After completing his high school classes in 1998, he joined Arba Minch Water Technology Institute (AWTI) currently known as Arba Minch University to pursue his study for B.Sc. degree. In July 2003, Fiseha received his B.Sc. degree in Irrigation Engineering and offered a lecturer position in the same institute. Courses like groundwater hydrology, soil and water conservation, hydraulics and principle of hydrology are few of which he has taught in the institute.

In 2006, he joined the International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, The Netherlands having a full scholarship from Nuffic. He received his M.Sc. degree in 'Geo-Information Science and Earth Observation with specialization in Integrated Water Resources Modelling and Management in March, 2008. His M.Sc. thesis was entitled "Satellite Image Based Rainfall Estimation for Hydrological Modelling in the Upper Blue Nile".

In January 2010, Fiseha received a full scholarship for his further study leading to Ph.D. from Italian government. He joined the University of Roma Tre, civil engineering department with a research interest including: hydrologic modeling, climate change impact assessment on water resources, GIS and RS application in water resources.

As part of his PhD research activity, Fiseha traveled to Florida International University (FIU) in Florida, USA as a visiting researcher for a duration of one year. He worked with a research team in Hydrology and Geo-Spatial Laboratory in the department of Earth and Environment from November, 2010 to December, 2011. In January 2012, Fiseha returned back to Roma Tre university and continued his research activity where he finalized his PhD thesis with some scientific publications.

PUBLICATIONS

- **Peer Reviewed Journal publication**

– **Fiseha, B.M.**, Setegn, S.G., Melesse, A.M., Volpi, E., Fiori, A., (2012). Impact of Climate change on the Hydrology of Upper Tiber River Basin Using Bias Corrected Regional Climate Model. *Water Resources Management (under Review)*

– **Fiseha, B.M.,**Melesse, A.M., Romano, E., Volpi, E., Fiori, A., (2012). Statistical Downscaling of Precipitation and Temperature for the Upper Tiber Basin in Central Italy. International Journal of Water Sciences 1. InTech, Available from: http://www.intechopen.com/journals/international_journal_of_water_sciences/statistical-downscaling-of-precipitation-and-temperaturefor-the-upper-tiber-basin-in-central-italy

– **Fiseha, B.M.**, Setegn, S.G., Melesse, A.M., Volpi, E., Fiori, A., (2012). Hydrological analysis of the Upper Tiber River Basin, Central Italy: a watershed modelling approach. Hydrol. Processes

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Muluneh, F.B ., S.G.G. Setegn, A. Melesse, A. Fiori,*Impact of climate Change on Groundwater Recharge in the Tiber River Basin (Central Italy)*

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