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HYDROLOGICAL MODELS FOR WATERSHED PLANNING AND WATER RESOURCES MANAGEMENT:
A DECISION SYSTEM SUPPORT FOR MARTA RIVER BASIN (CENTRAL ITALY)

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ABSTRACT

Fresh water is a finite and vulnerable resource, essential to sustain life and with a great economic value in all its competing uses and interactions with natural ecosystems as they strictly depend on water above all. Population and economies under rising growing lead to an increase in water demand while its availability remains constant in time. So that drought is actually an insidious hazard of nature for countries experiencing medium to high water stress due to its scarcity and to changed climate conditions showing a decreased amount of precipitation and higher temperature values. Drought is a severe problem in the Mediterranean basin: international conventions and Institutions such as the World Bank and the International Water Forum all consider the area in need of special attention due to problems resulting from its vulnerability to drought and its requirements for better water management. Moreover the European Community policy is directly involved in water scarcity issues, encouraging project development and actions to mitigate the effects of drought and to investigate measures to avoid or reduce drought risk in Mediterranean regions.

The project MEDDMAN is a transnational approach in the field of drought and water management involving competent national authorities, leading research institutes and regional authorities and financed by European Union according to its Interreg III B MEDOCC policy. The DAF Department, Department of Environment and Forestry, Agrarian Faculty, University of Tuscia in Viterbo, has been involved in this project with a study area on Marta River Basin, located in the northern part of Latium region. The project's target is to develop an integrated system, capable of evaluating the state of surface water and groundwater resources in the MEDOCC regions preserving and improving the economic growth, developing efficient tools for sustainable water resources exploitation. Special attention is given to the environmental impacts of extreme meteorological and hydrological events, which affect the means of development and best interest of the locals. The focus is on the understanding of the ‘water system’ dynamics and functioning, enhancing the capability to predict its behavior in view of changes (including climate change), and underpinning its sustainable management and development. A simulation model at catchment scale, has been implemented for Marta river basin using SWAT (Soil Water Assessment Tool) code, developed in 90’s by Dr. Jeff Arnold for USDA-ARS, United States Department of Agriculture, Agricultural Research Service. Swat is a comprehensive model that requires a diversity of information and produce reliable results with a rich dataset at disposal (morphological, soil, climatic, hydrologic data). It enables water balance estimation and models the loading of water, sediments and nutrients from land areas in a watershed or to the stream network from sources not associated with a land area and referred to as point sources, such as treatment plants.

The simulation period covers the years 1999-2006. The model was calibrated for the period 1999-2002 and then validated for the period 2003-2006. The implemented model shows a substantial reliability and accuracy in providing the watershed response in terms of discharge flowing and timing pointing out a rapid rebound on it as a consequence of heavy rainfall events. Statistical tests confirmed the truthfulness of its results.

A good correspondence between observed and simulated values can be obtained also regarding nutrients movement and processes even if the available data were not so complete and comparable in terms of nitrogen and phosphorous, and their compounds, concentrations.

Surely, the nitrate concentrations found in the monitoring campaigns carried out by the Regional Agency for Environmental Protection (ARPA Lazio) are quite well represented by model results.

Such a hydrological and nutrient transport simulation model, can be certainly a powerful and reliable tool for water and natural resources planning in order to achieve a rational and prudent management of them taking into account anthropic needs (water demand, agricultural activities, wastewater treatment plants, hydroelectric power production and so on) but also ecosystems preservation (ichthyic life requirements, river Minimum Flow Requirement, biological communities and so on) and economic aspects allowing to evaluate and compare benefits, disadvantages and consequences for each suggested or hypothesized technical solution on watershed.

For the particular characteristics and past of Marta basin, the implemented SWAT model can provides an overview of its multifaceted response to climatic and human pressures and also an estimation of the future available water resources quantity and quality.

To have a general overview of the whole basin hydrologic behavior, a seawater wedge simulation model has been implemented for the coastal alluvial aquifer of Maremma Laziale applying Sharp_sar code (Santini, 2008) modified version of SHARP (Essaid, 1990).

When the width of the transition zone is small relative to the thickness of the aquifer, saltwater and freshwater can be assumed as immiscible fluids separated by a sharp interface and this approach reproduces the general position, shape and behavior of the interface. SHARP model couples the freshwater and saltwater domains through the interfacial boundary condition of continuity for flux and pressure.

With a simulation period of 10 years, Sharp_sar model was implemented on Maremma Laziale coastal aquifer and the results show that after of a pumping period of 10 years, saltwater intrusion might occur in the area between Fiora river and Arrone stream.

The initial condition was set using the Badon-Ghyben (1889) e Herzberg (1901) laws to place the initial interface between fresh and salt water so that to ensure the model results after 10 years of simulation.

The interface appears located along the coastline without showing clear signs of intrusive phenomena taking place in the middle and southern part of the coastal aquifer, while a retreat of the fresh water is clear in the northern part of it up to 1.2 km inland, in the area between Fiora river and Arrone stream and then confirming what emerged from the study for the establishment of coastal environmental state "(Chiocchini et al., 2005).

Even with several uncertainties on number of existing wells, since it's not mandatory to declare a private well, on pumping amounts and periods the model results point out a supposed critical area with a particular vulnerability to saltwater intrusion phenomena.

Other smallest areas in southern part of the coastal aquifer seem to be interested by saltwater intrusion phenomena falling in Tarquinia municipality.

Coupling a SWAT model for hydrologic and nutrients transport simulation and investigation with a saltwater interface simulation model, such as SHARP_sar, for the coastal area of this basin, give the opportunity to take into account the several and different aspects and issues connected with the whole watershed behavior and evolution. A correct planning and management of the available natural resources involve a conscientious water bodies exploitation, with respect to habitats and local animal and plants requirements, avoiding saltwater intrusion phenomena and environmental damage, accomplishing people needs, economic, agricultural and tourist development and income, but, above all, ensuring citizens and buildings safety. In the local and actual context, regarding past and present events in the study area, an incisive and suddenly action from government is hoped in order to restore equilibrium conditions and environmental health for watershed. Going on in making information and investigation results available to all the stakeholders and people involved, directly or indirectly, in Marta river basin management, could allow an increase in awareness and consciousness and lead to quickening planning actions and works in a shared and advantageous way for all. Especially with regards to Minimum Flow Requirement, in relation with the water amount deviated for hydroelectric power generation, a rational regulation of the sluice-gates located on Marta river at the exit of lake Bolsena, is needed to ensure ichthyic life and ecosystem preservation together with simple turbines volumes required to correctly working.

A multifaceted and integrated approach could certainly be applied in such a complex problem-solving, with the help of hydrologic and nutrients transport simulation models, saltwater intrusion position and movement simulation models and building all the data and results in a GIS platform as to provide a real and concrete Decision System Support.

Key words: hydrologic model, SWAT, watershed simulation, water balance, Minimum Flow Requirement, water pollution, land use, saltwater intrusion, SHARP, coastal aquifer.

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INTRODUCTION

Water is a vital resource for human survival, health and dignity and a fundamental resource for human development but the world's freshwater resources are under rising pressure since populations and economies growing lead to an increase in water demand while the availability of the resource remains constant.

Fresh water is a finite and vulnerable resource, essential to sustain life and has an economic value in all its competing uses and should be recognized as an economic good. Some numbers about water: the global water on the earth is made of about 97% seawater, 3% freshwater. Of the freshwater 87% not accessible, 13% accessible (0.3% of total) (Bear, 1999). Today more than 2 billion people are affected by water shortages in over 40 countries and 263 river basins are shared by two or more nations; 2 million tones per day of human waste are deposited in water courses. Half the population of the developing world are exposed to polluted sources of water that increase disease incidence.

The increase in numbers of people from 6 billion to 9 billion will be the main driver of water resources management for the next 50 years.

Growth in population, increased economic activity and improved standards of living lead to increased competition for and conflicts over the limited freshwater resource. A combination of social inequity and economic marginalization forces people living in extreme poverty to overexploit soil and forestry resources, with damaging impacts on water resources.

Water research has been a major component of EU research since the late 1980s, covering a wide spectrum of water-related topics and evolving over the years in close correlation to EU water policy. Early Framework Programs mainly focused on enhancing scientific knowledge to support environmental quality standards and objectives and developing technologies for end-of-pipe treatment. They were mostly implemented through relatively small- and medium-sized projects that were then clustered to enable for integration and synthesis of results but also through large-scale integrated projects and networks of excellence that could accommodate integrated and holistic approaches and better embrace the critical mass and multi-disciplinarity needed to address the complexity of the system.

The project MEDDMAN is a transnational approach in the field of drought and water management involving competent national authorities, leading research institutes and regional authorities and financed by European Union according to its Interreg III B MEDOCC policy. The DAF Department, Department of Environment and Forestry, Agrarian Faculty, University of Tuscia in Viterbo, has been involved in this project with a study area on Marta River Basin, located in the northern part of Latium region.

The project's target is to develop an integrated system, capable of evaluating the state of surface water and groundwater resources in the MEDOCC regions preserving and improving the economic growth, developing efficient tools for sustainable water resources exploitation. Special attention is given to the environmental impacts of extreme meteorological and hydrological events, which affect the means of development and best interest of the locals. The focus is on the understanding of the ‘water system’ dynamics and functioning, enhancing the capability to predict its behavior in view of changes (including climate change), and underpinning its sustainable management and development.

CHAPTER 1

INTEGRATED NATURAL AND WATER RESOURCES MANAGEMENT

1.1 Sustainable development and natural resources management

Sustainable development has been defined in many ways, but the most frequently quoted definition is from *Our Common Future*, also known as the Brundtland Report (1987):

"*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."*

All definitions of sustainable development require the vision of the world as a system connecting space and time.

Sustainable development focuses on improving the quality of life for all of the Earth's citizens without increasing the use of natural resources beyond the capacity of the environment to supply them indefinitely. It requires an understanding that inaction has consequences and that we must find innovative ways to change institutional structures and influence individual behavior. It is about taking action, changing policy and practice at all levels, from the individual to the international.

Sustainable development is not a new idea. Many cultures over the course of human history have recognized the need for harmony between the environment, society and economy. What is new is an articulation of these ideas in the context of a global industrial and information society.

Progress on developing the concepts of sustainable development has been rapid since the 1980s. In 1992 leaders at the Earth Summit built upon the framework of Brundtland Report to create agreements and conventions on critical issues such as climate change, desertification and deforestation. They also drafted a broad action strategy—Agenda 21—as the work plan for environment and development issues for the coming decades.

In 1987 the World Commission on Environment and Development recommended seven critical actions needed to ensure a good quality of life for people around the world: revive growth, change the quality of growth, meet essential needs and aspirations for jobs, food, energy, water and sanitation, ensure a sustainable level of population, conserve and enhance the resource base, reorient technology and manage risk, include and combine environment and economics considerations in decision-making.

These recommendations are as valid today as they were when first written. They are a call to change our actions and to do things differently.

Throughout the rest of the 1990s, regional and sectoral sustainability plans have been developed. A wide variety of groups—ranging from businesses to municipal governments to international organizations such as the World Bank—have adopted the concept and given it their own particular interpretations. These initiatives have increased our understanding of what sustainable development means within many different contexts. Unfortunately, as the Earth Summit +5 review process demonstrated in 1997, progress on implementing sustainable development plans has been slow.

Around the world signs of severe stress on our interlocked global economic, environmental and social systems continuously appear. As the United Nations Environmental Programme's GEO-2000 report points out, the "time for a rational, well-planned transition to a sustainable system is running out fast" since full-scale emergencies through freshwater shortages, tropical forest destruction, species extinction, urban air pollution, and climate change are urgently to be faced.

1.2 Desertification and drought hazard

Water withdrawals have increased more than twice as fast as population growth and currently one third of the world's population live in countries that experience medium to high water stress and pollution is further enhancing water scarcity by reducing water usability downstream.

This situation can also engender water use conflicts, both in terms of quantity and quality and *drought* is an insidious hazard of nature.

Together with the increase of water demand according to population growth and development needs, the effects of permanent features of climate in some regions of the world or the consequences of somewhat climate changes in others, make drought a reality in several countries and expose countries and people to drought risk.

Although the numerous definitions, drought originates from a deficiency of precipitation over an extended period of time, usually a season or more. This deficiency results in a water shortage for some activity, group, or environmental sector. Drought is relative to some long-term average condition of balance between precipitation and evapotranspiration (i.e., evaporation + transpiration) in a particular area, a condition often perceived as “normal”. It is also related to the timing (i.e., principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and the effectiveness (i.e., rainfall intensity, number of rainfall events) of the rains. Other climatic factors such as high temperature, high wind, and low relative humidity are often associated with it in many regions of the world and can significantly aggravate its severity.

Drought should not be viewed as merely a physical phenomenon or natural event. Its impacts on society result from the interplay between a natural event (less precipitation than expected resulting from natural climatic variability) and the demand people place on water supply. Human beings often exacerbate the impact of drought. Recent droughts in both developing and developed countries and the resulting economic and environmental impacts and personal hardships have underscored the vulnerability of all societies to this "natural" hazard.

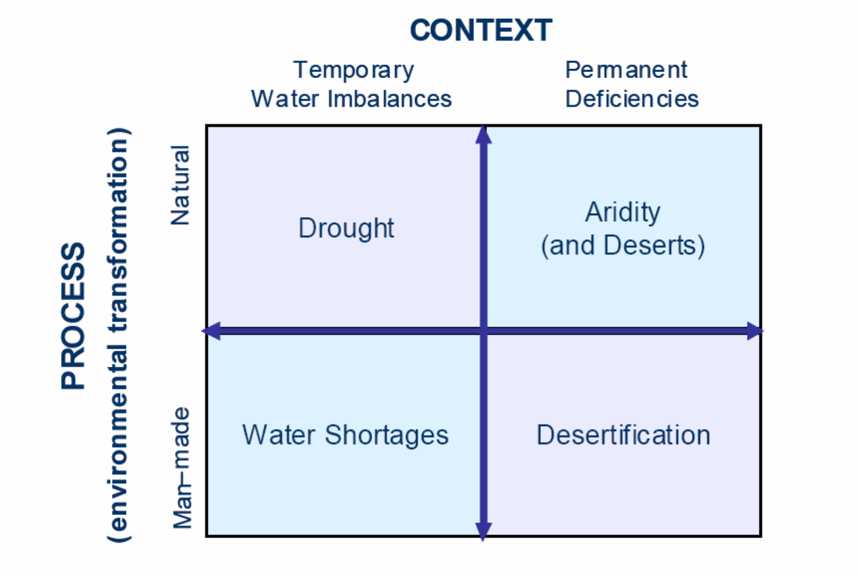


Fig. n°1.1 Typology of water stress conditions (Vlachos, 1982)

1.3 Shortening of coastline: natural and human induced phenomena

The effects and consequences of drought may also be seen and felt in coastal areas due to freshwater scarcity and/or degradation including saltwater intrusion phenomena. As Kay and Alder (1999) suggested, within 30 years coastal areas may be occupied by more people than there are now living on the entire planet, reaching 6 billions people. This great population growth means a great water demand increase as well, and it may lead to critical and conflicting situation between nature and ecosystems on one side and human needs and economic development on the other. Freshwater scarcity should be direct consequence of increased unregulated pumping extraction, water courses deviations and man made cutoffs along rivers in coastal areas to satisfy domestic and irrigation requirements but the mentioned above pumping extraction of freshwater may also cause saltwater intrusion phenomena with further deterioration of natural systems. Wharfs and infrastructures at seaside, strongly alter coastal landscape and evolution processes stressing erosion and coastline shortening. Studies about coastline evolution in southern Italy, showed that a retreat of more than 250 m took place between 1938 and 1997 for the area of Gela in Sicily region (Pelorosso and Colantoni, 2008). Changes in coastal structures are quite complex since they are involved in short-term and long-term natural processes too. Together with anthropic pressures and impacts, long terms variations, such as tidal variations (Fuhrboter, 1989) effects on estuaries and coasts (Jonge, 1983) or the North Atlantic Oscillations (Garrad and Colebrook, 1978; Selten et al., 1999) influence on the North Sea and its fringes, may lead to shortening of coastline. Changes in meteorological conditions may reduce flow discharges in rivers and induce varying wind and temperature climate which can be responsible of significant coastline shortening as well. With the help of high resolution satellite imagines and monitoring network along the coastline, the Italian National Agency for Environmental Protection carried out studies and investigations on erosion effects on the coasts obtaining that about 63 km of coastline were loss in Italy during the last 50 years (APAT, 2006).

Shortening of coastline due to natural and human induced processes, may heavily impact on freshwater quantity and quality, with particular reference to saltwater wedge advancing that reduce groundwater availability and to river flow regime variations that threaten Minimum Flow Requirement respect. All these phenomena have to be seen as different aspects of drought, since they are linked together in cause-effect mechanism resulting in deficiency of water supply.

1.4 Drought in the Mediterranean region

Drought is a severe problem in the Mediterranean basin. International conventions and Institutions such as the World Bank and the International Water Forum all consider the area in need of special attention due to problems resulting from its vulnerability to drought and its requirements for better water management.

Drought has been defined as a natural cycle of stress and renewal inherent to those regions (Breman and Wit, 1983; Niemeijer and Mazzucato, 2002; Rasmissen et al., 2001; Tiffen and Mortimor, 2002) but increasing agricultural pressure on the land aggravates its consequences (Akhatar-Schuster et al., 2000). Drought depletes vegetative cover and may lead to human actions (suc as overgrazing) that propel dry lands rapidly towards a desert-like condition.

A major new threat is climatic change (Hillel and Rosenzweig, 2002).

Predictions on the future climatic conditions have been developed to investigate the effects of climatic changes on future availability of water and drought risk and forecasted consequences have been estimated to incisively face natural resources rational use and management issues.

Modeling results suggest that dry areas could become hotter and drier, especially semiarid Africa and South Asia (Parry, 2002).

Scenarios covering the entire Mediterranean Region suggest up to 35% rainfall reduction by 2071-2100 reducing inland water flows and water yields (www.emwis.net/topics/WaterScarcity).

The IPCC (Intergovernmental Panel on Climate Change) projects under an A1 scenario (rapid and successful economic development, in which regional average income per capita converge - current distinctions between "poor" and "rich" countries eventually dissolve) a 4 to 27% average decrease in precipitations for the south eastern Mediterranean with significant spatial and seasonal variation.

A 46% increase in “significantly drier than normal” years is expected for Mediterranean region with an exponential increase in drought probability and across the region drought is expected to reduce water availability severely, in some countries up to 60% in the coming century (Mediterranean Water Scarcity and Drought Report, Mediterranean Water Scarcity and Drought Working Group, 2006). If climatic change increases the frequency and7or intensity of droughts, it would aggravate desertification.

But all models have a “certain” uncertainty so that other outcomes are also possible: recent observations suggest that Sahel is re-greening (UNEP 2003). Although the reasons are not still understood, it’s clear that more factors than just rainfall and temperature, are involved.

The cause of water shortage may, in fact, depend not only on drought events or changed climatic conditions but more often on man-made actions like water contamination, inadequate planning or equipment, by an incorrect water resources management with huge consequences on the whole natural available resources.

Many possible solutions are being studied to improve the use of water in agriculture, which is the most important economic activity in these countries, encouraging a rational use of groundwater resources in times of drought, or invoking the construction of surface water reservoirs and economical solutions.

The European Community policy is directly involved in water scarcity issues, encouraging project development and actions to mitigate the effects of drought and to investigate measures to avoid or reduce drought risk in Mediterranean regions.

In 2006 and early 2007 the European Commission carried out an in-depth assessment of water scarcity and droughts in the European Union. Following this assessment the Commission presented an initial set of policy options to increase water efficiency and water savings in a Communication published in July 2007.

Water scarcity and drought was identified as one of the most important theme for the Mediterranean-UE Water Initiative/ Water Framework Directive Joint Process launched in 2004. A first draft report was produced in 2006 on the assessment of water scarcity and drought in the Mediterranean regions and then it was decided to continue the activities of the water Scarcity and Drought Working Group for a second period, 2007-2009.

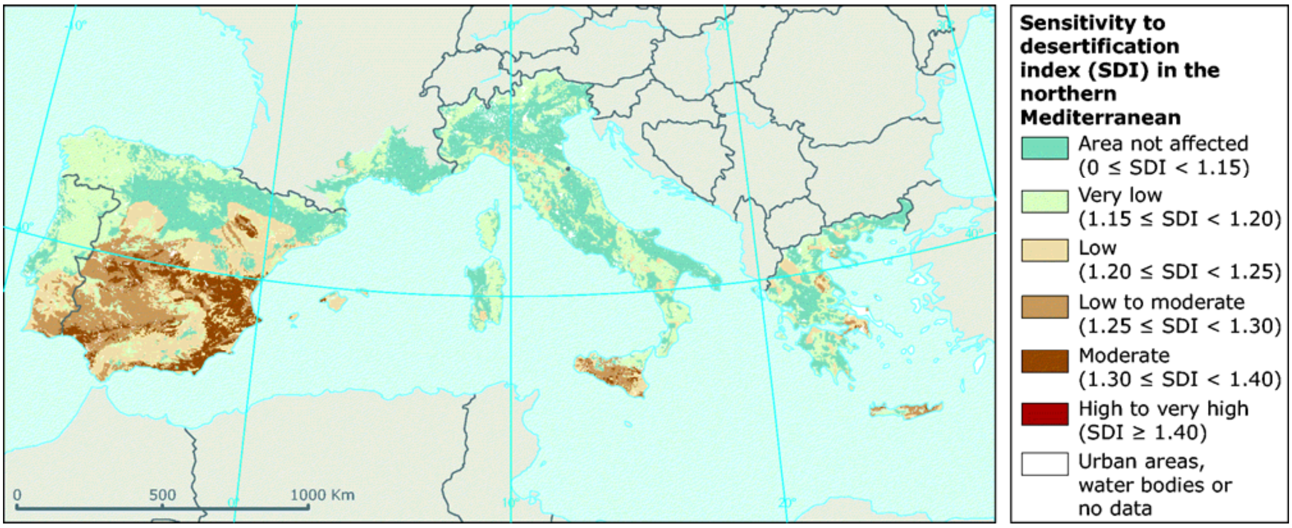


Fig. n° 1.2 Sensitivity to desertification index (SDI) in the northern Mediterranean basin (DISMED project, Desertification Information System for the Mediterranean, and EEA, 2005)

Several initiatives have been proposed by the European Commission to face drought and several projects have been financed throughout the European territories to encourage a rational and integrated natural resources management.

There is considerable variation across countries in laws and institutions related to water, and planning and project implementation ability is not uniform. Therefore The European Commission asks for cooperation between different regions and for the redaction of guidelines flexible enough and tailored to the different situations involving institutions, legal instruments, and the technical means to achieve an integrated approach to planning that considers all sources and uses of water in a given basin and all the available natural resources.

The community initiative INTERREG III is one of the Community Regional Policy tools oriented to the definition of common solutions to specific problems. The funds are mainly destined to favor a harmonious, balanced and sustainable development of the European territory recommending the constitutions of partnerships of beyond national borders to allow a balanced set up of multi regional territories.

Among Interreg III B projects, MEDDMAN (Gestion intégrée des ressources en eau, développeMEnt et confrontation Des méthoDologies comMunes et trAnsnatioNales pour la lutte contre la sécheresse aux régions MEDOCC) is a transnational approach just in the field of drought and water management with the aim to involve competent national authorities, leading research institutes and regional authorities. The project's target was to develop an integrated system, capable of evaluating the state of surface water and groundwater resources in the MEDOCC regions.

1.5 MEDDMAN Project

As the primary activity of the European Commission is now to encourage a comprehensive approach to water resources management activities, the integrated management of other resources in the watershed, such as soil and vegetation, has to be included in every action plan turned to water scarcity mitigation or water management plan.

The MEDDMAN project aims to develop an integrated system capable of assessing the state of surface water and groundwater resources in areas MEDOCC. In orde to preserve and improve economic growth, emphasis has been placed on the development of effective tools for sustainable water resources. Special attention has been made on the environmental effects of extreme weather events and water, affecting the livelihoods and citizens interests.

The improvement of the monitoring network was a target to be accomplished by choosing a suitable sensor system to perform a complete monitoring of meteorological, hydrological and environmental data to prevent and control drought. The leader of the project was Greece, with the National Technical University of Athens (NTUA), Department of Water Resources, Hydraulic & Maritime Engineering, Laboratory of Hydrology and Water Resources Management (www.ntua.gr, www.chi.civil.ntua.gr) and there were also involved: the Aristotle University of Thessaloniki, Department of Hydraulics, land and agricultural science (www.agro.auth.gr) from Greece too, the Prefecture of Pieria (www.pieria.gr) from Greece again, Water Research Institute (IRSA-CRN), National Research Council from Bari, Italy (www.irsa.it), University of Basilicata, Department of Environmental Engineering and Physics (DIFA), from Italy (www.unibas.it), University of Tuscia, Department of Engineering, Environmental Science & Forestry, Viterbo, Italy (www.unitus.it), Region of Latium, Department of Environment, Rome, Italy (www.regione.lazio.it), Interregional Authority of Basilicata River Basin from Potenza, Italy (www.basilicatanet.it), CEMAGREF, National Centre for Farming Mechanization, Rural Engineering, Water and Forestry, Hydraulic & Hydrology Research Unit, Lion, France (www.lyon.cemagref.fr), Polytechnic University of

Catalonia, Department of Hydraulic, Maritime and Environmental Engineering (EHMA), Barcelona, Spain (www.upc.edu).

The association involves territories in the Mediterranean region showing severe problems of water management, a problem of allocating resources, both geographically and seasonally, land degradation and drought risk real and potential. In particular the areas concerned are: a) Greece: The metropolitan area of Athens (Attica) and the islands of the Saronic Gulf, a watershed of Pieria (region in northern Greece), b) Italy: two regions: Basilicata and Lazio c) France: Rhône - Alpes and d) In Spain: the region of Catalonia (Llobregat basin).

For DAF Department, University of Tuscia, the study area was Marta River basin, located in Latium region, mostly falling in the province of Viterbo. The Marta river (Central Italy, about 1089 km2 basin) is the emissary of Lake Bolsena (9,20 km3 volume) and its flow is regulated by a system of floodgates, on the basis of irrigations needs of more water districts. Consequent main environmental constraints are: the actual very small Marta river flow (not sustainable for water wildlife), in the whole stream, its water quality and the saline infiltration at the mouth.

1.6 Research purposes and applied methodologies

The Marta River Basin is a complex reality since several particular situations make this watershed management hard to do. The level variations in the lake Bolsena are strictly related to erosion events and to Marta River level fluctuations affecting tourism with negative implications on economics and wasting money. As the lake level grows up, there’s a decrease of available beach for tourists; on the other hand, a high level of water in the lake allows to guarantee the Minimum Flow Requirement in the Marta River and it’s basic and fundamental for wild-life. A kind of sluice directing the flow coming out of the lake and getting into Marta river, regulates the discharge according to the crops irrigations needs.

Within Fiume Marta SCI, the Tuscania Natural Reserve develops along Marta river banks but just in this area, some fluvial weirs for hydroelectric purposes, affect fish-wildlife cause they interrupt the fluvial continuity with heavy consequences on going up the river ichthyic habits. Industrial drainage and agricultural activities are threatening Marta River water quality. At the mouth of Marta River there’s also saltwater intrusion and it could be interesting a monitoring plan to take under control all the chemical parameters fluctuations as to determine the entity of saltwater intrusion.

In the last few years, following significant rainfall amounts, flood events occurred (1987, 2004, 2005 and 2008) causing huge damages to the local residential area of marina Velca.

Fig. n° 1.3 Flood event of Marta River, 16th December, 2008 (photo by Filippo Salvo, www.marinavelca.com).

So a proper basin management is needed to correctly manage flow conditions in the river, ensuring the minimum flow requirement for ichthyic life and reproduction, providing water for irrigation needs, allowing hydro-electrical energy production, making tourism industry flourishing, improving water quality and avoiding saltwater intrusion phenomena at the mouth of the stream.

All the local authorities are directly involved in facing and solving the several and different management aspects of the basin and efficient and operative planning actions are hoped to prevent and control environmental damage and to ensure citizens safety.

Since no plan or action has been set out for this basin, with the exception of a piece of artificial dyke realized along the last stretch of the river not so far from the mouth, the urge of rational and incisive intervention is more and more deeply felt among people.

Choosing Marta river basin as study area for the MEDDMAN project had the meaning of a technical contribution in hydrologic behavior investigation and planning definition in order to point out an integrated management scheme for a correct and rational water and natural resources exploitation taking into account not only the environmental preservation but also the anthropic impact and needs. From a cultural and society requirements point of view, it seems to be time for considering also anthropic activity as an element of the environmental system that is as a part of it in interaction with all the rest. As a consequence, the sustainable development strategy for natural systems comes out (Leone et al., 1999). Applying these general concepts to agriculture, guidelines for a concrete definition of sustainable agriculture can be obtained (Leone et al., 1997). Politic and administrative tools to face Marta River basin planning are available and these tools could be seen as a synthesis of an advanced society which is no more threaten by the spectrum of hunger and poverty and is no more looking at rural land as the means to satisfy its primary needs (Leone et al., 1996).

Coupling all these aspects and integrating information about the different forms of management and planning, a deep hydrological analysis of Marta River Basin was carried out as basis of investigation on the watershed behavior, laying the foundations for a suitable River Basin Planning and a DSS (Decision System Support) which integrates environmental aspects, both agronomic and socio-economics ones, relating to water resources quality and availability.

The aim of this research is, exactly, a deep study of the watershed characteristics and responses to meteo-climatic and anthropic constraints and the creation of a Decision System Support, DSS, based on the implementation of a physically based hydrologic model, SWAT model, and on a saltwater intrusion sharp interface model, SHARP in a recent modified version Sharp_sar to predict eventual seawater wedge movement phenomena in the coastal aquifer Maremma Laziale at the mouth of the river. The organization of all the available data in a GIS platform which was essential to the SWAT and SHARP model application.

SWAT is a three-dimensional / continuous time watershed model operating on a daily time step at the basin scale and it’s a continuation of USDA-ARS modeling experience that spans a period of roughly 30 years. Early origins of SWAT can be traced to previously developed USDA-ARS models as described by Arnold and Fohrer (2005) and Krysanova et al. (2005). The major objective of the model is to predict long term impacts of management and agricultural practices in large basins within a year (i.e., crop rotations, planting and harvest dates, irrigation, fertilizer, and pesticide application rates and timing). It can be used to simulate water and nutrient cycles in landscapes where the dominant land use is agriculture. It can also help in assessing the environmental efficiency of best management plans and alternative management policies. The chemicals considered in the model include nutrients (N-based, P-based, O-based and algae) and pesticides.

Climatic, soil classes and properties, land use and anthropic pressure data are required for SWAT model running.

SHARP simulates freshwater and saltwater flow separated by a sharp interface in layered coastal aquifers accounting for temporal variations in recharge and pumping. For the considered aquifer, the vertically integrated freshwater and saltwater flow equations are solved and coupled by the boundary condition at the interface. Morphologic and geologic characteristic but also climatic and meteo-hydrographic characteristics of the coastal area are needed in order to implement such a sharp interface model.

The results from these two models application and all the deriving considerations could be directed toward supporting water resources planning, policy making and management eventually through development of a strategy that aims to consider several issues associated with the core problem of developing multiple sources and managing multiple uses (municipal, industrial, irrigation) of water and natural resources so that, over time, more efficient environmental resources exploitation systems and use patterns emerge, while maintaining or improving ambient water quality.

CHAPTER 2

HYDROLOGIC MODELING AND PLANNING

Hydrologic modeling has become commonplace over the last 25 years and now virtually all hydrologic design is based on the results of applying a hydrologic model. The ready availability of models and computers and the “user-friendly” nature of many hydrologic models ensures continued and absolute reliance on such models. Haan et al. (1982) presented a detailed treatment of hydrologic modeling for small watersheds. The availability of very complex hydrologic models has strongly improved our ability to perform sophisticated and accurate hydrologic analysis so that many different designs can be evaluated at minimal cost once baseline data are collected. Today software not only provides hydrologic analysis but also suggests appropriate model parameters using “pop-up” screens and professional-look reports can be prepared almost automatically.

Models are used for a variety of hydrologic studies and probably the most common use is to evaluate the impact of some physical change or land use within a catchment on its hydrology.

The model must contain parameters sensitive to the phenomena taking place: for example if the model has no way to reflect the modifications occurring on an internal channel, it’s obviously not able to define its hydrologic behavior. Nonpoint-source pollution concerns has led to regulatory requirements for showing how land management will mitigate adverse water quality impacts and now most of the available models are required to predict the potential effectiveness of various control efforts such as best management practices.

Once a model is operational for a single catchment then combinations of storage, channel modifications and land use changes can be modeled even tending to an economic objective that could result in considerable savings over the life of the presumed project. If a planning administration has a development plan for a particular area and a timetable for that plan, a hydrologic model can be used to determine the type and timing of various storm water control works required to meet an agreed on flow objective. It is the case of Marta river basin which is under anthropic pressure heavy modifying its hydrologic response with considerable consequences on flora and fauna and above all on human safety so that a basin plan should be hoped. To reconstruct the hydrologic behavior of this system and to better design a suitable plan, a hydrologic model should be very useful.

There is also a great tendency for planners to consider each development unit as a separate entity and design conveyance and storage facilities independently for that particular unit. But it has to be noted the great advantages of considering storm water management on regional basis and the hydrologic model makes it feasible to evaluate the impact of a structure or plan locally and its regional impact as well. A well-conducted model study requires detailed knowledge of the system being modeled but models also allow and encourage the use of “what if” scenarios and the use of innovation.

Hydrologic models have been classified in many ways such as deterministic, parametric, statistical, stochastic, physically based, empirical, black-box, lumped, linear, non-linear, distributed, theoretical, predictive, operational, research, design, similarity, iconic, analog, numerical, regression, even, continuous simulation and conceptual (Haan , Barfield, Hayes, 1994).

Generally speaking, a mathematical model range from single prediction equations to complex computer simulation algorithms and the mathematical basis for that model may be theoretical or empirical.

A completely theoretical model would contain only relationships derived entirely from physical laws such as conservation of mass, conservation of energy, laws of thermodynamics etc. Empirical relationships are based on observations and/or experimentation such as Manning’s equation for uniform open channel flow or the Darcy’s law fro flow through a porous media. There exists no completely theoretical model in hydrology since all hydrologic models contain empirical relationships. So that a hydrologic model can be better defined as a collection of physical laws and empirical observations written in mathematical terms and combined in such a way as to produce hydrologic estimates (outputs) based on a set of known and/or assumed conditions (inputs) (Haan , Barfield, Hayes, 1994).

Regardless of how models are classified, they can generally be described as:

$$O = f\left(I, P, t\right) + e \tag{2.1}$$

Where O is an n x k matrix of hydrologic responses to be modeled, f is a collection of l functional relationships, I is an n x m matrix of inputs, P is a vector of p parameters, t is time, e is an n x k matrix of errors, n is the number of data points, k is the number of responses and m is the number of inputs. Responses in O may range from a single number, such as a peak flow or a runoff volume, to a continuous record of flow, soil water content, evapotranspiration, and other quantities. Model classification refers to the nature of f. The distinction between I and P is not always clear where I generally represents inputs, some of which are time varying, such as rainfall, temperature and land use while P represents coefficients particular to a watershed that must be estimated from tables, charts, correlations, observed data, or some other means. The error term, e, represents the difference between what actually occurs, O, and what the model predicts, O_p:

$$O_p = f(I, P, t) \tag{2.2}$$

$$e = O - O_p \tag{2.3}$$

A parametric model is a model having parameters that must be estimated based on observed data (calibration), tables and/or charts (Manning's n or Curve Number), correlation-type relations (regional analysis) of site-specific information (water-holding capacities of soils etc), experience, or by some other means. An empirical model is a model containing any empirical relationship based on observation and even Darcy's law or Manning's equation are empirical equations. A lumped model describes processes on a scale larger than a point. A completely distributed model would be one in which all processes are described at a point and then integrated over three-dimensional space and time taking into account variations in space and time to produce the total watershed response. Based on somewhat restrictive definitions, all hydrologic models are to some degree parametric, empirical, and lumped.

2.1 A brief look back

Many of the current developments in hydrologic modeling depend more heavily on computational improvements than on improved representations of hydrologic processes when compared to models of 25-30 years ago.

The 1960's might be thought as the golden years for hydrologic modeling since computers were becoming widely available and hydrologic researchers began taking advantage of their power. The Stanford Project in Hydrologic Simulation was initiated in 1959 and, under the general leadership of R.K. Linsley, developed approaches to hydrologic modeling that continue to play a major role in this field to this day. The most famous of the models developed at Stanford was the Stanford watershed Model, SWM (Crawford and Linsley, 1962 and 1966). In their 1966 report, Crawford and Linsley stated:

"The objective of the research is to develop a general system of quantitative analysis for hydrologic regimes. The most effective way or doing this has been to establish continuous mathematical relationships between elements of the hydrologic cycle. The operation of these mathematical relationship is observed and improved by using digital computers to carry the calculations forward time…. As mathematical relationships are developed, every attempt is made to realistically reproduce physical processes in the model. Experimental results and analytical studies are used wherever possible to assist in defining the necessary relationships."

This statement of their researchers objective has been paraphrased and repeated by others in many locations throughout the world.

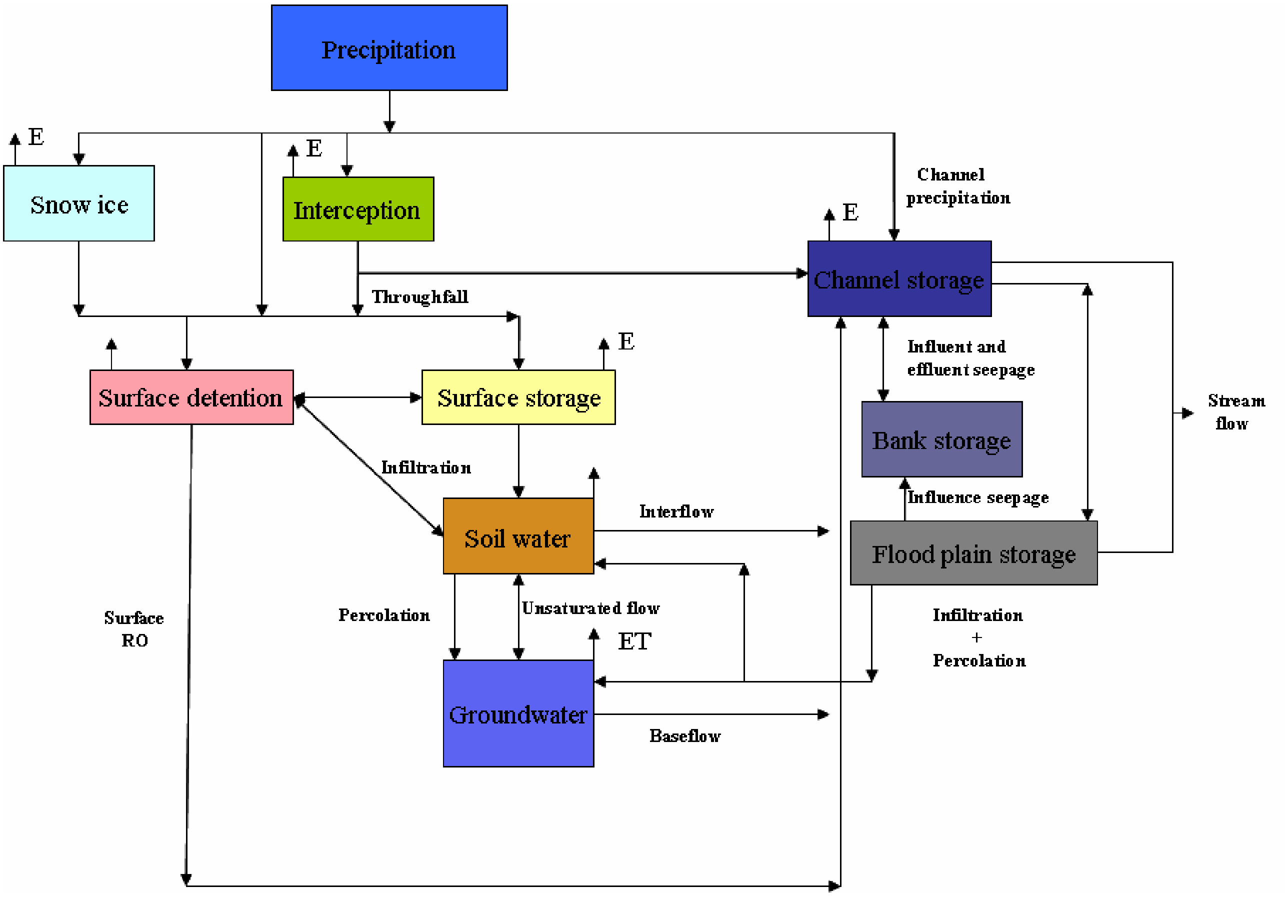


Fig. n° 2.1 A representation of the hydrologic cycle.

In 1966, Huggins and Monke (1966) presented the first developments of what has become known as ANSWERS (Beasley and Huggins, 1981). This model is representative of a class of models that breaks a watershed into a grid system, simulates the hydrology of each grid and interaction of the grids with their neighbors integrating these results over the watershed to produce the total watershed response. Generally with models of that type, the goal is to use physically based parameters, since a set of parameters must be defined for each grid within the watershed. In addition to general purpose models applicable to a wide range of watersheds, hydrologic models have been developed to address specific questions. The model developed at Iowa State University (Haan and Johnson, 1968; DeBoer and Johnson, 1971; Campbell et al., 1974) to evaluate the impact of subsurface drainage on flood flows in north central Iowa represents such a model.

Since the 1960's there have been thousands of papers, articles and books written dealing with hydrologic modeling. In these years hydrologic modelers spent a great deal of time justifying with hydrologic models should be developed and their applicability to certain problems. Today everyone wants to use models for every conceivable hydrologic question and their implementations are often outside the verified domain of the model being used. But many modern hydrologic investigations would not be possible without computer models.

2.2 Basic modeling approaches

One way of differentiating hydrologic models is based on time scale of importance, so that to have two main approaches: event simulation and continuous simulation. Event simulation refers to modeling the hydrologic response to a single isolated storm while continuous simulation refers to modeling the ongoing hydrology of a catchment over a long period of time (years). To design storm water control facilities for small catchment, event based models are useful while continuous models are used where long term flow volumes and storage considerations are important. Hydrologic models are constructed on the base of flow and storage processes considering not only the inflow and outflow of water to the system in a hydrologic cycle, but also other factors such as solar radiation and air masses that play an important role since they import energy to drive evaporative processes and govern vegetative growth, which in its turn, influences evapotranspiration.

Also the capacity limits in the various storage (bank storage, channel storage, flood plain storage etc., see Fig. n° 2.1, the rate of release of water from the storage and the rate of water movement in the various flow phases must be taken into account. It's really important to define the processes in as physically based a manner as possible so that model parameters can be almost conceptually, if not actually, related to physical watershed characteristics.

For example, soil water storage might be referred to the available water-holding capacity of the soil in the root zone and soil water flow processes might related to the water-transmitting properties of the soil. In general, event-based models requires less detailed information than continuous simulation models and often subsurface flow processes and abstractions with the exception of infiltration, evapotranspiration and baseflow are neglected in event-based models based on time scale and order of magnitude arguments. An event simulation model is built combining algorithms representing flow and storage processes in a logical manner and providing a means of estimating the various parameters required as a result of the representations.

A continuous simulation model is always much more complex than an event one where the complexity is increased as the step is decreased: if a 1 day time step is used in a small catchment, detailed overland flow routing and infiltration calculations cannot be done and in this case the storage processes become dominant in the model. For an event-based model a short time increment is used and for small catchments the time increment is in minutes. For an event-based model, antecedent conditions in terms of soil storage, have to be specified or implicitly assumed by the model. Another classification concerns the manner to represent physical processes. Processes and parameters can be defined as average representations over the entire watershed or specified at points or within cells and then integrated over the watershed to define the total basin response. The former approach is termed as lumped and the latter distributed. So that distributed models represent averages over some finite area (a hectare or so) being lumped to some extent while lumped models may be applied to very small catchments with the results combined and routed. In this way, lumped models may become distributed models. Whether the model is distributed or lumped, event-based or continuous, parameters must be correctly estimated to evaluate the flow and storage processes.

2.3 Parameter estimation

To estimate model parameters some criteria must be adopted and they may include: 1) personal judgment of goodness of fit of simulated hydrographs to observed hydrographs, 2) direct measurement of physical properties in the field or in the lab, 3) indirect measurement of physical properties through their relationship with other hydrologic processes and watershed characteristics, 4) optimization of some objective function either computationally or by trial and error, 5) satisfaction of agency requirements and 6) compliance with published tables and charts. But it is often hard to define the appropriate criteria for parameters selection, to find correlation among parameter due to the amount of computation involved in many models, to the restrictions on appropriate values for some of the parameters and to the non-uniqueness of parameters sets for certain objective functions and finally due to data errors.

Problems in parameters estimation have been investigated by Dawdy and O’Donnel (1965) foreseeing the possibility of obtaining an efficient automatic procedure for finding numerical values of the various parameters of a watershed model. Beard (1967) and DeCoursey and Snyder (1969) addressed computer procedures to estimate optimal parameters for a hydrologic model. Jackson and Aron (1971) reviewed parameter evaluation techniques in hydrology. An objective function is often a minimization of a sum of squares and search techniques were employed to find the parameter set optimizing such an objective function. Sorooshian (1983) shifted his attention from a deterministic, mathematical interpretation of parameters toward a stochastic interpretation of them.

For Klemes (1982) causal models were being viewed as “somewhat structured empirical constructs whose elements are egression coefficients with physical sounding names” and the adoption of this viewpoint led to parameter estimation in a statistical framework and focused attention on treating a parameter as a random variable with a probability density function. Troutman (1985) made an extensive investigation referring to this approach. The majority of the research was on the evaluation of parameters using a single objective function related to the prediction of peak flow or storm runoff volumes or daily stream-flow. Diskin and Simon (1977) investigated 12 such univariate objective function while attempts to use multiple objectives have been reported by Edwards (1988) applying them to the Soil Conservation System (SCS) runoff model. If model parameters estimation is based only on the minimization of prediction error sum of squares for peak flow for example, then the resulting parameter set would be reliable in predicting peak flows but give very poor estimates of runoff volumes.

If interest is on runoff peaks, then choice of the simpler univariate objective function may be useful; however the estimated parameters may be skeptical when the poorly estimated SCS curve number parameter is compared to more conventional estimates of this parameter as commonly found in tables. So to overcome this problem, a measure of prediction errors on volumes was included in the objective function. Runoff typically accounts for only 10 to 35% of annual runoff and estimation of all models parameters based only on runoff ignores 65 to 90% of the processes due to water loss for a catchment.

There's no clear justification on the thought that if runoff is well predicted then all model parameters must have been adequately determined and including some measure of performance in the optimization that reflects some of the flow and storage processes occurring within a watershed in addition to runoff should improve the stability (reducing variance) and accuracy (reducing the absolute error) of the evaluated parameters. Traditionally, parameter estimation criteria measured how well predicted stream flow agreed with observed stream flow but these criteria are really difficult to apply especially for continuous models.

An alternative could be the measure of performance as how well the model performs in a design situation for example selecting the parameters of a daily flow model so that the estimated capacity of a reservoir to meet some demand would be as close as possible to the capacity estimated on the basis of observed stream flow data using the same capacity estimation algorithm.

2.4 Parameter estimation criteria

Parameter estimation methodologies can be divided into two main categories: personal and objective. The first one relies on a personal judgment of the modeler while objective parameter optimization generally deals with some function of the error term, e of Eq. n° 2.3 and thus requires observed data on the quantity being modeled. A probability density function for e, as well as other properties such as independence, constant variance, and zero mean is assumed. Generally e is a function of the parameters P.

2.4.1 Personal parameter estimation

The most commonly used parameter estimation technique is the personal judgment of the modeler where parameters are initially assigned on the basis of judgment, published guides and physical properties and characteristics of the watershed and then adjusted again based on judgment as to the appropriateness of the model results. If observed data are available, the parameters may be adjusted several times in an effort to obtain a “satisfactory” fit to the observations. This method has the advantages to weight mentally the importance of various flow components such as peak flows, low flows, runoff volumes whereas most objective estimation techniques can focus only on a single objective. But it has the disadvantages of sole reliance on the judgment of the modeler and generally a poorly defined objective function in the mind of the user. Different hydrologists would arrive at different parameters assessment on the basis of the same model using the same data.

2.4.2 Least Squares

In the last squares procedure, a sum, *S*, is defined as the sum of squares of the e_i :

$$S = \sum_{i=1}^{n} e_i^2 \tag{2.4}$$

Values of the p parameters minimizing the sum *S* are sought. For hydrologic models, numerical search techniques are generally employed in p-dimensional space.

2.4.3 Absolute Errors

To minimize the absolute errors a sum *A* has to be computed:

$$A = \sum_{i=1}^{n} \left| e_i^2 \right| \tag{2.5}$$

Values of parameters minimizing *A* in p-dimensional parameter space are sought, generally through numerical search techniques.

2.4.4 Method of Moments

This method requires equating the first *p* sample moments of e_p with the first *p* population moments of the pdf (probability density function) of *e*. The population moments will be a function of the *p* model parameters so that to have *p* equations in *p* unknowns to be solved for values of the *p* unknown parameters.

2.4.5 Maximum Likelihood

The likelihood function, *L*, of **e** is:

$$L = \prod_{i=1}^{n} p(e_i / P) \qquad (2.6)$$

Where $p(e_i/P)$ is the pdf of **e** given *P*. Values of *P* that maximize *L* are sought and for hydrologic models, numerical search techniques are generally required.

2.4.6 Arbitrary Objective Functions

Any objective function or criterion function, *C*, can be used to find *P* and in general:

$$C = G\left[f_i(O), f_2(O_p)\right] = G\left[f_1(O), f_3(P)\right] \qquad (2.7)$$

Where *G* is the arbitrary function, f_1 is a function of the observed values of *O*, and f_2 is a function of the estimated values of O_p. Using numerical search techniques, *P* optimizing C is sought so for example $f_1=\ln(O)$, $f_2=\ln(O_p)$ and $G = \sum\left[f_1(O) - f_2(O_p)\right]^2$ and *P* is found minimizing *G*.

This would be a minimization of the sum of squares of the difference in the logarithms of the observed and predicted outputs. For all the above four estimation procedures, e is a *n* x 1 vector, point estimates for the parameters are obtained, and a single objective is used.

2.4.7 Bayesian Estimation

This procedure is different from the above methods cause it evolves from probabilistic considerations rather than some arbitrarily specified objective function. Bayesian estimation is concerned with the probability distribution of the parameters rather than point estimates. However point estimates may be derived as the mode of the resulting distribution.

Some references to Bayesian estimation are Box and Tiao (1973), Kuczera (1983), Vicens et al. (1975), Edwards (1988) and Edwards and Haan 81988, 1989). Bayesian estimation has the advantage that multiple objectives may be incorporated into the analysis. Box and Tiao (1973) show that the point estimates for P may be found by minimizing the determinant of **S(P)**, **|S(P)|,** with respect to *P*, where **S(P) = e' e** for the case where **e** is a *n* x *k* matrix of sums of squares and cross products of errors. Since **|S(P)|** is simply a number (the determinant of **e'e**), numerical search procedures can be used to find the *P* that minimizes **|S(P)|.**

2.4.8 Considerations

James and Burges (1982) present an excellent discussion of parameter estimation and estimation criteria. If a model structure is such that only a subset of parameters impact one particular aspect of model output, those parameters may be estimated on the basis of an optimization criteria related to that particular aspect of model output. While strict division of influence between parameter sets and outputs generally does not occur, it is common for some parameters to have relatively little influence on optimization criteria and thus be poorly determined. James and Burges (1982) define sensitivity coefficients that can help identify this possibility. To include multiple objectives, a weighted criterion function could be used:

$$C = w_1 \sum e_1^2 + w_2 \sum e_2^2 \qquad (2.8)$$

Where the subscripts refer to different objectives (i.e., peaks and volumes), w is a weight and *e* is the error. The selection of the weights is arbitrary and reflect the relative importance of the two objectives. In that interaction between the two objectives is not included. For the case where k=2 it's:

$$C = \sum e_1^2 \sum e_2^2 -_2 \left(\sum e_1 e_2 \right)^2 \qquad (2.9)$$

This equation can be generalized to any number of objectives and it is not necessary that all e_i used in that equation be related to flow. For example e_2 might refer to some measure of soil water content if observed data were available and the model provided estimates of soil water.

2.5 Event modeling

Event based models are used to describe the response of a catchment to a single hydrologic event or rainstorm thus components of the model must deal with the characteristics of the input rainstorm, abstractions from the rainfall, routing of overland and shallow subsurface flow to the channel system and finally the routing of the channel flow to the catchment outlet. Model development becomes one of choosing algorithms for representing the various model components and combining them in a logical and functional manner to produce a runoff hydrograph. For example a SCS type II rainfall distribution can be used to define the storm input, the curve number approach to determine abstractions from rainfall, the SCS curvilinear unit hydrograph for overland and shallow subsurface flow routing and the Muskingum routing procedure for channel routing. A basin to be modeled may also be divided in subcatchments defining the physical properties of them so that to combine the responses obtained and have the total catchemnt hydrograph. In a modeling effort such as this, the manner in which catchments are defined can have a pronounced influence on the conclusion reached. It is also useful to point out the possibility to resort to lumping and the impact of lumping on results: if the effect of a small change on a large watershed is to be investigated, the lumping of the area undergoing change with the rest of the catchment will often mask any impacts so generally, catchments with widely varying characteristics should not be lumped. Basins with different land uses, soils, surface topography, stream characteristics, etc, should be identified and treated separately with the flow combined through a routing process (Haan, Barfield, Hayes, 1994).

Certainly different degrees of lumping should not be used to delineate some hydrologic impact. Models are also often used to evaluate relative impacts, but overreliance on the absolute numerical predictions should be avoided, especially for uncalibrated model applications (no observed data used to temper parameter estimates. Hydrologic models produce hydrologic estimates and for comparison between estimates to be valid, a consistent modeling approach must be used.

The USDA's **EAH** model (Everglades Agro-Hydrology) is an event-based model that was used to assess the various impacts of both the present and the proposed water management systems on hydrologic conditions, flood mitigation, agricultural production and water quality for farms.

The **EAH** model simulates the following processes at a specific farm using a given rainfall event as an input: 1) Plant transpiration, soil evaporation, root zone soil moisture, and storm runoff, 2) crop yield under the current and alternative hydro-meteorological regime, 3) pesticide and nutrient movement within the root zone, 4) dissipation/degradation of pesticide residues and their subsequent fate in aquatic ecosystems, and 5) mitigation actions which might be taken to reduce exposure to pesticides. After the model's parameterization and evaluation, it can be used for selecting the Best Management Practices for the given region, on the base of either the present or proposed water management system.

The **EAH** model can also be used to help conservation efforts by quantifying water quality improvements over time in areas with the potential to deliver the highest rates of nutrients and pesticides to the aquifer.

A computer model, the **Everglades Agro-Hydrology Model (EAHM),** has later been developed by Savabi and Shinde (2003) to evaluate the impact of agricultural practices on the water quantity and quality. The objective of that research was to present the **EAHM** governing equations and develop the interface of the model.

HIRO2 (Hortonian Infiltration and Run-Off/On) is, instead, a spatially distributed rainfall-runoff model for event-based studies of space-time watershed processes and it was developed by USDA. A grid-based routing hierarchy was defined over the watershed using the D-infinity contributing area algorithm. Computation of ponding time was included to handle variable run-on and rainfall intensity. The Green-Ampt model was adopted to calculate surface infiltration, and the kinematic wave model was used to route Hortonian runoff and channel flow. The model can handle input rainfall, soil parameters, surface roughness, and other properties that vary in space and time.

A grid-based distributed hydrologic model called **BTOPMC** (Block-wise use of **TOPMODEL**) was develop by Wang, Zhou, Takeuchi (2007) from the original version of **TOPMODEL**.

TOPMODEL developed by Beven and Kirkby (1979) and widely used for all hill slope hydrologic simulations, is a physically based distributed watershed model that simulates hydrologic fluxes of water (infiltration excess overland flow, saturation overland flow, infiltration, exfiltration, subsurface flow, evapotranspiration and channel routing) through a watershed. The model simulates explicit groundwater/surface water interactions by predicting the movement of the water table, which determines where saturated land surface area develop and have the potential to produce saturation overland flow. It bases its distributed predictions on the watershed topography assuming that the local hydraulic gradient is equal to the local surface slope and implies that all points with the same value of the **Topographic Index** *a/Tan B* will respond in a hydrologic similar way. This Topographic Index is derived from the basin topography where a is the drained area per unit contour length and tan B is the slope of the ground surface at the location. The model needs to make calculations only for representative values of the index.

The **Block-wise use of TOPMODEL (BTOPMC)** was, instead, developed by the University of Yamanashi for the hydrological modeling in large watersheds and MC represents the Muskingum.-Cunge routing method. The runoff generation is based on saturation excess mechanism and it works well in humid regions yet it performs poor for arid catchments as the runoff generation mechanisms are different in arid regions. Leaf Area Index (LAI) based canopy interception model and time compression approximation (TCA) based infiltration model are incorporated into the model structure so that by using TCA method, the atmosphere controlled infiltration conditions can be switched to soil controlled conditions (ponded infiltration).

2.6 Continuous simulation models

Continuous simulation models differ from event based models in that they attempt to simulate hydrologic response of a catchment over long period of time. Continuous input streams of precipitation and frequently temperature or solar radiation are required. The hydrologic processes that are occurring on a catchment than event models. When using continuous models, it is often required to define a continuous accounting of soil water content and groundwater storage and also to represent the interaction between soil water content, evaporative demand and stage of plant growth. Many more parameters are required by continuous simulation models than by event-based ones: some continuous simulation models require that 30 or more parameters to be estimated before the model can be run. Obviously a large number of parameters implies a fairly complex model structure to incorporate their individual impacts. It’s really difficult not only to visualize the effects of so many parameters but also to determine a unique set of them to fulfill some objective function. There is no generally accepted simple criteria to use in evaluating continuous simulation models since the evaluation of these models has always been depending on the judgment of the modeler, on the comparison of observed and predicted hydrographs and on how the model could predicts extreme or changing conditions in comparison to the modelers expectations.

Some quantitative comparisons that can be made include: variances, correlation between observed and predicted, standard error of estimate, first order auto-correlations of flows integrated over some finite time period such as 1 day or 1 month, flood peaks for various frequencies, such as the 5-years peak flow, low-flow duration-frequency estimates such as the 10-day, 2-year low-flow volume. Another valuative approach is to compare design or operational decisions that would be made based on model results and observed data. Such things as required storage capacity in a detention basin, storage to meet a projected water supply demand, or size of bridge opening or culvert to meet a given criteria might be compared. Certainly if the model-predicted flows agree very well with observed flows, then design decisions based on modeled and observed flows should also agree. Certain design decisions are more sensitive to certain flow quantities than others.

Thus what appears to be good representation of a flow hydrograph may produce a substantially different design if the critical flow quantity is not properly modeled. An example would be the importance of modeling the persistence in low flow for water supply storage requirement determinations. There are several currently available continuous flow simulation models since they are especially popular as a foundation for water quality models because of the importance of antecedent conditions at the time of a storm event.

The **Stanford Watershed Model** (Crawfod and Linsley, 1966) and its many derivatives and the precipitation-runoff modeling system **(PRMS)** of the U.S. Geological Survey (Leavesley et al., 1983) represent two widely diffuse continuous simulation models that can generate daily stream flow hydrographs and storm flow hydrographs. T

hese and other continuous models require numerous computations in the form of water budgets for the various storages in the model. Parameter estimation, if based on observed data, requires running the model using a number of different potential parameter sets and selecting the parameter set optimizing the desired objective function. **PRMS** and some other models have an option for automatic parameter estimation even if for some catchments the model results are not very sensitive to the values used for some of the parameters. This makes estimation of these parameters really difficult; a difficulty that may not be of importance unless some watershed modification or change over time whose hydrologic impact should be reflected in the insensitive parameter is being evaluated. The use of a model such as **PRMS** or **SWM** or one of its derivatives requires considerable time to become familiar with the model, to fully understand all of the internal workings of the model and to comprehend the interactions and interrelationships of the various flow components. Before selecting a model, the adequacy and suitability of the model for the intended purposes must be ensured.

SWAT (Soil Water and Assessment Tool) is a continuous time model too and it operates on a daily time step at basin scale. The objective of such a model is to predict the long-term impacts in large basins of management and also timing of agricultural practices within a year (i.e., crop rotations, planting and harvest dates, irrigation, fertilizer, and pesticide application rates and timing). It can be used to simulate at the basin scale water and nutrients cycle in landscapes whose dominant land use is agriculture. It can also help in assessing the environmental efficiency of BMP's and alternative management policies. SWAT uses a two-level dissagregation scheme; a preliminary subbasin identification is carried out based on topographic criteria, followed by further discretization using land use and soil type considerations. Areas with the same soil type and land use form an HRU (Hidrologic Response Unit – which means that for the same climate produces the same hydrology).

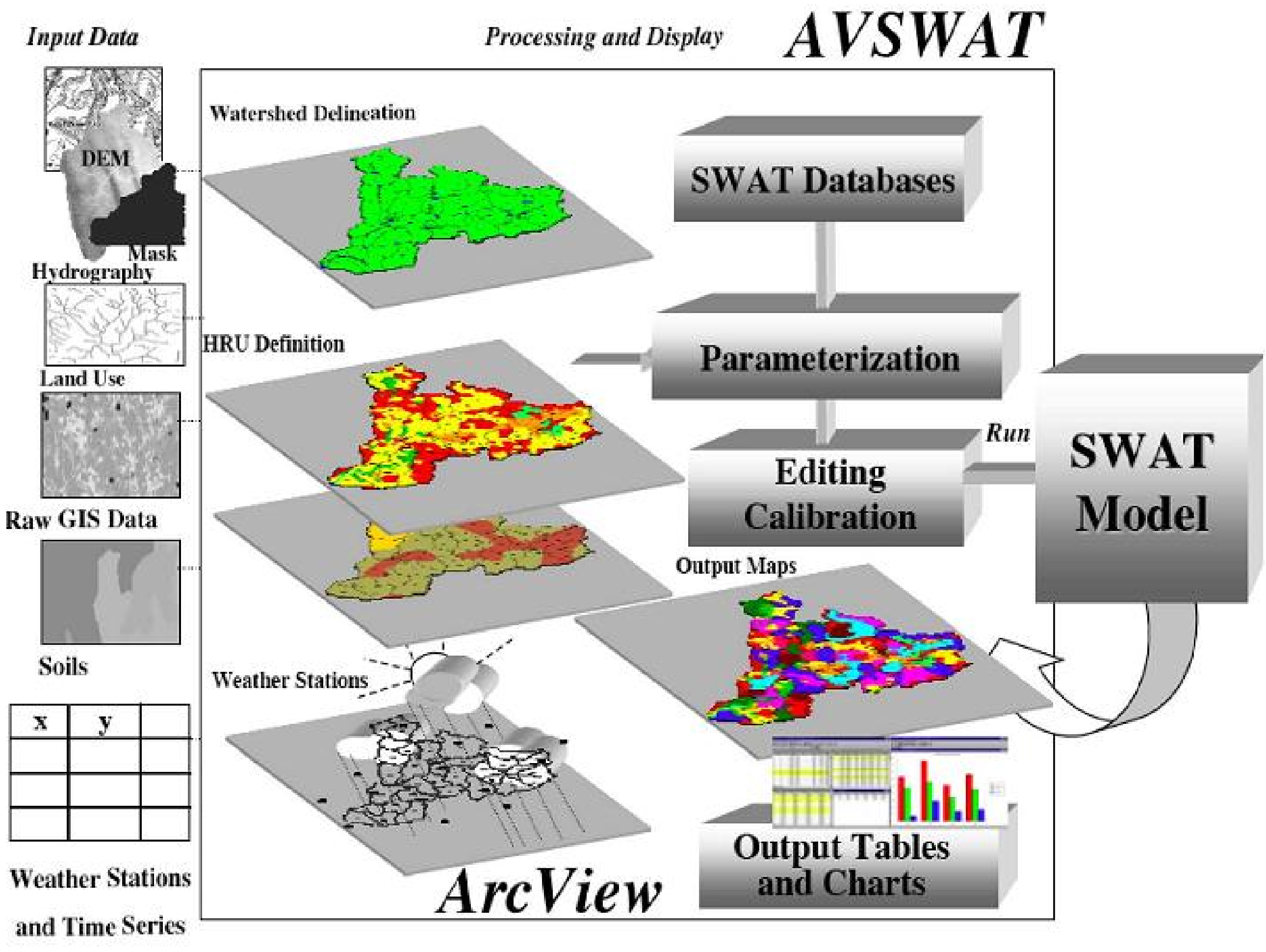


Fig. n° 2.2 Watershed simulation with the SWAT Model

It is a public domain model and decision support tool developed and actively supported by the USDA Agricultural Research Service (ARS). It is a river basin model developed to predict the impact of land management practices on daily water, sediment, and agricultural chemical yields in watersheds with varying soils, land use, and management conditions (Arnold et al., 1998).

SWAT uses a geographic information system (GIS) based interface and GIS coverage of digital elevation models to divide a drainage basin into similar-sized sub-basins that are further divided on the basis of soil type and land cover, into areas of like hydrologic characteristics, called hydrologic response units (HRUs). HRUs are portions of a sub-basin that has unique combinations of land use, management, and soil attributes. The GIS module also estimates the stream length, stream slope and geometrical dimensions, accumulation area, and aspect.

Applied research with SWAT at NASA Ames Research Center is directed toward innovative uses of satellite remote sensing imagery and data products to enhance and update the characterization of HRUs in selected watersheds of the western United States. In addition, SWAT model output data are being summarized and visualized in new internet-based applications that can be easily displayed from any web page browser.

2.7 Information System Technologies-Geographical Information System

A characteristic of sophisticated, distributed parameter, hydrologic models is the large amount of spatially oriented data they require. GIS (Geographical information System) is a technology for manipulating spatial data (Zhang et al. 1990) so that data of various type are collected in the form of layers. Typical layers might be soils, topography, land use. The ability to extract, overlay and delineate land characteristics. The ability to extract, overlay and delineate land characteristics makes GIS eminently suited to the delineation of hydrologically homogeneous areas and sub-areas.

A complete GIS includes the hardware and the software used to perform geographic analysis as well as the databases and the people who use the system to meet a specific set of objectives (Brown, 1986). A GIS will have a means of encoding and converting geographically (or spatially) oriented data and the capacity to retrieve and display the information through a variety of media including computer screens, printers and plotters.

Two basic techniques or representing spatial data are employed: the first is a vector format where the basic unit of data is a single vector or map line so that vectors form polygons that enclose like information within a data layer while the second data model is a raster format made up of cells or pixels. The raster format is commonly called a grid-cell system so that data layers are converted to cells having attribute values and these layers can form the required data base for input into a hydrologic model or they can be combined by overlaying techniques to generate the input data. A hydrologic model can perform an analysis on the basis of the imported data and export results by cell back to the GIS. The GIS can then prepare visuals or maps of the resulting hydrologic analysys. Zahng et al. (1990) have interfaced a root-zone chemical transport model with a GIS to produce maps showing the probability of the applied chemical exceeding the health advisory limit of the U.S. Environmental Protection Agency at the depth of 1 m. Most GIS are data managers and do not themselves contain hydrologic modeling capabilities but hydrologic models must be interfaced with the GIS. The GIS managers data for the model and the model, in its turn, provides the GIS with the results that can be made into GIS layer and mapped in various ways.

a spatial dimension. Armstrong (1992) provided an abstract overview of data design and geometric representations needed for a spatial water resources DSS. Walsh (1993) presented more practical research challenges to be faced in the development of such DSS. He emphasized the need for an open architecture, interdisciplinary collaboration in prototype development, and the development of models which are more spatially aware. Djokic (1993) made a strong case for the use of commercially available software within a spatial decision support system shell. He argued that the one-time effort of developing interfaces between the software components would require much less effort than customizing existing or writing new software. Similarly, Frysinger et al. (1993) stressed the need for an open architecture to facilitate the integration of GIS and water resources and environmental models in a DSS. Kilgore et al. (1994), however, stated that the use of commercial GIS in DSSs would impede integration and even the sharing of data because the GIS and models do not reside in the same environment.

Others have evaluated the use of GIS in DSSs with respect to more specific applications. Fürst et al. (1993) recommended that GIS components be used for supporting model based scenario analysis in DSSs for groundwater management. They identified the advantages of efficient spatial data analysis and display, as well as the disadvantages of poor three-dimensional data representation, poor performance of interactive graphical tasks, and the sometimes tedious procedures required to interface GIS tools with groundwater models.

Leipnik et al. (1993) provided an excellent overview of implementing GIS in water resources planning and management. The process described involves the initial decision to use a GIS, the selection of a system, data-base development and product generation, and installation and training. Kaden (1993) focused on some of the problems of GIS implementation, identifying some common pitfalls in the integration of software components, the acquisition of adequate data, the management of time-varying data, and increasing levels of complexity which may constrain user-friendliness

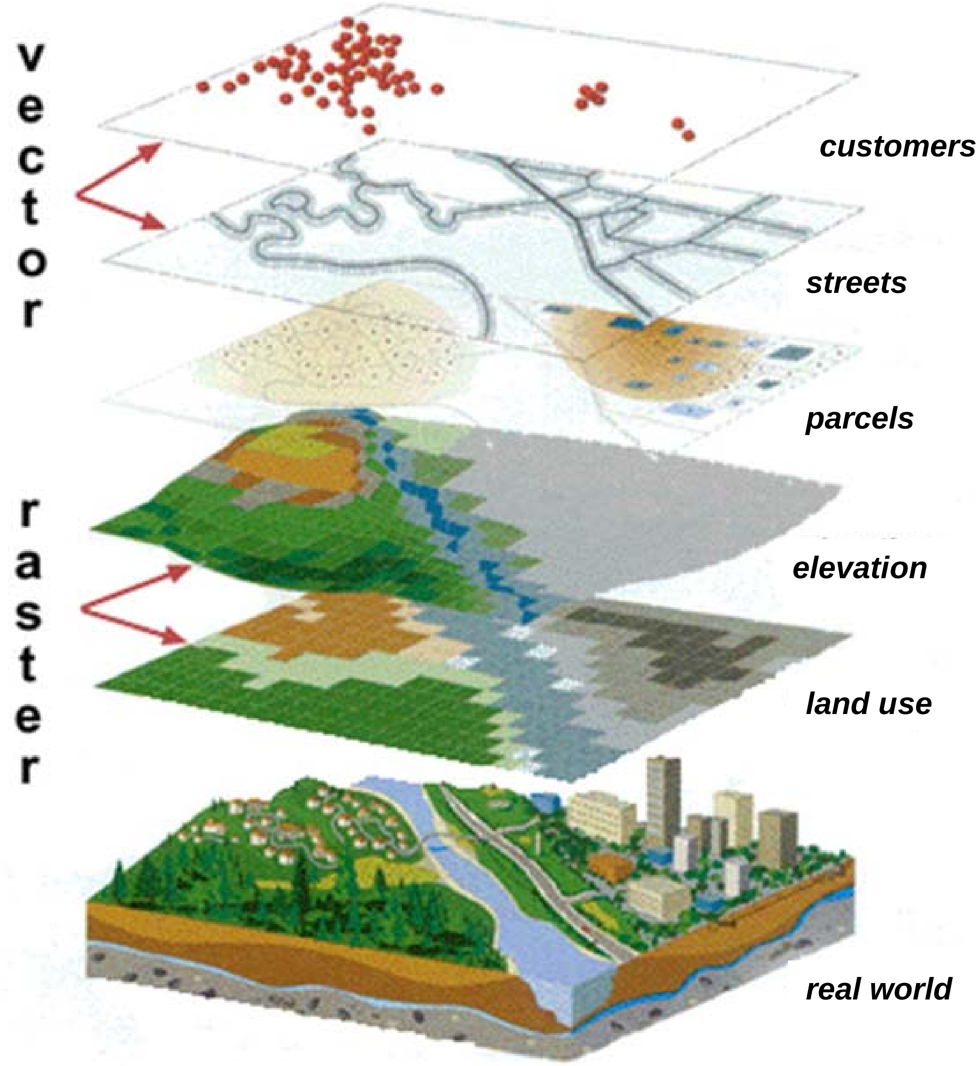


Fig n° 2.3 A schematic representation of how GIS works.

2.8 Integration of GIS and Hydrologic Models-DSS

Since many water resources problems require more than just the analysis of spatial data, several authors have offered guidelines for the development of spatial decision support systems that is the merging of geographic information systems and water resources models in a DSS for problems with . These problems have led researchers to investigate expert system (Morse, 1992), (Hu,1993) and object-oriented (Berrill and Moon, 1992) approaches to the implementation of GIS in a DSS. Such approaches considered the GIS to be the primary analytical tool of the DSS, with the integration of other technologies supporting its use as intelligent front ends. Consisting of a set of rules and user-supplied data which interact through an inference engine, an expert or knowledge-based system is able to derive or deduce new facts or data from existing facts and conditions. In the past four years, expert-system shells have become more widely available, allowing users to define the data base and rule base without using artificial intelligence programming languages. Many water resources DSS designers have thus seen expert systems as a powerful complement to numerical and spatial analysis tools.

Fedra (1993) reviewed the use of expert systems in water resources and identified three types of applications: purely knowledge driven systems, expert systems components in an intelligent front end, and fully embedded expert systems. Of these, intelligent front ends have been the most common. In general, they assist the user in selecting the appropriate numerical model or technique, specifying input parameter values, and interpreting model output. Lam and Swayne (1993) presented such an approach to the integration of virtually any computer technology useful to water resources planners. The role of the expert system was to provide an intelligent interface between the model and data, as well as descriptive dialogue between the user and machine.

Palmer and Spence (1992) used the programming language **PROLOG** and natural language to represent knowledge about water resources management. Their purpose was to help users who were unfamiliar with formal database management or computer programming to access hydrologic and other data. Other examples of expert systems as intelligent front ends were given by Simonovic (1991) for open channel flow measurement, Simonovic (1992) for reservoir management, Bender and Simonovic (1994) for long-range water supply forecast modeling, and Crowe and Mutch (1994) for assessing groundwater contamination potential. Besides aiding decision makers, each of these systems could be useful in training inexperienced analysts.

Related to intelligent front ends, which help the user to select the appropriate model, are knowledge-based model support systems, which help the user build the appropriate model. Rozenblit and Jankowski (1991) proposed such an approach to simulation modeling of natural systems and emphasized the following advantages: modular model specification facilities; high degree of model reusability; and support for model selection and coupling. Jankowski (1992) discussed the role of these model support systems within a DSS, illustrating their ability to create new models quickly and easily, to integrate model building blocks, and to interrelate models through a database.

Fully embedded or hybrid expert systems are typically problem-oriented rather than methodology-oriented. Whereas intelligent front ends enhance the use of models in a DSS, fully embedded expert systems enhance model results.

An example of such a system was given by McKinney et al. (1993). They developed an expert-GIS for long-term regional water-resources planning in which the expert system aided the user in analyzing the social, legal, and political aspects of the problem. Hidden from the user, the rules invoked by the expert system eliminated planning options which did not meet certain qualitative constraints supplied by the user.

Other embedded expert systems were developed for irrigation systems planning (Nir, 1991) and for crop planning during droughts (Raman et al., 1992). Finally, purely knowledge driven systems, based solely on a qualitative, causal understanding of how things work, have not been so common in water resources. Arnold and Rouve (1991) illustrated the concept and application potential of this type of system for water resources protection. Examples of other potential uses are operational control of a wastewater treatment plant and hazardous waste site assessment (Fedra, 1993).

An increasing number of water resources problems have been formulated in a multiobjective fashion. Due to the conceptual difficulties involved in using multiobjective models for the first time (i.e., selecting criteria, specifying satisfactory values, and evaluating trade-offs), several researchers have developed multiobjective decision support tools which meet two of the three requirements of a DSS. Namely, these tools provide analysis and interpretation capabilities, but not necessarily information management capabilities. Nonetheless, the potential of these tools in a fully developed DSS has become well known.

Recent examples of multiobjective decision support in water resources include Bogardi and Duckstein (1992), who presented an interactive multiobjective analysis method to embed the decision maker's implicit preference function; Ridgley and Rijsberman (1992), who employed multicriteria decision aid for a policy analysis of a Rhine estuary; and Theissen and Loucks (1992), who presented an interactive water resources negotiation support system. In the last two examples, the authors concluded that the use of multicriteria evaluation effectively provided a group DSS for the analysis.

Other work has focused on integrating technologies to support the multiobjective analysis. Simonovic et al. (1992) presented a rule-based expert system to facilitate and improve the choice of multiobjective programming weights to be used in a reservoir operation model. Short- and long-term operating goals represented the trade-offs in the model. Lee et al. (1991) developed a DSS for dredge-fill management based on a modified fuzzy-composite programming method for multiobjective problems under uncertainty. Values of risk and cost were transformed into fuzzy numbers to incorporate uncertainties into the trade-off analysis.

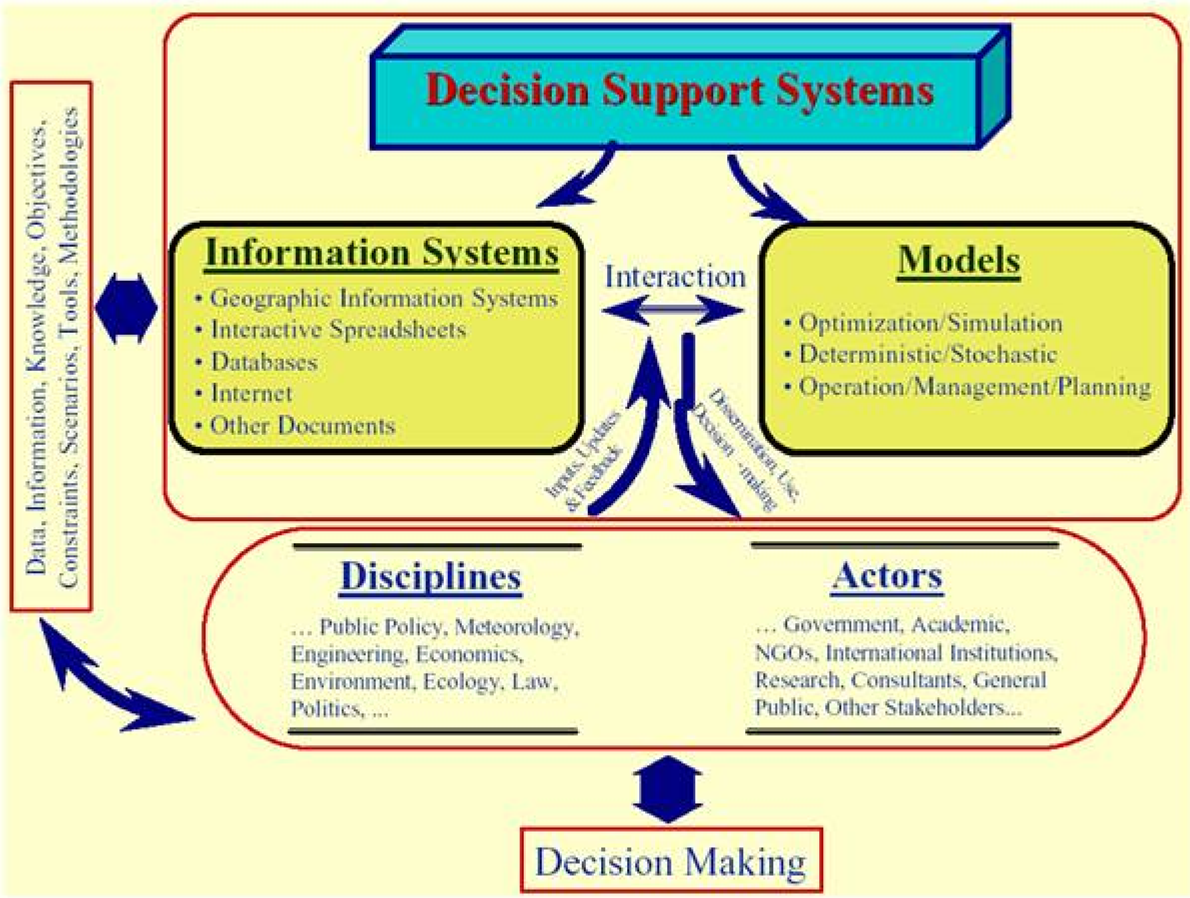


Fig. n° 2.4. The role of GIS in the Decision Support System

2.17 Role of hydrologic models in water resources management and land use planning

The vital needs of society, whether agricultural or industrial, demand the planning and the realization of various types of water management projects and the responsibility for the implementation of them relies on individuals and organizations, water authorities politicians, developmental, planning and environmental agencies, consulting engineers and building constructors.

An accurate dataset of the past hydrologic data and information is required for a correct planning, design and construction and a continuous stream flow of new data for use in forecasting future conditions and optimizing the day-today operation of the system is essential. In recent years, special studies on hydrology and on its reactions to climate change and on its interactions with social and environmental aspects have been increasing strongly. In addition, the rising demand for water, has led the authorities to apply a more integrated approach to water resource management, incorporating surface and underground water, including return flows, with consideration of all potential uses: industrial, river navigation, irrigation, municipal and environmental.

Water management now requires much more information extending well beyond the purely hydrological. An efficient and reliable water resource management system depends on the quantity and quality of hydrologic information used in planning and operation highlighting the important role of the hydrologist in investigating the spatial and temporal distribution of the earth's water resources, and their quality, at all scales. A strictly cooperation between water management and water use disciplines with economics, ecology and social sciences lead to the best results in planning and water resource management systems.

Unfortunately many important political, economic and social decisions, with significant impacts on environment and on hydrologic regime and water resources, are still made today without cooperation with hydrologic experts. In recent years the growing concern over the possible impact of climate change involved hydrologists and climatologists in the medium-long term planning of water resources development and decision making. Changes of economic environment , an increased water demand along with the evolution of social attitude towards water resources have led to an escalation of local conflicts on water use and conservation involving a growing number of users and citizen groups. In response to this situation, several European countries and the European Union, have promoted cooperation and inter-disciplinarily approach to design water management policies and have established institutions to solve disputes through negotiation processes.

Such negotiations have not always been successful.

The difficulties encountered may be partially attributed to the lack of interactive tool to investigate and compare the impact of various water management scenarios. Due to the consequent strong emphasis put by decision-makers and politicians on integrated and sustainable water resources management, decision-support systems showed a marked increase since the mid 1990's (Jamieson, 1996, Parker et al., 2002) involving social and economic sciences, ecology but also particular and unusual disciplines like game theories.

Water resource management is, in fact, a multifaceted issue that becomes more complex when considering multiple nations' interdependence upon a single shared trans-boundary river basin. With over 200 trans-boundary rivers shared by two or more countries (Wolf, 2002), it is important to develop tools to allow countries to cooperatively manage these shared and often limited water resources. Cooperative game theory provides tools for determining if cooperation can exist across jurisdictional boundaries through a suite of mathematical tools that measure the benefits of cooperation among basin stakeholders (Teasley, McKinney, 2007). Cooperative game theory can be also a useful tool for trans-boundary negotiation since it provides a range of possible solutions satisfying all players in the game and provides methods to fairly and equitably allocate the gains of that cooperation to all participating stakeholders, if the cooperation is shown to be feasible.

Cooperative game theory has been applied to water sharing in the Ganges and Brahmaputra basin (Rogers, 1969; Rogers, 1993), the Nile basin (Wu and Whittinghton, 2006; Wu, 2000), and Euphrates and Tigris (Kucukmehmetoglu and Guldmann, 2004; Kucukmehmetoglu, 2002) basins and for water trading from the Nile among the Middle east countries of Egypt and Israel, and the Gaza Strip and the West bank (Diner and Wolf, 1994). In all these cases the individual countries were considered as players in the game. Cooperative game theory was also applied to the water scarce trans-boundary Rio Grande/Bravo in the northern part of United States.

Fig n° 2.5 Rio Grande/Bravo location map.

2.10 Water resource planning in the history

Throughout the history, the development, management and policy of water resources have evolved in a variety of ways (Cech, 2004). For example, in the arid Middle East elaborate irrigation projects were constructed thousands of years ago to provide food and fiber while in the region between Tigris and Euphrates rivers was known as the Fertile Crescent in large part because of the abundance provided by ancient irrigation structures. The Chinese canals actually in use, were built during royal dynasties around 600 B:C: and earlier to transport people and armies. Later in Western Europe similar techniques were used to develop sophisticated water transport networks.

The technology of waterwheels, developed in Greece and Rome approximately 2000 years ago, were used for centuries to divert water for crops, to provide water for fountains in royal gardens, to supply drinking water.

The Roman Aqueduct in Italy is the base and foundation for water-based ancient civilization and most of the actual knowledge in hydraulics derives from the standing ruins.

Fig. n° 2.6. Appio Aqueduct in Rome, built in 312 B.C. on orders of censors Appius Claudius Caecus and Caius Plautius Venox carrying water from Tiber River to the city of Rome.

Ancient societies, in fact, prospered in such a florid way, when water supplies were properly managed while poor water management led to a decline in health and well-being of people and, in extreme cases, to the death of the entire civilization. The first Roman Aqueduct was (an elevated water delivery system made of stone) was built in 312 B.C. and by 300 B.C. there were 14 aqueducts in Rome delivering over 1.5 million liters per day of water to Roman citizens.

The water in excess was used to power the city's fountains and flush sewage into the Tiber River. The construction of aqueducts, pipelines, other water delivery structures sometimes altering the natural water resources features by digging canals to drain lakes and marshes allowed roman cities to grow in size and population.

The Roman Empire also developed extensive water delivery systems in France, Netherlands and Great Britain.

Fig. n° 2.7. The Segovia Roman Aqueduct, built during the reign of the Roman Emperor Traianus (reigned 98-117 B.C.); it carried water 16 km from Frio River to the city of Segovia (Spain).

So the origins of water resources planning can be retrieved thousand of years ago in the roman ancient society but, generally, planning projects were operational along major rivers of the world, such as Nile, Indus, Yangtze. The ancient Egyptians relied on monsoonal rains in the mountains of

Ethiopia to the south to bring floodwater and fertile sediments to the Nile River Valley of Egypt. Egyptians used lifting devices to withdraw groundwater to irrigate crops. In China the Huang He River (also called the Yellow River) was the cradle of Chinese civilization. Levees (earthen and rock dykes) were constructed over 2500 years ago along smaller branches of the Huang He River to control floods.

In most recent years very few governmental functions have been more important historically than managing water. Early in United States history, for example, despite some questions over the constitutionality of the federal government getting involved in local and regional economic development, for most of the people a partnership between government and the private sector was needed in order to plan for and manage the coastal and inland waterways of the new nation. The expenses involved in such activities as dredging rivers, constructing levees, and building canals were too great for private enterprise to undertake alone. Hence, federal agencies were created to assist with regional economic development projects and waterborne transportation systems (Clarke, 2003).

The Army Corps of Engineers was created with a statute in 1802, and its original purposes were to improve navigation on existing waterways and to explore western water routes for an expanding nation. Throughout the nineteenth century, army engineers distinguished themselves in the exploration and mapping of the continent. The most famous expedition was one by Lewis and Clark, who set out from St. Louis, Missouri, in May 1804 to find a route to the Pacific Ocean.

In 1824 with an act of Congress, The Army Corps of Engineers became the nation's preeminent water resources manager for improving navigation on the Mississippi and Ohio Rivers, and to use their expertise in determining the most practicable way of doing so.

Legislation passed in 1850 added water resources planning to the Corps' responsibilities, and in 1879 a Mississippi River Commission was established, with the Corps in charge of planning for an entire river basin. The agency's interest in planning and managing the nation's waterways continues to this day in the form of numerous activities, including channelization projects, dredge and fill activities, harbor improvements, floodplain management, and the construction and maintenance of a vast system of locks and dams on the nation's largest rivers (Clarke J.N., 2003). So the first example of water resources planning as institutional duty in the United States appeared in 1850 with The Army Corps of Engineers.

Whereas the Army Corps of Engineers was given authority to undertake projects throughout the entire United States, the Bureau of Reclamation, a second federal agency created in 1902, was limited by statute to working in the sixteen westernmost states. Nevertheless, the Bureau, like the

Corps, developed into a powerful planner and manager of water resources during the twentieth century.

Another federal agency with a regional focus is the Tennessee Valley Authority (TVA) that was created in 1933; the TVA today continues to be a significant component of the nation's water planning and management infrastructure.

Throughout most of the twentieth century, the U.S. Army Corps of Engineers and the Bureau of Reclamation, and the TVA applied concepts of conservation and multipurpose development to guide their planning of water resources projects. Conservation at the turn of the century meant using a scarce resource such as water to the fullest extent possible. The president Theodore Roosevelt (1858–1919) and other policymakers stressed the need for comprehensive river basin planning as the best approach to the conservation of the nation's resources.

In 1950, policymakers in Washington, D.C. undertook a comprehensive review and analysis of water resources planning and management. Known as the Green Book for the color of its cover, the report presented the classic economic efficiency model as the standard for analysis.

In 1958, the Green Book was revised and published with the title, Proposed Practices for Economic Analysis of River Basin Projects. It covered the basic concepts of benefit-cost analysis, principles and procedures for project and program formulation, analysis of various project purposes, and cost allocation methods. Most of the report's findings were incorporated into the President's Bureau of the Budget guidelines for water planning and management known as Circular A-47. This document went into effect in 1953.

For more than 150 years, water planning and management in the United States had as its principal goals economic and social development. It was spectacularly successful. By the end of the Second World War (1939–1945), the United States was an economic superpower rivaled only by the former Soviet Union.

But beginning about mid-twentieth-century, the recognition spread in the United States that economic development, urbanization, and population growth came at a heavy cost to the natural environment. A major change in societal values occurred in the 1960s and 1970s, and these values became increasingly reflected in the water resources policy arena.

In Italy the management of water resources have been developing during the years passing through the medieval wide construction of weirs and canals to the dam realizations in VIII-IX centuries especially in the northern part of Italian peninsula and to the hydraulic works and structures realized all over the national land to manage and control the available water resources with particular reference to the numerous shallow and fold events occurring in the second post-war period.

In the years from the second world war to 1990, hydro-geological instability phenomena likes shallow landslides and flood events, caused 3480 victims and damages for more than 17 millions of actual euros (National Geological Service, 1992). To face to the numerous natural disasters happening in 1989 the Law n° 183 was introduced deeply innovating the soil defense discipline in Italy and substantially ordering the integration of the previous existing institutions in a new organizational setting and the actions scheduling with the River Basin Plan.

2.11 River Basin Plan evolution in Italy and Europe

2.11.1 The Italian soil and water conservation act

Before the law n°183/89 was enacted, water management, hydraulic works, mountain settlements, pollution and public health have been regulated by the following historical norms:

-Royal Decree n° 523, 25th July 1904 on hydraulic works regulation;

-Royal Decree n° 1809/1922 that assigns soil reinforcement, ground stabilization works and reforestation to the Department of Public Works;

-Royal Decree n° 3267/1923 on reordering and reform of forests and mountain lands legislation where hydro-forest settlement works were defined with reference to reforestations, soil reinforcement and connected works and other hydraulic eventually needed works;

-Royal Decree n° 1726/1929 that recognized reforestation and mountain land reclamation competences to the Department for Rural Affairs;

-Law n° 1775/1933 on water resources and electrical systems set-up;

-Royal Decree n° 215/1933 bringing new rules for integral land reclamation and defining the works to realize in mountain lands under hydro-geologic disaster as land reclamation works.

The laws reading and historical investigation shows a soil defense concept based above all on requalification and socio-economic development with particular reference to hydraulic and land reclamation works, water uses regulations, the award of hydraulic concessions and deliveries, land and forest reclamation, hydro-geological settlement, mining activities discipline, internal navigation systems. So in the Italian legal order, the soil defense expressions have always show a functional character pointing at public actions for ground stabilization and hydraulic safety often with reference to distinct objects in soil, groundwater, water resources as clearly separated and independent matters. Only with the law n°183/1989 there was a substantial review and reorganization of soil defense in a new integrated and all-accomplished point of view leading to the River Basin Plan as a tool for water resources and ground stability planning and management incorporating environmental protection.

Planning activities , programming and accomplishing include:

-settlement, preservation and recovery of soil in river basins with hydraulic, hydro-geological, forest, land reclamation and botany actions and nature and fauna requalification processes;

-water courses, mouths, humid zones settlement, regulation and defense;

-peak flow moderation also with ponds, laminated and expansion reservoirs, draining channels, delivery devices for flood prevention and control;

-mining activities discipline to prevent soil erosion, hydro-geological instability, river bed degradation and retreating coastline;

-slope and unstable areas consolidation and defense, landslides and avalanches prevention and control;

-soil subsidence phenomena containment and saltwater intrusion constraint to restore equilibrium conditions in groundwater and fresh water resources;

-coastal protection from saltwater intrusion also with sand depositions and dune bars reconstruction;

-superficial water and groundwater resources protection to avoid deterioration and making them adequate to national and European Community laws, ensuring their rational use and management for agricultural and human uses, tourist and recreation activities with agricultural, urban and industrial wastewaters purification actions;

- a rational use of superficial water and groundwater resources with an efficient water and irrigation network granting a minimum flow requirement in the water courses even with all the necessary delivery devices;

-hydraulic police services, internal navigation, hydraulic emergency services and plant management;

-ordinary and extraordinary maintenance activities for works and plants;

-environmental protection and lands legislation defining criteria for government properties protection and preservation and the institution of protected areas, river and lake parks;

-the integrated management of water public services based on cheapness and performance efficiency criteria;

-hydro-geological constrain reorder;

-alert and prevention activities reorganization by public territorial agencies.

Starting from the Law n°183/89, water reclaimation and reuse and all the environmental connected aspects have been adopted as objectives of a complex and organized planning system where a river basin plan is seen as sector-based territorial plan and cognitive, normative and technical tool to program and plan actions and rules for soil preservation and landscape and valorization and the correct and rational water management on the base of physical and environmental characteristics of the interested land. Synthetically to define and produce a national, interregional, regional river basin plan it's necessary to delineate the standard contents grounding on:

-cognitive characters contents as knowledge about physical environment elements and hazard general conditions, soil uses according urban plans, natural resources utilizations and constraints, preventing evaluation of costs-benefits rates, of environmental impacts and financial resources and of the effects consequent to expected plans, programs and works;

-strategic and programming contents as directives and plans for soil defense, hydraulic and hydro-geological settlements, water, soils, forests, mining resources management, planning of the future uses of the natural resources of the basin, integrated water resources management according to cheapness and performance efficiency criteria;

-technical-operative contents as definition of necessary actions and works, distinguished by zone, purposes and technical characteristics according to flood hazard and hydro-geological instability phenomena and subsidence seriousness and to the socio-economic development objectives;

-limitations and normative contents as limitations, constraints and rules for soil and environment preservation, hydro-geologic constrain reorder, limitations against soil pollution and civil and industrial wastewater drainage, hydraulic policy and emergency services and internal navigation disposals.

The redaction of this planning tool together with all the connected activities for hydro-geological instability phenomena prevention and control, is responsibility of the Regional or Interregional River Basin Authority.

2.11.2 The 2000/60 European Union Directives

The Water Framework Directive (Directive 2000/60) prescribes that management activities should aim to achieve the goals of the directive within geographical areas or river basin districts (RBDs). These are based largely on surface water catchments, together with the boundaries of associated groundwater and coastal water bodies.

The river basin management plan will:

-record the current status of water bodies within the river basin district;

-set out the measures planned to meet the objectives;

-act as the main reporting mechanism to the Commission and the public.

The whole process of river basin management planning includes the preparation of programs of measures at basin level for achieving the environmental objectives of the Water Framework Directive cost-effectively. The planning, implementation and evaluation of the program of measures is an iterative process that will probably include the river basin management plan of the first (2009), second (2015) or further cycles (2021, 2027). Basic measures include control of pollution at source through the setting of emission limit values as well as through the setting of environmental quality standards. The use of economic instruments, such as water pricing, is part of the basic measures. Here, in particular, the 'polluter pays' principle should be taken into account.

The directive aims to ensure that pricing policies improve the sustainable use of water resources. The planning process together with the implementation of the program of measures is often referred to as river basin management. These RBMPs should be made available for information and consultation by the public. For each river basin district, a river basin planning process must be set up. The first milestone of this planning process (analysis, monitoring, objective-setting and consideration of measures to maintain or improve water status) is the initial river basin management plan. In Italy the Water Framework Directive was implemented with the redaction of the Law 152/06 on environmental norms, best known as Environmental Code. Physically based hydrologic models, such as SWAT or other continuous and event-based hydrologic models for watershed are important tools to support water resources management and planning and can be successfully applied to provide a river basin plan.

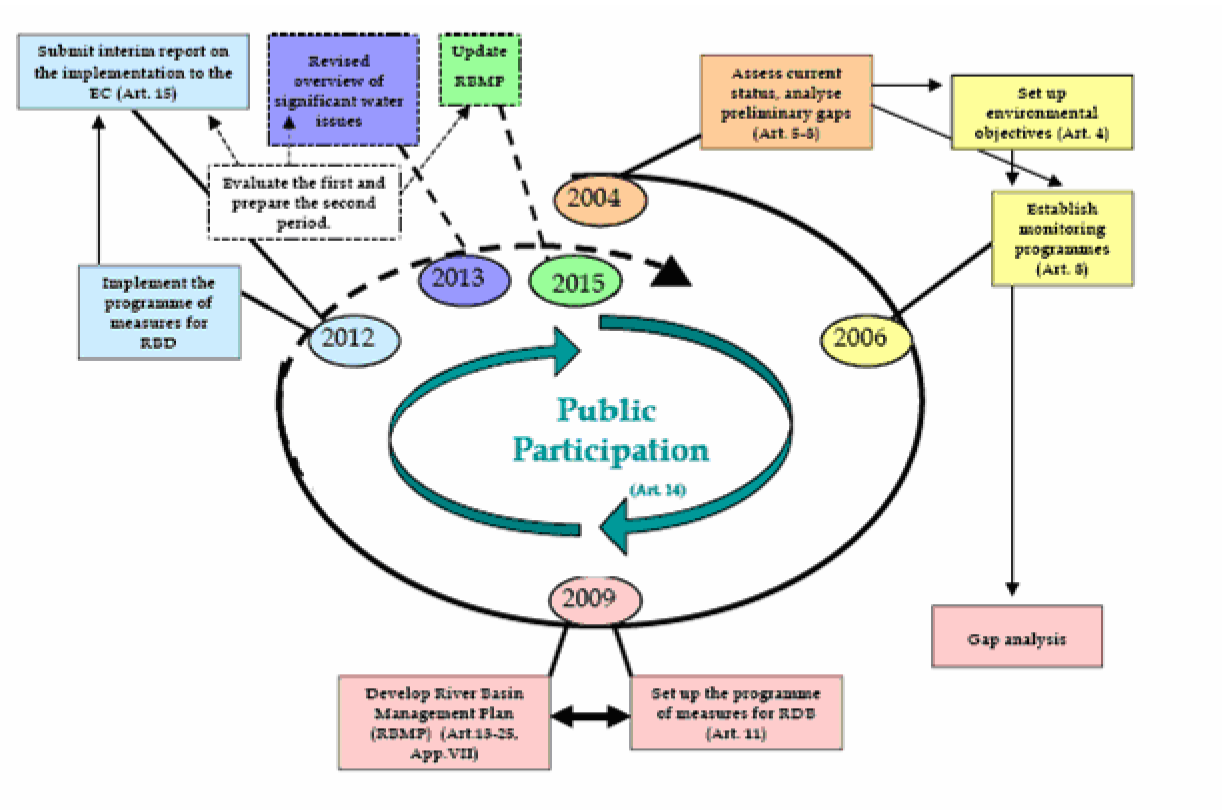


Fig. 2.8 River basin planning processes (www.eea.europa.eu)

CHAPTER 3

SWAT MODEL

3.1 General description of SWAT Model.

All the intrinsic difficulties in the analysis of interactions between soil and water on a mainly agricultural area and the investigation of diffuse sources pollution phenomena, request hydrologic models application at catchment scale. These models are able to evaluate loads from both point and diffuse sources and to describe the pollutants generation processes and transport, transformations and iterations that happen before they move downstream.

After an accurate comparison between the available models in literature, Swat model, that is Soil and Water Assessment Tool, developed in 90's by Dr. Jeff Arnold for USDA-ARS, United States Department of Agriculture, Agricultural Research Service, was chosen for Marta River basin simulation.

Swat is a comprehensive model that requires a diversity of information in order to run and it can produce reliable results when you have a rich dataset at your disposal (morphological, soil, climatic, hydrologic data), enables water balance estimation and directly models the loading of water, sediments and nutrients from land areas in a watershed or to the stream network from sources not associated with a land area and referred to as point sources, the most common of which is, for example, a treatment plant. Swat allows to model daily or average daily loading data for point sources to the main channel network: these loadings are then routed through the channel network along with the loadings generated by the land areas. But, above all, Swat was developed to predict the impact of land management practices on water, sediments and agricultural chemical yields in large or complex watersheds with varying soils, land use and management conditions over long periods of time. It's also a GIS integrated model with a really widespread international network of users and developers and it boasts of a full range of applications performed in the United States and it is usually implemented in 90 nations all over the world. To support this "global" use of this model, ARS-USDA and Texas A&M University teams, in cooperation with several European research canters, set up a permanent internet forum and organized 4 international conferences on Swat use and development and the next one will be held in August 2009 in Colorado, United States, University of Colorado at Boulder.

Swat, acronym for Soil and Water Assessment Tool, is a physically based river basin, or watershed, scale model. Rather then incorporating regression equations to describe relationships between input and output variables, it requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling etc are directly modeled by Swat using this input data.

Benefits of this approach are:

-watersheds with no monitoring data (e.g. stream gauge data) can be modeled;

-the relative impact of alternative input data (e.g. changes in management practices, climate, vegetation etc) on water quality or other variables of interest can be quantified. While Swat can be used to study more specialized processes such as bacteria transport, the minimum data required to make a run are commonly available from government agencies. It is also computationally efficient since simulation of very large basins or a variety of management strategies can be performed without excessive investment of time or money. It enables users to study long term impacts and many of the problems currently addressed by users involve the gradual buildup of pollutants and the impact on downstream water bodies. To study this type of problems, results are needed from runs with output spanning several decades. Swat is a continuous time model and it is not designed to simulate detailed, single event, flood routing. It's a long term yield model and it's provided with a weather generator to simulate climatic parameters for long periods of time even in the absence of observations (Neitsch, Arnold, Williams, 1999).

3.2 Development of Swat

Swat incorporates features from several ARS models and is a direct outgrowth of the SWRRB model, Simulator for Water Resources in Rural Basins (Williams et al. 1985, Arnold et al. 1990). SWRRB is a continuous time step model that was developed to simulate nonpoint source loadings from watersheds. Many other models contributed to the development of Swat: CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems), (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al. 1987) and EPIC (Erosion-Productivity Impact Calculator) (Williams et al. 1984). SWRRB derived from some modification on the daily rainfall CREAMS model hydrology.

So the CREAMS model was expanded to allow simultaneous computations on several sub-basins to predict basin water yield, a groundwater or return flow component was added, a reservoir storage component was also added to calculate the effects of farm ponds and reservoirs on water and sediment yield, a weather simulator incorporating data for rainfall, solar radiation and temperature was created to facilitate long term simulations and provide temporally and spatially representative weather. The method for predicting the peak runoff rates was also improved.

The EPIC growth model was added to account for annual variation in growth and a simple flood routing component was added. Sediment transport components were added to simulate sediment movement through ponds, reservoirs, streams and valleys. Finally calculation of transmission losses was incorporated. The first development of SWRRB reflected the emphasis for water quality assessment and noticeable modifications of it included the incorporation of: the GLEAMS pesticide fate component, the optional SCS technology for estimating peak runoff rates, newly developed sediment yield equations. These modifications extended the model's capacity to deal with a wide variety of watershed management problems. In the late 1980's the Bureau of Indian Affairs needed a model to estimate the downstream impact of water management within Indian reservation lands in Arizona and New Mexico and wanted to simulate stream flow for basins extending over several thousand square kilometers.

To study this extended area, it needed to be divided in sub-unit, several hundred of sub-basins but watershed division in SWRRB was limited to ten sub-basin and the model routed water and sediment transported out of the sub-basins directly to the watershed outlet. These limitations led to the development of a new model called ROTO (Routing Outputs To Outlet) (Arnold et al. 1995) which took output from multiple SWRRB runs and routed the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB sub-basins limitation by linking multiple SWRRB runs together.

Although this approach was effective, the input and the output of multiple SWRRB files requires considerable computer storage. All SWRRB runs had to be made independently and then input to ROTO for the channel and reservoir routing. To overcome the awkwardness of this arrangement, SWRRB and ROTO were merged into one single model, SWAT.

While allowing simulations of very extensive areas, Swat retained all features which made SWRRB such a valuable simulation model.

Since its creation, Swat has undergone continued changes and expansions of capabilities and the most important improvements of the model include:

-SWAT 94.2 Multiple Response Unit (HRU) incorporated;

-SWAT 96.2 Auto-fertilization and auto-irrigation added as management options, canopy storage of water incorporated, a CO_2 component added to crop growth model for climatic change studies, Penman-Monteith potential evapotranspiration equation added, lateral flow of water in the soil on kinematic storage model incorporated, in-stream nutrient water quality equations from QUALE2 added and in-stream pesticide routing added;

-SWAT 98.1 snow melt routines improved, in-stream water quality improved, nutrients cycling routines expanded, grazing, manure applications and tile flow drainage added as management options. This model was modified to be used in the Southern Hemisphere;

-SWAT 99.2 Nutrient cycling routines improved, rice7wetlands routines improved, reservoir/pond/wetland nutrient removal by settling added, bank storage of water in reach added, routing of metals through reach added, all year references in model changed from last 2 digits of year to 4-digits year, urban buildup/wash off equations added along with regression equations from USGS;
-SWAT 2000 Bacteria transport routine added, Green & Ampt infiltration added, weather generator improved. The model allows daily solar radiation, relative humidity and wind speed to be read in or generated. Also Evapotranspiration values can be read in or calculated by the model. It enabled simulation of unlimited number of reservoirs, Muskingum routing method added and modified dormancy calculations for proper simulation in tropical areas;
-SWAT 2005 Bacteria transport routines improved, weather forecast scenarios added, sub-daily precipitation generator added, the retention parameter used in the daily CN calculation may be a function of soil water content or plant evapotranspiration.
In addition to all the changes described, interfaces for the model have been developed in Windows (Visual Basic), in GRASS and Arcview and ArcGis.

3.3 Overview of Swat Model

SWAT allows a number of different physical processes to be simulated in a watershed partitioning it in sub-watershed or sub-basins and this device is particularly useful when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. By partitioning the watershed in sub-basins, different areas of the watershed can be referenced to one another spatially.
For each sub-basin all information needed is grouped or organized in categories: climate, hydrologic response unit (HRU's), groundwater, main channel or reach, draining the sub-basin. Hydrologic response unit are lumped land areas within the sub-basin with a unique land cover, soil and management combinations. Whatever process is to be studied by SWAT, water balance is the driving force behind everything that happens in the watershed.
The hydrological water balance simulated by the model has to be conform to the watershed behavior in order to accurately predict the movement of pesticides, sediments and nutrients. The hydrology of a watershed is simulated with a two parts division: land phase and routing phase or water phase.
The land phase of the hydrological cycle controls the amount of water, sediments, nutrients and pesticide loadings to the main channel in each sub-basin while the water phase or routing phase can

be defined as the movement of water, sediments, nutrients and pesticide loadings through the channel network of the watershed to the outlet.

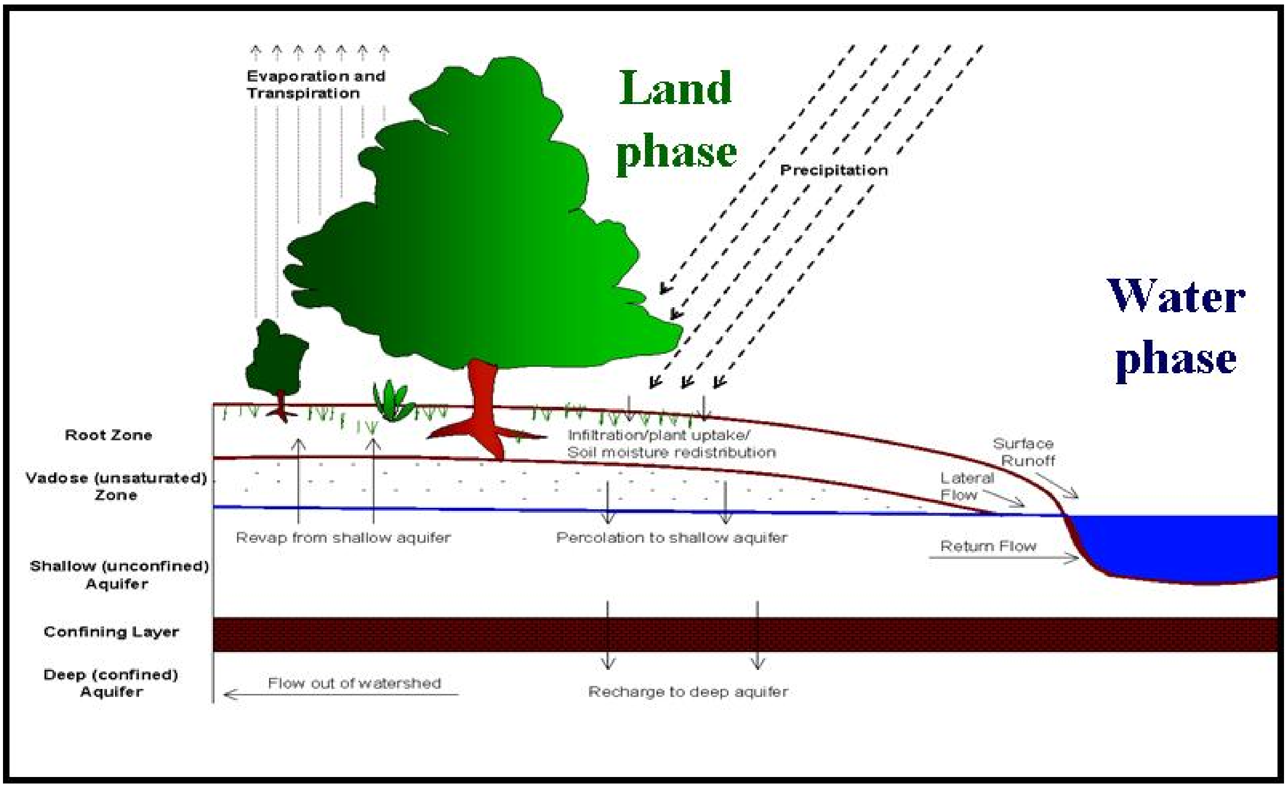


Fig 3.1 Land phase and Water phase processes schematization by SWAT

3.4 LAND PHASE of the Hydrologic cycle

The hydrologic cycle simulated by SWAT follows the equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \tag{3.1}$$

where SW_t is the final soil water content (H_2O mm), SW_0 is the initial soil water content on a day i (H_2O mm), t is the time in days, R_{day} is the daily rainfall amount (H_2O mm), Q_{surf} is the total amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i (H_2O mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (H_2O mm), Q_{gw} is the amount of return flow on day i (H_2O mm).

Thanks to the watershed subdivision differences in evapotranspiration due to different soils and crops can be taken into account. Also runoff is predicted separately for each HRU and routed to obtain the total runoff of the watershed.

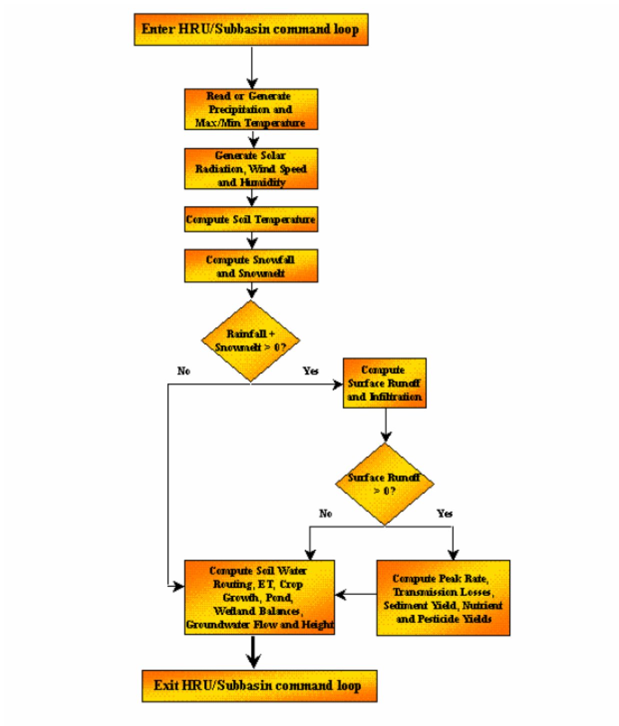


Fig.3.2. Sub-basin command loop. It shows the general sequence of processes used by SWAT to model the land phase of the hydrologic cycle.

3.4.1 Climate

The climate of the watershed provides soil moisture and energy input to control water balance and determine the relative importance of the different components of the hydrologic cycle. The climatic variables required by SWAT consist of daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. The model allows values for daily precipitation, maximum/minimum temperature, wind speed, solar radiation and relative humidity to be input from records of observed records or to be generator by SWAT during the simulation. Daily precipitation which are not read in measured data, are generated using a model developed by Nicks (1974) also to fill in missing data in measured records. The precipitation generator uses a Markov chain model to define a day as wet or dry comparing a random number (0.0-1.0) generated by the model to monthly wet-dry probabilities input by the user. If the day is classified as wet, the amount of rainfall is determined from a skewed distribution or a modified exponential distribution. Sub-daily precipitation values are derived from a double exponential function to represent the intensity patterns within a storm so that rainfall intensity exponentially increases with time to a maximum, or peak, intensity. Once the peak intensity is reached, the rainfall intensity decrease with time until the end of the storm.

Maximum and minimum air temperature and solar radiation are generated from a normal distribution and the generator account for temperature and radiation variations caused by dry vs rainy conditions through a continuity equation. Maximum air temperature and solar radiation are adjusted downward when simulating rainy conditions and upwards when simulating dry conditions. The adjustments are made so that the long term generated values for the average monthly maximum temperature and monthly solar radiation agree with the input averages. A modified exponential equation is used to reproduce daily mean wind speed given the mean monthly wind speed. The relative humidity model uses a triangular distribution to simulate the daily average relative humidity from the monthly average. As with temperature and radiation, the mean relative humidity is adjusted to account for wet-and-dry day effects.

SWAT also classifies precipitation as rain or freezing rain/snow using the average daily temperature. At first SWAT snow cover model was a simple, uniform snow cover model but it has been updated to a more complex model allowing non-uniform cover due to shading, topography, drifting and land cover. A threshold snow depth can be defined above which snow coverage will always extend to 100 % of the area while, below this value, the snow coverage is allowed to decline non-linearly based on an areal depletion curve. Snow melt is controlled by the air and snow pack temperature, the melting rate and the areal coverage of snow. Snow melting starts when temperature is greater than 0°C following a linear function of the difference between the average snow pack maximum air temperature and the base or threshold temperature for snow melt. Melted snow is considered as rainfall for runoff production and percolation. For snow melt, energy is set to zero and the peak runoff rate is estimated assuming uniformly melted snow for a 24 h duration.

Soil temperature is one of the main parameters impacting on water movement and the decay rate of residue in the soil. Daily average soil temperature is calculated at the spoil surface and in the centre of the soil layer. The temperature of the soil surface is function of snow cover, plant cover and residue cover, the bare soil surface temperature and the previous day’s soil surface temperature. The temperature of a soil layer is a function of the surface temperature, mean annual air temperature and the depth in the soil at which variation in temperature due to changes in climatic conditions no longer occurs. This depth is called damping depth and it depends on bulk density and the soil water content.

3.4.2 Hydrology

Precipitation descending, can be intercepted and held in the vegetation canopy or fall to the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff moving relatively quickly toward a stream channel and contributing to short term stream response. Infiltrated water can be held in the soil and later evapotranspired or it may slowly make its way to the surface-water system via underground paths.

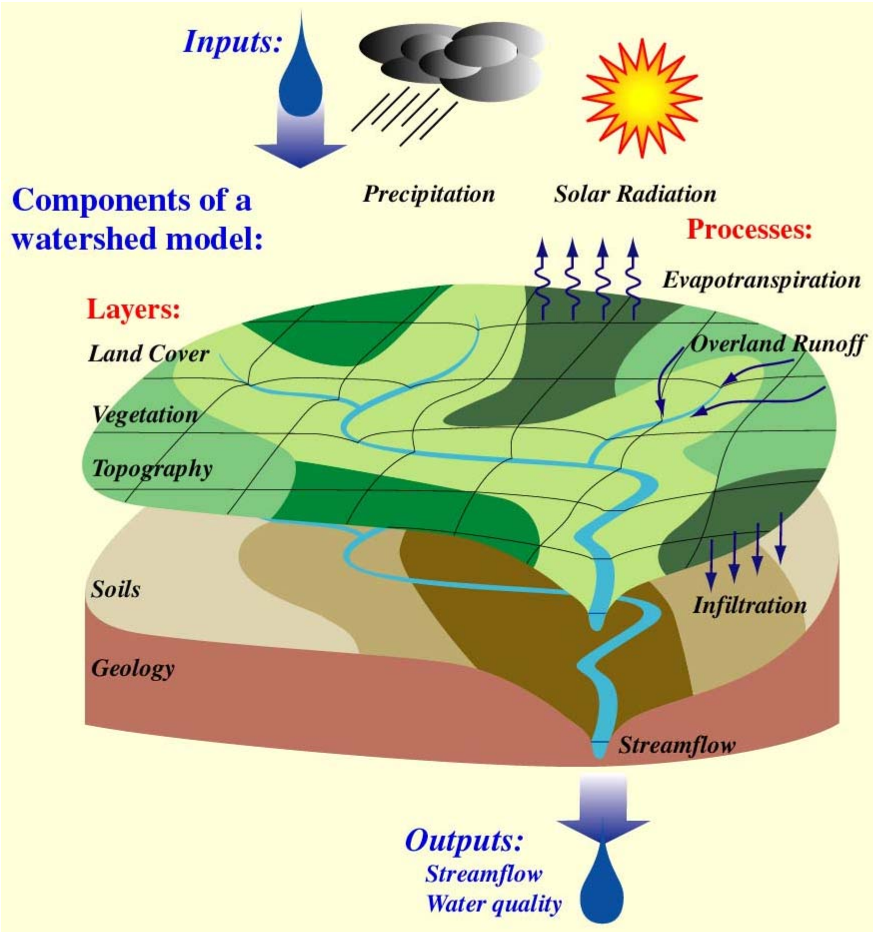


Fig. 3.3 Main inputs and outputs in SWAT model

The potential pathways of water movement can follow several possible steps and phenomena.

3.4.3 Canopy storage

Canopy storage (interception by vegetative surface) phenomenon can significantly influence infiltration, surface runoff and evapotranspiration. When rainfall descends, canopy interception reduces erosion energy from drops and holds a part of it. Canopy storage influence on these processes depends on leaf area density and plant species morphology. When using the curve number method to compute surface runoff, canopy storage is taken into account during surface runoff calculations. Canopy storage must be modeled separately when using other methods such as Green & Ampt to evaluate infiltration and runoff.

With SCS (Soil Conservation Service) method, leaf interception is considered in terms of initial subtraction. This variable includes also surface storage and infiltration before runoff starting and it's estimated as about 20% of the retention parameter value for a specific day. SWAT allows the users to input the maximum water quantity that can be intercepted by canopy varying it daily depending on leaf area index and calculated as follows:

$can_{day} = \frac{can_{mx} \cdot LAI}{LAI_{mx}}$ where can_{day} is the maximum water quantity that can be intercepted by canopy in a given day (H_2O mm), can_{mx} is the total maximum amount of water that can be held by canopy when it's at its maximum growth (H_2O mm), LAI is the leaf area index for a given day and LAI_{mx} is the maximum leaf area index for the plant.

3.4.4 Infiltration

Infiltration refers to the water entering into a soil profile from the soil surface. Infiltration rate depends on the moisture content of the soil prior to the introduction of water at the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conducitivity of the soil. Since the Curve Number method used to evaluate surface runoff run on daily time steps, it is not able to directly model infiltration. So the amount of water entering in the soil profile is calculated as a difference between the amoun of rainfall and the amount of surface runoff. Green & Ampt infiltration method can directly model infiltration but it requires rainfall data for sub-daily time steps.

3.4.5 Redistribution

Redistribution refers to the continued movement of water through a soil profile due to irrigation or precipitation input of water. It is caused by the differences in water content in the profile. Once the water content throughout the entire profile is uniform, redistribution stops. This component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. According to it, percolation occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is dominated by the saturated conductivity of the soil layer and it's influenced by soil temperature. If the temperature is 0°C or below, no redistribution is allowed for that layer.

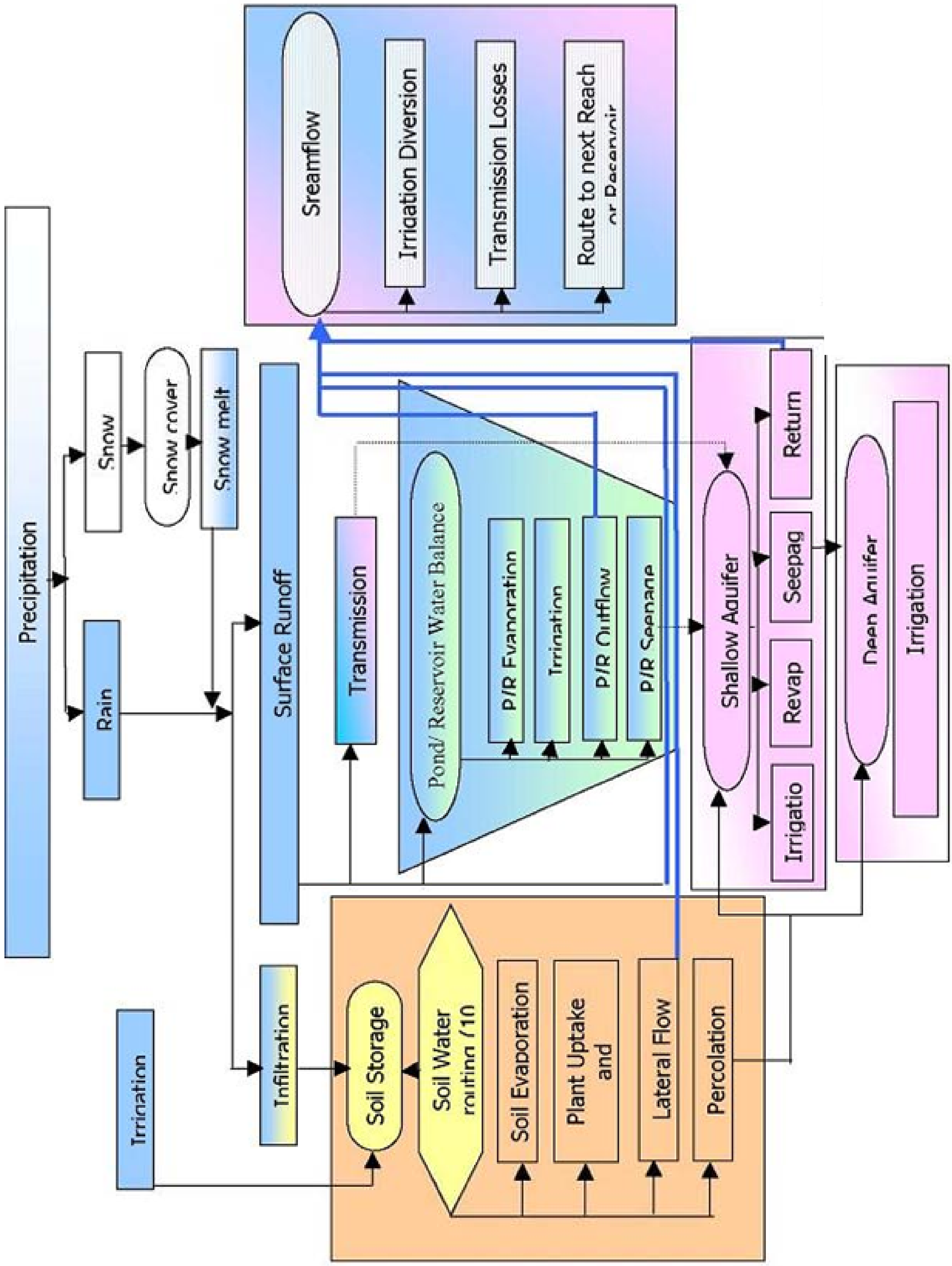


Fig. 3.4 Schematic representation of water movement pathways by SWAT.

3.4.6 Evapotranspiration

Evapotranspiration is a collective term for all processes in which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapor. It includes evaporation from rivers and lakes, bare soil and vegetative surface, evaporation from within leaves of plants (transpiration), sublimation from ice and snow surfaces. The evapotranspiration is a function of temperature, at increasing of which it increases almost until the temperature is so high to cause vegetation to die. It also increases as available water increases but not indefinitely. The model evaluate separately soil and vegetation evaporation. The potential evaporation from soil is estimated as a function of potential evapotranspiration and leaf area index (leaf area and HRU surface ratio) while the real soil evaporation is calculated using exponential functions of soil depth and moisture. Transpirationn is simulated as a linear function of potential evapotranspiration and leaf area index. The threshold value, given by really evaporated water column when water available quantity is almost equal to the quantity that can be transformed in vapor by means of all atmospheric and vegetation factors, is called potential evapotranspiration. The potential evapotranspiration (ETp) concept was introduced by Thornthwaite for the first time (1948) as a part of a climatic classification scheme. He defines ETp as the ratio at which evapotranspiration can occur from a wide uniformly covered by vegetation in growth phase that is able to access to an unlimited quantity of water present in the soil and it is not exposed to advection and thermal excursions. Since the evapotranspiration rate strongly depends on vegetation characteristics,, Penman (1956) defined again Etp as the amount of transpired water from a grassland covering the surface totally with a uniform depth and always saturated. Several methods have been developed to estimate Etp and three of those are incorporated in SWAT and they are:

-Penaman-Monteith method (Monteith, 1965; Allen, 1986; Allen et al., 1989),

$$\lambda E = \frac{\Delta\left(H_{net} - G\right) + \rho_{air} \cdot \left(e_z^0 - e_z\right) / r_a}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \tag{3.2}$$

where λE is the latent heat flux density (MJ m^{-2} d^{-1}), E is the depth rate evaporation (mm d^{-1}), Δ is the slope of the saturation vapor pressure-temperature curve, de/dT (KPa $°C^{-1}$), H_{net} is the net radiation flux (MJ m^{-2} d^{-1}), G is the heat flux density (MJ m^{-2} d^{-1}), ρ_{air} is the air density (kg m-^{3}), c_p is the specific heat at constant pressure (MJ kg^{-1} $°C^{-1}$), e_z^0 is the saturation vapor pressure of air at height z (KPa), e_z is the water vapor pressure of air at height z (KPa), γ is the psychometric constant

(KPa °C^{-1}), r_c is the plant canopy resistance (s m^{-1}) and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1}).

-Priestley-Taylor method (Priestley and Taylor, 1972),

$$\lambda E_0 = \alpha_{pet} \cdot \frac{\Delta}{\Delta + \gamma}\left(H_{net} - G\right) \quad (3.3)$$

where λ is the latent heat of vaporization (MJ kg^{-1}), E_0 is the potential evapotranspiration (mm d^{-1}), α_{pet} is a coefficient, Δ is the slope of the vapor pressure-temperature curve, de/dT (KPa °C^{-1}), γ is the psycrometric constant (KPa °C^{-1}), H_{net} is the net radiation (MJ m^{-2} d^{-1}), and G is the heat flux density to the ground (MJ m^{-2} d^{-1}).

-Hargreaves method (Hargreaves et al. 1985)

$$\lambda E_0 = 0.0023 H_0 \left(T_{mx} - T_{mn}\right)^{0.5} \cdot \left(\overline{T}_{av} + 17.8\right) \quad (3.4)$$

where λ is the latent heat of vaporization (MJ kg^{-1}), E_0 is the potential evapotranspiration (mm d^{-1}), H_0 is the extraterrestrial radiation (MJ m^{-2} d^{-1}), T_{mx} is the maximum air temperature for a given day (°C), T_{mn} is the minimum air temperature for a given day (°C) and $\overline{T}_{av}$ is the mean air temperature for a given day (°C).

SWAT also allows to input measured or calculated evapotranspiration values from records to read in. According to the chosen method for evapotranspiration assessment, different types of input are required. Penaman-Monteith method needs solar radiation, air temperature, relative humidity and wind speed.

Priestley-Taylor requires solar radiation, air temperature and relative humidity while Hargreaves method only uses air temperature to estimate evapotranspiration. Once the potential evapotranspiration is determined the real one has to be calculated. At first SWAT considers the evaporation from rainfall intercepted by canopy which is an important factor in forested areas above all where the leaf area intercept a great quantity of water. Later it calculates the maximum amount of transpiration and sublimation from soil, from that part of soil that is directly exposed.

3.4.7 Lateral Subsurface Flow

Lateral subsurface flow, or interflow, is stream-flow contribution which originates from below the surface but above the zone where rocks are saturated with water. This contribution is fundamental in areas with soil characterized by high hydraulic conductivity in surface layers and low or null hydraulic conductivity at low depth. This system allows flow to percolate vertically until the water proof layer and here water stops creating a saturated zone that becomes source for subsurface lateral flow. To predict lateral flow, in every soil layer, SWAT uses a cinematic model, whose parameters vary depending on hydraulic conductivity, slope and soil moisture.

3.4.8 Surface runoff- Curve Number method (SCS-CN)

Surface runoff, or overland flow, is flow that occurs along a sloping surface. Using daily or sub-daily rainfall data, SWAT simulates surface runoff volumes and peak runoff rates for each HRU. SWAT incorporates two method to estimate runoff: SCS Curve Number procedure (Soil Conservation Service, 1972), and Green & Ampt infiltration method (1911).

For SCS Curve Number method, surface runoff equation follows an empiric model that was of common use in 1950. It's the result of more than 20 years of study on relationships between rainfall and runoff on small watersheds in the United States and it was developed to provide a substantial base for runoff flow evaluation in correspondence of different land uses and soil classes (Rallison and Miller, 1981).

SCS Curve Number equation (SCS, 1972) is:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \tag{3.5}$$

where Q_{surf} is the runoff amount or rainfall excess (H_2O mm), R_{day} is the total daily rainfall amount, I_a is the initial subtraction that includes surface storage, interception and prior runoff infiltration (H_2O mm), S is the retention parameter.

The S retention parameter varies spatially with soil class, land use and practice management, with slope and soil moisture. It is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{3.6}$$

where CN is the Curve Number of a given day. The initial subtraction (I_a) is commonly rounded at 0.2 S. When R_{day} is greater than I_a then runoff occurs. A graphic solution of the equation for different CN values is represented in the following figure.

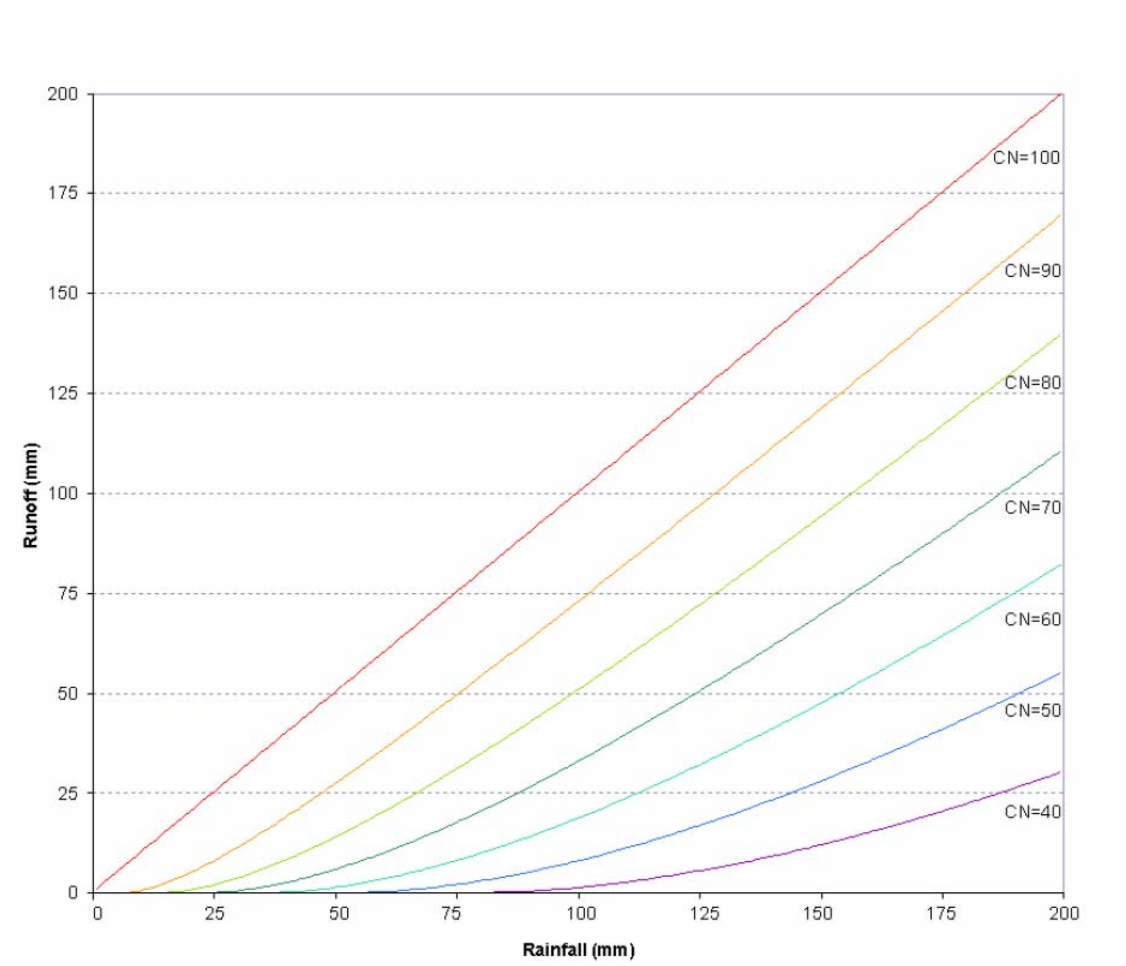


Fig. 3.5. Runoff-rainfall relationship in SCS curve number method.

Cover			Hydrologic Soil Group			
Land Use	Treatment or practice	Hydrologic condition	A	B	C	D
Fallow	Bare soil	- - - -	77	86	91	94
	Crop residue cover*	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row w/ residue	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured w/ residue	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured & terraced w/ residue	Poor	65	73	79	81
		Good	61	70	77	80
Small grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row w/ residue	Poor	64	75	83	86

* Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

Cover			Hydrologic Soil Group			
Land Use	Treatment or practice	Hydrologic condition	A	B	C	D
		Good	60	72	80	84
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured w/ residue	Poor	62	73	81	84
		Good	60	72	80	83
	Contoured & terraced	Poor	61	72	79	82
		Good	59	70	78	81
	Contoured & terraced w/ residue	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured & terraced	Poor	63	73	80	83
		Good	51	67	76	80

Cover		Hydrologic Soil Group			
Cover Type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing[1]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay	- - - -	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element[2]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30	48	65	73
Woods—grass combination (orchard or tree farm)	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods[3]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	- - - -	59	74	82	86

Cover			Hydrologic Soil Group			
Cover Type	**Hydrologic condition**	**Average % impervious area**	**A**	**B**	**C**	**D**
Fully developed urban areas						
Open spaces (lawns, parks, golf courses, cemeteries, etc.)†	Poor		68	79	86	89
	Fair		49	69	79	84
	Good		39	61	74	80
Impervious areas:						
Paved parking lots, roofs, driveways, etc. (excl. right-of-way)	- - - -		98	98	98	98
Paved streets and roads; open ditches (incl. right-of-way)	- - - -		83	89	92	93
Gravel streets and roads (including right-of-way)	- - - -		76	85	89	91
Dirt streets and roads (including right-of way)	- - - -		72	82	87	89

Poor: < 50% ground cover or heavily grazed with no mulch; *Fair:* 50 to 75% ground cover and not heavily grazed; *Good:* > 75% ground cover and lightly or only occasionally grazed

Poor: < 50% ground cover; *Fair:* 50 to 75% ground cover; Good: > 75% ground cover

Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning; *Fair:* Woods are grazed but not burned, and some forest litter covers the soil; *Good:* Woods are protected from grazing, and litter and brush adequately cover the soil.

SWAT will automatically adjust curve numbers for impervious areas when IURBAN and URBLU are defined in the .hru file. Curve numbers from Table 6-3 should ***not*** be used in this instance.

Poor: grass cover < 50%; *Fair:* grass cover 50 to 75%; *Good:* grass cover > 75%

Fig. 3.6 Runoff curve numbers from SCS Engineering Division (1986).

SCS Curve Number is a function that correlates soil hydraulic conductivity, land use and antecedent soil moisture conditions. The Natural Soil Conservation Service (NRCS) classifies soils in four hydrologic groups on the base of infiltration characteristics. The Soil Survey Staff (1996) defines an hydrologic group as a set of soils having very similar potential runoff volumes in the presence of the same rainfall and land cover conditions. A given soil could be represented with one of the four following groups:

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

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

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

-D (High runoff potential) The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have a high swelling potential, soils that have a permanent water table, soils that have a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. They have a very slow rate of water transmission.

Dual hydrologic groups are given for certain wet soils that can be adequately drained. The first letter applies to the drained condition and the second to the undrained. Only soils that are rated D in their natural condition are assigned to dual classes.

3.4.9 Green & Ampt infiltration method

Green & Ampt equation has been developed to predict infiltration assuming a water excess on surface at every moment (Green & Ampt, 1911). The equation considers the soil profile ad homogeneous and the antecedent soil moisture condition as uniform. When water starts infiltration, the model assumes that soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front. The figure n°…. shows the difference between soil moisture distribution with depth in the real case and according to Greem & Ampt equation.

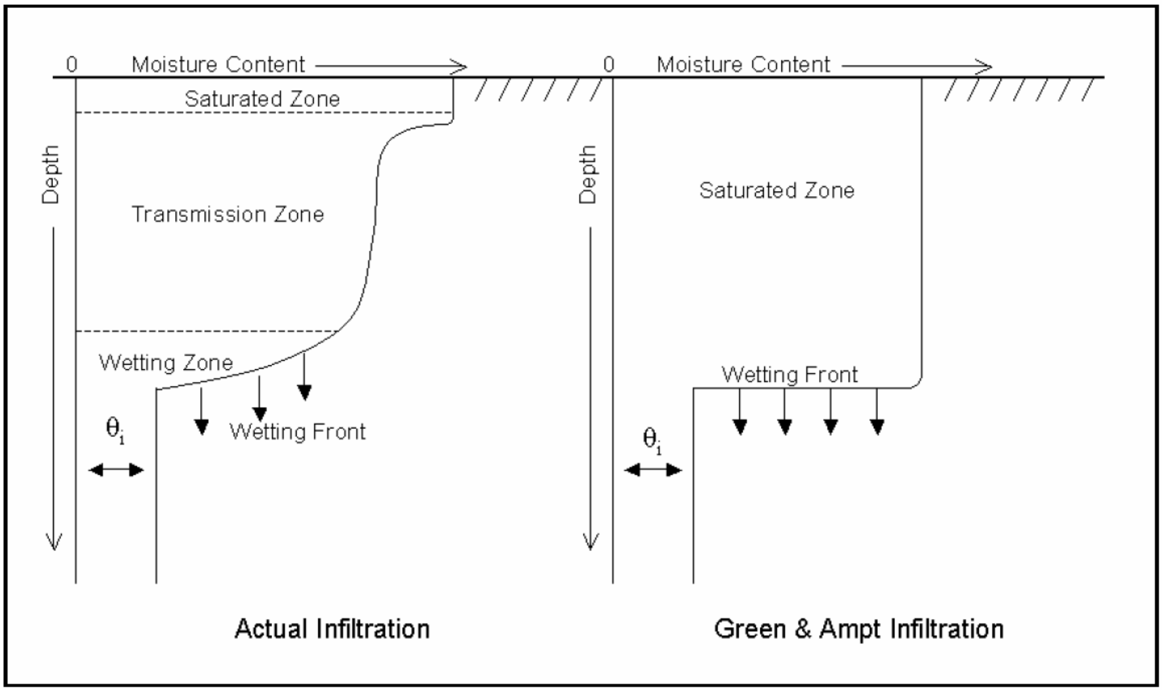


Fig. n°3.7. Comparison of moisture content distribution modeled by Green & Amp and a typical observed distribution.

Mein and Larson (1973) developed a particular methodology to determine ponding time with infiltration using the Green & Ampt equation. The Green & Ampt Mein and Larson excess rainfall method was incorporated into SWAT to provide an alternative options for determining surface runoff. This method needs sub-daily precipitation values to be applied and the Green & Ampt Mein Larson infiltration rate is defined as:

$$f_{\inf} = K_e \left(1 + \frac{\Psi_{wf} \cdot \Delta\Theta_v}{F_{\inf,t}} \right) \tag{3.7}$$

where f_{inf} is the infiltration rate at time t (mm/hr), K_e is the effective hydraulic conductivity (mm/hr), Ψ_{wf} is the wetting front matric potential (mm), $\Delta\Xi_v$ is the change in volumetric moisture content across the wetting front (mm/mm) and $F_{inf,t}$ is the cumulative infiltration at time t (mm H_2O). When rainfall intensity is less than infiltration rate, all the rainfall will infiltrate during the time period and the cumulative infiltration for that time period is calculated as:

$$F_{\inf,t} = F_{\inf,t-1} + R_{\Delta t} \tag{3.8}$$

where $F_{inf,t}$ is the cumulative infiltration in a given time step (mm H_2O), $F_{inf,t-1}$ is the cumulative infiltration for the previous time step (mm H_2O), and $R_{\Delta t}$ is the amount of rain falling during the time step (mm H_2O). The infiltration rate depends on infiltrated volume, which in turn is a function of the infiltration rates in previous time steps. To avoid numerical errors over long time steps, f_{inf} is replaced by d F_{inft}/dt and integrated to obtain:

$$F_{\inf,t} = F_{\inf,t-1} + K_e \cdot \Delta t + \Psi_{wf} \cdot \Delta\Theta_t \cdot \ln\left[\frac{F_{\inf,t} + \Psi_{wf} \cdot \Delta\Theta_v}{F_{\inf,t-1} + \Psi_{wf} \cdot \Delta\Theta_v} \right] \quad (3.9$$

This equation must be solved iteratively for $F_{inf,t}$ the cumulative infiltration at the end of the time step. A successive substitution technique is used. The Green & Ampt effective hydraulic conductivity is approximately equal to one-half the saturated hydraulic conductivity of the soil (Bouwer, 1969). Nearing et al. (1996) developed an equation to calculate the effective hydraulic conductivity as a function of saturated hydraulic conductivity and curve number. This equation incorporates land cover impacts into the calculated effective hydraulic conductivity. The equation is:

$$K_e = \frac{56.82 \cdot K_{sat}^{0.286}}{1 + 0.051 \cdot \exp(0.062 \cdot CN)} - 2 \tag{3.10}$$

where K_e is the effective hydraulic conductivity (mm/hr), K_{sat} is the saturated hydraulic conductivity (mm/hr) and CN is the Curve Number. Wetting fron matric potential, Ψ_{wf} is calculated as a function of porosity, percent sand and percent clay (Rawls and Brakensiek, 1985):

$$\Psi_{wf} = 10 \cdot \exp\begin{bmatrix} 6.5309 - 7.32561 \cdot \phi_{soil} + 0.001583 \cdot m_c^2 + 3.809479 \cdot \phi_{soil}^2 + \\ + 0.000344 \cdot m_s \cdot m_c - 0.049837 \cdot m_s \cdot \phi_{soil} + 0.001608 \cdot m_s^2 \cdot \phi_{soil}^2 + \\ + 0.001602 \cdot m_c^2 \cdot \phi_{soil}^2 - 0.0000136 \cdot m_s^2 \cdot m_c - 0.003479 \cdot m_c^2 \cdot \phi_{soil} - \\ - 0.000799 \cdot m_s^2 \cdot \phi_{soil} \end{bmatrix} \tag{3.11}$$

Where φ_{soil} is soil porosity (mm/mm), m_c is the percent clay content and m_s is the percent sand content. The change in volumetric moisture content across the wetting front is calculated at the beginning of each day:

$$\Delta\Theta_v = \left(1 - \frac{SW}{FC}\right) \cdot \left(0.95 \cdot \phi_{soil}\right) \tag{3.12}$$

Where $\Delta\Xi_v$ is the change in volumetric moisture content across the wetting front (mm/mm), SW is the soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm H_2O), FC is the amount of water in the soil profile at field capacity (mm H_2O), and φ_{soil} is the porosity of the soil (mm/mm). If a rainfall event is in progress at midnight, $\Delta\Xi_v$ is calculated as:

$$\Delta\Theta_v = 0.001 \cdot \left(0.95 \cdot \phi_{soil}\right) \tag{3.13}$$

For each time step, SWAT calculates the amount of water entering in the soil and the water does not infiltrates into the soil becomes surface runoff.

Variable Name	Definition	File
IEVENT	Rainfall, runoff, routing option.	.bsn
IDT	Length of time step (min): Δt=IDT/60	file.cio
PRECIPITATION	$R_{\Delta t}$: Precipitation during time step (mm H_2O)	.pcp
SOL_K	K_{sat}: Saturated hydraulic conductivity of first layer (mm/hr)	.sol
CN2	CN: Moisture condition II curve number	.mgt
CNOP	CN: Moisture condition II curve number	.mgt
SOL_BD	ρ_b: Moist bulk density (Mg/m^3): ϕ_{soil}=1 - ρ_b / 2.65	.sol
CLAY	m_c: % clay content	.sol
SAND	m_s: % sand content	.sol

Fig. n°3.8. SWAT input variables for Green & Ampt infiltration calculations.

3.5 Routing phase of the hydrologic cycle

Once SWAT determines the loadings of water, sediments, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed. In addition to keeping track of mass flow in the channel, SWAT models the transformation of chemicals in the stream and streambed.

Routing in the main channel can be divided in four components:

-**Flood routing**: as water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another portion may be lost due to removal of water from the channel for agricultural or human use. The volume of water may also increase as rainfall falls directly on the channel or from point source discharges. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

-**Sediment routing**: the transport of sediments in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. In SWAT model the maximum amount of sediments that can be transported from a reach segment is a function of the peak channel velocity. Available stream power is used to reentrain loose and deposit material until all the material is removed. Excess stream power causes bed degradation. Bed degradation is adjusted for stream bed erodibility and cover.

-**Nutrient routing**: Nutrients transformations in the stream are controlled by in-stream water quality component of the model. The in-stream kinetics used by SWAT for nutrient routing are adapted from QUAL2E (Brown and Barnwell, 1987). The model tracks nutrients dissolved in the stream and nutrients adsorbed to the sediment. Dissolved nutrients are transported with water while adsorbed ones are allowed to be deposited with the sediments on the channel bed.

-Channel pesticide routing: while an unlimited number of pesticides may be applied to the HRU's, only one pesticide may be routed through the channel network of the watershed due to the complexity of the simulated processes.

The total pesticide load in the channel is partitioned into dissolved and sediment-attached components.

The dissolved pesticide is transported with water while the sediment-attached ones are affected by sediment transport and deposition processes. Pesticide transformations in the dissolved and sorbed phases are governed by first order decay relationships.

The main in-stream processes simulated by the model are settling, burial, resuspension, volatilization, diffusion and transformation.

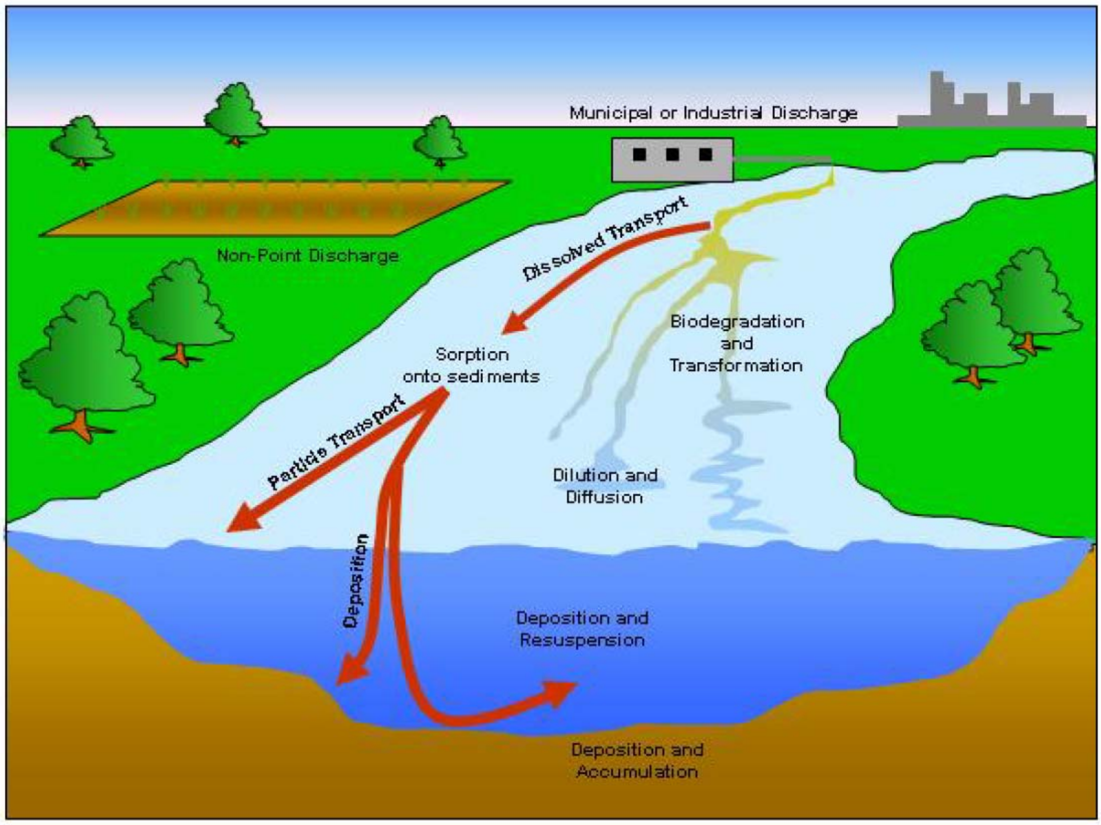


Fig. n° 3.9. In-stream processes modeled by SWAT.

The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom and diversions. SWAT models these processes according to the following components:

-**Reservoir outflow**: the model offers three alternatives to estimate outflow from reservoirs. The user may input measured outflow, may specify a water release rate (designed for small, uncontrolled reservoirs) or he may specify monthly target volumes (designed for larger, managed reservoirs).

-**Sediment routing**: Sediment flow may originate from transport through the upstream reaches or from surface runoff within the sub-basin. The concentration of sediment is estimated using a simple continuity equation based on volume and concentration of inflow, outflow, and water retained in the reservoir. Settling of sediment in the reservoir is governed by an equilibrium sediment concentration and the median sediment particle size. The amount of sediment in the reservoir outflow is the product of the volume of water flowing out of the reservoir and the suspended sediment concentration in the reservoir at the time of release.

-**Reservoir nutrients**: SWAT follows a model developed by Chapra (1997) and it assumes that the lake is completely mixed, ignoring lake stratification and intensification of phytoplankton in the epilimnon, that phosphorous is the limiting factor, and that the total phosphorous is a measure of the lake trophic status, implying that a relationship exists between total phosphorous and biomass.

-**Reservoir pesticide**: also to simulate lake pesticide balance SWAT uses Chapra model assuming well mixed conditions. The system is partitioned into a well mixed surface water layer underlain by a well mixed sediment layer. The pesticide is partitioned into dissolved and particulate phases in both the water and sediment layers. The major processes simulated by the model are loading, outflow, transformation, volatilization, settling, diffusion, resuspension and burial.

3.5.1 Land cover/Plant growth

SWAT uses a single plant model to simulate all types of land covers. It allows to distinguish between annual and perennial plants: the annual plants growth from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant while the perennial ones maintain their root system throughout the year, becoming dormant in the winter months. The growth starts again when the mean air temperature exceeds the minimum required one. The growth simulation method assesses removal of water and nutrients from the root zone, transpiration and biomass/yield production. The potential increase in plant is given by the biomass increase under ideal growing conditions. The potential increase in biomass for a day depends on intercepted energy and plant's efficiency in concerting energy to biomass while energy interception

is estimated as a function of solar radiation and the plant's leaf area index. The actual potential plant transpiration is also a function of potential transpiration and soil water availability.
Plant use of nitrogen and phosphorous are estimated with a supply and demand approach where the daily plant nitrogen and phosphorous demands are calculated as a difference between the actual concentration of the element in the plant and the optimal concentration that varies with growth stage as described by Jones (1983). Potential plant growth and yield are usually not achieved due to constraints imposed by the environment but the model estimates stresses caused by water, temperature and nutrients.

3.5.2 Heat units

Temperature is one of the most important factors governing plant growth. Each plant has its own minimum and maximum optimal temperature range. For some plants the minimum temperature or base temperature has to be reached before growth and once the base temperature is reached, higher temperatures allow a more rapid growth rate. Once the optimal growth is achieved, the plant growth begin to slow and at the maximum temperature it stops. The heat unit theory postulates that plants need a heat quantity to be evaluated together with time to maturity. A plant can't growth when the mean temperature is less than the base temperature and so the only daily temperature values contributing to plant growth are those ones greater than the base temperature. To estimate the total heat quantity required by the plant, the accumulation of daily mean air temperatures above the plant's base temperature is recorded over the period of the plant's growth and expressed in terms of heat units. For example, assume sweet peas are growing with a base temperature of 5°C temperature. If the mean temperature on a given day is 20 °C, the heat units accumulated on that day are 20-5=15 heat units. Knowing the planting date , maturity date, base temperature and mean daily temperature, the total number of heat units required to reach maturity can be estimated. SWAT uses a direct summation index and each degree above the base temperature is considered as one heat unit. The model assumes that the rate of growth is directly proportional to the increase in temperature. It's important to note that heat unit theory does not take into account the damaging impact that high temperatures can have on crops. The total potential number of heat units required by a plant to reach maturity is calculated as:

$$PHU = \sum_{d=1}^{m} HU \tag{3.14}$$

Where HU is the number of heat units accumulated on the d day while d=1 is the planting date and d=m is the number of days needed to reach maturity. To evaluate the potential heat units for a plant, the number of days to reach maturity must be known. For most crops this number is easily estimated but for some others, such as forest or range, the time that the plants begin to develop should be used as the beginning of the growing season while the time the plant seeds reach maturity is the end of the growing season. SWT allows management operations to be scheduled by day or by fractions of potential heat units and for each operation day and month may be specified; if they aren't, the model requires to indicate the fraction of potential heat unit. As a general rule, if the exact dates for operations scheduling are known, these dates should be used. The heat unit scheduling allows the model to calculate operations as a function of temperature. This method is useful with large watersheds where the climate is different in different portions of it and it is also valid when the simulation years shows great climatic variations. Using the heat units only one file on management practices is needed and it can be applied to the entire watershed.

3.5.3 Potential growth

For each day of simulation, the plant potential growth is calculated in the optimal conditions where the optimal conditions are related to a suitable water and nutrients availability and opportune climate. The plant growth is considered by the model simulating leaf area development and light absorption and conservation of the latter in biomass. The amount of solar radiation intercepted by plant leaf area is calculated according to Beer law (Monsi & Saeki, 1953):

$$H_{phosyn} = 0.5 \cdot H_{day} \left(1 - \exp\left(k_l \cdot LAI\right)\right) \quad (3.15)$$

Where H_{phosyn} is the amount of intercepted photosynthetically active radiation on a given day (MJ m^{-2}), H_{day} is the incident total solar (MJ m^{-2}), k_l is the light extinction coefficient, equal to 0.65 for each plant and LAI is the leaf area index. Photosynthetically active radiation is the radiation with a wavelength between 400 and 700 mm (McCree, 1972). Direct solar beam radiation contains about 45% of photosynthetically active radiation while the diffuse radiation contains about 60% of it (Monteith, 1972; Szeicz, 1974; Stanhill and Fuchs, 1977). The efficiency of the used radiation is equal to the amount of biomass producted per intercepted solar radiation unit. SWAT defines this efficiency in growth crops database and considers it as independent from their growth.

3.5.4 Erosion

The erosive process produced by rainfall and runoff is evaluated through the Modified Universal Soil Loss equation (MUSLE) (Williams, 1975). MUSLE is a modified version of the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1965, 1978). USLE considers the mean annual erosion as a function of rainfall energy. In MUSLE equation, the factor due to rainfall energy is substituted with a runoff factor. This method improves the prediction of sediment production and avoids to input delivery rates while allows its applicability to a single storm event. The prediction of sediment production is improved since runoff is a function of antecedent soil moisture and rainfall energy. Delivery rates, that is sediment yield at any point along the channel divided by the source erosion above that point, are required by USLE because the rainfall factor represents energy used in detachment only. Delivery ratios are not needed by MUSLE because the runoff factor represents energy used in detaching and transporting sediment.

3.6 MUSLE

The Modified Universal Soil Loss Equation (Williams, 1975) is:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad (3.16)$$

Where sed is the sediment yield on a given day (ton), Q_{surf} is surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the of the HRU (ha), K_{USLE} is the soil erodibility factor (that is 0.013 ton m^2 hr/(m^3 ton cm), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and CFRG is the coarse fragment factor. Direct measures of erodibility factor are so expensive so Wischmeier et al. (1971) developed a general equation to estimate soil erodibiliy factor when the silt fraction and very fine sand fraction are less than 70% of the particle size spatial distribution:

$$K_{USLE} = \frac{0.00021 \cdot M^{1.14} \cdot (12 - OM) + 3.25 \cdot (c_{soilstr} - 2) + 2.5 \cdot (c_{perm} - 3)}{100} \qquad (3.17)$$

Where K_{USLE} is the soil erodibility factor, M the particle-size parameter, OM is the percent organic matter (%), $c_{soilstr}$ is the soil structure code used in soil classification, c_{perm} is the profile permeability class. The particle-size parameter M is calculated as:

$$M = \left(m_{silt} + m_{vfs}\right) \cdot \left(100 - m_c\right) \qquad (3.18)$$

Where m_{silt} is the percent silt content (0.002-0.05 mm diameter particle), m_{vfs} is the very fine sand percent content (0.05-0.10 mm diameter particle) and m_c is the clay percent content (<0.002 diameter particle).

The organic matter percent content, OM, in a layer can be calculated as:

$$OM = 1.72 \cdot orgC \quad (3.19)$$

Where orgC is the layer organic carbon percent content.

The soil structure is referred to the aggregation of primary soil particles into compound particles which are separated from adjoining aggregates by surfaces of weakness. A single natural soil aggregate is called a ped. Field description of soil structures note the shape and arrangement of peds , the size of peds and the distinctness and durability of visible peds. USDA Soil Survey terminology for structure consists of separate sets of terms defining each of these three qualities. Shape and arrangement are designed as type of soil structure; size of peds as class; degree of distinctness as grade. The soil structure codes for K_{USLE} are defimed by the type and class of soil structure present in the layer and they correspond to four main types of structure (Platy, Prismlike, Blocklike or polyhedral and Spheroidal).

3.7 Cover and management factor

The USLE cover and management factor C_{USLE} is defined as the ratio of soil loss from land cropped under specified conditions to the corresponding loss from cleaned-tilled, continuous fallow (Wishmeier and Smith, 1978). The plant canopy affects erosion by reducing the effective rainfall energy of intercepyed rainfall drops. The reduction rate depends on leaf area coverage density and since it varies with plant growth cycle, SWAT allows to daily calculate C_{USLE} using the following equation:

$$C_{USLE} = \exp\{[\ln(0.8) - \ln(C_{USLE,mn})] \cdot \exp(-0.00115 \cdot rsd_{surf}) + \ln(C_{USLE,mn})\} \quad (3.20)$$

Where C_{USLE} is the minimum value for cultivated land cover and management factor, rsd_{surf} is the amount of residue on the soil surface (kg/ha). The minimum C_{USLE} can be estimated knowing the mean annual C factor value with:

$$C_{USLE,mn} = 1.643 \cdot \ln(C_{USLE,aa}) + 0.1034 \quad (3.21)$$

Where $C_{USLE,aa}$ is the mean annual C factor for land cover.

3.8 Nitrogen cycle

The complexity of nitrogen cycle and the importance of nitrogen in plant growth makes this element to be investigated by numerous researchers. Nitrogen cycle is a dynamic system that includes water, atmosphere and soil. Plants require nitrogen more than the other elements, with the exception of carbon, oxygen and hydrogen.

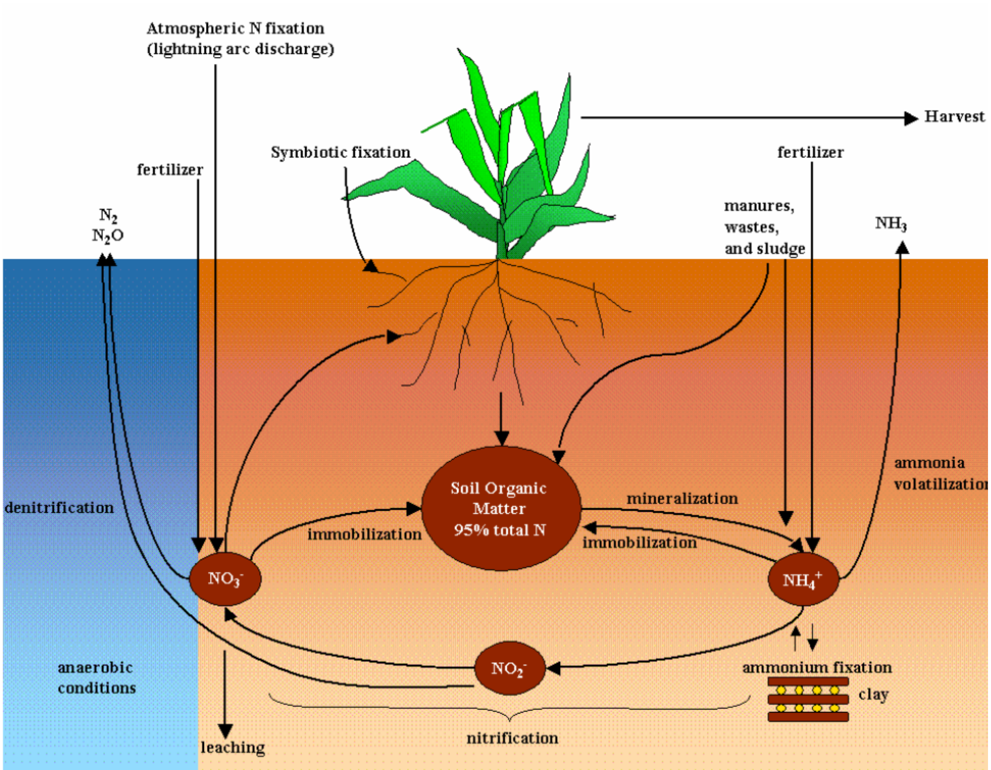


Fig. n° 3.10. Nitrogen cycle.

The major form of nitrogen that prevails in the soil is the organic one and it's slowly converted in inorganic forms much more easily available (ammonia and nitrates). The nitrate is very soluble and it easy infiltrates below the crop root zone or it can be removed by runoff water. The organic nitrogen and ammonia are adsorbed by soil particles and then tend to remain if they are not removed by erosion. The mineralization process transform nitrogen from organic form into inorganic form, making it available for the plants. The denitrification process causes nitrogen losses in atmosphere and it can reduce the nitrogen quantity loss by percolation and leaching. Nitrogen can be dispersed in atmosphere in gassy form also due to chemicals processes without requiring microorganisms presence as in the case of heavy urea and ammonium fertilizer applications.

Practices that increase oxygenation or drainage, also increase mineralization and allows nitrates available for plants and for meteoric water runoff and percolation. Nitrogen compounds content in the soil normally increase until to about 30 cm and then it decrease under the action of circulation water. The fertilizer application period is important since a use near the maximum vegetative development favors a loss reduction. In particular, for groundwater it's known that, in some cases, most of responsibility in nitrates migration is due to the fertilizer abuse, both chemical and organic fertilizer abuse, in relation to the excessive applied quantity and to the not so optimal use of them respect to the germinating cycle of plants. A factor that favors this migration is also represented by organic matter mineralization in the soil that is linked to not so suitable agricultural practices.
SWAT allows to define nitrate and organic nitrogen quantities contained in humus matter for all the soil layers at the beginning of the simulation. Without specifying the initial nitrogen concentration, SWAT initializes the nitrogen level in the different forms. The initial nitrogen level in the soil as a function of depth is given by:

$$NO_{3conc,z} = 7 \cdot \exp\left(-\frac{z}{1000}\right) \qquad (3.22)$$

Where $NO_{3conc,z}$ is the nitrogen concentration in the soil at the depth z (mg/kg or ppm) while z is the soil depth from surface (mm).

The nitrogen concentration trend calculated with this equation for different depths, is shown in the figure.

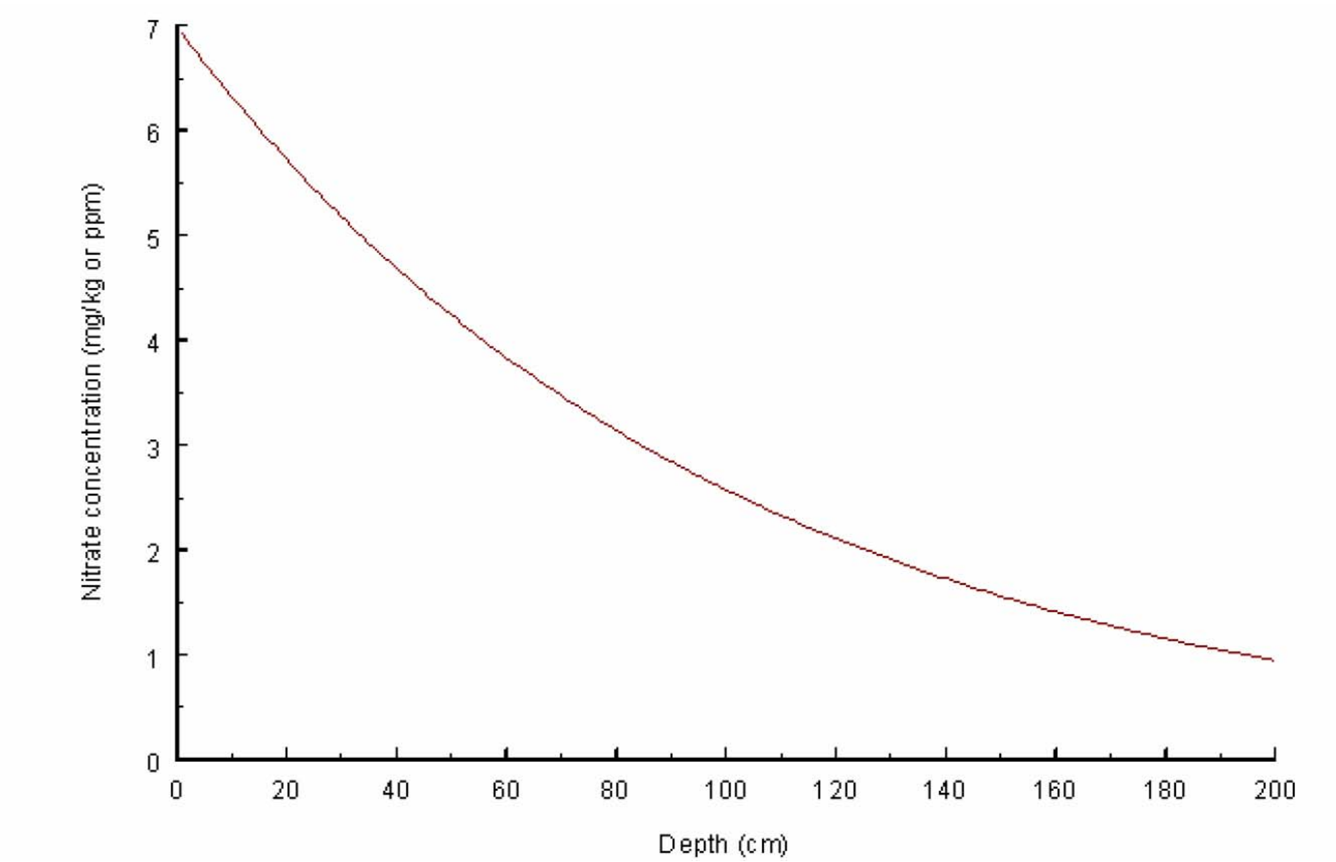


Fig. n°3.11. Nitrate concentration with depth

The organic nitrogen levels are assigned assuming that the C:N ratio for the humic substance is equal to 14:1. The organic humic nitrogen concentration in a soil layer is calculated as:

$$orgN_{hum,ly} = 10^4 \left(\frac{orgC_{ly}}{14} \right) \tag{3.23}$$

Where $orgN_{hum,ly}$ is the organic humic nitrogen concentration in a layer (mg/kg or ppm) and $orgC_{ly}$ is the organic carbon percent in the layer.

The organic humic nitrogen is distinguished in one active portion and one stableportion using the following equations:

$$orgN_{act,ly} = orgN_{hum,ly} \cdot fr_{act,N} \tag{3.24}$$

$$orgN_{sta,ly} = orgN_{hum,ly} \cdot \left(1 - fr_{act,N}\right) \tag{3.25}$$

Where $orgN_{act,ly}$ is the active organic nitrogen concentration (mg/kg), $orgN_{hum,ly}$ is the organic humic nitrogen concentration in a layer (mg/kg or ppm), $fr_{act,N}$ is the humic nitrogen fraction in active phase and $orgN_{sta,ly}$ is the organic nitrogen in stable phase (mg/kg). The humic nitrogen fraction in the active phase, $fr_{act,N,}$ is set to 0.02 by the model. The fresh organic nitrogen is set to zero in all the layers except the first 10 mm of soil where it assumes the value of 0.15% of the initial amount of residue on the soil surface, that is:

$$orgN_{frsh,surf} = 0.0015 \cdot rsd_{surf} \tag{3.26}$$

Where $orgN_{frsh,surf}$ is the fresh organic quantity in the first 10 mm (kg N/ha9 and rsd_{surf} is the residual material present in the soil surface (kg/ha). The ammonium nitrogen $NH_{4,ly}$ is set to o ppm in the soil.

3.9 Phosphorous cycle

Although plant phosphorous demand in considerably less than nitrogen demand, phosphorous is necessary for several vital functions. The most important of its role is to transfer and storage the energy derived from photosynthesis and carbohydrates metabolism. Phosphorous acts in reproductive and growth processes. The three forms of phosphorous are: the organic one associated with humus, the insoluble one in mineral form and the soluble one in the soil, easy usable by plants. Phosphorous is the most important nutrient for aquatic ecosystems but an excess causes an accelerated eutrophication due to the accelerated algae growth and organisms rich in chlorophyll growth. The eutrophication rate in several water bodies can be exclusively regulated by phosphorous concentration since the other nutrients are not limiting factors. The phosphorous quantity derived from diffuse sources changes as soil, climatic and environmental factors vary. Phosphorous is not particularly mobile in the soils and phosphorous ions do not percolate so easily. Phosphorous is fixed by clay and by organic matter and it is mostly removed by erosive processes. The main factors controlling phosphorous fixation are:

-Al and Fe oxides are responsible of retention in acid soils;

-calcium compounds control solubility in calcareous soils;

-clay and organic matter percent contents contribute to adsorption.

The adsorption is not an instantaneous process and it occurs in an rapid initial phase followed by a slower one. The adsorption characteristics are much more different in soils then in transported sediments characterized by a greater specific surface. Most of phosphorous is not directly available for plants and it remains adsorbed by solid particles in the soil. A portion of particulate inorganic phosphorous is the dissolved form source but this change is really slow and it occurs in the presence of a continuous subtraction from the root system and so the dissolved phosphorous concentration is always less then that one obtained from the total present phosphorous. Phosphorous applied as fertilizer should hardly be loss in solute form. The element transport to the water bodies would occurs mostly as particulate or adsorbed form. Also the equilibrium between particulate portion and dissolved one depends on chemical and biological characteristics of the environment. The soluble phosphorous concentration can varies during the movement from agricultural soil to receiving water bodies and later within the latter. A diminishing runoff can involve a smaller loss of total phosphorous but it can have a low effect on phosphorous available in the receiving water due to the variation in transformation rate of the dissolved forms. Just for this particular behavior, phosphorous appears of specific interest in environmental damage of surface water bodies since it is the eutrophication main factor especially in inland water. SWAT allows to define soluble and organic phosphorous in humic matter for all the layers in the soil from the beginning of the simulation. If the initial concentration is not specified, SWAT initializes phosphorous levels in the layers. He solution phosphorous concentration in all the layers is initially set to 5mg/kg of soil.

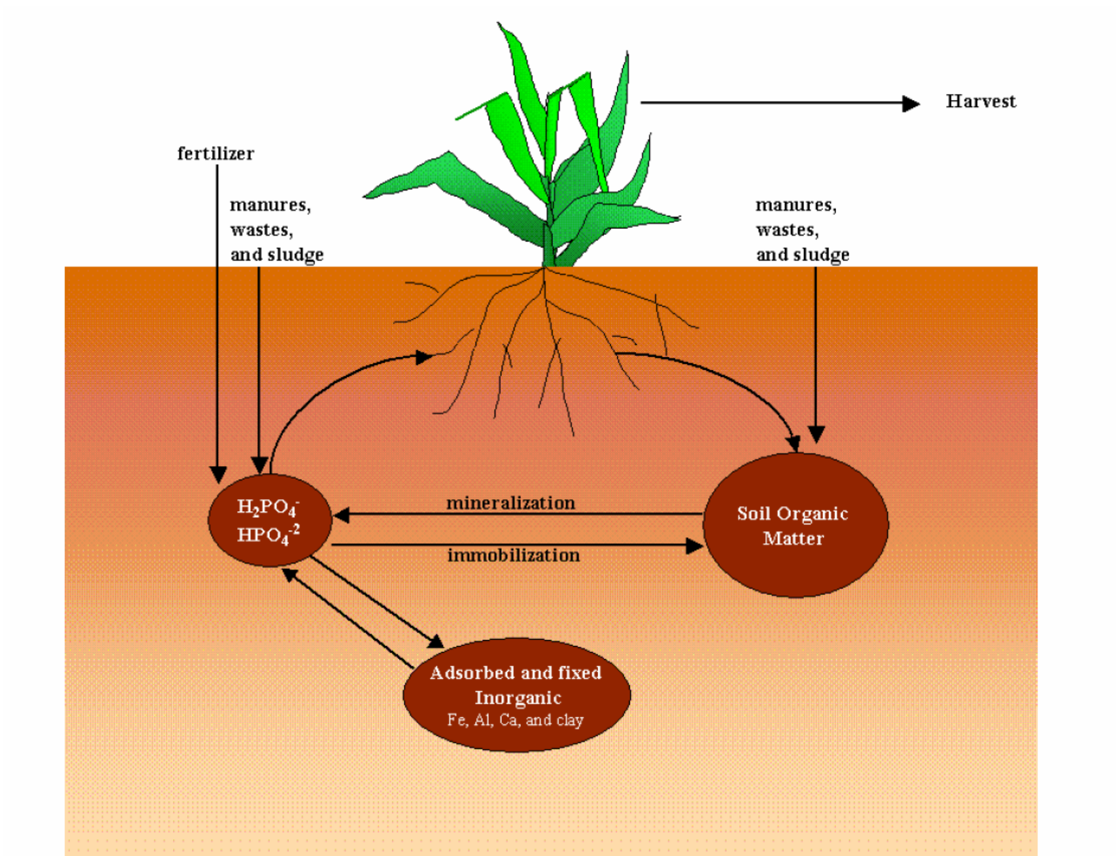


Fig. n° 3.12. Phosphorous cycle

3.10 Pesticides

Although SWAT does not simulate questions relative to plant growth due to the presence of weeds, damaging insects, and other pests, pesticides may be applied to an HRU to study the movement of the chemical in the watershed. SWAT simulates the pesticides movement in the stream network (in solution and adsorbed by sediments transported by flow), in the soil profile and in aquifers through percolation (in solution). The equation used to model pesticides movement in the hydrologic cycle phase was developed by Leonard et al. (1987). The agricultural pollutants (pesticides in particular) reach the surface water bodies essentially because of water movement which represents the primary vector. The processes controlling this movement are erosion and soil particle sedimentation, surface runoff and sub-surface flow, infiltration and percolation. During the transfer of a pollutant to the receiving body three phases can be distinguished: substance availability, extraction, transport and impact on the receiving water body. During these phases, pollutants undergo physical, biological and chemical transformations which determine the transfer modalities. For substances that are strongly adsorbed on soil particles, erosion and sedimentation processes are dominant even if subsequently they can detach from the particle and become dissolved. For weakly and moderately adsorbed matter solution transport due to surface runoff or deep percolation are dominant.

3.11 Management practice

Quantifying impact of agronomic practices on water storage and quality is one of the most important interests in environmental modeling. SWAT allows to particularly investigate this aspect since it includes really detailed information on management practices in simulation. SWAT defines management practices for each HRU. The starting and the end of growth have to be specified and also type and quantity of fertilizer, pesticides applications, irrigation and crop operations have to be defined. In addition to the these management practices of base, operations as pasture, fertilization and irrigation are available.

3.12 Planting/beginning of the growing season

With this operation the growth plant starts. This operation can be used to define the effective period of planting for agricultural crops or to represent the spring waking up for plants requiring several years to reach maturity (forests, orchards etc). SWAT allows the input of those operations only if there's not antecedent planting in the soil, on the contrary it's necessary to apply a new operation to remove the previous plant. If two planting operations are subsequently applied,, the second one will be ignored by the model. The information required by SWAT for planting operations include the temporal duration (month, day or the potential heat unit fraction), the total number of heat units needed by the crop to reach maturity and what type of plant must be simulated in the HRU. If the crop is transplanted, the leaf area index has to be input and the biomass quantity present in the crop at planting time must defined. Also for transplanted crops, the total number of heat units required to reach maturity can be input from the transplant time and not from seed generation. The Curve Number can be varied in the HRU during all year long for each applied operation. And the Curve Number values relative to the different operations, depends on soil moisture. For simulation in which yield and biomass specific amount are required, the model can be forced to obtain the desired results.

3.13 Harvest operation

It is referred to plant biomass removal without killing the plant. This operation is most commonly used to cut hay or grass. The only information required by the harvest operation is the date. However, a harvest index override and a harvest efficiency can be set. When no harvest index override is specified, SWAT uses the plant harvest index from the plant growth database to set the fraction of biomass removed. The plant harvest index in the plant growth database is set to the fraction of the plant biomass partitioned into seed for agricultural crops and a typical fraction of biomass removed in a cutting for hay. A harvest efficiency may also be defined as a fraction of harvest plant biomass removed from the HRU. The remained fraction is converted to residue on the soil surface. If the harvest efficiency is left blank or set to zero, the model assumes this feature is not being used and removes 100% of the harvested biomass. (no biomass is converted to residue).

3.14 Grazing operation

The grazing operations simulate plant biomass removal and manure deposition over a specified period of time. This operation is used to model pasture or range grazed by animals. Information required in the grazing operation includes the time during the year at which grazing begins (month and day or fraction or fraction of plant potential heat units), the length of grazing period, the amount of biomass removed daily, the amount of manure deposited daily and the type of manure deposited. The amount of biomass trampled is an optional input. Biomass removal in the grazing operations is similar to that in the harvest operation but, instead of a fraction of biomass being specified, an absolute amount to be removed very day is given. In some cases, it can result in a reduction of plant biomass to a very low level increasing erosion in the HRU. To prevent this situation, a minimum plant biomass for grazing may be specified (BIO_MIN) and when the plant biomass falls below the amount specified by BIO_MIN, the model will not graze, trample or apply manure in the HRU on that day.

3.15 Harvest and kill operation

The harvest and kill operation stops plant growth in the HRU. The fraction of biomass specified in the land cover's harvest index, in the plant growth database, is removed from the HRU as yield. The remaining fraction of plant biomass is converted to residue on the soil surface. The only information required by the model is the timing of operation (month and day or fraction of potential plant heat units). The option of updating the moisture condition II curve number can also be chosen.

3.16 Kill/end of growing season

The kill operation stops plant growth in the HRU and all plant biomass is converted to residue. The only information required by the kill operation is the timing of this operation (month, day or fraction of potential plant heat units).

3.17 Tillage

The tillage operation redistributes residue, nutrients, pesticides and bacteria in the soil profile. Information required includes the timing of operation (month and day or fraction of base zero potential heat units) and type of tillage operation. The curve number in the HRU may be varied throughout the year. New curve number values may be entered in a plant operation, tillage operation and harvest and kill operation. These curve numbers are referred to moisture condition II. SWAT adjusts the input values to reflect changes in water content. The mixing efficiency of the tillage implement defines the fraction of a residue/nutrient/pesticide/bacteria pool in each soil layer redistributed through the depth of soil that is mixed by the application.

3.18 Fertilizer application

The fertilizer operation applies fertilizer or manure to the soil and the information required includes the timing of operation (month and day or fraction of plant potential heat units), the type of fertilizer/manure applied, and the depth distribution of fertilizer application. SWAT assumes that surface runoff interacts with the top 10 mm of soil and nutrients, present in this layer, are available for transport to the main channel in surface runoff. The fraction of fertilizer applied to the top 10 mm of soil may be specified and the remainder of the fertilizer is added to the first layer defined in the HRU. In the fertilizer database, the weight fraction of different types of nutrients and bacteria are defined for the fertilizer.

3.19 Pesticide application

The pesticide operation applies pesticide to the HRU and information required includes the timing of operation (month and day or fraction of plant potential heat units), the type of pesticide applied and the amount of pesticide applied. Field studies have shown that even on days with little or no wind, a portion of pesticide applied to the field is lost and the fraction of pesticide that reaches the foliage or soil surface is defined by the pesticide's application efficiency. The amount of pesticide that reaches the foliage or ground is:

$$pest' = ap_{ef} \cdot pest \tag{3.27}$$

Where pest' is the effective amount of pesticide applied (kg_{pest}/ha), ap_{ef} is application efficiency and pest is the actual quantity of pesticide applied.

3.20 Irrigation

Irrigation in the HRU may be scheduled by the user or automatically applied by SWAT in response to a water deficit in the soil. The timing and application amount and the source of irrigation water have to be specified. A minimum in-stream flow may also be defined and a maximum irrigation water removal amount cannot be exceeded on any given day and/or a fraction of total flow in the reach that is available for removal on a given day may be specified too. For a given irrigation event, SWAT determines the amount of water available in the source and the amount of available water is compared to the amount of water specified in the irrigation operation. If the amount available is less then the amount specified, SWAT will only apply the available water. Water to be applied to the HRU may come from one of these five types of source: river, reservoir, surface aquifer, groundwater or sources out of the watershed. In addition to the source type, SWAT has to know the location of it with the exception of external sources. In the case of aquifers and reservoirs, the model needs the sub-basin number in which they fall. A reservoir is always located on the main channel network and no distinction is made between natural and artificial reservoirs. The water balance for a reservoir is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \tag{3.28}$$

Where V is the volume of water in the impoundment at the end of the day (m^3 H_2O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3 H_2O), V_{flowin} is the volume of water entering the water body during the day (m^3 H_2O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3 H_2O), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O).

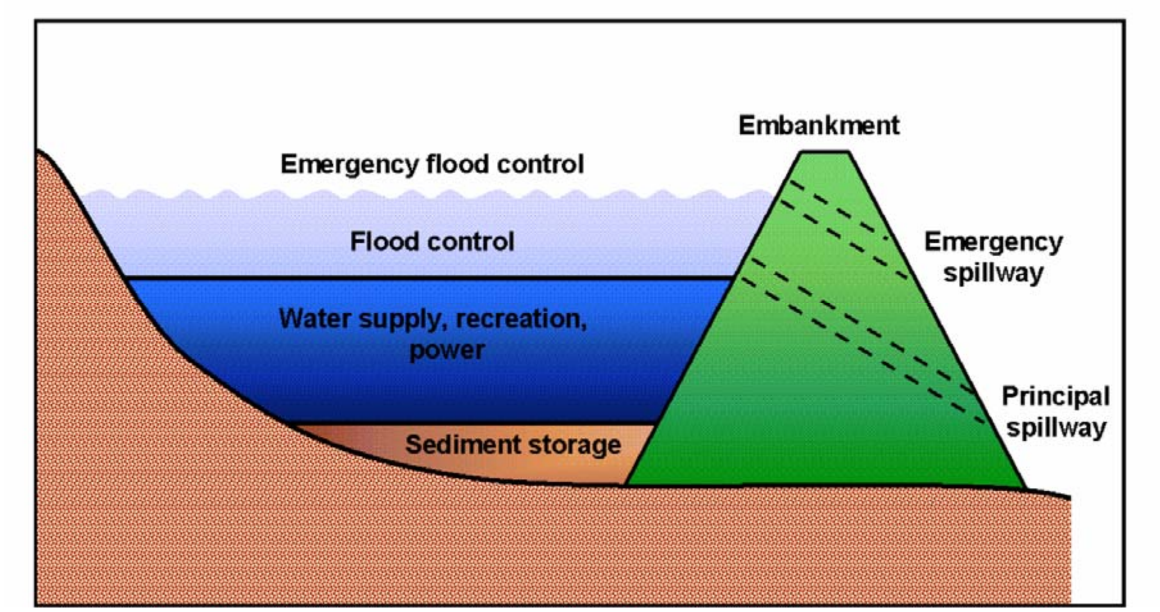


Fig. n°3.13. Components of a reservoir with flood water detention features (AfterWard and Elliott, 1995)

CHAPTER 4

STUDY AREA: MARTA RIVER BASIN DESCRIPTION AND INVESTIGATION

4.1 Study area general description

The Marta River basin is located in the northern part of Latium Region, falling in several municipalities of Viterbo Province and including the Lake Bolsena, from which Marta River is the effluent.

Marta River starts flowing in the neighbourhood of the homonym village, main and active fishermen's port, to pour in the Tyrrhenian sea near Tarquinia city.

It runs for about half of its course (70 km) in a land belonging to Tuscania Municipality; it passes through the Natural Reserve of Tuscania (established in 1997 with Regional Law N°29), defining its borders in part.

This basin drains a global area of 1.081 km^2 and it’s delimited by Fiora river divide westerly, by the lake Bolsena watershed northwards, by the Cimini Mountains eastwards.

It has an average slope of about 11% and a maximum elevation of 960 m a.s.l. while the minimum elevation is -2 m a.s.l. in correspondence to the mouth of the River.

The Natural Reserve of Tuscania covers a land for agricultural use essentially and more than 60% of the area (1200 ha) is cultivated to olive grove and arable land and it represents a significant economical and environmental resource since it’s perfectly suitable with a sustainable development looking at productive activities also as land preservation measure.

Well four SCI (Site of Community Importance) fall within the Marta River basin and according to the laws in force (Directives 79/409/CEE and 92/43/CEE) you can find also a SPZ (Special Protection Zone) in correspondence of lake Bolsena and its islands, Bisentina and Martana.

Lake Bolsena is a crater lake of central Italy, of volcanic origin, which was formed 370,000 years ago following the collapse of a caldera of the Vulsini volcanic complex. Roman historic records indicate activity of the Vulsini volcano occurred as recently as 104 BC, since when it has been dormant. The two islands in the southern part of the lake have been formed by underwater eruptions following the initial collapse of the caldera. The lake has an oval shape typical of crater lakes. Its total surface is 113.5 km^2; the altitude of its surface is 305 m; it is 151 m deep at its lowest point and 81 m deep on average. The lake lies within the northern part of the province of Viterbo that is called *Alto Lazio* ("Upper Latium") or *Tuscia*. It is bordered mostly by the Roman consular road Via Cassia. Lake Bolsena has numerous tourist establishments, particularly for nature tourism, largely in the areas of camping, agrotourism and bed and breakfasts. The Romans called it *Lacus Volsinii*, adapting the Etruscan name, Velzna, of the last Etruscan city to hold out against Rome, which was so thoroughly eradicated after 264 BC, and its inhabitants moved, that its site has not be securely identified. One third of the lake was donated to the Church by the noble family Alberici of Orvieto. In recognition of the generous donation the Alberici family was honored with a three times a year observance performed by the Bishop of Orvieto.

The lake has a theoretical estimated Retention/Replacement Time of 120 year; the water residence time is higher then 120 years because of the difficulties encountered, during the summer period, by deep water reaching the effluent in consequence of the lake thermal stratification.

So the emissary Marta which leaves Lake Bolsena to the right of the community of Marta is a river which empties into the Tyrrhenian Sea. After passing through Marta, Tuscania and Tarquinia, it reaches the sea in the area of the lido of Tarquinia. There, in a magnificent region located between the mouth of Marta and that of Mignone, was created the natural reservoir "Saltworks of Tarquinia". The annual average discharge flow coming out of Lake Bolsena is about 2 m^3/sec while at the outlet it is raises about 8 m^3/sec owing to the principal tributary Traponzo stream with a very high contribution in flow up to 9-10 m^3/sec.

The hydraulic status of the system experienced periods of imbalance owing to:

-flow decrease from hydrogeological watershed springs;

-flow progressive reduction towards Marta River effluent;

-significant lake level drop.

For all that, unchecked actions have been made on the sluice-gates of regulation, situated 303.41 meters high in the port of Marta at the beginning of Marta River to adjust the level of the lake according to local people needs and varying Marta River flow discharge arbitrarily with consequences on the natural fluvial ecosystem. During the last twenty years a natural recharge decrease in connected aquifer and a contemporary increase in pump extractions from local wells also happened just making the watershed hydraulic status get worse.

Along the stream course several plants for hydroelectric power generation are localized and the presence of side-stream intakes and barriers in the river bed gives rise to discontinuity and interruptions to the natural fluvial being just endangering native ichthyic species conservation and procreation.

Numerous stream deviations along the watercourse make the river discharge swing and anomalous and the Minimum Flow Requirement is not always guaranteed during the year especially referring to the summer period which seems to be at major drought hazard. Often on July or August values next to zero are being observed and can be ascribed only in part to the rainfall intensity reduction of the few last years but, for the most, to the heavy and mishandled extraction both from aquifer and from superficial water body.

Against drought months with zero flow, the Marta River shows it can't keep up enough high intensity precipitation events giving rise to unexpected and sudden flood phenomena.

Huge damages to the residential area of Marina Velca, near the mouth of Marta River, have been caused by flood in consequence of intense and abundant rainfall events; one great flooding phenomenon occurred in 1987 as far as nowadays, on 10th December 2008.

On 15th November 2005 a significant precipitation interested the Province of Viterbo on the borderline between Latium and Tuscany. The registered flood flows in Marta River stirred up flooding and landslides movements and a resulting alert status monitored by a task force from Latium Region Functional Centre and Civil Defence for several days.

After exactly three years from the destructive flood event dragging mud and ruin, on 14th November 2008, a gigantic work as outstanding security measure for the banks at the mouth and along the last stretch of the stream.

Recently on 10th December 2008 Marta River overflowed on the fields owing to heavy raining of the entire week and Mignone River also overcame the banks and several houses had to be evacuated. The local Land Reclamation Consortium, Consorzio di Bonifica della Maremma Etrusca, also went into alarm just to monitor the hydrometric level in the secondary tributaries and ditches such as Fosso Dei Giardini which often flooded during the past events.

All these events lead to a fervent awareness of flood phenomena risks and to a more and more vibrant interest on Marta River basin hydraulic behavior and management urge to ensure citizens safety and natural ecosystem protection.

The level variations in the Bolsena lake are strictly related to erosion events and to Marta River level fluctuations and it is a matter of interest for tourism: a kind of sluice-gates, which are regulated manually, direct the flow coming out of the lake and getting into Marta.

As a consequence, when the level in the lake level grows up, there's a decrease of available beach for tourists; on the other hand, a high level of water in the lake allows to guarantee the Minimum Vital Flow in the Marta River and it's basic and fundamental for wild-life.

At the mouth of Marta River, the coastal alluvial aquifer (called "Maremma Laziale"), has the morphotypes characteristics of this area and they includes Marta River watershed.

The current structural, morphological and litostratigraphic Maremma Laziale setting comes from the palaeographic and tectonic evolution that has been involving Tuscany and Latium basins since

Superior Miocene up to nowadays. Showing a decreasing aquifer thickness toward the sea, the system may be affected by saltwater intrusion phenomena due to the anthropic pressures and impacts (e.g. pumping from wells) since its natural lean for saline contamination.
Within Fiume Marta SCI the Tuscania Natural Reserve develops along Marta river banks but just in this area, some fluvial weirs for hydroelectric purposes, affect fish-wildlife cause they interrupt the fluvial continuity with heavy consequences on going up the river ichthyic habits.
Industrial drainage and agricultural activities may also threaten Marta River water quality as a consequence of wastewater discharges, fertilizers applications, water extraction from wells.
Therefore a deep hydrological analysis in the Marta River Basin is hopefully and it'll lead us to a needful Basin Planning through the creation of a DSS (Decision System Support) which integrates environmental aspects, both agronomic and socio-economics ones, relating to water resources quality and availability.

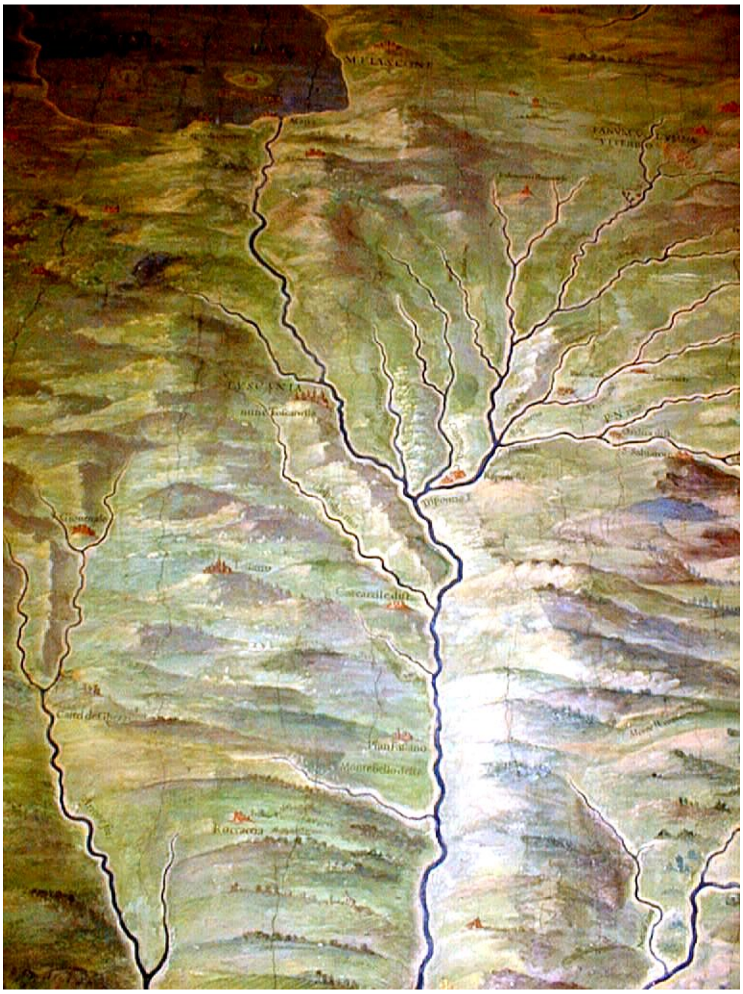
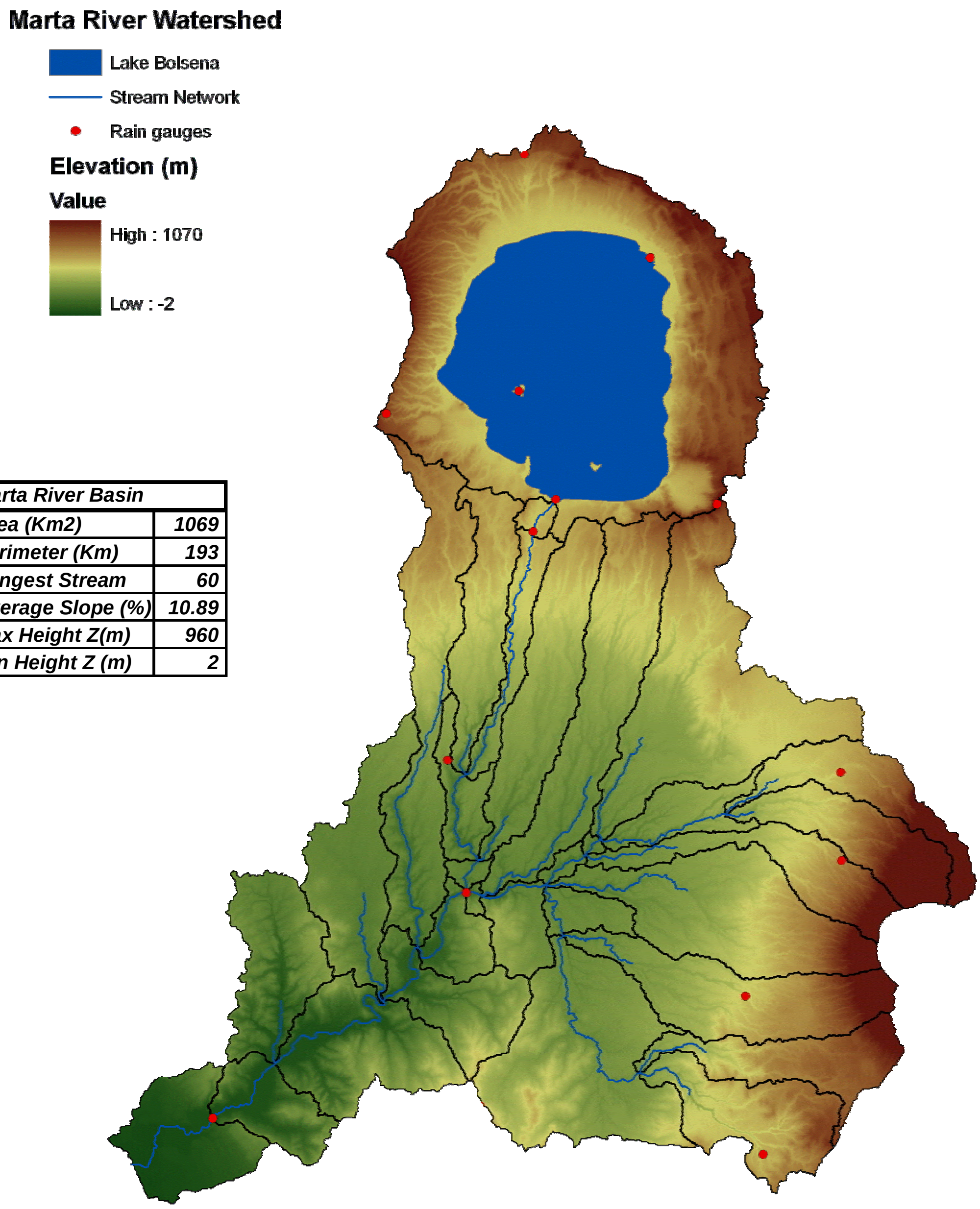


Fig. n° 4.1 An ancient map describing Marta river basin (Vatican Museum, Rome,Italy).



Marta River Basin	
Area (Km2)	1069
Perimeter (Km)	193
Longest Stream	60
Average Slope (%)	10.89
Max Height Z(m)	960
Min Height Z (m)	2

Fig. n° 4.2 Marta river basin in Latium region (Italy)

4.2 Climatic characterization

The zone climatic trend deeply affects landscape evolution and relief shaping, weighing on hydrography, soil origin and setting and on vegetation spatial distribution. Temperature and both liquid and solid precipitations are the principal parameters to be taken into account while climatically characterizing the study area. Besides the meteorological data, resorting to indexes, diagrams and equations to describe the physical behavior and leaning towards drought help to define the hypothetical or effective aridity status or trend of the soil-water system. Climatic and hydrometric historical series of data will have been gathered for a statistical analysis, aimed to assess meteo-hydrographic characteristics of the region, collecting all the available meteorological information from The Regional Hydrographic Service: monthly and daily (not for all the years) rainfall amount from rain-gauges and mean monthly temperature data and, in some cases, daily minimum and maximum data from meteorological stations, hydrometric daily levels from hydrometric stations. The Regional Hydrographic Service has developed an extensive automatic and telemetric network of meteorological stations in the Latium region, keeping the monitoring system of the entire Region, and getting and controlling all the incoming hydrometereological data from rain-gauges and hydrometric stations. The following table (*Tab 4.1*) specifies the station name and location and the equipment for each of them.

STATION	EQUIPMENT	UTM COORDINATES	
		E UTM	N UTM
Centrale Traponzo	Hydrometer	243729	4694662
Barbarano Romano	Rain gauge	258170	4681921
Bolsena	Hydrometeorological station	253232	4726022
Isola Bisentina	Rain gauge	246282	4719056
Marta	Rain gauge	248056	4713788
Monte Romano	Hydrometeorological station	244391	4684274
Montefiascone	Rain gauge	255879	4713543
Ponte della Cartiera	Hydrometer	246925	4711964
San Lorenzo Nuovo	Rain gauge	246540	4730593
Roccarespampani	Rain gauge	246986	4712221
S. Martino al Cimino	Rain gauge	261947	4696216
Tarquinia	Rain gauge	231382	4683668
Tarquinia	Hydrometer	231382	4683668
Tuscania	Hydrometeorological station	242820	4701113
Valentano	Rain gauge	239848	4717941
Vetralla	Rain gauge	257285	4689623
Viterbo	Hydrometeorological station	261919	4700520

Tab. n° 4.1 Hydro-meteorological stations coordinates (UTM coordinate system, zone 33) in Marta watershed.

The network stations are suitably equipped for the measurement of rainfall amount by rain gauges and temperature by thermometers and even hydrometric height by flow gauges in the hydrometric stations. The actual network of monitoring stations covers almost the entire Marta River basin making it continuously monitored under the regional system.

Just to set the climatic characteristics of the watershed, the main temperature and rainfall parameters are reported here for the representative meteorological station of Tuscania, located, more or less, in the middle of the basin, Bolsena, in the upper part of it and Tarquinia, in the southern one.

Tuscania-Meteo Station Lat. N. 42° 25' (Rome Mer.) 0° 35' W ; m s. m. 166												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T °C (Average)	6.72	7.55	9.90	12.60	16.71	20.80	23.91	23.97	20.78	16.24	11.56	7.96
P mm (Average)	76.23	76.60	68.33	65.94	61.17	41.74	20.60	43.98	77.27	102.62	117.96	97.36

Tarquinia-Meteo Station Lat. N. 42° 15' (Rome Mer.) 0° 42' W ; m s. m. 149												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T °C (Average)	7.43	7.58	10.14	13.42	18.21	20.94	22.63	24.10	21.28	17.71	13.08	2.33
P mm (Average)	73.14	70.83	57.02	50.20	43.00	28.53	10.84	25.85	64.23	96.30	93.51	84.89

Bolsena-Meteo Station Lat. N. 42° 39' (Rome Mer.) 0° 28' W ; m s. m. 348												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T °C (Average)	5.53	6.38	8.15	11.05	15.30	19.13	22.09	22.44	19.26	14.92	9.87	6.42
P mm (Average)	74.31	79.10	71.38	66.79	59.75	48.39	26.04	37.03	77.12	97.70	116.15	92.58

Tab. n° 4.2 Mean monthly values for rainfall amount and temperature for Tuscania, Tarquinia and Bolsena measurement stations respectively calculated over the period 1930-2006.

The study area corresponds to oceanic Mediterranean climate domain and it is characterized by high temperature values during summer period, mild ones in winter, heavy precipitations, not so strong summer drought with high atmospheric humidity.

According to the comparison between *Pavari* and *De Philippis* parameters for peninsula Mediterranean climates subdivision, Tuscania station could be located in a II Type phitoclimatic zone, Lauretum II Type (summer drought), medium sub-zone.

While the total annual rainfall amount can reach 854.9 mm, during the summer period, precipitation seems to round on 106.3 mm. At the same time the maximum temperature values appear and lead to a summer drought situation for the months of June, July and August. This dry season is mitigated by the edaphic characteristics of this site since the soil can keep some water in, at the depth of about 70 cm, and controls humidity mainly during July and August.

Cold remains from November to April being not so bitter, with an average minimum monthly temperature of 2.5 °C in the colder month.

To better define the local climatic trend some of the most important bio-climatic classification have been investigated and applied, pointing out the obtained results graphically and other meteorological parameters have been gathered such as relative humidity, solar radiation and wind velocity.

Tuscania-Meteo Station Lat. N. 42° 25' (Rome Mer.) 0° 35' W ; m s. m. 166				
	RH Ave (%)	Sol. Rad. (MJ/cm^2)	Wind Vel. (km/d)	Dew Point T (°C)
January	2.90	124.00	141.00	8.00
February	2.90	185.00	160.00	9.10
March	6.30	180.00	165.00	10.20
April	6.70	213.00	150.00	12.00
May	10.10	363.00	114.00	13.80
June	13.60	310.00	106.00	14.90
July	18.30	447.00	97.00	16.00
August	16.40	442.00	87.00	16.00
September	13.50	316.00	108.00	15.00
October	11.00	180.00	115.00	13.80
November	6.00	125.00	120.00	11.90
December	4.80	124.00	118.00	9.90

Tab. n° 4.3 Averaged monthly climatic parameters for Tuscania measurement station, RH Ave = Average Relative Humidity, Sol. Rad. = Solar Radiation, Wind Vel. = Wind Velocity and Dew Point T = Dew Point Temperature for the period 1930-2006.

According to the Aridity Index suggested by Bagnouls and Gaussen, a dry period is characterized by a rainfall amount which is lesser than twice the measured temperature for the same period, that is:

$P < 2T$ where P is the mean annual precipitation in mm and T is the mean annual temperature expressed in °C.

As the diagram shows, a drought period can be found in the summer months.

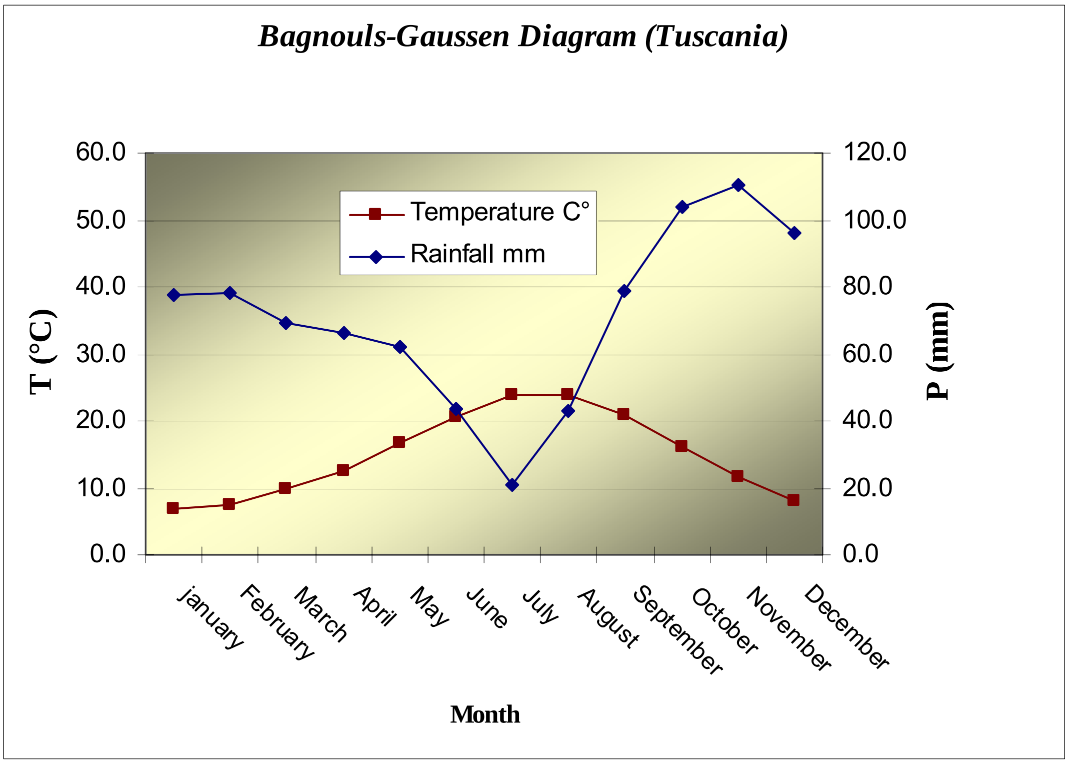


Fig. n° 4.3 Bagnouls-Gaussen diagram for Tuscania station.

Thornthwaite theory is based not only on rainfall amount and temperature but also on evapotranspiration as a measure of water losses from canopy. When potential evapotranspiration (that is evapotranspiration occurring in continuous water availability in the soil and depending on several climatic parameters such as solar radiation, air temperature, wind velocity, atmospheric humidity) is greater than rainfall amount, soil water resources are being consumed; in the contrary, a storage is taking place while less.

However vegetation doesn't feel the effect of the possible deficit until some reserves are still keeping up since the "physiological aridity" period starts just with the exhaustion of those reserves.

By definition, only when rainfall amounts are greater then potential evapotranspiration, the real one overlaps the latter, provided that the water reserve of the soil is really saturated.

According to Thornthwaite estimates, the maximum water retention can be supposed equal to 100 mm for arable land and equal to 200 mm for forest.

Taking into account the land cover reality and the particular characteristics of the soil (e.g. clay presence and remarkable depth) the Potential Evapotranspiration Index was calculated using a

formula linking potential evapotranspiration and temperature by annual and average indexes, corrected with established coefficients depending on latitude.
Thornthwaite relationship, on monthly base, is:

$$ET_{oi} = 16 \times \left(10 \times \frac{t_i}{I}\right)^a \tag{4.1}$$

where: $ET_{oi} = ith$ month potential evapotranspiration (mm/month), t_i= *ith* month temperature (°C), *I* = heat annual index, sum of the twelve monthly indexes from following equation:

$$i = \left(\frac{t_i}{5}\right)^{1.514} \tag{4.2}$$

$$a = 675 \times 10^{-9} \times I^3 - 771 \times I^2 + 1792 \times 10^{-5} \times I + 0.49239 \tag{4.3}$$

ET_o has to be corrected with coefficient depending on site and latitude.
All the calculations have been carried out in order to compare them with the values in output from the SWAT simulation model implemented for Marta river watershed (see Chapter 5) and making in evidence also deficit and surplus periods, recharge and reserve consumption time in the soil.

Precipitations and PET		
	P	**PET**
January	77.30	14.10
February	79.10	18.30
March	69.50	30.50
April	65.60	48.30
May	62.90	80.40
June	42.40	112.60
July	20.80	141.50
August	43.10	133.20
September	79.60	97.50
October	105.10	60.00
November	110.50	31.80
December	96.22	17.10

Tab. n° 4.5 Mean monthly values of Potential Evapo-transpiration, (PET) according to Thornthwaite formula.

Regarding Tuscania station, almost five months show precipitation less then potential evapotranspiration and they reduce to two month of physiological aridity (water deficit) for canopy, from July to September, after soil water reserve consumption. The first month with precipitation greater then water losses after summer drought seems to be October while with the November and December rainfall water reserves are to be reconstructed. The mean annual value for PET is 785 mm.

Mitrakos instead considers summer aridity and winter cold as critical factors for land cover vegetation in a Mediterranean climate. He proposed two indexes to measure, on monthly base, the two types of stress starting from the hypothesis that canopy undergoes to a stress due to aridity when rainfall amount is less then 50 mm while 10 °C value is the thermal threshold for vegetative activity to start. The aridity stress D (drought) can be derived from: $D = 2 \times (50 - p)$ where p is the monthly precipitation in mm (when p=0 then D=100; when p>50 mm then D=0).
The stress from cold C (cold) is calculated as

$$C = 8 \times (10 - t) \tag{4.4}$$

where t is the minimum monthly temperature in °C (when $t > 10$°C then C = 0; when $t < 2.5$°C then C = 100 is fixed).
Computing D and C, the measure of cold stress (MCS) and aridity stress (MDS) can be obtained. The annual aridity stress value (YDS), sum of monthly ones, is equal to 87.4, while the annual cold stress (YCS) is 261.1.
Emberger, instead, distinguished several types of climate according to the so-called pluviothermic ratio (Q2): a climate is much drier as Emberger's ratio decreases. It expresses the aridity referring to the considered meteo-station.
The applied formula is:

$$Q_2 = 100P / \left(M^2 - m^2\right) \tag{4.5}$$

where P is the annual rainfall mean in mm, M is the maximum temperature mean of the warmest month in °C, m is the minimum temperature mean of the coldest month in °C. Since the difference $(M - m)$ is proportional to the evaporation, Q_2 is nothing but the ratio P/T.
Entering the Tuscania station data in that formula, Q_2 is equal to 88.7 .

Land use

A large part of Marta watershed area is dedicated to agricultural activities: first of all cereals and horticulture crops but also vineyard and olives. Forests and shrubs cover the most of the surface with more than 57000 ha and about 3000 Ha respectively. Olives interest more than 10000 Ha and vineyards are cultivated in about 970 Ha.

The upper part of the watershed, corresponding to lake Bolsena basin, is mainly dedicated to intensive agricultural activities with particular reference to cereals, especially wheat, barley and oats, potatoes, sugar beets, rotated forage, industrial and wooden crops, vineyards and olives.

Here are some results from the management plan for SPZ IT6010007 lake Bolsena and Bisentina and Martana isles (DAF Department, University of Tuscia, 2008).

CROP	Ha		CROP	Ha
Arable land	15223.8		**Orchards**	533.4
Wheat	6760.6		*Apple tree*	12.29
Barley	5338.48		*Pear tree*	8.38
Oats	659.42		*Peach tree*	26.97
Corn	134.63		*Hazelnut*	77.72
Other cereals	285.31		*Chestnut*	46.26
Dry legumes	80.1		*Other fruits*	112.85
Potato	795.5		Garden centres	6.62
Sugar beet	10.12		Permanent meadow and pasture	2080
Industrial crop	1027.76		Wooden arboriculture	72.9
Horticultural crops	78.36		**Wood**	4635
Rotational forage	6471.33		Forest	547.15
Wooden crop	3368.07		Copse	3887.9
Vineyard	941.35		Mediterranean shrubs	199.62
Olive	1881.58		**Irrigable land**	3410

Tab. n° 4.6 Crops allocation in lake Bolsena basin from the Management Plan for SPZ IT6010007 lake Bolsena and isles (DAF Department, University of Tuscia, 2008).

In the central part of Marta watershed, forests are the main land cover and, especially in The Natural Reserve of Tuscania, cork forest-oaks, holm oaks, broadleaved oaks, evergreen forests, black locusts and elms. Smaller formations with strongly rare wood covers less than 40% of the Natural Reserve area (Ceccarelli, 2001) and consists of Mediterranean shrubs and holm oak or mixed rare wood, broadleaved shrubs with evergreen or broadleaved wood.

	Turkey oak	**Oak wood**	**Mixed**
	Ha	*Ha*	*Ha*
Closed	80.66	19.06	2.24
Open	15.32	2.25	1.59
Rare	11.38	2.99	4.11

Tab. n° 4.7 Oaks allocation between the different cover classes (Ceccarelli, 2001).

As coming nearer to the mouth of Marta river, the land assumes a mainly agricultural aspect again with cereals and horticultural crops for the most with particular reference to wheat and tomato.

The traditional local production is made of tomato and watermelons but on a surface of 18500 ha, 1300 tonnes/year of corn, 21000 tonnes/year of wheat and 250 tonnes/year of oats are also provided. Artichoke, straw, fennel, colza and sunflower are typical crops of this area too. The main profits are, anyway, from cereals and tomato production for whom the area is climatically and physically particularly suitable.

Product	**Quantity (quintal/year)**
Wheat	327.791
Seed wheat	7.974
Corn	4.738
Oats	2.533
Barley	877
Sunflower	9.616
Colza	83
Tomato	245.886

Tab. n° 4.8 Main production classes for the coastal area in Marta watershed (Pantano Cooperative dataset)

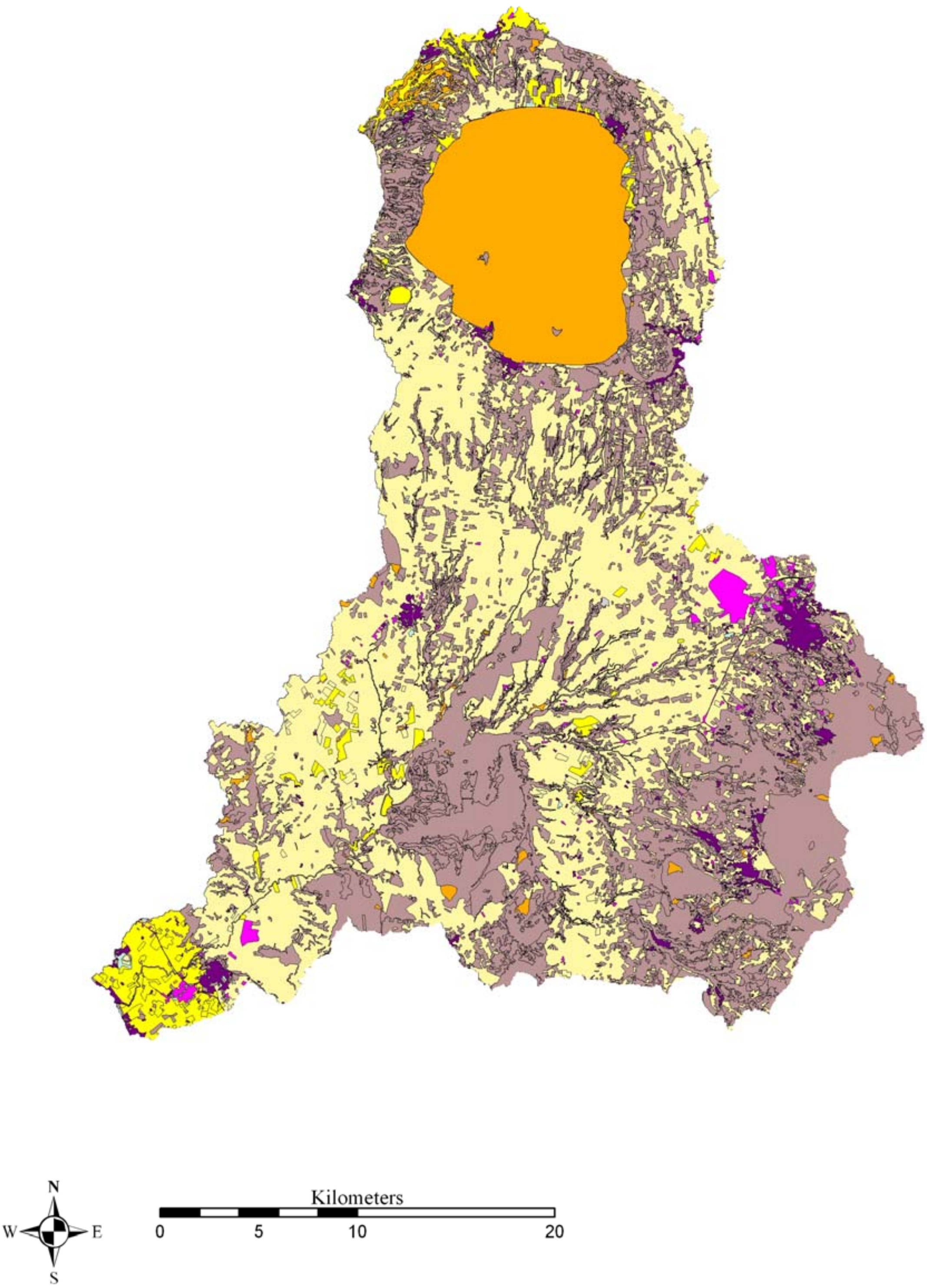


Fig. n° 4.4 Land cover types in the study area according to Regional Soil Map (2005) based on Corine (IV° level).

Fig. n°4.5 Legend for land cover types in the study area according to Regional Soil Map (2005) based on Corine (IV° level).

4.3 Hydrography

Marta River basin takes up a total area of 1089 km^2, and 270 km^2 of them, belong to Lake Bolsena sub-basin. The watershed shows landscape homogeneity which is determined by the volcanic complexes of Cimini Mountains, Vulsini and Vicani ones. The volcanic activity started 0.9-1 million years ago for Cimini Apparatus, 0.8-0.09 million years ago for Vicano Apparatus and 0.7-0.3 million years ago for Vulsino Apparatus.

The geologic origin of this area is almost uniform: volcanic ashes, thrown down for a great distance, created a thick plate made of stratified tufa with varying color and texture, covering the land below. The three volcanic groups dominate a quite regular wide terrace, in a level land with a weak slope. Since tuffs is a soft and easily erodible material, the numerous streams, coming down along the volcanic mountains slopes with a pattern like spokes radiating from a centre, etched deep canyons during several millenniums. Canyons and tuffs plates are the two main elements characterizing the landscape. The stream network etched by water courses in the tufa slab is fairly branched dividing the ancient surface in stretched terraces. Closer to the cost, clay soils prevail on tufa plates beneath; Marta downstream valley appears, therefore, surrounded by wavy hills made of pliocenic clay. Canyons system is clearly distinguished from the rest of the land and it often offers a great naturalistic significance. The tufa deep valleys house animal and plant populations and they represent safe places for native flora and fauna, that once lived in surroundings plains. Moreover they are important movement passageways for wild animals. Marta river origins from Lake Bolsena, only effluent of which. During its course it touches Marta and Tuscania villages down to Marina Velka and Lido di Tarquinia seaside resorts. In its first 20 km Marta river does not receive any tributary; the first significant confluence is with Maschiolo stream at a level with Tuscania. 5 km south of Tuscania, Pantaccione ditch goes in and, after 1.5 km more, Traponzo stream merges into Marta River and its sub-basin covers about 60% of the entire surface of Marta River basin, with the exception of Lake Bolsena basin, and it falls back in Montefiascone, Viterbo, Vetralla, Villa san Giovanni in Tuscia, Blera, Barbarano Romano and Monteromano municipalities. Later Copecchio ditch, rising from Piansano land and crossing Tuscania village, Civitella ditch from Monteromano municipality, Mignattara ditch from Tuscania and an endless series of narrow moats drain into Marta River. Traponzo stream consist of a short fluvial branch (about 4 km) rising from the confluence of Leia ditch, Rigomero and Biedano water courses and, before flowing into Marta River, receive water from Catenaccio stream. Leia buds from Montefiascone area and along its course joins Urcionio ditch, crossing Viterbo city, and Risiere, coming from S. Martino al Cimino village. Rigomero originates from several moats draining straddle between Viterbo and Vetralla territories. Biedano starts from Barbarano Romano zone, almost touch Blera and receives water from Villa S. Giovanni in Tuscia, Monteromano and Vetralla.

4.3.1 Water drawings

According to the Legislative Decree n° 275/1993, starting from 1994, new and existing wells for domestic and/or irrigational purposes have to be declared to the competent authority (Regional and Provincial Offices) in order to create an organic and complete database accompanied by a stratigraphy and geological description of the realized well. Regarding to surface water deviations, a license for water pumping extraction has to be granted by the competent Provincial Office according to Royal Decree n°1775/1933.

Municipality	Area (km^2)	Declared drawings (n°)	Water drawing density
Bagnoregio	72.63	127.00	1.75
Barbarano Romano	37.26	135.00	3.60
Blera	92.98	241.00	2.60
Bolsena	63.78	545.00	8.60
Canepina	20.73	79.00	3.80
Capodimonte	61.74	218.00	3.59
Capranica	40.58	403.00	9.86
Caprarola	58.00	360.00	6.27
Gradoli	44.03	43.00	0.98
Grotte di Castro	34.55	80.00	2.39
Latera	22.71	26.00	1.16
Marta	33.51	202.00	6.04
Monte Romano	86.03	81.00	0.94
Montefiascone	105.18	514.00	4.91
Piansano	26.39	18.00	0.68
Ronciglione	52.24	408.00	7.79
San Lorenzo Nuovo	25.82	81.00	3.04
Tarquinia	279.88	1629.00	5.84
Tuscania	208.06	1055.00	5.07
Valentano	43.02	75.00	1.71
Vetralla	114.40	1561.00	13.88
Viterbo	405.85	4019.00	16.19

Tab n°4.9 Declared pumping wells according to the law in force.

Municipality	Area (km^2)	Water drawing density	Drawings (n°)	Volume (m^3/year)
Bagnoregio	72.63	0.47	6.38	36199968.36
Barbarano Romano	37.26	0.21	3.80	1017014.62
Blera	92.98	0.30	8.04	45633956.92
Bolsena	63.78	1.55	97.56	553815216.38
Canepina	20.73	0.91	0.38	2185046.30
Capodimonte	61.74	0.59	36.24	205715074.27
Capranica	40.58	0.47	1.70	9635179.08
Caprarola	58.00	1.79	0.14	781012.59
Gradoli	44.03	4.20	182.48	1035850113.01
Grotte di Castro	34.55	1.97	28.86	163821142.44
Latera	22.71	0.63	0.05	264783.18
Marta	33.51	0.87	29.15	165481075.48
Monte Romano	86.03	0.06	0.48	2747855.57
Montefiascone	105.18	2.16	12.60	71551245.88
Piansano	26.39	0.30	3.28	18641973.87
Ronciglione	52.24	2.56	9.59	54411588.02
San Lorenzo Nuovo	25.82	1.72	35.90	203762854.92
Tarquinia	279.88	0.51	14.92	84696260.43
Tuscania	208.06	1.48	210.72	1196141135.63
Valentano	43.02	0.91	3.29	18700309.78
Vetralla	114.40	1.50	171.55	973781860.60
Viterbo	405.85	1.63	438.85	2491105152.93

Tab. n° 4.10 Surface water deviations for each municipality

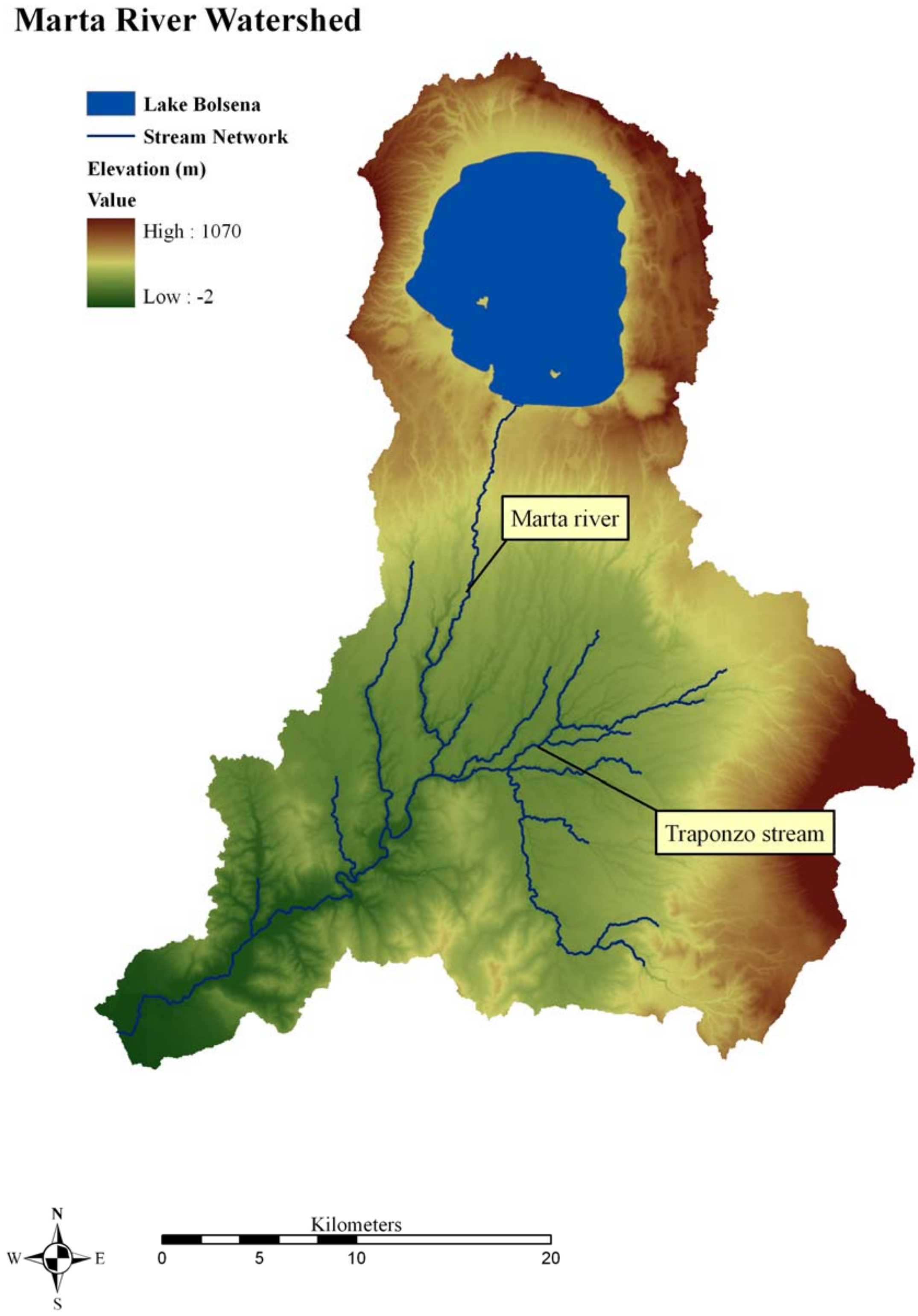


Fig. n° 4.6 Study watershed stream network delineation

4.4 Water quality and monitoring

The water quality status for Marta River is monitored by The Regional Environmental Protection Agency (Agenzia Regionale per la Protezione dell'Ambiente della Regione Lazio, ARPA Lazio) with scheduled field campaigns and data elaborations for defining the river status according to the laws in force. The last twenty years saw and increasing interest in environmental protection and ecosystems preservation with particular attention to superficial and underground water bodies. Actually the environmental legislative academia knows the focus of its attention on quality water status and in particular on receiving water body ecosystem role according to Law n° 152/06 and above all The Water Framework Directive n°60/2000/CE. On 23 October 2000, the "Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy" or, in short, the EU Water Framework Directive (or even shorter the WFD) was, in fact, finally adopted.

The environmental objectives are the core of the Directive and the definition of "good ecological status" is essential.

Acknowledging the EU Water Framework Directive, Italian Parliament introduced the Legislative Decree n°152/2006 to discipline identification and environmental quality targets for water bodies. To evaluate water quality, in addition to chemical and bacteriological analysis, survey methodologies, taking into account the health of the whole fluvial system, have been added: microhabitat presence, aquatic plants, environmental diversity, hydraulic regime or river bed degeneration.

As a method to evaluate the habitat quality, the Biotic Index was introduced in Italy starting from 80's and it enables us to determine water quality and self-cleaning capacity of river stretches under waste water discharge, depending on aquatic organisms presence and using them as indicators.

Using a close mesh landing net, sediments from the river bed are sampled and they are examined to find and take a census of micro-invertebrates (Systematic Units SU). The correspondent Quality Indexes are derived from a table (Ghetti, 1993) and they go from 0 value, very bad status, up to 14 pointing at a very good status.

The Legislative Decree n° 152/06 fixes minimum environmental quality targets and quality targets for specific purposes:

-water resources for drinking water production

-water resources for bathing purposes

-water resources that need protection and improvement to be suitable for ichthyic life.

The water quality target fixed by national laws, is defined on the basis of water bodies capacity to keep self-cleaning natural processes and to support well varied plant and animal communities.

The Environmental quality status for a surface water body comes from the cross between chemical status and ecological status.

The definition of the ecological status passes through the evaluation of the following elements:

-biological elements (aquatic flora, benthonic macro-invertebrates, ichthyic fauna)

-hydro-morphological elements in support of biological elements (hydrologic regime, fluvial continuity, morphological conditions)

-Chemical and chemical-physical elements in support of biological elements (temperature, oxygen, salinity)

-Specific pollutants (pollution from all the priority substances, the discharge of which has been found out in heavy quantities.

The chemical status is instead defined on the basis of the arithmetic annual mean of the dangerous substances concentrations in superficial waters.

The analysis of these two status lead to a five class subdivision:

-very good

-good

-sufficient

-low

-very bad

According to the Legislative Decree n° 152/06, within 22nd December 2015, the following environmental quality goals should be reached:

-all the significant water bodies have to keep or reach the good quality status

-where it already exists, the high quality status have to be kept

To ensure the achievement of those targets, within 31st December 2008, every superficial water body should get the sufficient quality status at least.

According to the laws in force, all these water quality improvement targets should be reached through the Water Resources Protection Plan editing of every single region.

With regional deliberation n°687 del 30 July 2004, the Regional Council adopted the Regional Water Resources Protection Plan which represents a fundamental setting and planning instrument for the region to accomplish water resources protection and management compatibly with all the other uses to guarantee life quality and socio-economic activities for the whole region people.

Following The Regional Water Resources protection Plan, Latium Region identified water courses and artificial canals to keep under control and which can be defined “significant”.

In the Province of Viterbo they are:

-Tiber River

-Mignone River

-Arrone River

-Fiora River

-Marta River

To evaluate the environmental quality of rivers and lakes in Latium Region, the Regional Agency for Environmental Protection of Latium Region carries out monitoring campaigns with monthly cadence on 172 measurement stations which are distributed along all the significant water courses in the region. Tuscia land (the territory in the Province of Viterbo is called Tuscia) is covered by 14 monitoring stations on superficial water bodies, they are codified and geo-referenced.

Monitoring stations along Marta River course	***UTM Coordinates***	
Name	*Nord*	*Est*
La Birreria	4711914	246947
Ponte Strada Tuscania-Marta	4706531	245784
Ponte Strada Tuscania-Viterbo	4699409	243114
Sbarramento Maremmano	4684107	231941
Ponte Via Litoranea	4682204	228570

Tab n° 4.11 Monitoring stations along Marta river course (UTM Coordinate System, 33 zone).

To define the ecological status, two indicators, representing chemical and ecological conditions of the water body, are considered. The two indexes are:

-LIM (Livello di Inquinamento da Macrodescrittori) which is the pollution level by macro-descriptors. It takes into account the concentrations of some chemical and micro-biological parameters and in particular it is defined by dissolved oxygen, nutrients, biodegradable organic matter and micro-biological pollution. On the basis of table values, summing up the obtained results, different quality with conventional colors can be assigned that is:

-class 1: very good with blue color,

-class 2. good with green color,

-class 3. sufficient with yellow color,

-class 4: low with orange color,

-class 5: very bad with red color.

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
100-DO (%sat)	≤ 10	≤ 20	≤ 30	≤ 50	≤ 50
BOD5 (O_2 mg/l)	< 2.5	≤ 4	≤ 8	≤ 15	> 15
COD (O2 mg/l)	< 5	≤ 10	≤ 15	≤ 25	> 25
NH_4	< 0.03	≤ 0.10	≤ 0.50	≤ 1.5	> 1.5
NO_3	< 0.3	≤ 1.5	≤ 5	≤ 10	> 10
Total Phosphorus	< 0.07	≤ 0.5	≤ 0.30	≤ 0.60	> 0.60
Escherichia coli	< 100	≤ 1000	≤ 5000	≤ 20000	> 20000
Score to assign for every parameter to analyse (75° percentile in the survey period)	80	40	20	10	5
LIM	480-560	240-475	120-235	60-115	<60

Tab. n° 4.12 LIM classes definition

-EBI (Extended Biotic Index) measures the chemical and chemical-physical water quality effects on benthonic macro-invertebrates living almost part of their biological cycle in river beds. Also in this case 5 quality classes are defied on the basis of the presence/absence of those organisms. Combining this index with LIM, the ecological status (called SECA) can be determined for water courses.

Classes	EBI	Quality assessment	Tematic color
I	10-11-12	No pollution environement	
II	8-9	Slightly polluted environment	
III	6-7	Polluted environment	
IV	4-5	Very polluted environment	
V	1-2-3	Strongly polluted environment	

Tab. n°4.13 EBI classes definition

To define the environmental status for the water body, the Ecological Status values have to be compared with data referring to organic micro-pollutants or heavy metals listed in Tab. 1 of Attachment 1, Legislative Decree n° 152/06. If the concentration of only one of such micro-pollutants is greater than the threshold value provided by law, the water quality status becomes low or very bad if the ecological status is already low or very bad.

	Class 1	Class 2	Class 3	Class 4	Class 5
EBI	≥10	8-9	6-7	4-5	1-2-3
LIM	480-560	240-475	120-2235	60-115	<60

Tab. n° 4.14 EBI and LIM classes definition

Ecological Status	Class 1	Class 2	Class 3	Class 4	Class 5
Pollutant concentrations					
≤ Threshold Value	Very Good	Good	Sufficient	Low	Very Bad
≤ Threshold Value	Low	Low	Low	Low	Very Bad

Tab. °4.15 Ecological status definition

A further indicator for water quality is the so called IFF (Indice di Funzionalità Fluviale), that is Fluvial Functionality Index, adopted by the Provincial Council of Viterbo. This index derives from the Riparian Channel Environmental Inventory (RCE-I; Petersen, 1992), created in Sweden and then modified to adapt it to the Italian environmental reality. The IFF index focuses on river ecosystem capacity to destroy the organic matter through self-cleaning processes, giving information about the ecosystem itself and, indirectly, on the possible deterioration causes and re-qualification actions. To compute the IFF index, an evaluation card is used. It is made up of 14 questions on the natural status of the water course to assess and judge several aspects of it, linked together to balance the questionnaire. This is a brief description of the subjects faced by the questions:

-Questions 1-4: on vegetation condition on banks and near the river bed;

-Questions 5-6: on banks morphological and physical structure;

-Questions 7-11: on wet bed structure, by the identification of the characteristics encouraging bio-diversity and self-cleaning processes;

-Questions 12-14: on biological aspects as energetic inputs acting on ecosystem throphic chain.

A weight is assigned to every single answer to calculate the final value which can vary from a minimum of 14 to a maximum of 300. Using a correspondence table (Tab n° 4.7) this value can be translated in a functionality level (from I to V level) with the presence of intermediate levels which enables a gradual level change. To assess the IFF index for a river, it’s necessary to determine homogeneous stretches of water course in respect of which, the questionnaire has to be compiled together with an independent analysis of both the banks. This method can be applied only with running water and without saltwater intrusion.

IFF Value	Functionality Level	Functionality Assessment	COLOR
261-300	I	High	BLUE
251-260	I-II	High-Good	GREEN-BLUE GREEN-BLUE
201-250	II	Good	GREEN
181-200	II-III	Good-Mediocre	YELLOW-GREEN YELLOW-GREEN
121-180	III	Mediocre	YELLOW
101-120	III-IV	Mediocre-Low	ORANGE-YELLOW ORANGE-YELLOW
61-100	IV	Low	ORANGE
51-60	IV-V	Low-Bad	RED-ORANGE RED-ORANGE
14-50	V	Bad	RED

Tab n°4.16 Conversion table from IFF values to Functionality classes.

Water Body	Measure Station	Municipality	Year	LIM	IBE	LIM Class	IBE Class	Ecological Status	Environmental Status
	La Birreria	Marta	2001	280	5.0	2	4	4	
			2002	400	7.0	2	3	3	
			2003	270	5.5	2	4	4	4
			2004	225	6.8	3	3	3	3
			2005	310	5.4	2	4	4	4
	Ponte Strada Tuscania-Marta	Tuscania	2001						
			2002	230	8.0	3	2	3	
			2003	250	7.4	2	3	3	3
			2004	260	6.1	2	3	3	3
			2005	250	6.6	2	3	3	3
	Ponte Strada Tuscania-Viterbo	Tuscania	2001	160	3.4	3	5	5	
			2002	120	3.0	3	5	5	
Marta			2003	95	4.3	4	4	4	5
			2004	95	2.8	4	5	5	5
			2005	200	4.8	3	4	4	4
	Sbarramento Maremma	Tarquinia	2001	170	7.0	3	3	3	
			2002	230	8.0	3	2	3	
			2003	230	8.1	3	2	3	3
			2004	210	6.1	3	3	3	3
			2005	270	/	2	/	2*	2*
	Ponte Strada Litoranea	Tarquinia	2001	200	7.0	3	3	3	
			2002	250	8.0	2	2	2	
			2003	145	6.5	3	3	3	3
			2004	180	5.9	3	4	4	5
			2005	190	6.4	3	3	3	3
	* values are given equal to LIM in the absence of IBE data.								

Tab n° 4.17 Water quality status for Marta river at monitoring stations

Marta river, one of the main water courses in the Province of Viterbo, originates from Bolsena lake and flows into the Tyrrhenian sea. It rises with a quite wide but not so deep bed on a substrate mostly made of sand and in little part of cobblestones and rocks: there's no riparian vegetation due to the presence of artificial dykes.

At this point, houses and residential areas are present both on right and left sides of the river. Then Marta river crosses Tuscania village where it receives wastewater from a paper-mill. The riparian vegetation is now made of reeds, herbaceous plants, shrubs and trees such as brambles, black locust, willow and alder but rubbish, plastic bags, bottles and much more all around, show clearly the environmental damage of this area.

Passing through Tuscania village, the river receives also civil and industrial wastewater and flows in an essentially cultivated or breeding areas. After Traponzo inlet, Marta river continues the course in its low-medium valley through a land characterized by an intense agricultural and breeding activity. The qualitative status of this river reflects the status of a stream under civil and industrial anthropic and diffusive type agricultural activities pressures.

The presence of Tuscania residential area causes a sudden deterioration in water quality noticeable at Ponte Strada Tuscania-Viterbo station where the Ecological Status always has values as "low" or "very bad". Water quality improves in the stretch subsequent to Tuscania village and at Sbarramento Maremma station this change is really evident and it's surely due to the dilution effect Traponzo tributary that flows into Marta river just in the reach between the two stations. The spatial and temporal LIM index evolution shows a condition which seems to be more or less stable but just enough "sufficient" with strong critical situations near the main towns.

The critical macro-descriptors characteristics induce to think of a concentrated civil type pollution together with a diffusive agricultural one: high BOD5 values and Escherichia Coli are observable at Tuscania station while heavy nitrates concentrations have been measured near he next Sbarramento Maremma station, after the river has crossed farming and cattle breeding.

Regarding chemical pollutants combining to define the Environmental Status of the river, the measured zinc values are quite high along all the water course although they are always below the legal threshold while the values of copper and mercury exceeded the limits provided by law at Tuscania during 2003 for copper (137 μg/l) and during 2004 for mercury (6 μg/l).

Analysis of monitoring campaign surveys during 2005 show instead the almost total absence of chemical pollutants along the river course.

About EBI index and biotic communities status, the situation seems to be totally unsatisfactory with quality classes only occasionally better than "sufficient" and mostly included between "low" and "very bad" values: during 2005 at Sbarramento Maremma station EBI data are not available while at Litoranea station they correspond to those ones measured during summer period.

4.5 Flow analysis

All the available hydrologic data have been acquired from The Regional Service to characterize the climate of the study area and define its hydrologic behavior even through an accurate flow analysis.

The Regional Hydrographic Service has developed an extensive automatic and telemetric network of meteorological stations equipped for the measurement of rainfall amount by rain gauges and temperature by thermometers and even hydrometric height by flow gauges in the hydrometric stations, in Latium region covering the whole pilot area and making Marta river basin continuously monitored. According to MEDDMAN project hydro-meteorological information has been collected in the form of monthly and daily (not for all the years) rainfall amount from rain-gauges and mean monthly temperature data and, in some cases, daily minimum and maximum data from metereological stations. Hydrometric information corresponds to hydrometric daily levels from hydrometric stations.

Rainfall amount historical series allow to place the basin on a climatic overview and to provide inputs for hydrologic SWAT simulation model.

Average flow regime has been investigated for the main river and also the extreme values have been taken into account for the MFR evaluation and comparisons: hydrograph analysis and decomposition led to baseflow estimation as an essential component in water balance.

4.5.1 Flow regime analysis

In flow regime analysis, average annual discharge, or water body annual module, is taken into account together with average seasonal flow variations obtained from monthly data and flow duration curves, and extreme values.

The mean flow discharge at the exit of the lake is about 2.42 m^3/s while at the outlet of the basin is about 7.72 m^3/s due to the tributary Traponzo inlet which increase the water amount flowing in the river.

Along the river five deviations for hydroelectric power generation alter the natural course of the stream affecting the ecosystem and the ichthyic life in it. Flows with values close to 0, are often observed, especially during the summer period, in proximity of the mentioned above deviations with heavy consequences on local animal and vegetal communities. According to national and European laws and directives, a Minimum Flow Requirement to preserve natural habitat and ecological quality, has to be ensured along the river for example taking into account the biological population needs and the reproduction cycle of the representative fish species for the considered river.

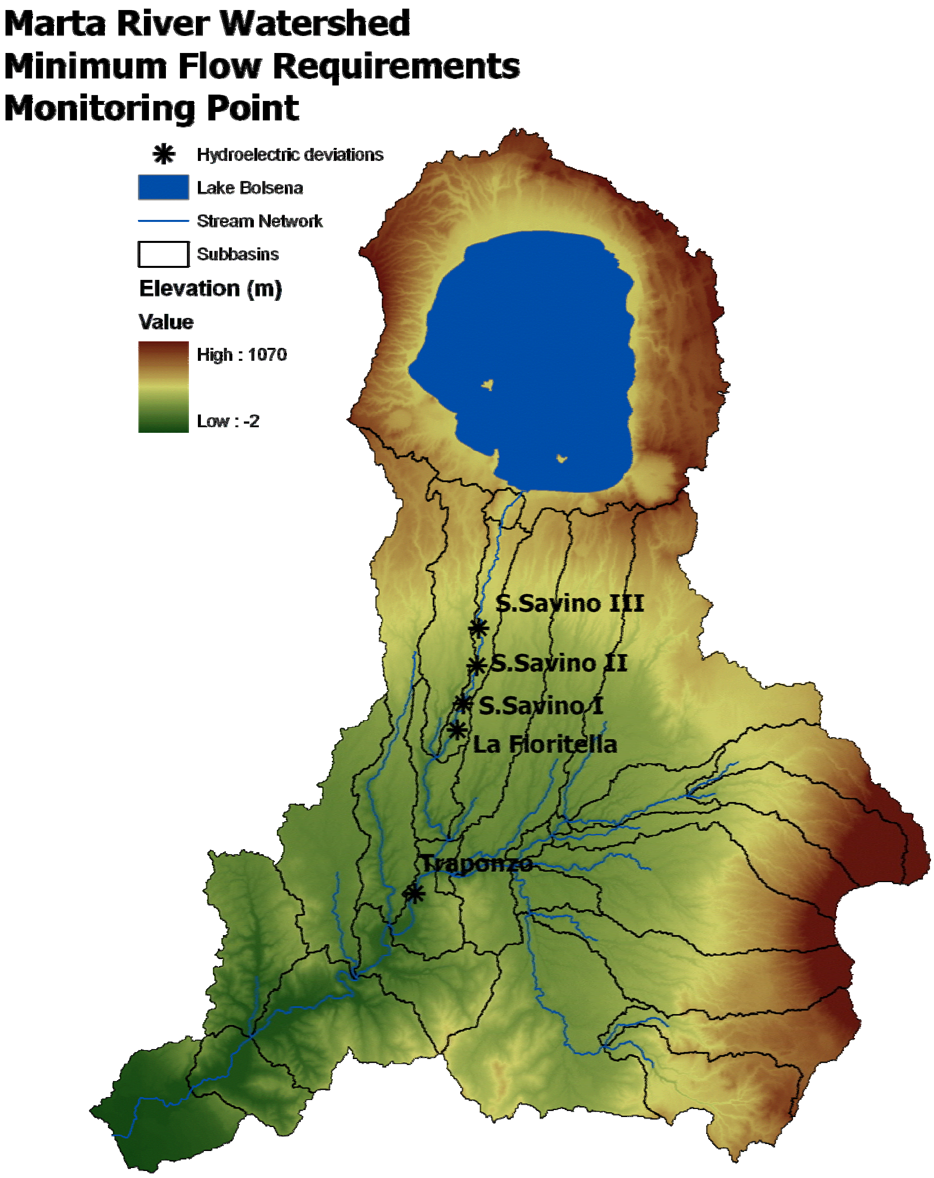


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Fig. n° 4.7 Deviations along Marta river for hydrolelectric power generation

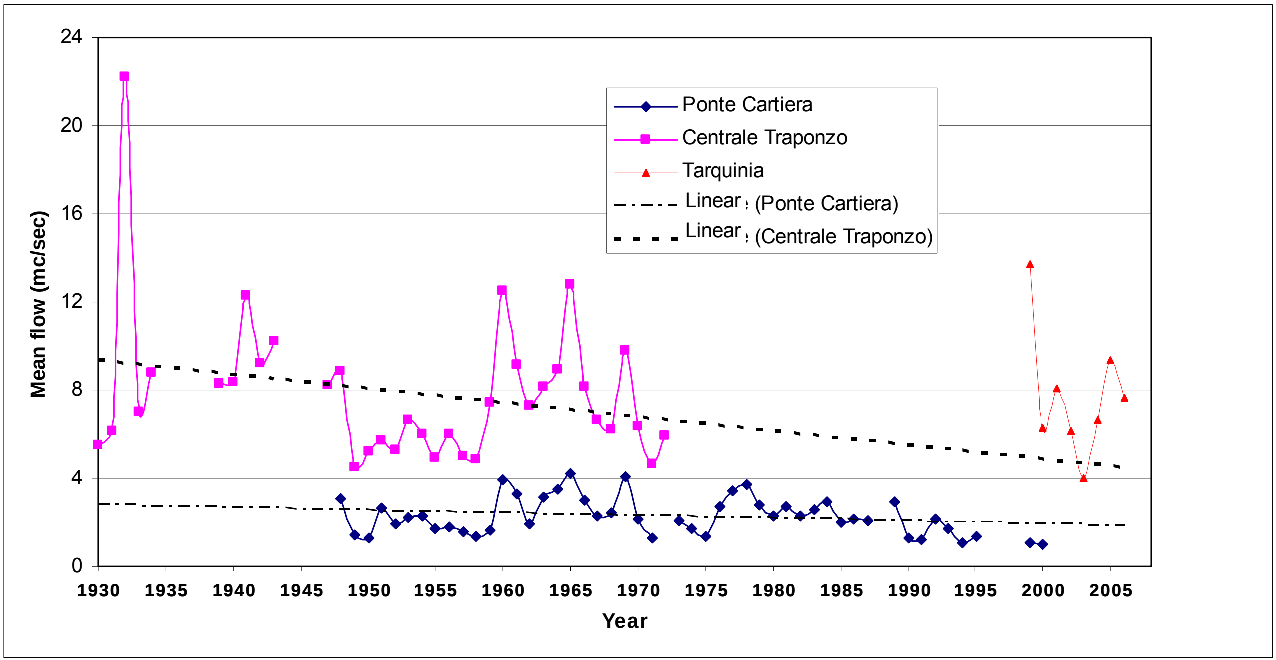

Fig. n° 4.8 Average annual registered flow historical series for Ponte Cartiera, Centrale Traponzo and Tarquinia hydrometric stations from Regional Hydrographic Service.

The registered data show a decrease in time during the last decades probably due to the changed climatic conditions but also to the increased exploitation of water resources.

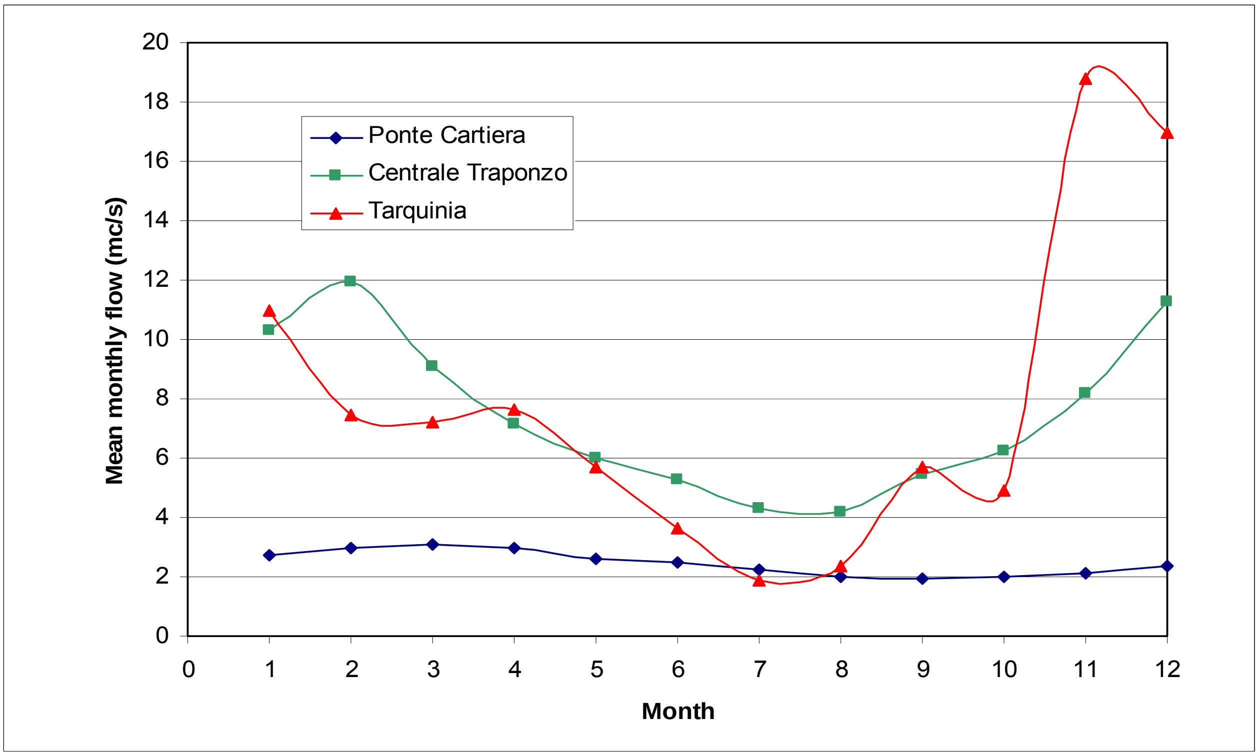

Fig. n° 4.9 Mean monthly registered flow in Ponte Cartiera, Centrale Traponzo and Tarquinia stations from the Regional Hydrographic Service.

The mean monthly observed flow, measured in Marta river immediately after the sluice-gates of regulation, follows a decreasing trend in time with a strong reduction in the last 30 years.

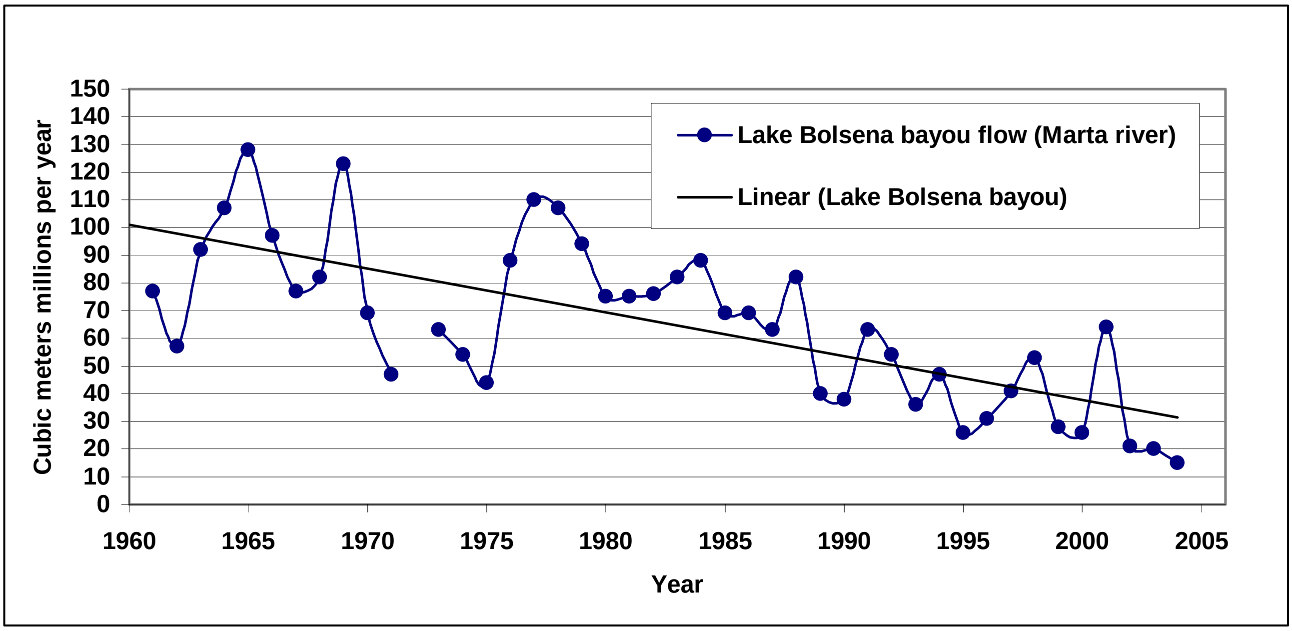

Fig. n° 4.10 Marta river flow discharge coming out of lake Bolsena

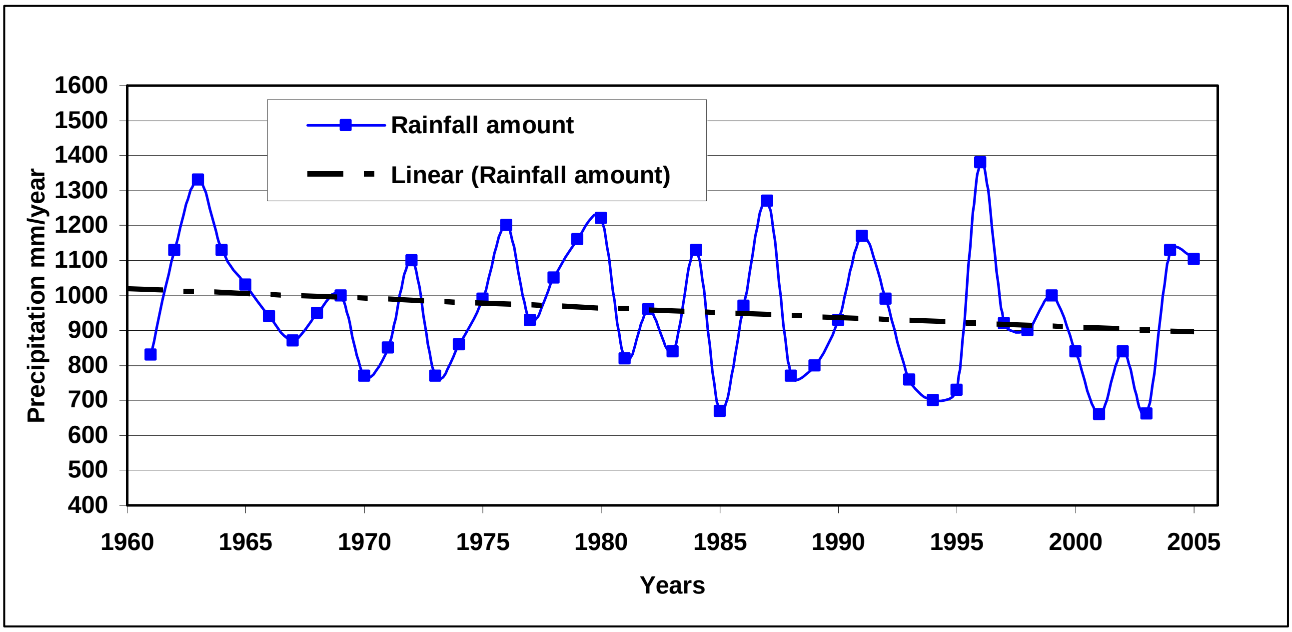

Fig. n° 4.11 Precipitation trend in Marta station (mean annual values)

This particular behavior can be only partially explained by the decreasing in precipitation intensity occurring in the same period so that to point out an anthropic responsibility in the observed phenomenon probably due to unregulated pumping extraction and water resources exploitation.

A decrease in natural recharge for the watershed might have affected the system and also an uncontrolled and irrational management of the sluice-gates of regulation at the exit of the lake should be taken into account in investigating dynamics and evolution mechanisms of hydrologic response.

4.5.2 Flow duration curve

To describe a flow regime of a water course, the duration curve is an essential tools as it associates to a given discharge value, the number of days in which that value is reached or exceeded; therefore this curve is a daily flow frequencies distribution curve and it's expressed in a cumulative form.

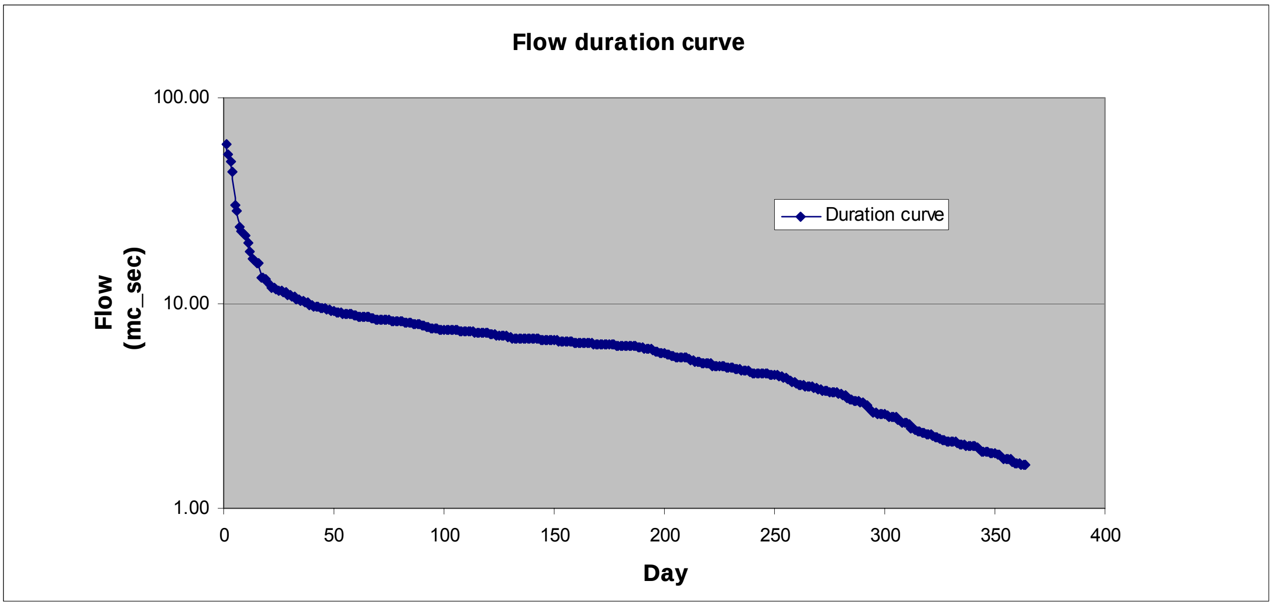

Fig. n° 4.12 Flow duration curve for Tarquinia station.

Flow characteristic values	
Q_{10}	21.41
Q_{91}	7.71
Q_{182}	6.20
Q_{274}	3.73
Q_{355}	1.74

Tab. n° 4.18 Flow characteristic values from flow duration curve

4.5.3 Fluvial hydrograph analysis

A stream hydrograph, in a given section, can be separated in three different flow contribution: surface runoff, subsurface runoff and groundwater flow. These components define the global flow which is equal to the area behind the curve. Separating the base flow or groundwater flow, the contribute due to groundwater resources can be identified and quantified. Using mean daily flows an average fluvial hydrograph was derived and using the Barnes method (1939) for hydrograph components separation and Maillet exponential model (1905) for falling limb (or recession limb) analysis, flow contributing volumes has been estimated for Tarquinia station.

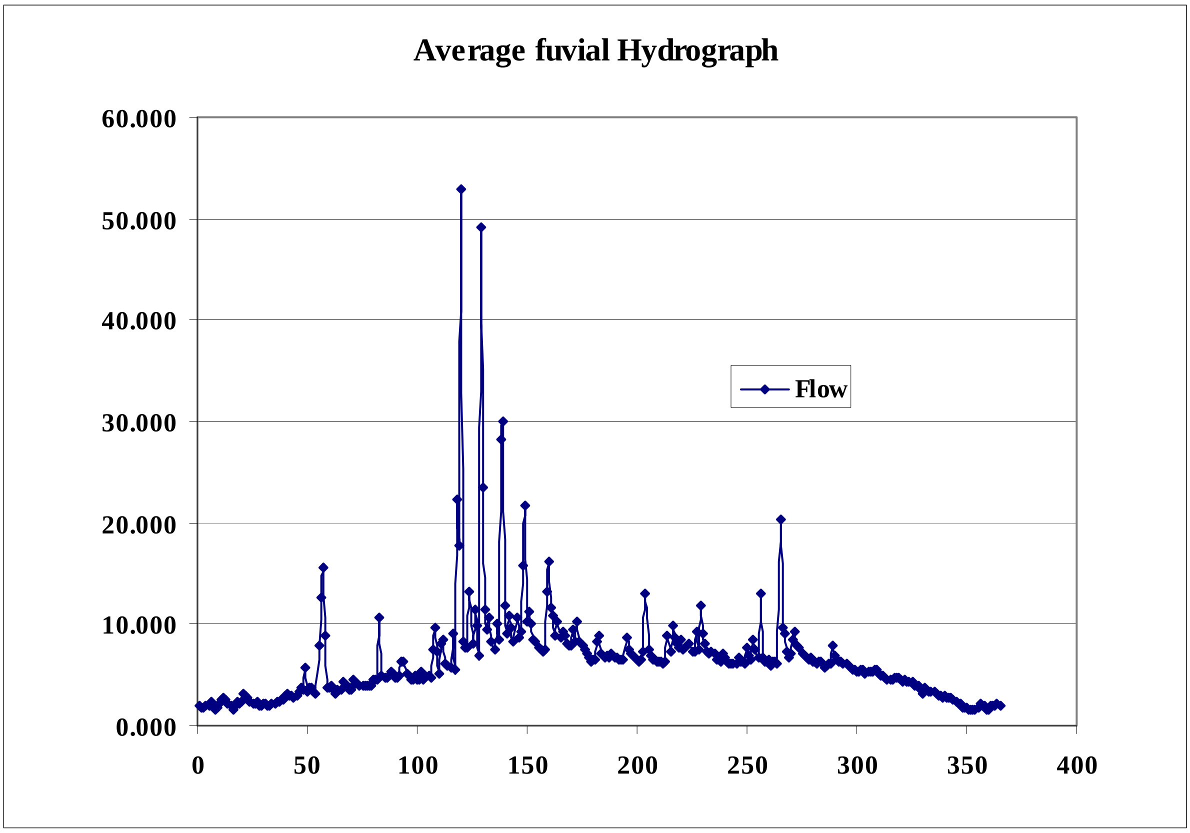

Fig. n°4.13 Average fluvial hydrograph for Tarquinia station.

The hydrograph analysis is based on mean hydrologic year definition which corresponds to the period of time elapsing between two consecutive minimums: 21th of July with 1.97 m^3/s flow and 20th of July with 2.02 m^3/s flow in Tarquinia station.

The total annual flow volume estimated from hydrograph, is equal to 207.8 m^3/s in Tarquinia section while from research work by Baiocchi (2007) the total annual flow volume in Ponte Cartiera section, is equal to 77.95 m^3/year.

The flow curve can be divided in a rising limb and a falling or recession limb after the peak discharge at the highest point. The rising limb of the curve is usually described by an increasing function Q= f(t) while after the peak discharge, a first part taking into account of surface flow and a second one corresponding to deep flow contributions. As Maillet suggested (1905), the recession limb of the hydrograph follow an exponential equation:

$$Q_t = Q_0 e^{-\alpha t} \tag{4.6}$$

Where Q_t is the flow at the give time t (m^3/s), Q_0 is the flow when recession begins (m^3/s), *e* is the neperian constant, equal to 2.71828 and α is a coefficient depending on morphological and geological characteristics of the watershed.

Solving for α,

$$\alpha = \frac{\log Q_0 - \log Q_t}{0.43429 \cdot t} \tag{4.7}$$

Water volume storage at recession starting point, at t = 0, is

$$W_0 = \int_0^\infty Q_0 e^{-\alpha t} dt \tag{4.8}$$

Solving for t = 0,

$$W_0 = \frac{Q_0}{\alpha} \cdot 86400 \tag{4.9}$$

while for t ≠ 0,

$$W_d = \frac{(Q_0 - Q_t) \cdot 86400}{\alpha} \tag{4.10}$$

To calculate the water storage, the point break between surface and deep exhaustion limb has to be identified, separating the contributing flow.

According to Barnes method, the last stretch of the curve called the emptying limb, is characterized by a weaker slope, going from 7.19 m^3/s flow value on 268th day to 2.30 m^3/s on the 365th. In a logarithmic scale, the linear equation describing the last part of falling limb is:

$y = -0.3048x + 0.6592$ with correlation $R^2 = 0.9131$ (4.11)

Where y = log Q and x = t

To derive the recession flow or groundwater flow, the correspondent law is to be extrapolated and projected going back in time on the graph until the peak discharge is reached, when the groundwater contribution begin to flow.

Assuming Q_{153} as peak discharge and applying the Barnes method:

$W_I = 76.55 \cdot 10^6$ m^3/s referred to the first limb of the curve, the rising one with α equal to 0.0139 and representing the replenishment curve,

$W_{II} = 90.75 \cdot 10^6$ m^3/s referred to the second limb of the curve, the falling one with α equal to 0.0165 and representing the emptying curve,

$W_{BF} = 167.3 \cdot 10^6$ m^3/s is the total groundwater flow in the mean hydrologic year.

The difference between the total water amount flowed at Ponta Cartiera section and the total water amount flowed in Tarquinia section provides the mean annual value of groundwater flow in the watershed: 2.83 m^3/s.

The baseflow index can be easy calculated as:

$$BFI = \frac{W_{BF}}{W_T} 100 = 80.51 \quad (4.12)$$

All these information gives useful data for hydrologic SWAT model calibration and validation for Marta river basin.

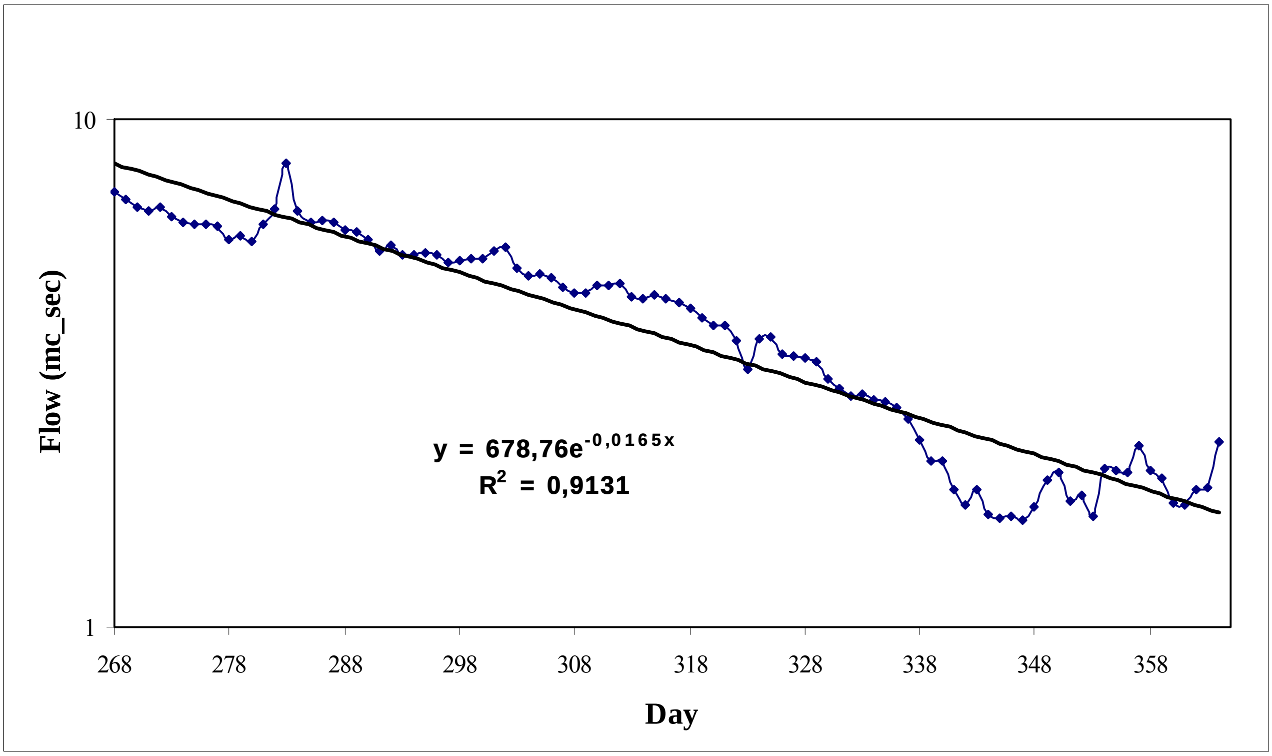

Fig. n°4.14 Recession limb of the hydrograph for Tarquinia measures.

4.5.4 Flashiness Index estimation

The term flashiness refers to the frequency and rapidity of short term changes in stream flow, especially during heavy runoff events so that the Flashiness can be an important component in stream's hydrologic regime investigation. A variety of land use and land management changes may also lead to increased or decreased flashiness, often to the detriment of aquatic life.

The Richards-Baker (R-B) Flashiness Index (Baker and Richards, 2004) measures stream flow variations in response to rainfall events and it is affected by climate, topography, land use, management, soil type, and other physical characteristics of the watershed. The Richards-Baker Flashiness Index (FI_RB) is expressed as:

$$FI\_RB = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \tag{4.12}$$

The Richards-Baker Flashiness Index has been calculated for the period 1999-2006 referring to the observed flow discharges in Tarquinia hydrometric measurement station.

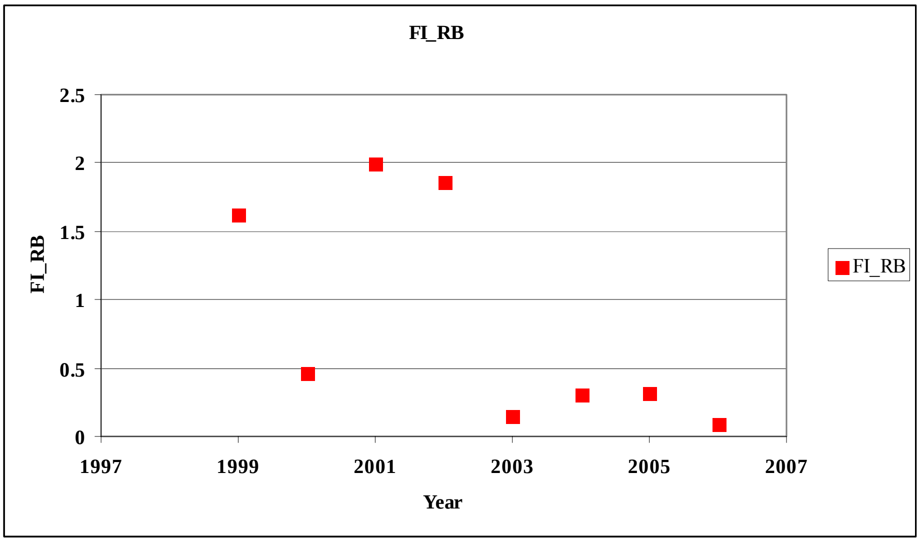

Fig. n° 4.15 Flashiness Index evaluation for Marta river according to Richards-Baker formula.

The average Flashiness Index FI_RB value is 0.84 and it is representative of a very quick response time of the watershed to a rainfall event and for this particular basin, it can also be considered as an expression of the extreme variability of volumes flowing in the water course. Given the river bed size and its condition at the bottom, sudden large-scale and heavy storms easy lead to flood phenomena resulting in damage to people and local residential areas.

In the last few years several flood events occurred (1987, 2004, 2005, 2008) causing the partial destruction of buildings and crops, frightening people and led to a urgent state of alert in the area.

In 2005 The Regional Council declared the State of Natural Disaster for the area of Tarquinia promising a sudden institutional and financial commitment to help people and preserve the local natural resources.

All these efforts were translated in the partial construction of an embankment along the Marta river but during the last heavy rainfall event on 16th December, 2008, big pieces and rocks have been wrecked from the embankment and fallen into the river and then waterborne.

Maybe more rational and incisive actions have to be planned and realized with the required investigations and technical solutions comparison in order to find the best compromise to fully response to the more and more urgent safety, economic and social needs.

4.6 Minimum Flow Requirements definitions and methods

As a consequence of the unregulated exploitation of the available water resources, pumping extraction or deviation of large amount of water from stream network, may heavily alter the frail equilibrium between the environment and the plant and animal life populating it.

The European political guidance is well oriented toward biological diversity preservation (bio-diversity) broadly speaking and of aquatic systems in particular: the Habitats Directive together with the Birds Directive, two milestones in environmental European legislation, are strictly focused on this issue. The European Parliament has now accrued awareness of its responsibility on natural resources preservation and usability by future generations.

Recent European Commission indications on water quality advise to perceive the ecological water quality as a general expression of biological structure and function taking into account all the natural, geo-morphological, geographical and climatic factors and the physical and chemical characteristics with particular attention to anthropic activities impacts. Also the aesthetic aspects should be accounted for. The Directive 2000/60/EC of the European Parliament and of the Council, well known as EU Water Framework Directive or EU WFD, which came into force in December 2000, represents a new framework governing the water policies of Europe. The directive requires governments to set water quality objectives based on "good" ecological status (European Parliament, 2000; Moss et al., 2003). Bodies of water are seen in contest with the corresponding catchment, which is especially relevant for the harmonization of the work in creating water-type specific model-zones and development of management plans. Rivers, lakes, transitional waters and coastal waters are to be characterized according to the criteria listed in Annex II to the WFD and assigned to water-bodies types. In contrast to previous directives, the WFD is not usage-oriented but has an ecological focus with the objective of restoring or preserving the habitat for water-type specific biotic communities. The WFD requires a "flow regime according to ecological criteria" and this requirement is to be intended in such a way that the discharge, both in quantitative terms and with respect to its dynamics, must meet the needs of the water-body ecology in terms of Minimum Flow Requirement. Minimum Flow Requirement (MFR) defines the minimum flow required along a river to meet water quality, fish & wildlife, navigation, recreation, downstream or other requirements. It seeks to protect the ecology and fish life of watercourses and should act as a limit on the government's abstraction licensing authority by barring any abstractions from watercourses above established limits. Minimum Flow Requirements may be designed specifically to protect river fish life, to protect the scenic and recreational values of streams and to attain ambient water quality objectives.

To identify the correct MFR for a fluvial habitat, the different typologies of investigation can be divided in:

-theoretical type of investigation: the discharge is estimated in a roundabout way calculating parameters related to discharge as those ones describing watershed and river bed characteristics;

-experimental type of investigation: the priority is given to specific objectives such as a reference species preservation and the discharge is calculated by a relationship between a water course hydraulic variable or structural variable and the considered species requirements.

Different methodologies belonging to theoretical type of investigation can be schematically organized in:

-hydrologic approach employs only hydrologic data and provides a minimum discharge value as a result, often corresponding to low water discharge value or a fraction of it. The application of this method is quite easy and fast on condition that all historical data are available: the results are hardly computable and they do not take into account the whole collection of environmental variables interacting each other and contributing to determine the fluvial habitat and its ecosystem.

-hydrologic-morphologic approach is based on correlation between released minimum discharge and watershed area behind the diversion or with other geographical or morphological variables.

-statistical approach requires natural discharge duration flow construction to single out the MFR setting a reference number of days (i.e. Q_{347}, Q_{355}, etc.)

Most of experimental methods are mainly based on biological approach which refers to environmental requirements of one or more species representing the fluvial biological community and provides a biomass value or a habitat quality index as a function of water course flow. The relation derives from experimental measures or from hydrologic simulation models. From the obtained curve, the slope change point (break point) defines the optimal value of the minimum flow. The limits are the complexity and the high experimental effort required and the results are to elaborated further to define MFR. The advantage is to provide flow values referring to aquatic biological community status and their reliability can be verified by means of field experimentation (i.e. Wetted Parameter Method, PHABSIM, HQI etc.).

All the methodologies based on hydrologic parameters give merely approximated MFR estimates as the aquatic life depends not only on minimum flow but also on a large number of variable which are often mutually dependent and whose influence can be frequently linked to development stadium of species to preserve. The hydrologic methods compute MFR starting from synthetic parameters such as annual or monthly mean flow or a particular value of low water discharge or flow duration.

4.6.1 Matthey's Formula

Among the suggested hydrologic methods, Matthey's formula is widely applied in Switzerland and it has been modified to be used also in Italian alpine watersheds. This empirical formula has been developed during 70's on the base of gathered observations on different rivers in Canton Vaud and it takes into account of "flow concentration" effect with the increasing of watershed area but it has the disadvantage to use duration curve percents requiring the availability of wide and reliable historical series of daily flows. Matthey's formula is based on a logarithmic function:

$$MFR = 15 \cdot \frac{Q_{300}}{(\ln Q_{300})^2} \tag{4.13}$$

Where Q_{300} is the meanly achieved or exceeded discharge during 300 days per year.

As the required data are often not available to apply the original formula especially in Italy, it has been modified introducing a mean annual $\overline{Q}$ which is much more easy to determine together with a coefficient α assumed near or equal to perennity coefficient (ratio between low water discharge and average discharge varying between 0.05-0.3):

$$MFR = k_1 \cdot 10 \cdot \frac{\alpha \cdot \overline{Q} \cdot k_2}{\left[\ln\left(\alpha \cdot \overline{Q} \cdot k_2\right)\right]^2} \tag{4.14}$$

MFR and $\overline{Q}$ are expressed in l/s, k_1 is a factor relative to the specific stretch of water course while k_2 is a factor depending on area; both of them can be greater or equal to 1.

4.6.2 Montana Method

Montana Method (Tennant, 1976), one of the most spread methods in U.S., is based on simple hydrologic variables. Starting from numerous filed observations on about 100 stretches of stream in Montana, Wyoming and Nebraska states, Tennant (1976) recognized that environmental quality of many water courses is appreciably constant when discharge are equal to an assigned percentage of the average annual flow. A method to estimate MFR was then created considering environmental water-body quality as a percentage of the average annual flow.

	Recommended base flow regimes (Percent of average annual flow)	
Description of flows	Oct-Mar	Apr-Sept
Flushing or maximum	200	200
Optimum range	60-100	60-100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Sever degradation	0-10	0-10

Fig. n° 4.19 Montana method for describing instream flow regimes for fish, wildlife, recreation and related environmental resources.

Montana Method states 10% of the average annual flow as the minimum flow able to ensure a just sufficient habitat for short intervals of time; 30% implies an excellent habitat while between 60% and 100% the best environmental conditions occur. Finally 200% is fixed as the maximum flow discharge. Values for two distinct periods of analysis are suggested, taking into account the natural seasonal variations: for humid season months between October and March are considered while for the dry season the period April-September is chosen.

Montana Method sprouted for responding to salmonide population requirements in water-bodies with a regime which is clearly different form Italian streams so that the application to Italian study cases may lead to improper values of MFR to be calibrated from time to time. It also provides a rule for regionalization cause it's based on discharge estimation for different environmental quality levels depending on average instream flow.

The last parameter, in a homogeneous climatic area, can be correlated to hydro-geo-morphological parameters that can be easily acquired such as mean rainfall amount, contributing area or baseflow index (Casadei & Manciola, 1990).

4.6.3 $Q_{7/10}$ Method

$Q_{7/10}$ Method was employed in U.S. as a standard quality indicator for aquatic habitats (Singh, 1974) but some recent investigations suggest the meaning of minimum flow for ichthyic life preservation to be assigned to $Q_{7/10}$ (Calednda & Ubertini, 1993) cause it could represent the threshold minimum low water flows ensuring aquatic biocenosis life in the stretch of interest, even if derived from flow historical data series. This assumption is partially confirmed by results from optimal flow regionalization for fluvial micro-habitat (Orth & Leonard, 1990).

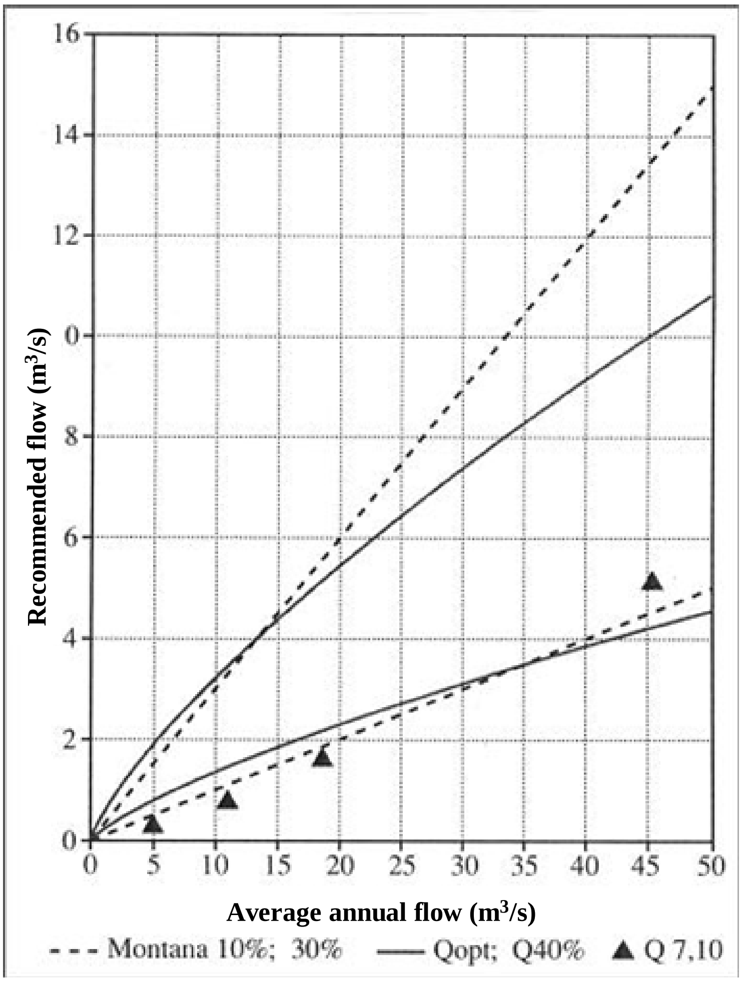

Fig. n° 4.16 Average annual flow and MFR recommended according to Montana Method (Orth & Leonard, 1990).

A technique for regionalization of $Q_{7/10}$ Method is based on BFI, baseflow index (Calenda & Ubertini, 1993) where for a watershed BFI expresses, in percentage terms, the entity of flows released by the aquifer system in different times. BFI can be estimated through Lvovitch Method (1972) which is based on daily flow hydrograph decomposition extended to a long enough period of time. Lvovitch Method provides a criterion to derive baseflow volume component from hydrograph. BFI can be calculated as a ratio between annual baseflow volumes (V_b) and the correspondent total flow volumes (V_a) registered in the considered station:

$$BFI = 100 \cdot \frac{V_b}{V_a} \tag{4.15}$$

BFI value estimated by Lvovitch procedure may be interpreted as low water flow indicator and, doing so, correlated to $Q_{7/10}$ (Manciola, 1991).

4.6.4 Flow Duration Method

Another widely employed technique for MFR estimate is based on flow duration analysis and mainly founded on flow duration curve (Bovee, 1997) expressing the cumulative frequencies of probability of a given flow to be equalized or exceeded. Commonly a 95% exceeding level to indicate that in 95% of time there would be almost the given quantity of available water. This concept, in U.S. known as *"firm yield"*, is seen as a possible way to determine a minimum flow.

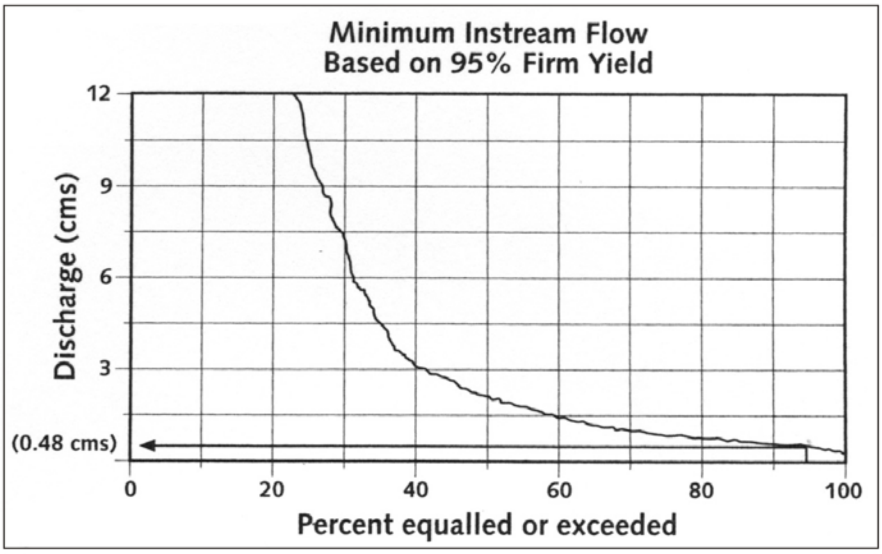

Fig. n° 4.17 Flow duration curve (Bovee, 1997).

4.6.5 Baxter Method

The methodology suggested by Baxter (1961) is oriented to Atlantic Salmon species preservation and it was calibrated with field observations on 15 small and great rivers in Scotland and England. Baxter evaluated the ratio between stream flow and the optimal hydraulic section width, gathering the percentage of average daily flow necessary to salmons vital cycle.

	Percentage of average daily flow	
Month	**Small streams**	**Great streams**
October	15-12.5	15-12.5
November	25	15
December	25-12.5	15
January	12.5	15-10
February	12.5	10
March	20	15
April	25	20
May	25	20
June	25-20	20-15
July	20-15	15-12.5
August	15	15-12.5
September	15-12.5	15-12.5

Fig. n° 4.20 Minimum flow values suggested by Baxter (1961).

4.6.6 Methods with a biological response

Biological methodologies have the main aim to evaluate how a water course is suitable for ichthyic species with particular biological and economical importance determining the environmental quality in a river with a specified species, salmonides in the most of cases, as a reference point. These techniques have an empirical base since the response is a biological quantity directly measurable in field and many of them recur to multiple regression models between environmental variables characterizing the water course and the response. So biological methods are subordinate to experimental data availability on responses and on variables to correlate with response variable.

The stability of ichthyic population in a river depends on numerous and complex variables and it's really hardly to select and assess them; moreover functional parameters derived from the chosen model application, are strictly related to the site and can be poorly generalized to different situations. Such models are reliable exclusively for areas similar to those ones in which the models has been developed and their application is subordinate to their reliability verify.

4.6.7 HQI (Habitat Quality Index)

HQI (Binns & Eiserman, 1979; Binns, 1979; Binns 1982) is a model initially developed as a tool to evaluate fluvial habitat for salmonides. Later it has been used also to predict bearing capacity of a river for salmonides and to evaluate the effects of environmental alterations on it. The model implemented in HQI can be applied as a criterion to define minimum flow requirements of a river since it allows to quantify the changes in bearing capacity for salmonides when different discharges occur. It is based on a multiple regression between trout biomass and 10 physical, chemical and biological environmental parameters relatives to the considered water course (Tab. N° 4…). Determining the 10 parameters values, on the base of interval times on which they fall, it's possible to assign them a score of 0, in the worst condition, and 4, in the best one. Through the application of the model equation, the theoretical bearing capacity can be estimated for the river in terms of trout biomass per hectare of water course.

The equation to apply is:

Model I: $(-1.18257) + (0.97329) \times \log_{10}(x_1 + 1) + (1.65824) \times \log_{10}(x_2 + 1) + (1.44821) \times \log_{10}(x_3 + 1) + (0.30762) \times \log_{10}(P) = \log_{10}(Y + 1)$

(4.16)

Model II: $(-0.903) + (0.807) \times \log_{10}(x_1 + 1) + (0.877) \times \log_{10}(x_2 + 1) + (1.233) \times \log_{10}(x_3 + 1) + (0.631) \times \log_{10}(F + 1) + (0.182) \times \log_{10}(S) = \log_{10}(Y + 1)$

(4.17)

where:

$Y = HQI$ = kg of trout ha^{-1};

$P = x_4 + x_5 + x_6 + x_7 + x_8 + x_{10} + x_{11} + 1$;

$F = x_3 + x_4 + x_9 + x_{10} + 1$;

$S = x_7 + x_8 + x_{11} + 1$;

with:

x_1 = late summer flow (% of average daily flow);

x_2 = annual flow variation (annual peak discharge/minimum annual flow);

x_3 = maximum water temperature in summer period (°C);

x_4 = nitric nityrogen (mg/l);

x_5 = macroinvertebrates abundance;

x_6 = macroinvertebrates diversity;

x_7 = % shelter (% of surface area);
x_8 = % eroded banks (% of total length);
x_9 = vegetation submerged relative quantity ;
x_{10} = water velocity;
x_{11} = river width (average).

Since the result from HQI is a biomass quantity, a relation between biomass and flow has to be defined to identify MFR through this methodology. For this purpose, the parameters are to be estimated varying with flow with different values of it and using this model the correspondent biomass is computed. The result consisted in a curve showing how trout biomass varying with flow and by means of this curve the critical flow that implies important biomass variation can be evaluated. The model is later calibrated through proper ichthyic fauna sampling.

4.6.8 Micro-habitat Methodologies

The Micro-habitat Methodologies are based on a procedure implemented in PHABSIM (Physical Habitat Simulation System) software and it is considered one of the most complete technique in minimum flow requirements analysis. This method lay down a correlation between ichthyic or biological reference population and the Weighted Usable Area required for a given species to live. The critical points are:
-the modeled stretch is not so representative of the whole water course;
-it does not take into account other important variables such as water quality or nutrients quantity and it considers velocity and substratum independent each other;
-it’s hard to choose the representative biological species for the give stretch of river;
-considerable uncertainties are on temperature, day cycle, season preferred by fishes in the habitat;
-preference curves from literature or obtained in different environmental contexts have to be used;
-calculation methods to derive curves and to extract MFR values are not so clearly defined.
This methodology is continuously in development and in the last few years many aspects has been deepened and several uncertainties has been removed on the model applicability.

4.6.9 Instream Flow Incremental Method (IFIM)

This methodology (Bovee, 1982) has been arranged by Instream Flow Group (IFG) under the responsibility of United States and Wildlife Service and it originates as an answer to environmental problems related to water resources exploitation and management. IFIM is a complex analytical and conceptual structure, created to understand and manage river flow regimes variations due to anthropic action. A functional relationship between flow and available habitat dimension is obtained for a fish or aquatic invertebrates species (Fig. n° 4.17).

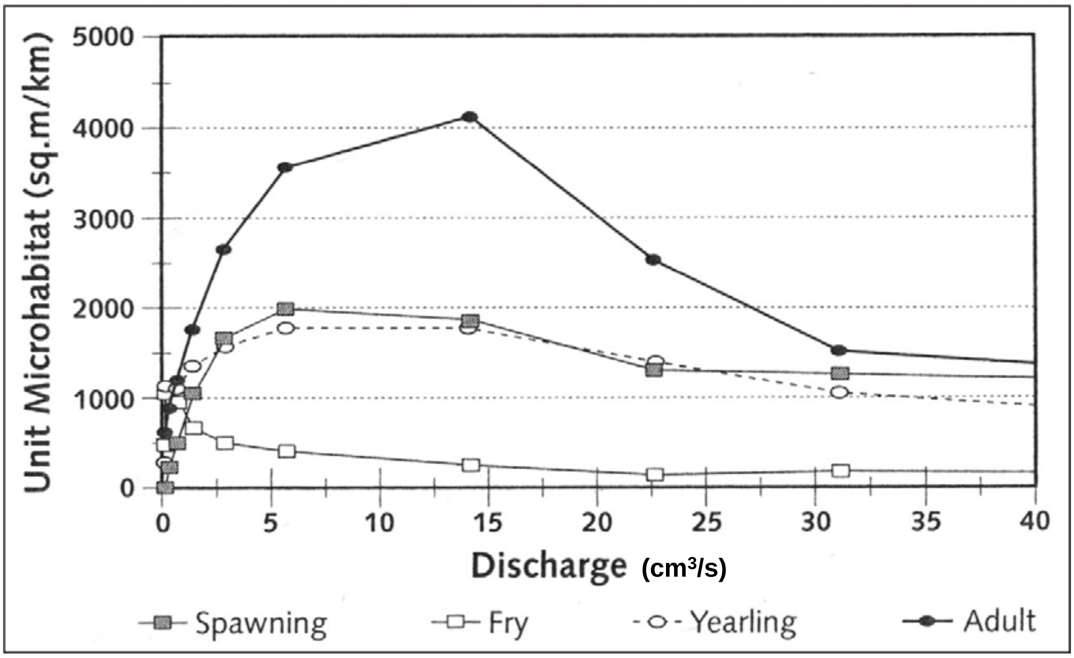

Fig. n° 4.18 Relation between micro-habitat units and flow (Bovee, 1997).

The choice of habitat as a variable decision of the aquatic organisms survival state is due to the fact that the IFIM was developed specifically to quantify the impacts on the environment; moreover habitat variations are the most obvious manifestations of flow variations (Stalnaker et al., 1995).
Through the combined analysis of several environmental variables, such as the physical structure of habitat, the chemical quality of groundwater and flow, IFIM can predict the changes undergone by a habitat for changing hydraulic conditions in a river. For a proper application of IFIM it was necessary to create a hierarchical classification of river habitats: there are three main levels: macro, meso and microhabitat.
Macrohabitat involve portion of the river in which the physical and chemical conditions affect the suitability of the entire river for all aquatic organisms. Macrohabitat means a portion of the river with similar characteristics in the bed geometry, such as slope, width, depth and substratum. These geomorphologic units of the watercourse are commonly defined by the *pool, run* and *riffle*. The microhabitat refers to small and localized areas within the mesohabitat used by aquatic organisms at different stages of their existence, such as spawning period. The microhabitat is identified as the

area of the river where there are uniform conditions of depth, speed, substratum and bottom coverage (the latter defined as Channel Index). These areas with similar characteristics, called cells, must be regarded as the basic unit in calculating the minimum flow on biological base.

When applying the method, a schematization of the river bed in uniform segments is considered and each of them can define a series of hydraulic and geometric variables input to the model and, consequently, with a summary of the state system on the segment.

Schematization in homogeneous stretches lead to a further discretization providing a map of river portions represented as a three-dimensional mosaic of cells. Each simulated cell presents a unique combination of depth, velocity, and substratum bed coverage (Channel Index) and hedge in information about the characteristics of the species, represented by the values of environmental suitability (S_i) reported on the curves of fitness, which multiplied by the cell surface (A_i) provide a value that, in its turn, can be added to the values obtained for the other cells of the homogeneous section, to determine the Weighted Usable Area in reference to a given value range in bed.

Then dividing each section of width w in n intervals Δw local values of average speed on the surface (v_i), height (d_i) and characteristics of substrate (s_i) and coverage (c_i) are detected, being the parameters affecting the fish microhabitat. Simultaneously fish samples are made to analyze the environmental preferences of each species, given the different life stages. The results are summarized in fitness curves expressing the degree of preference for the microhabitat. It varies depending on the (S_d), speed (S_v), of substrate (S_s) and bed coverage (S_c). Indicating A_i as the horizontal area of each cell of width Δw, Weighted Usable Area (WUA) may be given by the following equation:

$$WUA = \sum_{1}^{n} A_i \times (S_d \times S_v \times S_s \times S_c)_i \qquad (4.18)$$

The calculation is repeated for different values of flow and uses a combination of microhabitat quality and quantity to express area available unit.

The maximum value of WUA indicates the best water characteristics for biological and ecological fish needs.

4.6.8 Wetted perimeter Technique

The Wetted Perimeter Technique is one of the most common methods used in the U.S. (Collings, 1974; Cochnauer T., 1976). Th e wetted perimeter represents the portion of the perimeter of a steam channel cross section which is in contact with the water or “the distance along the bottom and sides of a stream, creek, or channel in contact with the water. Length of the wetted contact between a conveyed liquid and the open channel or closed conduit conveying it, measured in a plane at right angles to the direction of flow”(American Psychological Association (APA) Bureau of Reclamation Glossary, 2009) (Fig. n° 4.19).

The graph shows how the wetted perimeter decreases at decreasing outflow, while increases with the increase of runoff to reach the edge where the wetted perimeter growing very slowly.

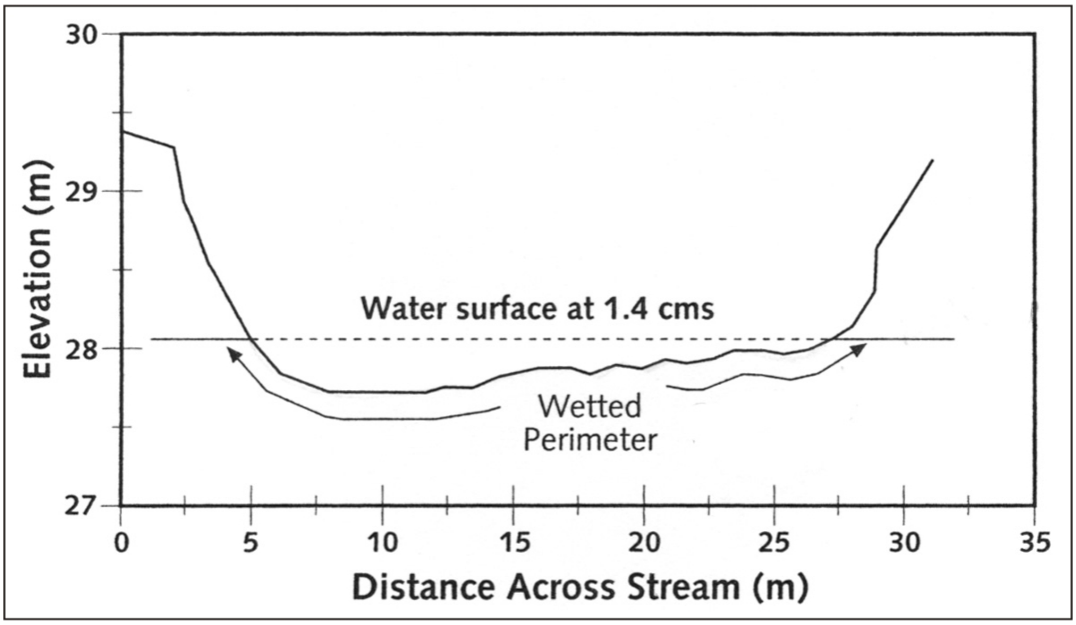

Fig. n° 4.19 Definition of wetted perimeter (Bovee, 1997).

The wetted perimeter rapidly increase with flow up to a flexure point beyond which they decline and to an increased flow corresponds a slow increase of the wetted perimeter so that the value associated with the minimum flow coincides with the point of inflection in the curve perimeter wet - flow.

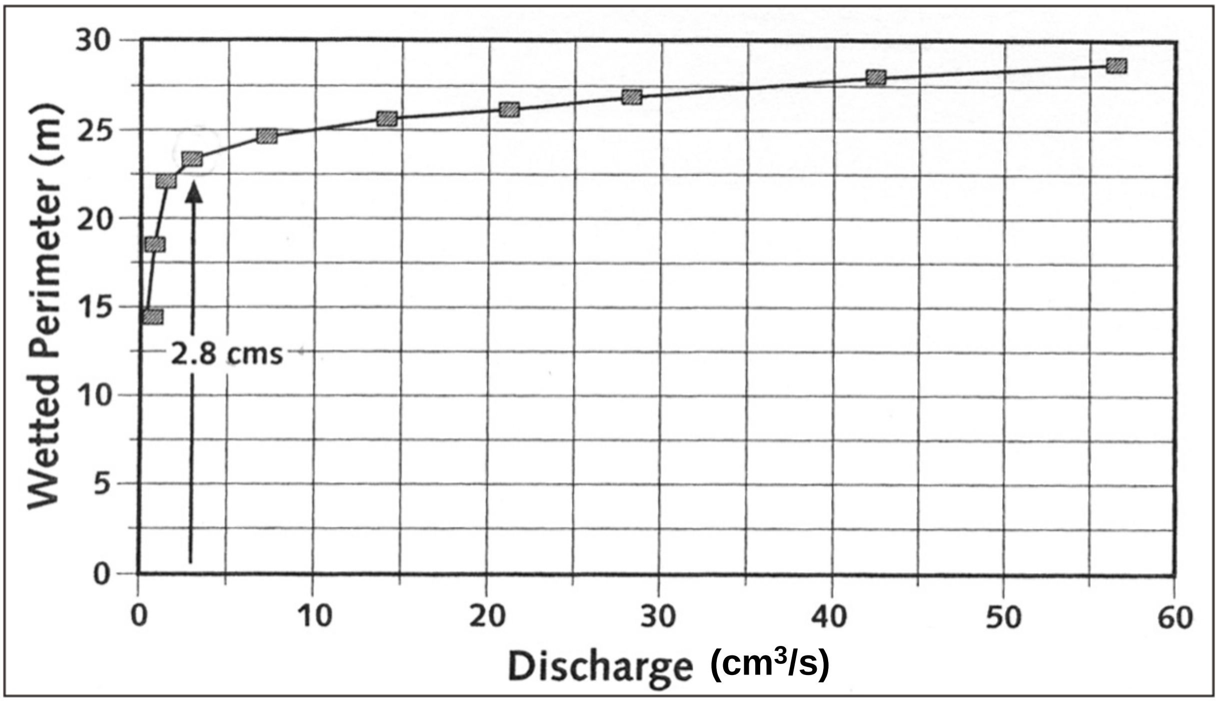

Fig. n° 4.20 Relation between wetted perimeter and flow (Bovee, 1997).

This method is widely used in some U.S. states, with easy application and requesting data input easy acquisition. One of the difficulties is that it only considers the bed hydraulic behavior in the reference section, without taking into account water, and water quality or other potentially important characteristics.

4.6.9 Physical Habitat Simulation System (PHABSIM)

Physical HABitat SIMulation System (Bovee, 1982; Milhous et al, 1989; Stalnaker et al., 1995, Bovee, 1996) allows to estimate the quality of the physical microhabitat (velocity, depth and substratum), according to flow variations in relation to the organism to be protected, properly chosen as target.

For this purpose, the wetted bed surface in the segment to be studied, is divided into homogeneous cells, for each of which parameters values are to be determined depending on flow changes, such as level of surface water, water velocity, depth, wetted surface, etc.. The measured data related to these parameters are used by the simulation programs contained in the hydraulic simulation PHABSIM to predict changes in the parameters themselves varying with flow rate. In addition, data are collected bed characteristics that do not change with flow, such as bed configuration, characteristics of the substratum, shape and abundance of shelters for the reference species studied. Using all this information and data from hydraulic simulation, a given river can be studied as a mosaic made by single cells, a tile to another, in which for every discharge value to be simulated, hydraulic specific data can be obtained.

The available habitat is estimated using different modules of the simulation model according to appropriate curves obtained experimentally on-site or adapted from literature curves, which can "weigh" each derived hydraulic parameter, in relation to the different levels of approval by the reference species. The combination of the simulated microhabitat parameters varying with flow with the curves of preference, allow to establish the degree of suitability for each cell to house the chosen species. All the combined results of each cell will be added together with the results of all the wetted cells in order to obtain the WUA (Weighted Usable Area). This is a surface value, obtained by adding the WUA of each cell, calculated by multiplying the surface of each cell with the index, between 0 and 1, obtained from a combination of the values from curve preference in relation to hydraulic-morphological data.

The result of PHABSIM therefore consist of a graphic placing flow in relation to the WUA for the indicator species, then the MFR is established by identifying the range of values for which the reduction of WUA is lower.

4.7 Minimum Flow Requirement estimates for Marta River

The Latium Regional Basins Authority carried out a study on the regional rivers in order to evaluate the available water resources to rationally manage water extraction for irrigational, hydro-electric and drinking purposes taking also into account the river ecosystem preservation and the landscape, recreational and aesthetic aspects. A General Report on "Surface water availability and minimum flows" was produced (AA. VV., 1998). For this study, Marta river basin was divided in 21 sub-basins , whose outlets have been chosen in correspondence of deviation and restitution works for the 5 hydroelectric plants located along the main river and tributaries. To determine MFR the micro-habitat method was applied (Bovee, 1982) and in particular the whole PHABSIM procedure was implemented. The most representative species were identified for the examined segments whose vital stages can be considered as biological indicators for the given water courses since they show a great sensitivity to aquatic ecosystem variations as a function of different hydraulic regimes. On the base of experimental observations, barbel (*Barbus plebejus)* and chub (*Leuciscus cephalus)* has been chosen as ichthyic representative species for Marta river and for each of them the suitability curves was derived at three vital phases (reproductive phase, spring phase and adult phase) as a function of water velocity, depth of water and substratum. In some sections of Marta river, in addition to hydro-biological observations, topographic surveys were carried out and

hydrometric levels were acquired for the simulation model. Through the suitability curves, the WUA values were estimated for each reference species and for the different flow discharges: finally a critical flow value was identified and the risk of excessive WUA reduction appears with values lower than the defined critical flow. These values calculated by the Latium Regional Basins Authority ensure 50% and 25% of the maximum WUA required by the indicator species ($Q_{50\%}$ and $Q_{25\%}$) and these values were compared with the minimum flow discharge of 7 days duration and return time of 10 years ($Q_{7/10}$). For Ponte Cartiera station, $Q_{25\%}$ values approximate about 70% of $Q_{7/10}$ so that the Authority chose the 70% of $Q_{7/10}$ as MFR; propagating this values to all the ungaged stations, MFR values were determined for all the sub-basins in Marta river watershed.
However in the General Report these quantities are assigned approximately and systematic verifications on water bodies are suggested. The MFR definition by the Regional Basins Authority is constrained by regionalization procedures in order to obtain values to be applied at the total number of basins in Latium region. Using the formula proposed by the Interregional Magra River Basin Authority:

$$DMV = S \times R_{SPEC} \times P \times Q \times N \times G \times L_{7.5} + M_{10} \quad (4.19)$$

Where :
S = watershed area behind deviation work until the divide is reached, expressed in km^2;
R_{SPEC} = 1.6 l/s per km^2 of watershed;
P = mean annual rainfall, in mm;
Q = biological quality in the stretch between deviation and restitution works;
N = natural conditions between deviation and restitution works ;
G = geomorphology;
$L_{7,5}$ = factor taking into account the stretch length between deviation and restitution works;
M_{10} = flow modulation factor.
This formula was suggested by the Interregional Magra River Basin Authority taking into account not only the long term preservation of a given species but also the preservation of the whole aquatic organisms communities and the fluvial ecosystem global functionality.
The biological quality Q is derived from the Extended Biotic Index, EBI (Ghetti, 1995):

Classes	EBI	Quality assessment	Q Factor
I	10-11-12	No pollution environement	1
II	8-9	Slightly polluted environment	1.1
III	6-7	Polluted environment	1.2
IV	4-5	Very polluted environment	1.3
V	1-2-3	Strongly polluted environment	1.4

Tab. N° 4.21 Q values estimation according to Interregional Magra River Basin Authority criteria

The N factor ca be calculated using almost three methods:

-applying the Index of Fluvial Functionality (IFF) to the river segment between deviation and restitution (Siligardi, 2000)

IFF Values	Functionality Level	Functionality Assessment	N factor
261-300	I	High	5
251-260	I-II	High-Good	4
201-250	II	Good	4
181-200	II-III	Good-Mediocre	3
121-180	III	Mediocre	3
101-120	III-IV	Mediocre-Low	2
61-100	IV	Low	2
51-60	IV-V	Low-Bad	1
14-50	V	Bad	1

Tab. N° 4.22 N values estimation according to Interregional Magra River Basin Authority criteria using IFF.

-considering the slopes insisting on the water course between deviation and restitution and the evaluation can be carried out on the basis of real and potential vegetation ratio according to the following table:

Values	Classes	Environmental characteristics	N index
55	I	Optimum natural condition	5
20	II	Good natural condition	4
8	III	Semi-natural condition	3
2	IV	Poor natural condition	2
1	V	Artificial condition with land cover	1
0	/	Strongly artificial condition without land cover	1

Tab. N° 4.23 N values estimation according to Interregional Magra River Basin Authority criteria taking into account environmental systems.

-comparing the N factor and N index estimated as above mentioned, and using the higher of them.

The geomorphology of a watershed (G factor) affects the natural flows following a water deviation; a numerical parameter that allows to adapt release amount to bed morphology was introduced but a scale of G values has not yet been developed so that G equal to 1 is always assumed.
The M factor, flow modulation factor, meets requirements of ensuring almost a fair percent of flow variations occurring and affecting aquatic organisms and riparian vegetation biological cycles.

Flow modulation	M_{10}
10% of the difference between natural flow and MFR without modulation	M_{10}=0.1 x ($Q_{natural}$-$MFR_{not\ moduled}$)

Tab. N° 4.24 M values estimation according to Interregional Magra River Basin Authority criteria.

MFR was calculated in sections corresponding to the release points of the hydro-electric plants Centrale S. Savino III and Centrale Fioritella. The obtained MFR value is equal to 0.83 m^3/s for Centrale S. Savino III measure section while it's equal to 0.87 m^3/s for Centrale Fioritella measure section (Prestinenzi, 2005).

Other methods for Marta river MFR estimates have been chosen grounding on morphological and hydrologic simple variables in three significant stations along the water course: Ponte Cartiera, immediately after coming out from lake Bolsena, Centrale Fioritella, corresponding to the last deviation for hydro-electric purpose, Centrale Traponzo, corresponding to the main deviation on Traponzo for hydro-electric purpose (Baiocchi, 2007).
These methods have been applied:
-Specific contribute method, assuming the specific contribute equal to 2 $l/s/km^2$
-Q_{347} method, choosing the Q_{347} and Q_{355} on the flow duration curve
-Montana method, as previously described
-$Q_{MIN/10}$ extracted from minimum flow historical series of 7 days duration.

		Ponte Cartiera	Centrale Fioritella	Centrale Traponzo
Watershed area		273 km^2	285 km^2	850 km^2
Average flow Q		2.46 m^3/s	----	7.54 m^3/s
Q_{347}		1.10 m^3/s	----	3.30 m^3/s
Q_{355}		0.90 m^3/s	----	3.0 m^3/s
Specific contribute method (Q_{MFR} = 2 l/s × km^2)		0.55 m^3/s	0.57 m^3/s	1.70 m^3/s
$Q_{mv} = f(Q_{347})$		0.44 m^3/s	----	1.16 m^3/s
$Q_{mv} = 0.5\ Q_{355}$		0.45 m^3/s	----	1.50 m^3/s
Montana method	$Q_{MFR} = Q_{MIN} = (0.1\ Q)$	0.25 m^3/s	----	0.75 m^3/s
	$Q_{MFR} = Q_{GOOD} = (0.3\ Q)$	0.74 m^3/s	----	2.26 m^3/s
$Q_{7/10}$ *** method**		0.69 m^3/s	----	2.43 m^3/s
IFIM * method	$Q_{MFR} = Q_{25\%}$	0.50 m^3/s	----	----
	$Q_{MFR} = Q_{50\%}$	0.80 m^3/s	----	----

*Tab. N° 4.25 MFR evaluations for some Marta river sections. The * symbol means values derived from AA.VV. (1998) and from Calenda et al. (2000 .*

4.8 Saltwater intrusion threat

The mediterranean basin is rich in groundwater draining in rocky slitted powerful aquifers and in alluvial debris coastal structures; these important water resources are often compromised by a wrong use of them with excessive not-planned well pumping and quality degradation due to pollution phenomena.

Because of the socio-economic development, the use of a big part of these resources, has often been higher than the capacity of auto-regeneration, causing an impoverishment of these water resources with resulting imbalance and accentuate critical situations

The Maremma Laziale quaternary sand-conglomerate hydro-structure is about 220 Km2 wide and it lies between the Fiora River mouth and the Mignone River mouth, including the terminal stretch of the Marta River which is the only bayou of the Bolsena lake.

4.8.1 Maremma Laziale aquifer structure

This aquifer, lying between Arrone River and Mignone River, can be divided in two sub-units because of the clay substrate with low permeability running along Marta River slopes. This substrate do not allow water exchange in and from the two sub-units:

-the first sub-unit, between Arrone River and Mignone River, is confined by the clay substrate and only around Fontanile Nuovo and Bandita S. Pantaleo, the surface substrate is represented by Tolfa Flysch setting up the macchia della Turchina relief. Therefore this small aquifer is bordered by Tolfa Flysch and S. Savino System pelites.

-the second sub-unit lies between Marta and Mignone rivers and it stretches to Tarquinia dorsal base. Also this aquifer is confined by waterproof surface substrate along the two rivers but it’s not isolated upstream because it’s in hydraulic connection with Tarquinia System. The aquifer sediments include second and third order terraces sediments but also fourth order terraces (Casale S. Martino Unit) and fifth order terraces ones. This hydrogeological complex is recharged by rainfall and by water draining from the close Tarquinia System aquifer which has high available water potentialities.

Capelli & Mazza (1994) better defined some of these hydrogeological complexes: 1) in S.Savino Unit Tolfa Flysch and pelites shape the low permeability substrate; 2) Pliocene and Pleistocene complexes with three aquifers: Tarquinia Unit aquifer; marine terrace aquifer; Fiora River paleoalveo aquifer; 3) dune deposits stretching to about 100 m towards the river mouth with productive groundwater areas.

These aquifers are continuous in plan and set up by the same litostratigraphic complex but they have almost no chance of hydraulic connection. The previously described hydro-geological systems are saturated by non-confined and semi-confined groundwater.The aquifer succession thickness is about 15-20 m and it reaches 40 m in correspondence to the terminal part of the Fiora River Valley. The groundwater circulation is generally freatic and it follows a trend from NE to SW, according to the principal river valley directions in the area. It has the morphotypes characteristics of this area and they includes Marta River watershed. The current structural, morphological and litostratigraphic Maremma Laziale setting comes from the paleographic and tectonic evolution that has been involving Tuscany and Latium basins since Superior Miocene up to nowadays.Two litostratigraphic units can be recognized: Casale S. Martino Unit (Apat, in printing) corresponding in part to Gruppo Pian di Spilli (Bosi et al., 1990) and the alluvial deposits. Casale S. Martino Unit is composed by sand inserting volcanic deposits which in part derives from second and third order terrace re-sedimentation. A lot of shellfishes can be found here. The age is Superior Pleistocene (Tyrrhenian). Recent and actual alluvial deposits relating to Marta River activity, are represented by gravel, sand and pebbles. The age is Holocene.

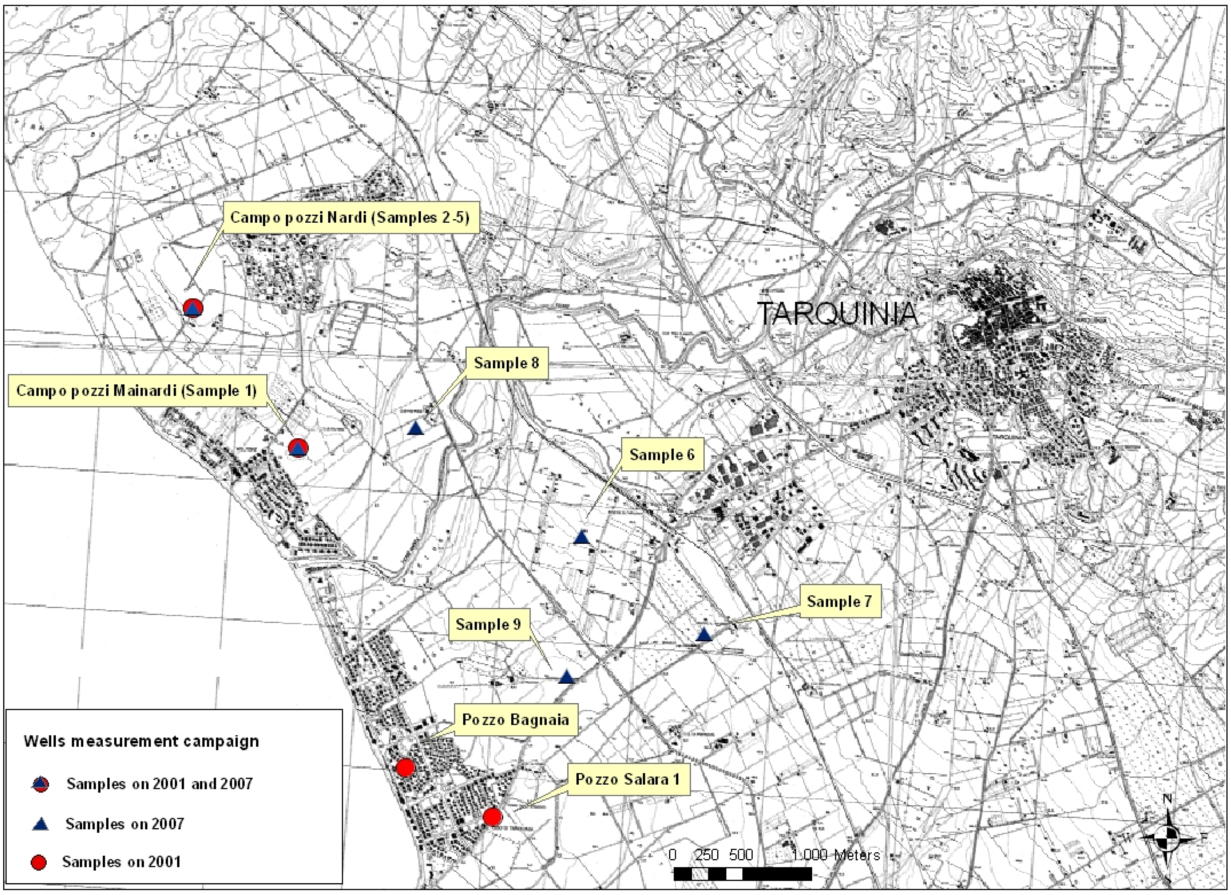

Fig. n° 4.21 Schematic map of the wells sampling area

The research activity scheduled in MEDDMAN project work plan, have pointed out the presence of areas which are particularly vulnerable to quality degradation processes in the groundwater as a consequence of saltwater intrusion phenomena from the sea. Surveys and measure campaigns were carried out on wells (about 10 wells in the Maremma Laziale minor aquifer) to characterize quality groundwater and to investigate the presence of seawater. The sampling campaign on private and public wells (Fig. n° 4.21) showed no evidence of saltwater intrusion phenomena in existence but only organic pollution in some layer while a high water temperature was found with water table clearly near the surface.
All the samples gathered on summer 2007, have been analyzed by the laboratory of the Biologically Active Substances Chemistry and Technology Department, University La Sapienza in Rome in cooperation with Prof. Fedele Manna.
The results show clearly that water from these wells, cannot be used for drinking as they do not comply with actual law in force (Legislative Decree n°31/2001) while they may be used for irrigation purposes yet. Saltwater intrusion cannot be confirmed by the samples: fixed residual values are not so high and there’s no reversals of concentration that are characteristic of sea water, such as the Ca/Mg (1:3 in seawater) or the significant concentration of chloride and sulfate compared with bicarbonates. This suggests that there is not a clear intrusion of seawater in the coastal study area. However, given the location of wells, especially those closest to the sea, changes that may occur over time are to be checked with further analysis at a distance of 6 - 12 months. Moreover, wells with lower depth, wells No. 7 and 8, respectively, 2.5 and 5 meters from surface, should be excluded since most likely these samples alteration arises from a kind of faecal pollution as both sites are within farms where surely livestock is bred and fertilizers are used.

The results show an alteration in water composition, but it would be premature to talk about intrusion of sea water as the level of ions concentration is not so high and salinity conductivity fall within the parameters recommended for irrigation water (see Tab. 4.26). (www.lennetech.com).

A continuous sampling seasonal campaign on wells should also be carried out in other sites of the coastal area; the choice must be made taking into account the spatial distribution of sampling points, as to be representative of the whole area.

Salinity risk	**TDS (ppm or mg/L)**	**dS/m or mmhos/cm**
No	<500	<0.75
Low	500-1000	0.75-1.5
Moderate	1000-2000	1.5-3.00
High	>2000	>3.0

Fig. n° 4.26 Salinity risk classes for irrigation water (www.lennetech.com)

Sample	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9
pH	7.48	7.28	7.34	7.14	7.19	6.4	7.1	6.99	7.36
T °C	19	18.7	18.8	18.1	18.3	22.5	22.7	19.5	19.4
Conductivity mS x cm	1.78	1.99	1.59	1.52	1.5	0.99	1.05	1.68	0.9

Fig. n° 4.27 Ph, temperature and conductivity values for wells samples.

Sample	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9
Dissolved Oxygen mg/l	7.056	7.84	7.056	7.056	7.84	5.488	6.272	2.352	6.272
CO2 mg/l	25.9688	20.9748	21.9736	22.9724	20.9748	182.7804	16.9796	47.9424	12.9844
Total water hardness (GF)	59.14	71.17	54.13	40.1	45.11	41.1	38.09	47.76	35.08
Bicarbonate mg/l	378	315	371.7	302.4	308.7	579.6	302.4	516.6	390.6
Sulphate mg/l	40	135	80	82	93	48	51	67.5	30
Chloride mg/l	251.695	212.7	173.705	152.435	145.345	31.906	70.9	145.345	67.355
Phosphate mg/l	6.5	2.25	21.5	2.25	2.25	5	assenti	2.25	1
Ammonium mg/l	absent	absent	absent	absent	absent	absent	absent	absent	absent
Nitrite mg/l	absent	absent	absent	absent	absent	absent	absent	absent	absent
Nitrate mg/L	8.22	8.5	10	14.34	10.83	2.89	14	13.76	3.67
Organic compound mg/l	7.68	8.72	8	7.6	14	7.76	7.92	8	6.96
Fixed residual 180°C mg/l	1209.41	1224.95	1177.2	1077.29	1062.92	1091.15	882.9	1350.45	860.12

Fig. n° 4.28 Analytical results for sample concentrations

Sample	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**Sample 7**	**Sample 8**	**Sample 9**
K mg/l	24.9	23.9	23.3	25.4	19.6	74.7	1.3	6.4	3.3
Ca mg/l	165.3	201.3	186.5	199	191.3	152	168.7	237.1	144.4
Mg mg/l	41.5	51.1	42.1	40	38.3	35	35.6	56.1	37.7
Na mg/l	283.3	264.8	258.4	249.5	243.6	152.1	229	295.4	172.1
Fe mg/l	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
Cu mg/l	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
Mn mg/l	<0,01	0.01	<0,01	<0,01	<0,01	0.02	<0,01	0.04	<0,01
Zn mg/l	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
Pb mg/l	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
Co mg/l	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01

Fig. n° 4.29 Results for samples metal concentrations.

CHAPTER 5

A SWAT MODEL FOR MARTA RIVER BASIN

5.1 Input data collection and elaboration

Reliability and accuracy in SWAT results strictly depend on quantity and above all quality of available information about the study area. Many parameters are to be set in model implementation and drawing on several and different documentation sources is needed to acquire correct and trustworthy data. The cooperation with local government with particular reference to the Regional Environmental Protection Agency (ARPA Lazio), led to the capture of quality monitoring campaign results on rivers and lakes in Marta river basin. The Regional Hydrographic Service, instead, provided all the hydrological and meteorological data from the monitored stations installed in the watershed: rainfall amount, temperature, hydrometric levels.

To completely run the model, some basic information are essential to the simulation setting-out:

-DEM, digital elevation model,

-land use map,

-agricultural practices database,

-climatic parameters and relative stations dataset,

-nutrient loads and release point

To calibrate and validate the model, flow and quality observed data are required.

The DEM used for Marta river basin delineation in SWAT, has 40x40 m resolution.

5.1.2 Soil data

About soil parameters observed data are not available for the study area and in the filed sampling or investigation was not feasible due to high expenses, specific skills and technology required. So the EUSIS database created by JRC was used. It’ s a collection of harmonized soil data. European Soil Information System (EUSIS) is the main source of georeferenced information on European soils. EUSIS allows the collection of specific soil data and integrates appropriate interpretation models. The outputs of the system can be both in cartographic and/or tabular formats. It is a multi-scale system giving answers to problems to be solved at different scales.

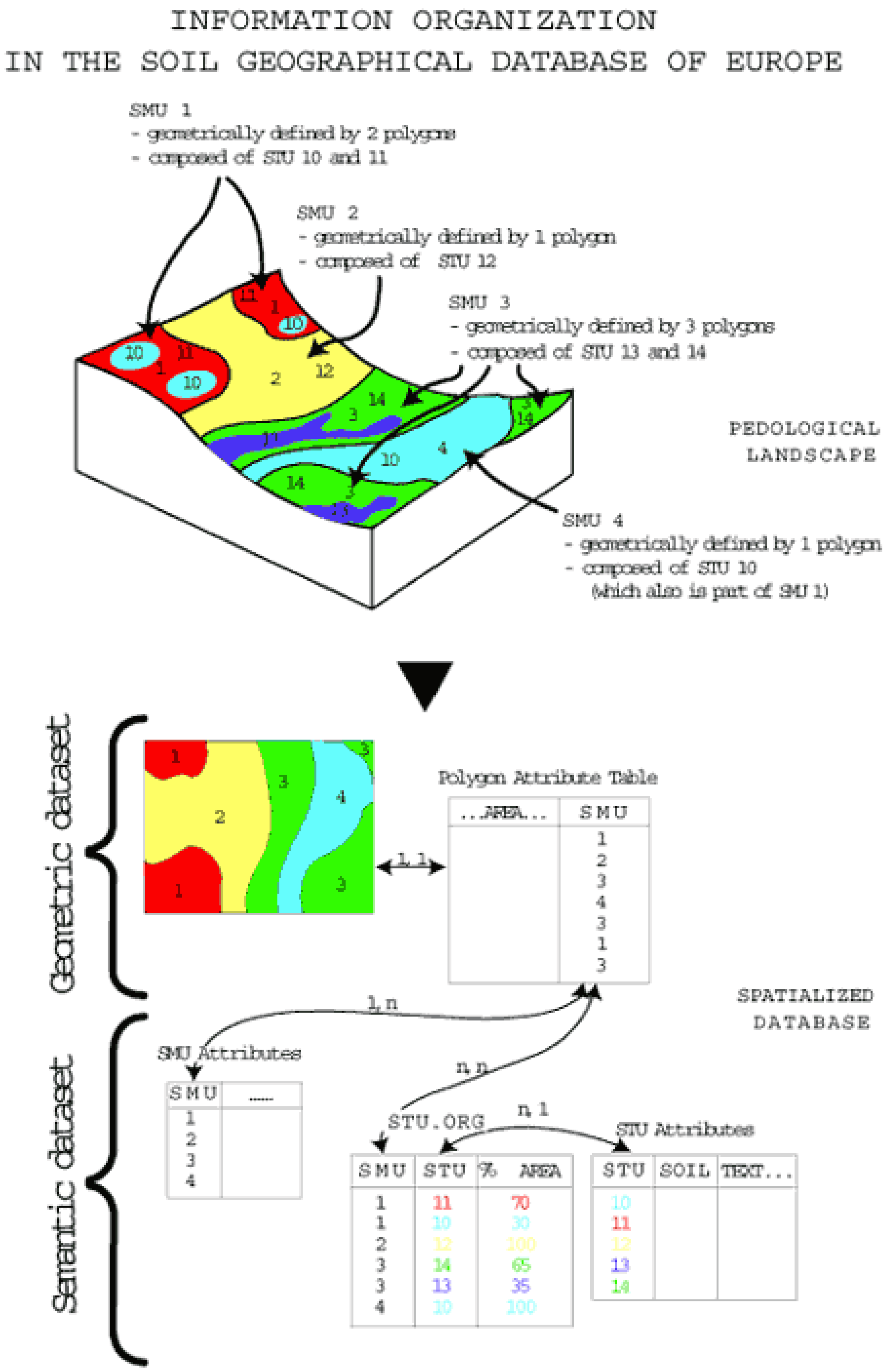

Fig. n° 5.1 Schematic representation of data extraction from EUSIS database.

Within EUSIS database a Soil Profile Analytical Database was complied in 1993-94 (Madsen and Jones, 1995). This database, called SPADBE contains soil profile characterizations with physical and chemical analyses. It is based on Measured Profiles from geo-located profiles taken in the field and on estimated profile from profiles that should be representative for a specific “Typologicall Unit”.

The Soil Profile Analytical Database of Europe is an integral part of the European Soil Database. It has been compiled through the collaboration of national experts of the 12 EU member countries and is currently being extended to include data from the eastern European and Scandinavian countries.

The driving force for compilation of the database was the need to model the water balance and map the available water content in the root zone for the MARS Project (Monitoring Agriculture by Remote Sensing, Joint Research Centre, Ispra, Italy). A number of pedotransfer functions or rules for calculating or predicting other soil attributes for use in land use and management was also perceived as important for future interpretation of soil maps.

The idea to develop the Soil Profile Analytical Data Base in different stages (levels) was generally regarded as the most realistic approach. The number of soil types to be computerized would vary according to the time available and the funding provided to establish the database system. It might therefore be necessary to start with data for a few soil types and add more later. That would mean making a first approximation (Level 1) to a comprehensive soil profile database system and then later following up with a second (Level 2), third (Level 3) and even a fourth approximation (Level 4). The soil map is made of polygons grouped into Soil Mapping Units (SMU) which in turn are sub-divided into Soil Typological Units (STU) holding the full description of each soil type present on the map (Fig. n° 5.1)

Soil Mapping Units (SMU): each SMU is identified by a unique integer number. It is generally represented by several polygons. Each SMU is generally formed of several STUs (the SMU is then a « soil association »).. Soil Typological Units (STU): a STU defines a soil type having a set of homogenous properties over a certain surface area. STUs with different names will have will a different set of characteristics or properties.

At level 1, the member states are treated as separate regions; in later stages the member states will be divided into sub-regions (i.e. level 4).

At level 1, typical soil profile descriptions and associated analytical data are identified for each major soil type present within each member state. The data are compiled for the dominant soil types on agricultural land only (and NOT for all the STUs identified in the SGDBE).

At level 2, typical soil profile descriptions and associated analytical data are identified for dominant as well as associated soil types on agricultural land (level 2 = level 1 + associated soil types).

At level 3, typical soil profile descriptions and associated analytical data are identified for dominant as well as associated soil types on agricultural and other land uses (level 3 = level 2 + non-agricultural land uses).

Level 4 allows for sub-national subdivision. At level 4 there may be more than one profile for each soil type to differentiate some soil types on other criteria such as parent material (pedo-landscapes). Level 4 = level 1 or 2 or 3 + regional sub-division.

Proforma I: soil profiles truly representative of soil types, preferably measured but can be estimated (as a 'theoretical' profile), exhaustive, harmonized, not geo-referenced, intended for spatial modeling at the 1:1,000,000 scale.

Proforma II: soil profiles not necessarily representative of soil types, measured data (from a 'real' profile), not necessarily exhaustive, not harmonized but measurement method specified, geo-referenced, intended as the first stage of compilation of a data set of measured data for all Europe.

Soil parameters needed by SWAT were extracted from the SPADBE Database referring to the STU covering Marta river basin basin.

The database includes analytical results for the different soil horizons as follows:

-Texture (& particle size grades)

-Electric conductivity

-Organic matter content (C, N)

-CEC and exchangeable bases

-Structure

-Soil water retention

-Total nitrogen content

-Bulk density

-pH

-Root depth

-ESP or SAR

-Groundwater level

-Calcium carbonate content

-Parent material

-Calcium sulphate content

5.1.3 Climatic parameters

To complete rainfall-temperature database and collect other climatic parameters, such as wind speed, solar radiation and relative humidity, MARS Database made by JRC was consulted. The Joint Research Centre is a research organization of European Commission. The MARS-STAT Data Base contains meteo interpolated data from 1975, covering the EU member states, the central European eastern countries, the new Independent states and the Mediterranean countries.

The Monitoring of Agriculture with Remote Sensing, MARS, project, was developed by JRC and started in 1988. It was initially designed to apply emerging space technologies for providing independent and timely information on crop areas and yields.

In compliance with the Commission policy these data are available to the scientific community.

The DAILY metereological interpolated data in to a 50x50 km Grids are the following:

maximum temperature (°C)	
minimum temperature (°C)	
mean daily vapour pressure (hPa)	
mean daily windspeed at 10m (m/s)	
mean daily rainfall (mm)	
Penman potential evaporation from a free water surface (mm/day)	
Penman potential evaporation from a moist bare soil surface (mm/day)	
Penman potential transpiration from a crop canopy (mm/day)	
daily global radiation in KJ/m2/day	
snow depth (cm) *	* data with no quality check

Tab n° 5.1 Meteorological data available by MARS Database (Jrc).

The interpolated meteorological data can be downloaded in the ASCII comma delimited text format.

The user will select the interested years, parameters and NUTS, names of the territorial units (nomenclature des unités territoriales statistiques) where the GRIDs belongs to (Fig. n° 5…).

For the selected cells in the 50 km x 50 km grid representing graphically the EU Member States, meteo data have been downloaded and elaborated in order to provide the required SWAT input data.

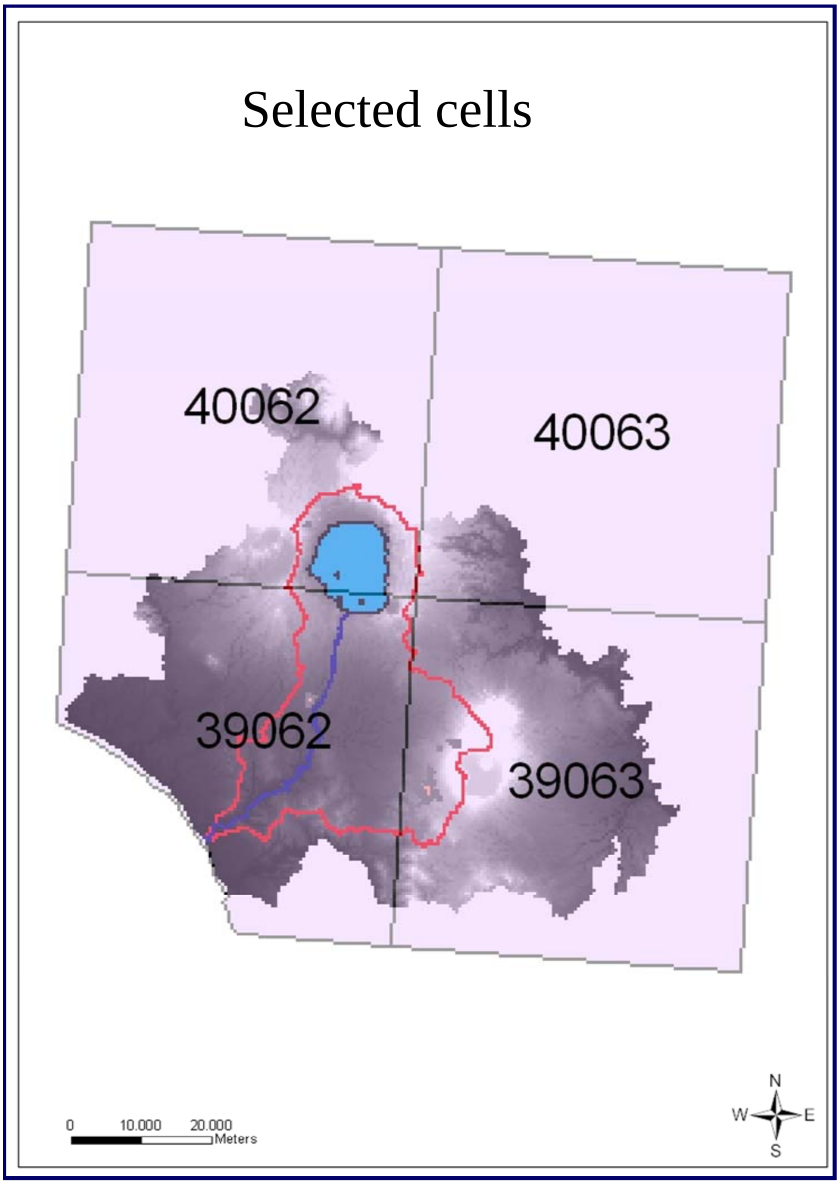

Fig n° 5.2 Selected cells in the 50 km x 50 km grid representing EU Member States in MARS Database.

5.1.4 Land use

The land use data were derived from the Corine land cover map (2000) updated by a Latium Region work project at 4th level of accuracy (2005). These data were received in the form of a digital map, with polygons representing different records of land covers and processing of the data was carried out with the use of GIS systems by categorizing known land cover types into larger groups.

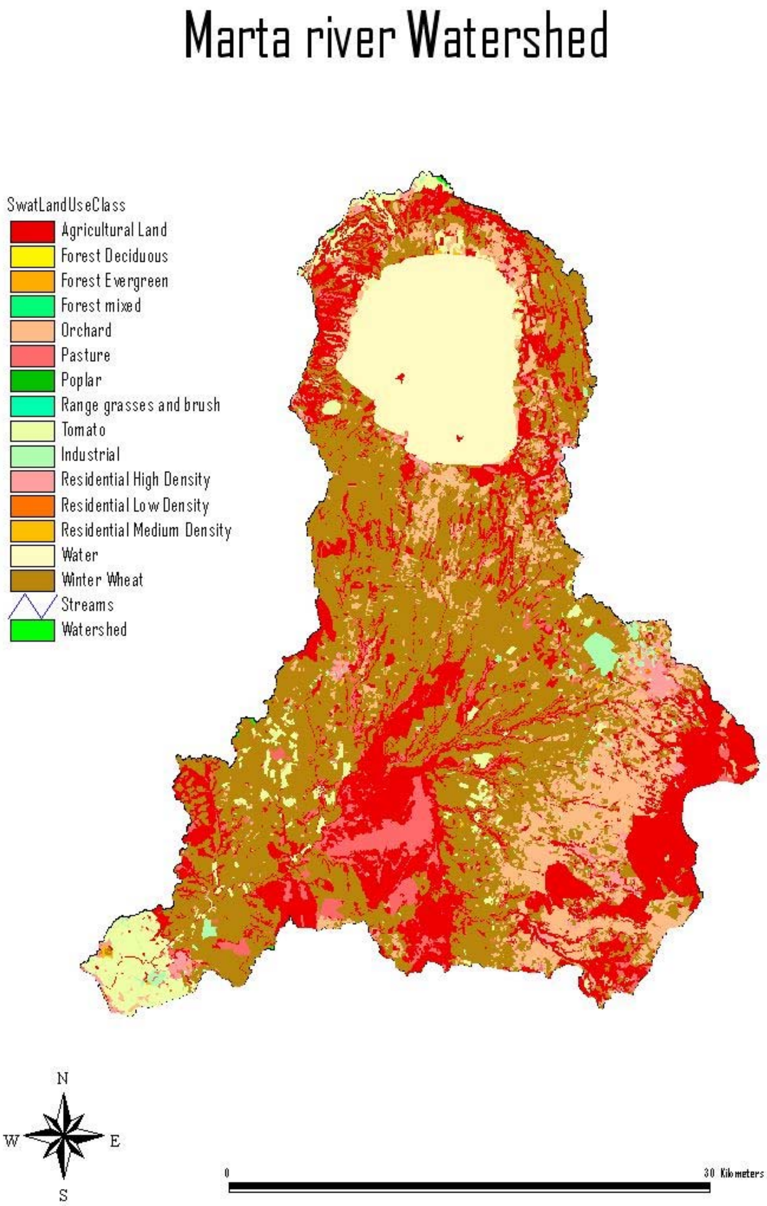

Fig. n° 5.3 Land use cover types in the study region according to Regional Soil Map (2005) at IV° leve of accuracy.

5.1.5 Agricultural practices

All the agricultural practices including crop rotations, fertilizers application and irrigation water amounts were derived from in the filed observations and from literature data. The cooperation with local farmers associations such as “Cooperativa Pantano” located in the southern part of the basin where horticultural crops prevail, led to the collection of the required input for SWAT model implementation. So that crop needs about nutrients and water were defined on basis of the existing crops and local habits.

Crop	Nitrogen crop requirement (Kg/Ha)	Total crop water requirement (m3/Ha/year)	Irrigation Period	Estimated crop yield (t/Ha/year)
Cereals	180			6
Spring wheat	140			4
Winter wheat	120			5
Barley	100			4.05
Oats	80			4
Segale	160			7
Rice	280			10
Corn		3600	July-August	
Pasture				
Alfalfa		6800-8400	July	
Summer pasture		4000	July-August	
Industrial crops				
Sugra beet	150	4200	July	4.05
Colza	180			3.05
Sunflower	100			3
Soybean	20			3

Tab. n° 5.2 Nitrogen and water requirements estimations for crops.

5.2 Model parameterization and simulation

After delineating the watershed by processing the DEM, the digitalized stream network in .shp file was given to SWAT model as input for the burn-in option and computing the contributing area the whole basin could be divided in 32 sub-basins for which inlet and outlet were defined.

Wastewater treatment plants, industrial wastewater discharge points and outlet at measurement stations were located in the watershed. According to the different combining of soil class and land use, each sub-basin has been divided again in HRU-Hydrological Response Units, imposing a threshold of 10% for land use and 20% for soil class as to obtain 195 HRU.

Soil class input from SPADBE dataset, land use information from Corinne (2005) project, climatic data from hydro-meteorological stations and from MARS database were elaborated by SWAT code to set up the model run. Penman- Monteith method was chosen for potential evapotranspiration estimate and Muskingum method was set for the channel water routing method and Curve Number method for runoff amount evaluation. On the basis of the available information and according to river basin planning targets and methods, an interval time of 8 years (1999-2006) was simulated by SWAT repeating the 8 years again in the top as to have a warm up period stabilizing the parameters setting and the model response. The model was calibrated comparing the simulated discharges at the outlet of Marta basin to the observed values on yearly at first at then monthly time step for the period 1999-2002. The reference station is Tarquinia station for which only hydrometric levels are available so that the extraction of flow curve for the whole simulation interval of time (1999-2002) was needed.

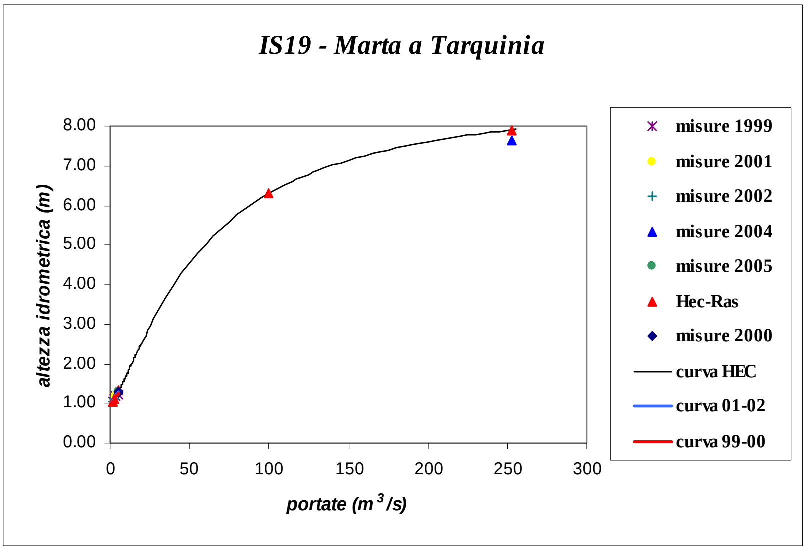

Fig. n° 5.4 Flow curve reconstruction using HEC-RES software application on observed hydrometric levels in the period 1999-2006 (Regional Hydrographic Service).

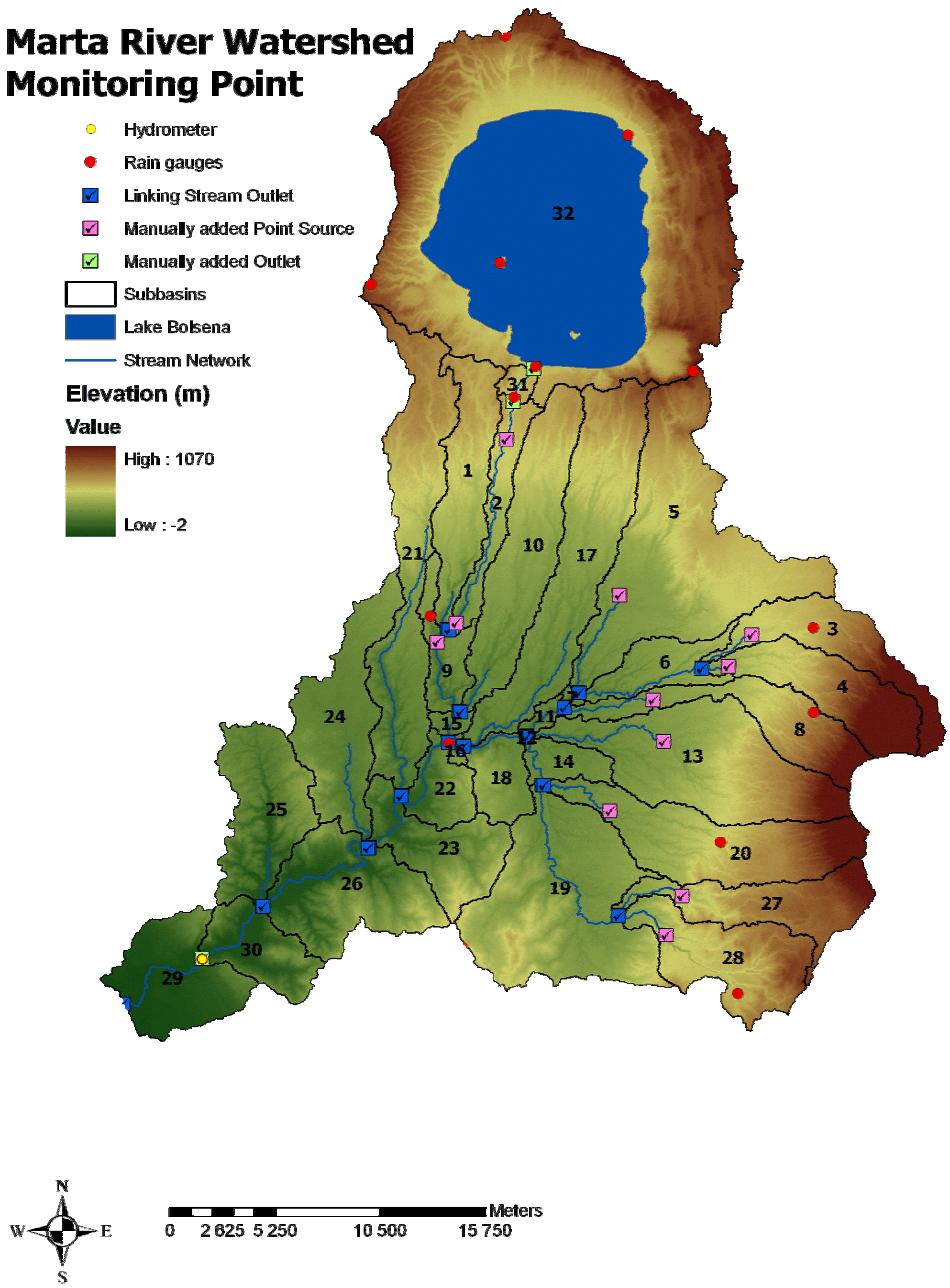

Fig. n° 5.5 Monitoring stations located in Marta river watershed.

5.3 Calibration and validation

In calibration phase, most pf the parameters affecting model behavior, have been modified manually and a sensitivity analysis was carried out to better understand the weight of each parameters on simulation results. The model sensitivity was expressed as a ratio of the relative change of the model output and the relative change of the input parameter:

- 0-0.05 Negligible (N)
- 0.05-0.2 Medium (M)
- 0.2-1.0 High (H)
- >1 Very High (VH)

Parameter	Index
Curve Number II (CN)	VH
Soil available water capacity (AWC)	N
Soil depth	N
Soil evaporation compensation factor (ESCO)	M
Satured hydraulic conductivity (SOL_K)	H
Maximum canopy storage	N

Parameter	Index
ALPHA_BF Factor	VH
REVAP Factor	H
Groundwater RevapFactor GW-REVAP	M
Groundwater Delay Factor (GW-DELAY)	M
Channel Erodibility Factor (CH-Erod)	N
BLAI (Potential maximum Leaf Area Index)	N

Tab. n° 5.3 Sensitivity analysis for SWAT model parameters.

According on sensitivity analysis, the most significant parameters have been slowly investigated and modified: ALPHA_BF represents the recession base flow coefficient, softening falling limb slope in the response hydrograph, and reliable values of ALPHA_BF factor were obtained applying a code called Baseflow (Arnold & Allen, 1999) to the available observed flow data so that to compute baseflow recession constant, Alpha factor, and to estimate baseflow Fr1, fraction of stream flow contributed by baseflow that is estimated at a first pass, and baseflow Fr2, fraction of stream flow contributed by baseflow that is estimated at a second pass until baseflow Fr3, at the third pass. To calibrate the model all this information were useful: the fraction of water yield contributed by baseflow should fall between the value fro baseflow Fr1 and baseflow Fr2 while ALPHA_BF could be set to the value calculated for Alpha factor by Baseflow code, 0.04 days.

Curve Number values (CN2) were also adjusted to meet the characteristics of land use and urban areas and soil evaporation compensation factor (ESCO) was adapted to the practiced crops behavior. GW_REVAP, ground water revap coefficient referred to water removed from the capillarity fringe by evaporation and GW_DELAY, groundwater delay time (days), referred to the lag between the time that water exits the soil profile and enters the shallow aquifer, were adjusted to calibrate the model. Regarding the water quality simulation processes, the calibration was carried out after the model was calibrated hydrologically and acting on phosphorous and nitrogen percolation coefficients (N_PERCO and P_PERCO).

The validation was carried out on the period 2003-2006.

The calibration and validation accuracy were checked by calculating several indexes: MAE Mean Absolute Error, RMSE Root Mean Square Error, and NS Nash and Sutcliff Efficiency Factor (Nush and Sutcliff, 1970) defined as follows:

$$NS = \frac{\sum_{i=1}^{n}(O_i - O)^2 - \sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - O)^2}$$

Where O_i is the observed time series, O is the numerical mean for the observed time series, S_i is the simulated time series and n is the total number of observed values.

A NS Factor equal to 1 means a perfect match of modeled values to the observed data while an efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero occurs when the observed mean is a better predictor than the model. Essentially the closer the model efficiency is to 1, the more accurate is the model.

The Nash and Sutcliff model Efficiency Factor is often used to assess the predictive power of a hydrological model but it can also be used to quantitatively describe the accuracy of different model outputs as long as there’s observed data to compare the simulated one.

Nash-Sutcliff efficiencies have been reported in scientific literature for model simulations of discharges, water qualities constituents such as sediment, nitrogen, and phosphorous loadings.

Flow		
Statistic Test	Calibration	Validation
MAE (Mean Absolute Error)	1.13	0.56
RMSE (Root Mean Square Error)	0.76	0.67
NS (Nush and Sutcliff)	0.96	0.98

Tab. n° 5.4 Statistical analysis for water quality simulation processes performance(NO3)

Nitrate		
Statistic Test	Calibration	Validation
MAE (Mean Absolute Error)	1.3	1.1
RMSE (Root Mean Square Error)	1.2	0.99
NS (Nush and Sutcliff)	0.65	0.78

Tab. n° 5.5 Statistical analysis for hydrologic simulation processes performance.

The results of model calibration and validation are given in Figure 5.. and 5….

The Nush and Sutcliff coefficient values show that a very good agreement between the observed and simulated monthly flow discharges while nutrients measured and simulated concentrations reasonably don’t match as well but the obtained results for water quality processes are anyway satisfactory taking into account the few available data and the complexity of these processes.

5.4 Results

In general, the model proved to be able to maintain a very good representation of the Marta basin behavior, showing high accuracy in estimating the total runoff volumes. Hence, it is surely useful to manage Marta river basin, since it allows to efficiently compare land use scenarios.

Some differences in peak runoff values can likely be explained by lack of detailed data regarding the physical characteristics of the watershed, the land use and soil characteristics, since they strongly affect the total runoff of the basin. Differences in discharge could also occur due to problems in the observed data since the flow values to compare with the simulated ones, derive from an extrapolated flow curve reconstructed from hydrometric levels and from direct measurements. The availability of hydrometric data only at the main outlet of the basin has also to be taken into account since it was not possible to calibrate and then validate the model at the outlet sub-basins composing Marta watershed but only at one control point (Tarquinia hydrometric station).

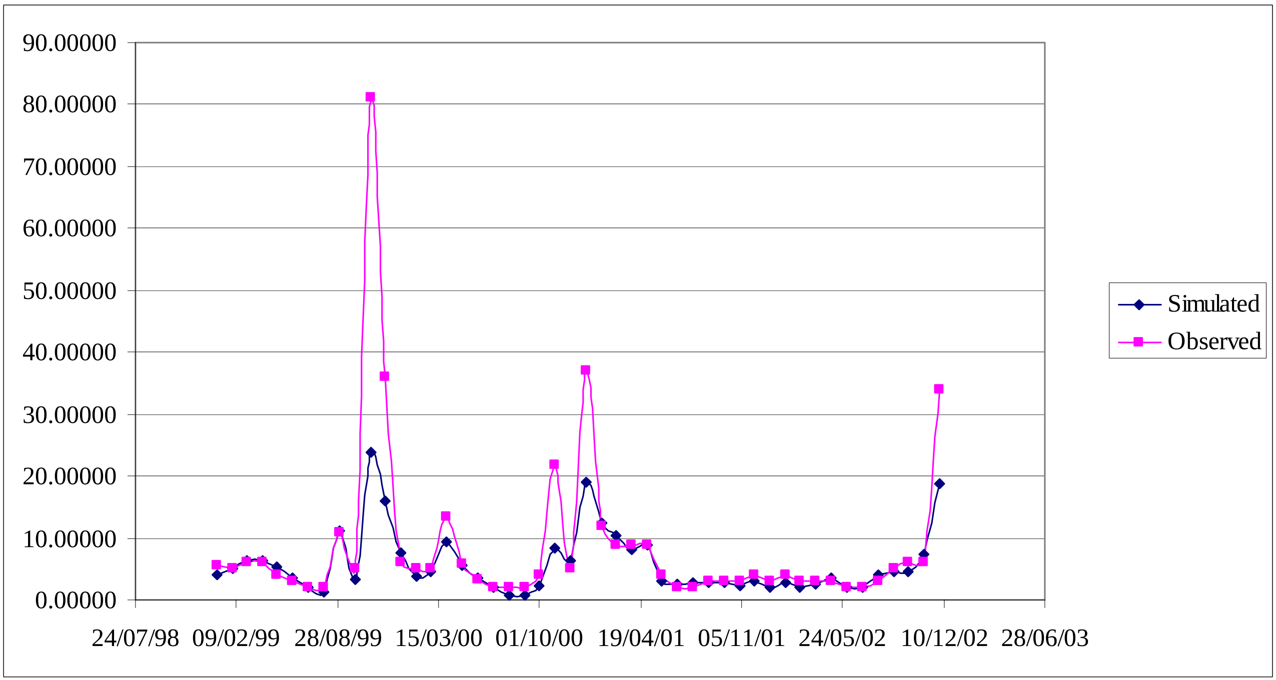

Fig. n° 5.6 Comparison between simulated and observed discharges (Model Calibration)

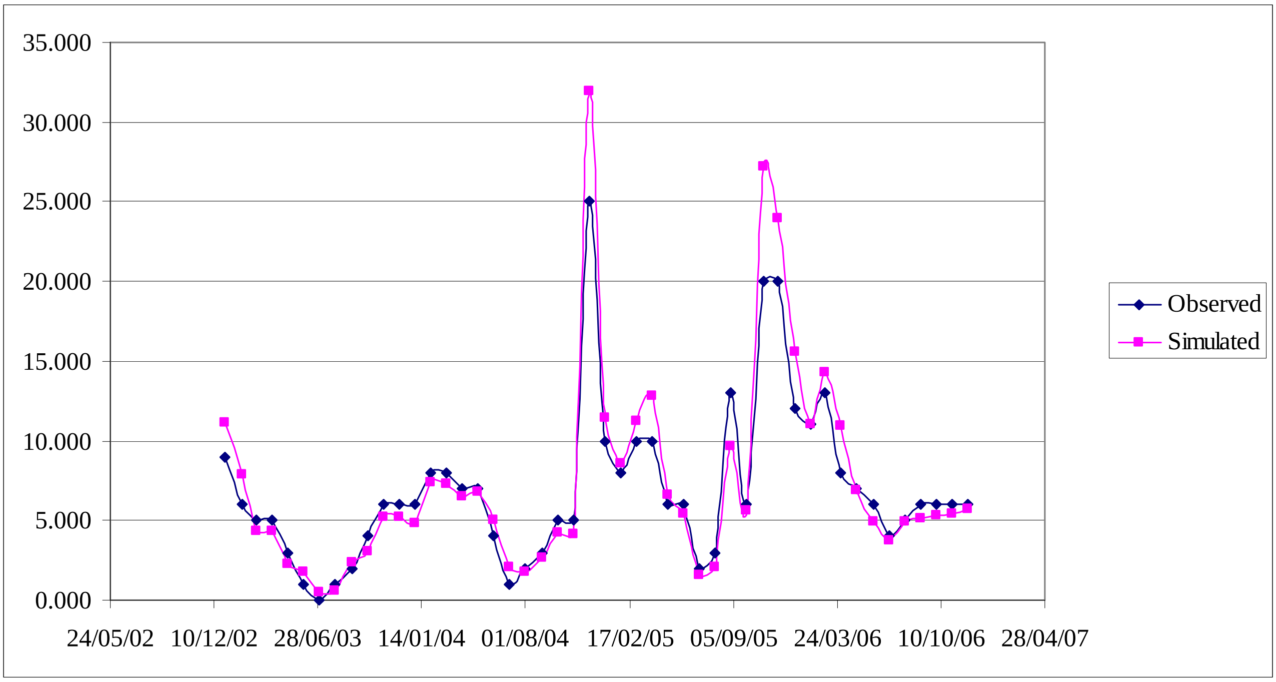

Fig n° 5.7 Comparison between simulated and observed discharges (Model Validation)

5.4.1 Water balance

Analyzing the obtained results, Marta river basin come across as rapid response watershed as confirmed by Flashiness Index elaborations and by the frequent and recent flood events occurring in the coastal areas where the river bed can't keep a fast increase in flow volumes.

Water balance components referred to calibration and validation periods are reported in the following tables while the correspondent whole hydrologic cycles are described in Tab. n° 5.6 .

Annual basin values-Validation	
PRECIPITATION	704.2
SURFACE RUNOFF	107.25
LATERAL FLOW	1.37
SOIL EVAPORATION	488.27
PERCOLATION	113.88
TRANSMISSION LOSSES	1.03
TOTAL WATER YIELD	244.51

Annual basin values-Calibration	
PRECIPITATION	650.56
SURFACE RUNOFF	64.19
LATERAL FLOW	2.15
SOIL EVAPORATION	0.74
PERCOLATION	63.47
TRANSMISSION LOSSES	493.75
TOTAL WATER YIELD	140.63

Tab n° 5.6 Averaged water balance annual components for the calibration and validation periods.

The potential evapotranspiration results were also compared with the calculated values (see Chapter 4) as you ensure the adequacy of simulation results in terms of order of magnitude. Data from FAO database referred to the nearest stations were also into account just to compare the entity of PET contributions to Marta simulated watershed with the available FAO data (Climagri project).

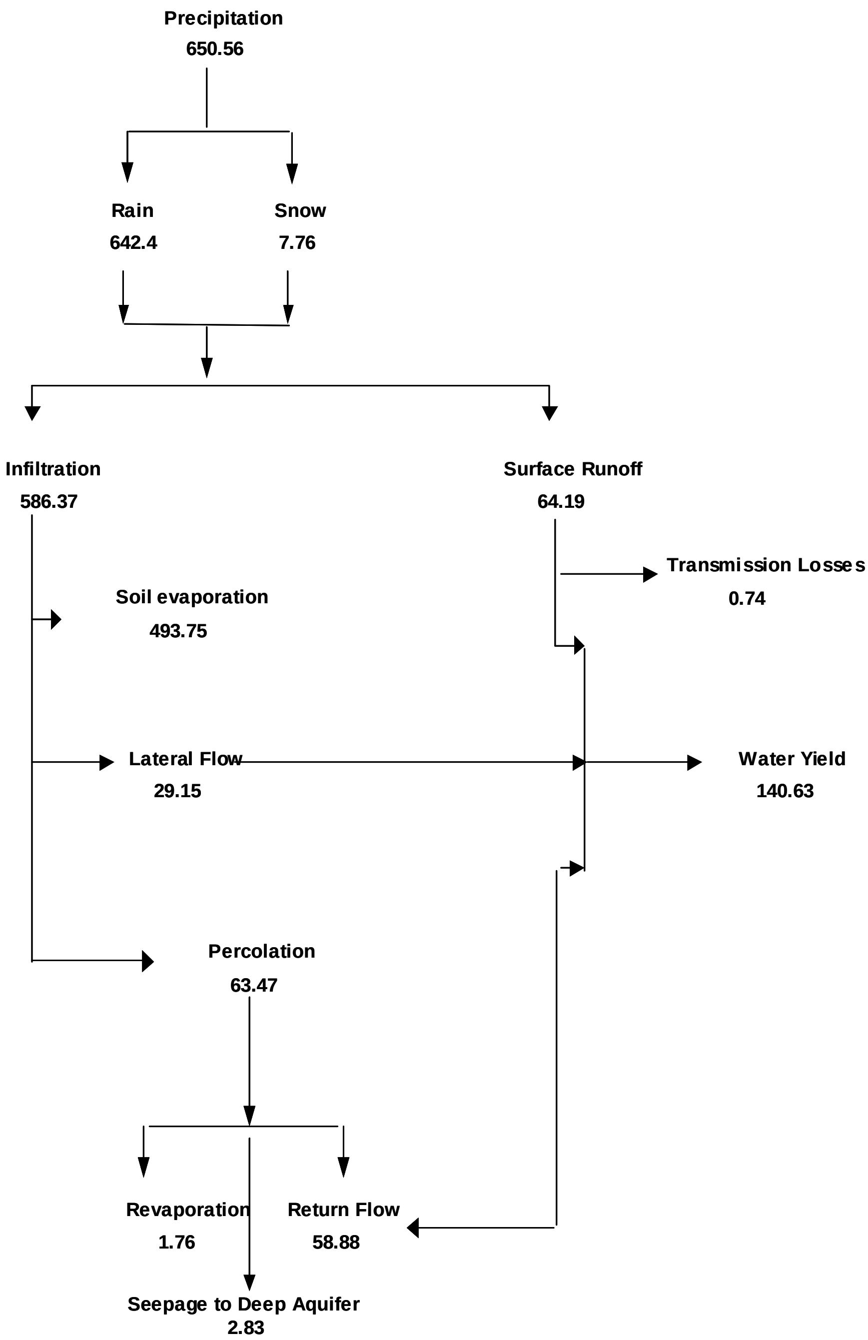

Fig. n° 5.8 Hydrologic cycle for the calibration period (1999-2002).

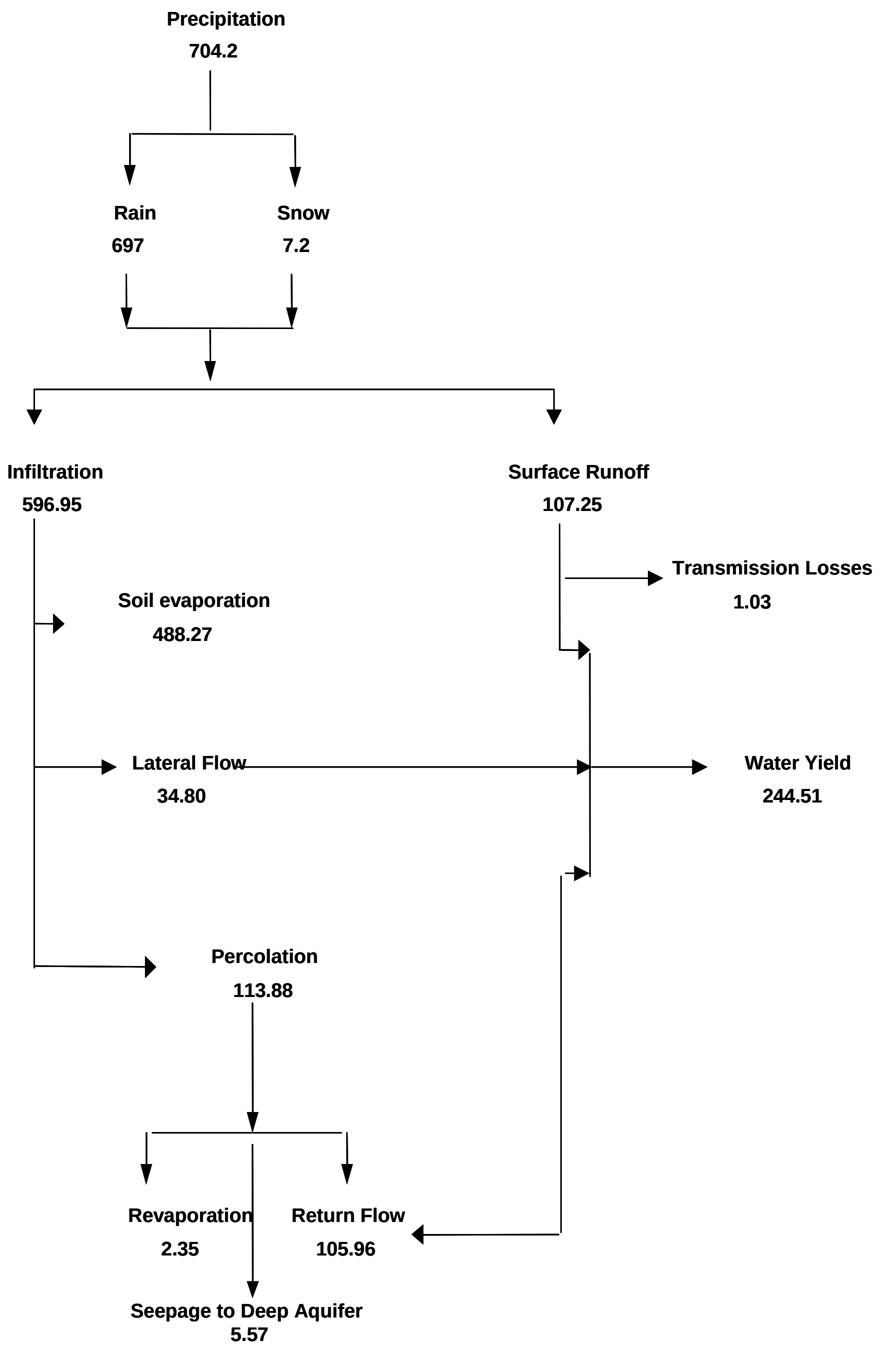

Fig n°. 5.9 Hydrologic cycle for the validation period (2003-2006

5.4.2 Nutrients

According to nutrient loads simulation, the incompleteness and not always comparable characteristics of the available data, makes difficult to evaluate the effective reliability and accuracy of simulation model. The statistical tests applications show a general correspondence between observed and simulated values even if some uncertainties waft on measured values due to the different methods and techniques used during the years to monitor regional water bodies.

Moreover most of the available data from monitoring campaign according to the law in force (Law n°152/06) are often represented as values below a specified threshold such as 0.23 mg/l for nitrate or 0.06 mg/l for phosphorous. So difficulties in evaluating the real observed values and in comparing the simulation results with the measured were found during this phase.

High efficiency indexes and encouraging statistical test results ensure a good model response to nutrient load on the basis of the certain available measurement for which a defined value can be identified.

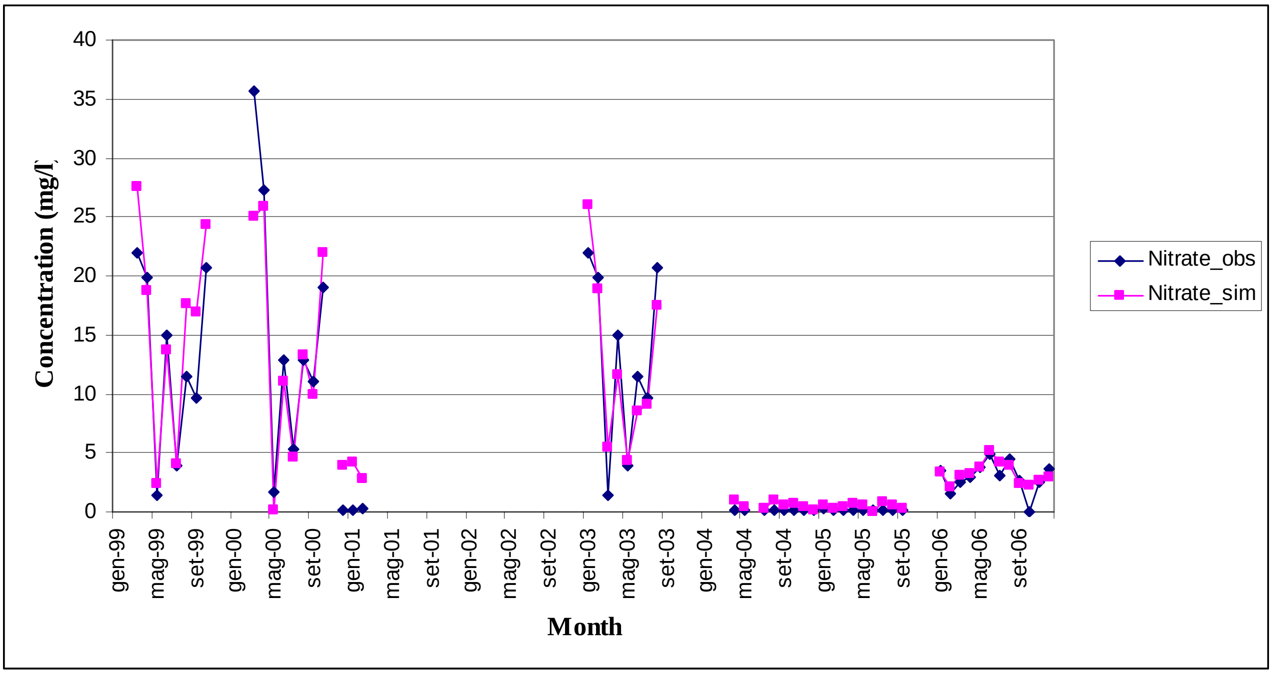

Fig. n° 5.10 Nitrate simulation results

5.5 Minimum Flow Requirement- estimated vs simulated values

Regarding Minimum Flow Requirement, a certain flow discharge must be ensured in river bed for the protection of the natural ecosystem according to national laws in force (Law 183/89, Legislative Decree 275/1993, Law n°. 36/1994, Law n°. 152/1999 and so on). The Latium Ragional Basins Authority, in the General Report on "Surface Water Availability and Minimun Flows” (AAVV, 1998) has divided Marta watershed in 21 sub-basins, whose sections are chosen in correspondence with deviation and restitution works for the five hydroelectric power plants arranged in sequence along the main water course. The Latium Ragional Basins Authority reffered to the method of microhabitat (Bove, 1982) for Minimum Flow Requirements estimations by implementing the procedure PHABSIM (Physical Habitat SIMulation System) identifying barbl (Barbus plebejus) and chub (Leuciscus cephalus) as the most representative species of the examined stream segments.
Other methods were applied to obtain reliable Minimum Floe Requirement estimations (see Chapter 4).

Minimum Flow Requirements			
	Ponte Cartiera	**Centrale Fioritella**	**Centrale Traponzo**
Q_347	1.10 mc/sec	/	3.30 mc/sec
Q_355	0.90 mc/sec	/	3.0 mc/sec
Q=f(Q_347)	0.44 mc/sec	0.57 mc/sec	1.70 mc/sec
Montana Method	0.25 mc/sec (0.1 Q)	/	0.75 mc/sec
	0.74 mc/sec (0.3 Q)		2.26 mc/sec
IFIM Method*	0.50 mc/sec (Q25%)	/	
	0.80 mc/sec (Q50%)	/	
$Q_{7/10}$*	0.69 mc/sec	/	2.43 mc/sec
* elaborations from Regional Authority			

Tab. n° 5.7 Minimum Flow Requirement estimations for Marta river sections.

The implemented SWAT model for Marta river, provides minimum and average flow values for the same sections of Marta river in which the Minimum Flow Requirements was calculated by PHABSIM (Latium Regional Basins Authority) and by other methods (Fig. n° 5.7).
The simulated values given by SWAT model are listed below:

SWAT Model		
	Q Mean (mc/sec)	Q Min (mc/sec)
Ponte Cartiera	0.16	0.00002
Centrale Fioritella	0.29	0.00005
Centrale Traponzo	3.73	0.44

Tab n° 5.8 Average and minimum flow discharges simulated by SWAT in the sections at which MFR was estimated by Latium Regional Basins Authority and using other methods.

The comparison between calculated values and simulated minimum and average flow discharges value, show clearly that a MFR cannot always be ensured in the considered sections since low water flows get about 0 m^3/s during the summer period.

Next to zero low water flows strongly threaten the ecosystem and can heavily compromise the ichthyic population and the whole natural, water and forest, resources in the watershed.

A correct and rational management plan is hoped for this watershed regulating water deviations for hydroelectric purposes as to never go below the needed Minimum Flow Requirement and to preserve fluvial habitat and water quality.

5.6 What if scenario simulation

Degrading water quality or limited water supply is usually the reason a watershed management plan is developed. Sources that contribute to water quality include two main categories: point and non point. The total pollutant load to a lake or stream is generally expressed as the total sum of the contributions due to point source loads and non point source loads.

In short, all activities, whether agricultural, industrial, municipal, or recreational, contribute to the water quality in a watershed. Depending on the constituent of concern, some activities may be more significant contributors than others.

Water quality models are tools that allow users (managers, engineers, planners, etc.) to mathematically simulate natural processes in a watershed even providing future representation of reality if hypothesis on climatic, natural and anthropic driving factors are made. A model can assist stakeholders in evaluating the impacts of various management strategies and land use changes on the watershed. Water quality models allow "what-if" scenarios to be developed and evaluated. So models can be a very useful tool, even with their limitations due to scale (size of the watershed) and available data (stream flow, water quality parameters, etc.) but often modeling efforts need to be combined with social acceptability and government commitment to achieve successful results.

In order to test the future effects of human actions and pressures, the implemented SWAT model was run simulating the malfunctioning of one or more wastewater treatment plant insisting on Marta watershed as to give a decision system support for basin planning and management and demanding scientific and government attention on the effective hazards threatening the local natural and water resources. Presupposing Tuscania at first and then Tarquinia wastewater treatment plant out of order, concentrations of nutrients corresponding to loads per equivalent inhabitant (e.i.) according to characteristics of the plant and to the fixed IRSA-CNR coefficients determined to estimate the average nitrogen and phosphorous individual production yearly.

In the first case, Tuscania plant not working, an increase of 10% in NO_3 was found since the measurement station is really far from the point load discharge. While in the second case, Tarquinia plant non functioning, the increase of NO_3 was estimated of 70% due to the grater dimensions of the treatment plant (150000 e.i. served) and due to the presence of the observation section in the neighborhood.

The what if scenarios results show clearly that a particular attention has to given to the watershed response to anthropic decisions and impacts and that a planned and rational management of it is required to avoid environmental damage with heavy consequences on people and ecosystems.

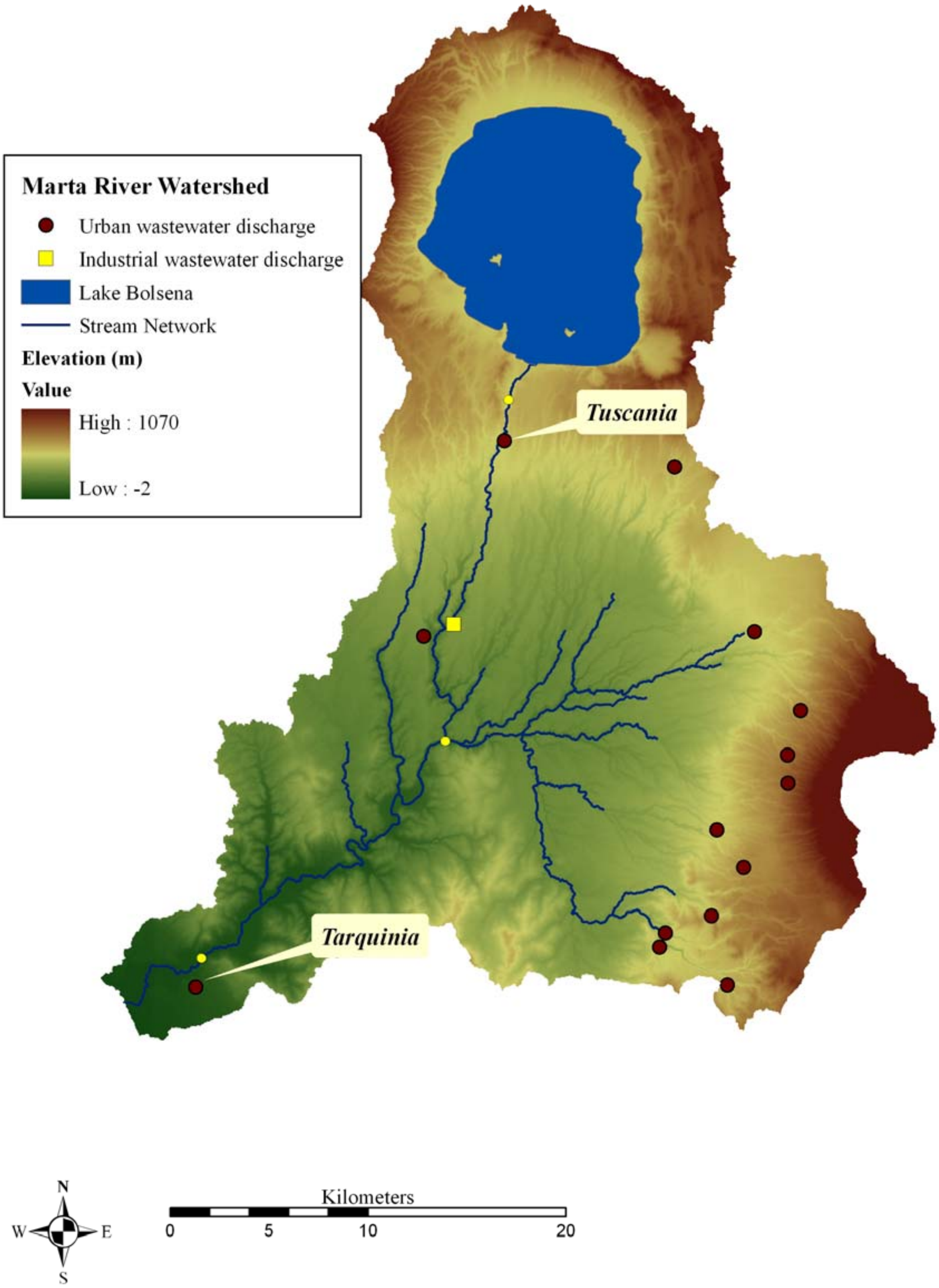

Fig. n° 5.11 Schematic representation of wastewater treatment plants locations considered for "what if" scenarios implementations.

CHAPTER 6

SALTWATER INTRUSION MODELING IN THE STUDY AREA

6.1 Saltwater intrusion-Historical development

It is estimated that 99.4 % (1.4 x 10^9 km^3) of all water on earth is made up of surface water while groundwater occurs only at 0.6 % (9 x 10^6 km^3) of the total. Most of the surface water is in the form of saltwater in oceans and inland seas (97%). Fresh surface water accounts for only 2% of the total volume of water (Bear & Cheng, 1999). Excluding saltwater, the proportion between surface and subsurface freshwater changes to 78% and 22%, respectively. In addition most of the surface water is in the form of ice-locked in ice-caps and glaciers in polar regions (77% of the total of freshwater). The freshwater available to humans for accessibility is concentrated in lakes (0.3 %) and in streams (0.003%) and as a water crisis is forecasted in the new future (Gleick, 1993), the welfare of the world population strictly depend on quality and quantity of water resources exploitation. Modern development and population growth has greatly increased water demand and led to depletion and often to contamination of surface water resources and also the demand of groundwater has been rising steadily so that now the groundwater use is about one third of the total freshwater consumption. Even if it's a quite abundant resource, unregulated extraction of groundwater in coastal zones can upset the established balance between freshwater and saltwater potentials, causing encroachment of saltwater into freshwater aquifers. About 70% if the population in the world dwells in coastal areas so that the optimal exploitation of fresh groundwater and the prevention and control of seawater intrusion are the challenges for the present-day and the future water supply management.

After the famous works by Badon-Ghyben (1888) and by Herzberg (1901), much progress has been made in research to understand the mechanisms governing saltwater intrusion. The dominant factors are, obviously, the flow regime in the aquifer above the intruding seawater wedge, the variable density and hydrodynamic dispersion. A large number of field investigations in coastal aquifers, especially during the 50's and 60's broadened the knowledge on the complicated mechanism causing saltwater intrusion and affecting the shape of the transition zone between fresh water and saltwater. At that time, computational tools were not available to predict the extent of saltwater intrusion under natural and man-made conditions and only simplified conceptual models could be used to obtain analytical solutions for the shape of seawater wedge considering, for example, a steady flow in a single homogeneous porous medium over a horizontal impervious bottom with an interface between freshwater and saltwater. Often it has been assumed that the flow was essentially horizontal, a statement corresponding to the Dupuit assumption that led to the to the famous Ghyben-Herzberg relationship. These analytical solutions provided estimates for the shape of a stationary interface in a coastal phreatic aquifer, with flow everywhere perpendicular to the coast while other analytical solutions gave the parabolic shape of an assumed sharp interface in an infinity thick confined aquifer.

Strack (1995) used the Dupuit-Forchheimer assumption to derive a solution for seawater intrusion in a horizontal two-dimensional domain. Even if such analytical solutions were roughly approximated, they provided the fundamental relationship between the rate of freshwater discharge to the sea and the length of the intruding seawater wedge. If the discharge is reduced, for example by pumping a larger proportion of the natural replenishment, the length of the seawater wedge will increase, causing wells to start pumping saline water. The Hele-Shaw analog was also useful to investigate the water balance in coastal aquifers, taking into account two-dimensional flow in the vertical cross-section, detailed geology and schedules of pumping. Actually all these conclusions are summarized by a single relationship that links the length of the wedge and, the water levels above it and the rate of freshwater flow to the sea and by controlling the rate of freshwater pumping, the length of the seawater wedge can be controlled as well while by controlling water tables elevations, for example by artificial recharge, seawater intrusion can be stopped even causing the interface advance seaward. The passage from freshwater domain to the saltwater domain, takes the form of a *transition zone*, rather than a sharp interface which is the result of hydrodynamic dispersion phenomena and it will be wide or narrow depending of the extension of seawater intrusion and on aquifer properties. Starting in the early 70's, mathematical models for seawater intrusion have been developed and applied to obtain numerical solutions, whether considering a sharp interface or a transition zone model. Due to the computer hardware and numerical algorithms advance of the last few years, a great efforts in investigating numerical solutions has been done also taking into account the economic aspects of groundwater utilization. In fact, the management of groundwater in coastal aquifers means making decisions elatives to the rates, temporal and spatial distributions of pumping and artificial recharge so that to recur to an optimization problem: increasing pumping, with its associated economic benefit, will produce more seawater intrusion which causes economic damages such as abandoning pumping wells. Moreover the restoration of the water quality in zone under saltwater intrusion, is really expensive and sometimes inefficient requiring a large amount of freshwater flushing for a long period of time. So, management of coastal aquifers involve more than the only management of seawater intrusion into aquifers cause the coastal regions overlying the aquifers, constitute a permanent threat to the freshwater in the aquifers, especially with phreatic aquifers.

6.2 Conceptual and mathematical models

Over the years, especially during the 50's and 60's many studies have been conducted to investigate the complex mechanism causing seawater intrusion and numerical solutions of the transition zone problem have been presented in the literature from time to time: Pinder and Cooper (1970), Lee and Cheng (1974), Segol et al. (1975), Segol and Pinder (1976), Huyakorn and Taylor (1976), Frind (1982), Huyakorn at el. (1987), Voss and Souza (1987), Diersch (1988), Galeati et al. (1992), Xue et al. (1995). Moreover a number of models and computer codes considering saltwater intrusion as a solute transport problem have been developed (Konikow et al., 1996).

Essentially all the investigations made by researchers in the past led to two fundamental assumptions to solve the problem:

-a sharp interface between saltwater and freshwater domains;

-a transition zone between saltwater and freshwater domains.

According to those conceptual models, mathematical models have been developed:

-two and three dimensional models of seawater intrusion with a sharp interface, generally called as **2DSIM** and **3DSIM** respectively (*Sharp interface approach);*

-three dimensional seawater intrusion model with a transition zone, called briefly **3DTZM** (D*isperse interface approach).*

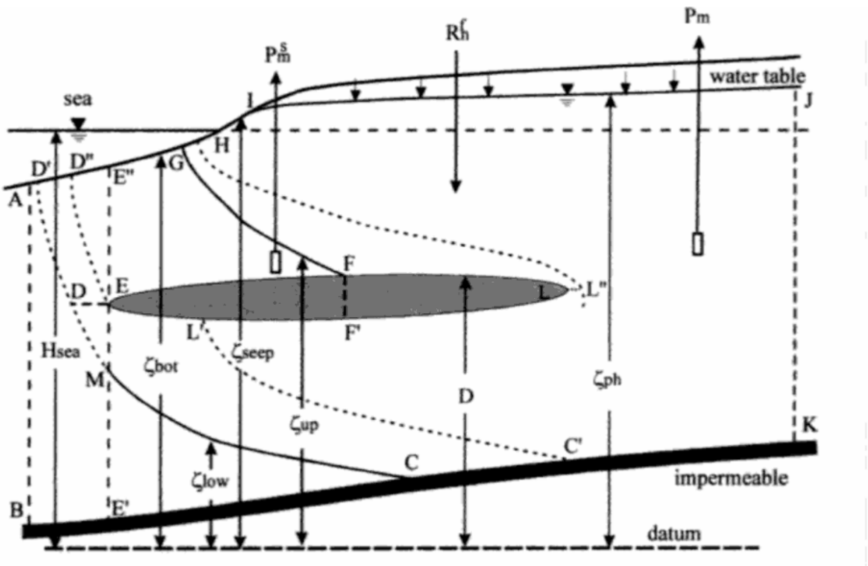

Fig. 6.1. A typical cross-section (perpendicular to the cost) of a three dimensional aquifer domain (Bear, 1999).

Figure 6.1 shows a typical cross-section of a three dimensional two layers aquifer on an impervious bottom and the impervious layer extends both seaward and land-ward to the cost (3DSIM example)

To illustrate coastal possible conditions, Figure 6.2 a represents an idealized hydrogeologic section through a layered coastal aquifer system extending offshore to a submarine canyon outcrop while Figure 8.3 describes an equilibrium seaward hydraulic gradient within an aquifer with freshwater discharging to the sea under natural, undisturbed conditions while the Figure 6.2 b shows a transient system with intruding seawater and inland interface movement.

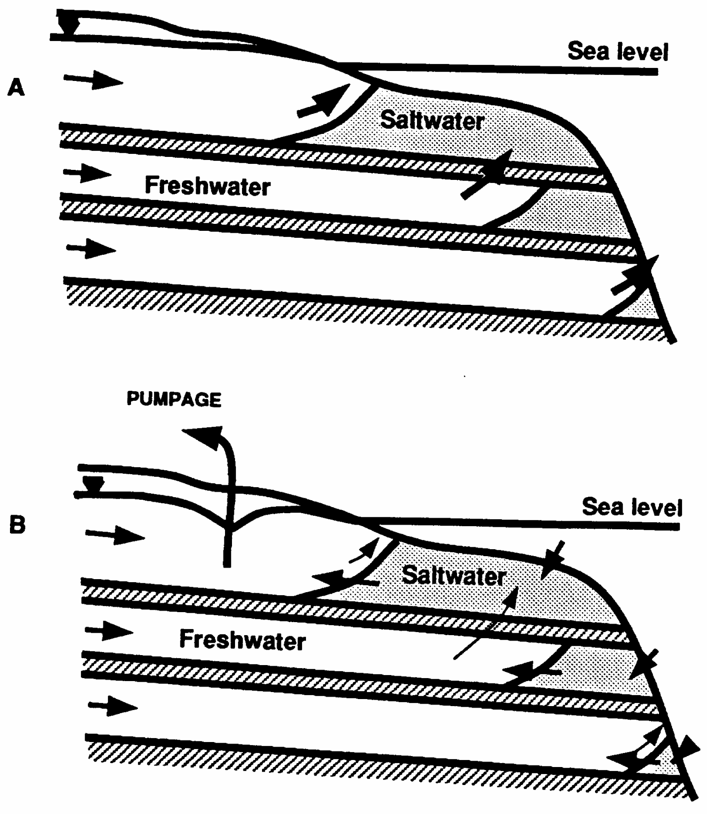

Fig 6.2 Idealized cross-section of a layered coastal aquifer system showing paths of freshwater discharge and potential paths for saltwater intrusion: a) steady-state system with constant freshwater discharge offshore, b) transient system with intruding saltwater and inland interface movement. (Essaid, 1999)

Disperse and sharp interface approaches have been used to analyze saltwater intrusion in coastal aquifers (Reilly and Goodman, 1985) and while the disperse interface approach explicitly represents the transition zone, where there's a mixing of freshwater and saltwater due to the effects of hydrodynamic dispersion (molecular diffusion and mechanical dispersion), the sharp interface approach simplifies the analysis by assuming that freshwater and saltwater do not mix and are separated by an abrupt interface. Both approaches have been used to successively develop models to predict the flow of ground water in coastal aquifers and a summary of saltwater intrusion problems is given in table 6.1.

Author	Approach	Method	Geometry	Time Dep.	Dup. App.	G-H App.	Field Application
Reddell & Sunada, 1970	DI-NDD	FD	A2-D	TR	YES	NO	
Bredehoeft & Pinder, 1973	DI-NDD	FD	A2-D	TR	YES	NO	Brunswick, Georgia
Andrews, 1981	DI-NDD	FE	A2-D	TR	YES	NO	Costa de Hermosillo, Mexico
Pinder & Cooper, 1970	DI-DD	FD	VCS	TR	NO	NO	
Volker & Rushton, 1982	DI-DD	FD	VCS	SS	NO	NO	
Sanford & Konikow, 1985	DI-DD	FD	VCS	TR	NO	NO	
Segol and others, 1975	DI-DD	FE	VCS	TR	NO	NO	Biscayne aquifer, Florida
Lee & Cheng, 1974	DI-DD	FE	VCS	SS	NO	NO	Biscayne aquifer, Florida
Frind, 1982	DI-DD	FE	VCS	TR	NO	NO	
Voss, 1984	DI-DD	FE	VCS	TR	NO	NO	Southern Oahu, hawaii
INTERA, 1979	DI-DD	FD	3-D	TR	NO	NO	
Kipp, 1987	DI-DD	FD	3-D	TR	NO	NO	
Huyakorn and others, 1987	DI-DD	FE	3-D	TR	NO	NO	
Fetter, 1972	SI-F	FD	A2-D	SS	YES	YES	South Fork, Long Isalnd
Anderson, 1976	SI-F	FD	VCS	TR	YES	YES	South Fork, Long Isalnd
Ayers & Vacher, 1983	SI-F	FD	A2-D	TR	YES	YES	Sommerset Island, Bermuda
Guswa & LeBlanc, 1985	SI-F	FD	3-D	SS	NO	YES	Cape Cod, Massachussetts
Sapik, 1988	SI-F	FD	Q3-D	SS	YES	YES	
Voss, 1984	SI-F	FE	A2-D	TR	YES	YES	Southest Oahu, Hawaii
Teigbenu and others, 1984	SI-F	BIM	A2-D	TR	YES	YES	
Volker & Rushton, 1982	SI-F	BIM	VCS	SS	NO	YES	
Shamir & Degan, 1971	SI-FS	FD	VCS	TR	YES	NO	
Bonnet & Sauty, 1975	SI-FS	FD	A2-D	TR	YES	NO	Morrocan Atlantic Coast
Mercer and others, 1980	SI-FS	FD	A2-D	TR	YES	NO	Maui, Hawaii
Polo & Ramis, 1983	SI-FS	FD	A2-D	TR	YES	NO	Spain
Pinder & Page, 1977	SI-FS	FE	A2-D	TR	YES	NO	North Haven, New York
Wilson & Sa da Costa, 1982	SI-FS	FE	A2-D	TR	YES	NO	Algarve, Portugal
Contractor, 1983	SI-FS	FE	A2-D	TR	YES	NO	North Guam
Liu and others, 1981	SI-FS	BIM	VCS	TR	NO	NO	

Tab. 6.1. Summary of numerical saltwater intrusion models (DI-disperse interface, DD-density dependent, NDD-non density dependent, SI-sharp interface, F-freshwater only, FS-freshwater and saltwater, FD-finite difference, FE-finite element, BIM-boundary integral method, A2-D-areal two-dimensional, VCS-vertical cross section, Q3-D-quasi-three-dimensional, 3-D three dimensional, Time Dep.-time dependence, TR-transient, SS-steady state, Dup. App.-Dupuit approximation, G-H App.-Ghyben-Herzberg approximation.

6.3 Disperse Interface Approach

The physics of a disperse interface separating freshwater and saltwater can be represented through the solution of the equations governing fluid flow and of the solute transport equation for a conservative chemical species (Bear, 1979):

$$\frac{\partial(n\rho)}{\partial t} = -\nabla \rho q \qquad \text{fluid mass balance} \qquad (6.1)$$

$$q = -\frac{\underline{\underline{k}}}{\mu}\left(\nabla p + \rho g \nabla z\right) \qquad \text{Darcy's Law} \qquad (6.2)$$

$$\frac{\partial(nc)}{\partial t} = \nabla n \underline{\underline{D}}_h \cdot \nabla c - \nabla qc \qquad \text{transport equation} \qquad (6.3)$$

Where: $\underline{\underline{k}}$ is the permeability tensor (L^2), $\mu = \mu(c)$ is dynamic viscosity ($ML^{-1}T^{-1}$), $\rho = \rho(c)$ is fluid density (ML^{-3}), p is pressure ($ML^{-1}T^{-2}$), z is the vertical dimension (L), g is the gravitational acceleration (LT^{-2}), n is the porosity, c is the concentration (ML^{-3}), $\underline{\underline{D}}_h$ is the hydrodynamic dispersion coefficient tensor (L^2T^{-1}), q is the specific discharge or Darcy velocity (LT^{-1}), t is time (T) and $\nabla(...) = \frac{\partial(\ )}{\partial x}x + \frac{\partial(\ )}{\partial y}y + \frac{\partial(\ )}{\partial z}z$ where x, y, z are unit vectors in the x, y, z directions.

Because density is a function of concentration, these equations have to be solved simultaneously to simulate coupled density-dependent fluid flow and solute transport. If the transition zone is very disperse and chloride concentrations gradients are low, the effects of variable density may be neglected and this simplification make it possible to decouple the equations, solving first or the flow field and subsequently for the concentration field. In conjunction with the Dupuit assumption of horizontal flow, this approach can be successfully used for area modeling of aquifers systems with low chloride concentration gradients or when vertical resolution is not needed. However if the density gradient is significant, then it must be taken into account. Generally the flow and transport equations can be solved simultaneously by iterations so that the needed computational effort limited most solutions to two-dimensional vertical cross-sections. Three dimensional density-dependent solute transport codes have been developed (INTERA, 1979, Huyakorn et al., 1987, Kipp 1987; Anderson et al., 1988) but have restricted applicability for regional studies due to computational constraints (Esseid ,1990).

6.4 Sharp interface approach

When the width of the transition zone is small relative to the thickness of the aquifer, saltwater and freshwater can be assumed as immiscible fluids separated by a sharp interface and this approach reproduces the general position, shape and behavior of the interface. These models couple the freshwater and saltwater domains through the interfacial boundary condition of continuity for flux and pressure. In three dimensions this boundary condition is highly non-linear (Bear, 1979) and solution really difficult. Simplifying the problem, the flow equation over the vertical can be integrated assuming horizontal flow within the aquifer. So sharp interface models generally can be divided in two groups: those models coupling freshwater and saltwater flow (two-fluid approach) and models considering freshwater flow only (one-dynamic-fluid approach).

Badon-Ghyben (1889) and Herzberg (1901) related the freshwater head above the sea level (Φ_f) to the depth to the interface below sea level (h_s) for a system in static equilibrium: steady horizontal freshwater flow and stationary saltwater. At the interface, the pressure due to the overlying column of freshwater must be equivalent to that due to the column of saltwater:

$$h_s \gamma_s = (h_s + \Phi_s)\gamma_f \tag{6.4}$$

$$h_s = \delta \Phi_f \tag{6.5}$$

Where $\delta = \gamma_f / (\gamma_s - \gamma_f)$ and γ_f, γ_s are the fresh and saltwater specific weights, respectively. Using the common values for densities that is 1.0 g/cm^3 for freshwater and 1.025 g/cm^3 fro saltwater, the value of δ is 40 so that the depth to the interface below the sea level is forty times the freshwater head. Flow simulation by sharp interface models in the freshwater only, incorporates the Ghyben-Herzberg relation assuming that at each time step saltwater adjusts instantaneously to changes in the freshwater zone until an equilibrium interface position is achieved. The two-fluid approach implies the freshwater and saltwater equations to be solved simultaneously. On the basis of continuity of pressure, the interface elevation can be expressed as a function of the freshwater head and the saltwater head and the movement of the interface is determined by the freshwater and saltwater flow dynamics.

6.5 Considerations about different approaches

Each of the above approaches has advantages and limitations and can be successfully employed only under the appropriate conditions (Bear, 1990). The disperse interface is necessary in areas where the transition zone is wide while density effects can be neglected when chloride concentration gradients are low and the governing equations can be solved areally on a basin-wide scale. When the flow is density-dependent, the vertical dimension has to be included. Applications of this approach have been generally limited to two-dimensional vertical cross-sections due to computational constraints and there are also numerical instabilities and errors in simulating the movement of a narrow concentration front especially in zones where the transition zone approaches a sharp interface. Frind (1982) showed that when a velocity-dependent dispersion coefficient is used, instabilities appear in areas with stagnant saltwater. Voss and Souza (1986, 1987) indicate that when flow is predominantly horizontal, the vertical discretization must be of the same order of magnitude as the transverse dispersivity in order to avoid introducing numerical dispersion.

The sharp interface approach, in conjunction with the application of the hydraulic approach (integration of the flow equations over the vertical), the problem can be reduced to one dimension. This approach does not give information on the nature of the transition zone but it represents the overall flow dynamics of the system and reproduce the general response of the interface to applied stresses. Volker and Rushton (1982) compared steady-state solutions for both the disperse interface and the sharp interface approaches and showed that as the coefficient of hydrodynamic dispersion decreases, the two solutions approach each other.

Sharp interface models simulating flow in the freshwater region only and incorporating the Ghyben-Herzberg approximation assume that the saltwater zone adjusts rapidly to the applied stresses and it gives reliable results for long-term studies. However, to reproduce the short-term response of a coastal aquifer, it’s necessary to include the influence of saltwater flow (Essaid, 1986).

As a point of fact, none of the described approaches can fully characterize the behavior and complexities of coastal aquifer systems but the choice of the approach depends on the nature of the system to represent as on the goals of the modeling effort.

The sharp interface approach can represent the overall flow characteristics of the system but it cannot give details about the nature of the transition zone but the ideal characterization of such system may involve a two-step processes integrating the sharp interface and disperse interface modeling approaches.

6.6 Saltwater flow model SHARP

SHARP is a quasi-three-dimensional, finite difference model that simulates coupled freshwater and saltwater flow separated by a sharp interface in multilayered coastal systems and it can be used for regional and cross-sectional studies.

For each aquifer within a layered coastal system, freshwater and saltwater flow domains are considered and the two domains share a common boundary at the interface (Bear 1979). Within each flow domain the equation of continuity must hold:

$$S_f \frac{\partial \Phi_f}{\partial t} = -\nabla q_f \qquad \text{freshwater flow domain} \qquad (6.6)$$

$$S_f \frac{\partial \Phi_s}{\partial t} = -\nabla q_s \qquad \text{saltwater flow domain} \qquad (6.7)$$

Where $\Phi_f = z + p_f / \gamma_f$ is the freshwater head (L), $\Phi_s = z + p_s / \gamma_s$ is the saltwater head (L), z is the elevation (L), p_f, p_s are the fresh and saltwater fluid pressures ($ML^{-1}T^{-2}$), S_f ,S_s are the fresh and saltwater specific storages (L^{-1}), γ_f ,γ_s are the fresh and saltwater specific weights ($ML^{-2}T^{-2}$), q_f, q_s are the fresh and saltwater specific discharges (LT^{-1}).

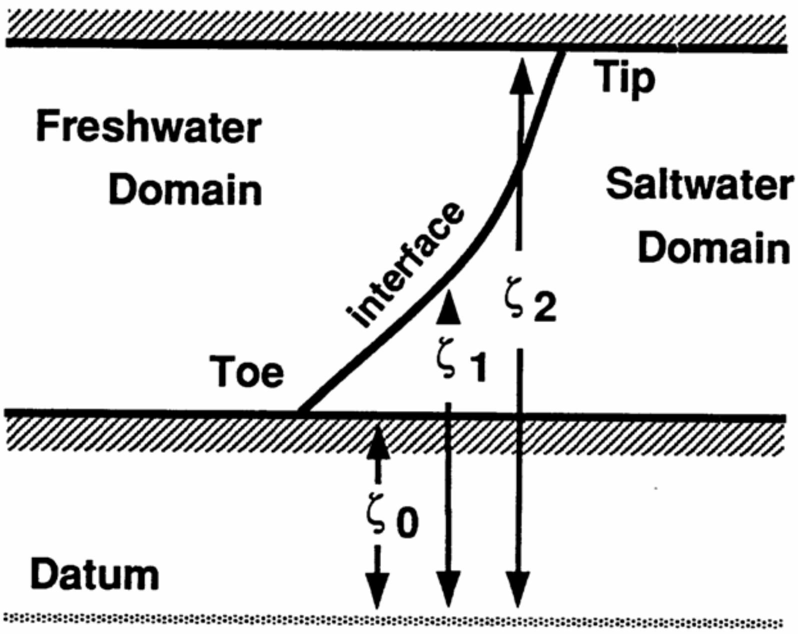

Fig. 6.3 Freshwater and saltwater flow domains in a confined aquifer.

The equations (6.6) and (6.7) can be integrated over the vertical dimension, within the two domains. In the vicinity of the interface, the lower boundary of the saltwater domain is the bottom of the aquifer which has an elevation of ξ_0; the interface is, instead, the upper boundary of the saltwater domain and has an elevation is ξ_1. The freshwater domain is limited on the bottom by the interface (ξ_1). If the aquifer is confined the elevation of the top of the aquifer (ξ_2) is the upper boundary while if the aquifer is unconfined, the top of freshwater domain (ξ_2) is given by the water table elevation. Integrating vertically the freshwater and saltwater flow equations implies the Dupuit approximation of vertical equipotential lines and horizontal flow within the aquifer reducing to two spatial dimensions (x and y). For a confined aquifer, integration of the freshwater flow equation from the interface (ξ_1) to the top of the aquifer (ξ_2) and substituting Darcy's Law yields:

$$\int_{\zeta_1}^{\zeta_2}\left(\nabla q_f + S_f \frac{\partial \Phi_f}{\partial t}\right)dz \cong \nabla'\cdot\left(-B_f \underline{\underline{k_f{}'\cdot\nabla'\tilde{\Phi}_f}}\right) + S_f B_f \frac{\partial \tilde{\Phi}_f}{\partial t} - q_f{}'\big|\zeta_2 \nabla'\zeta_2 + q_{fz}\big|\zeta_2 + q'_f\big|\zeta_1 \cdot \nabla'\zeta_1 - q_{fz}\big|\zeta_1 =$$

$$= 0 \tag{6.8}$$

where $\tilde{\Phi}_f = \frac{1}{B_f}\int_{\zeta_1}^{\zeta_2}\Phi_f\, dz \cong \Phi_f$ the vertically averaged freshwater head (L)

$q'_f = \frac{1}{B_f}\int_{\zeta_1}^{\zeta_2} q_f\, dz \cong -K'_f \cdot \nabla'\Phi_f$ the vertically averaged freshwater flux (LT^{-1})

$q' = q_x lx + q_y ly$

$\nabla'(\ ) = \frac{\partial(\ )}{\partial x}x + \frac{\partial(\ )}{\partial y}y$

$B_f = \zeta_2 - \zeta_1$ Thickness of the freshwater zone (L)

q_{fz} is the vertical component of freshwater flux (LT^{-1}) and $\underline{\underline{K'_f}} = \underline{\underline{K'_f}}(x,y)$ is the vertically averaged freshwater hydraulic conductivity (LT^{-1}).

Similarly, the vertical integrated saltwater equation becomes:

$$\int_{\zeta_0}^{\zeta_1}\left(\nabla q_s + S_s \frac{\partial \Phi_s}{\partial t}\right)dz \cong \nabla'\cdot\left(-B_s \underline{\underline{k_s}}'\cdot\nabla'\tilde{\Phi}_s\right) + S_s B_s \frac{\partial \tilde{\Phi}_s}{\partial t} - q_s'|\zeta_2 \nabla'\zeta_2 + q_{sz}|\zeta_2 + q'_s|\zeta_1\cdot\nabla'\zeta_1 - q_{sz}|\zeta_1 =$$

$$= 0$$

(6.9)

Where $\tilde{\Phi}_s = \frac{1}{B_s}\int_{\zeta 0}^{\zeta_1}\Phi_s dz \cong \Phi_s$ is the vertically averaged saltwater head (L)

$q'_s = \frac{1}{B_s}\int_{\zeta_0}^{\zeta_1} q_s dz \cong -K'_s\cdot\nabla'\Phi_s$ the vertically averaged saltwater flux (LT^{-1}),

$B_s = \zeta_1 - \zeta_0$ the thickness of the saltwater zone (L)

q_{sz} is the vertical component of saltwater flux (LT^{-1}) and $\underline{\underline{K_s^{'}}} = \underline{\underline{K_s^{'}}}(x,y)$ is the vertically averaged saltwater hydraulic conductivity (LT^{-1}).

The last four terms in the equations (6.8) and (6.9) are the boundary conditions at the top and bottom of each domain and they are given by the boundary condition at the interface, and at the top and at the bottom of the aquifer. The continuity of pressure at the interface has to be satisfied and the fluid pressure in the freshwater domain must equal the fluid pressure in the saltwater domain:

$$p_f = (\Phi_f - \zeta_1)\gamma_f = p_s = (\Phi_s - \zeta_1)\gamma_s \tag{6.10}$$

Where ξ_1 is the interface elevation. Solving for the interface elevation:

$$\zeta_1 = (1+\delta)\Phi_s - \delta\Phi_f \tag{6.11}$$

Where $\delta = \gamma_f / (\gamma_s - \gamma_f)$

The geometry of the interface is described in terms of elevation and the freshwater and saltwater heads:

$$F = z - \zeta_1 = z - (1+\delta)\Phi_s + \delta\Phi_f = 0 \tag{6.12}$$

The interface is a moving surface and its velocity depends on the velocities of the water on both sides of the interface. No changes in F takes place as the interface moves and the substantial derivative of F is equal to zero (Bear, 1979):

$$n\frac{DF}{DT} = n\frac{\partial F}{\partial t} + q_f \nabla F = n\frac{\partial F}{\partial t} + q_s \nabla F = 0 \quad (6.13)$$

Where F is multiplied by n that is the effective porosity. Using the equations (8.10) and (8.11) it can b shown that:

$$-q'_f \left|\zeta_1 \cdot \nabla' \zeta_1 - q_{fz}\right|\zeta_1 = -q'_s \left|\zeta_1 \cdot \nabla' \zeta_1 - q_{sz}\right|\zeta_1 = n(1+\delta)\frac{\partial \Phi_s}{\partial t} - n\delta \frac{\partial \Phi_f}{\partial t} \quad (6.14)$$

The remaining terms:

$$-q_s'\left|\zeta_0 \nabla' \zeta_0 + q_{sz}\right|\zeta_0$$

$$-q_f'\left|\zeta_2 \nabla' \zeta_2 + q_{fz}\right|\zeta_2$$

are the boundary conditions at the top and the bottom of the aquifer respectively. If the boundaries are impermeable, these terms are equal to zero. If the aquifer is unconfined, the upper boundary is a free surface and the drainage from the water table is given by $n\partial\Phi_f / \partial t$, If the boundaries are permeable these terms are equal to the leakage through the overlying and underlying confining layers.

6.7 Leakage terms

Leakage through a confining layer can be calculated using the Darcy's Law in one dimension if the following assumptions are made (Bredehoeft and Pinder 1970): the effects of storage within the confining layer are negligible and flow through the confining layer is essentially vertical. If the conductivity of the aquifer is two or more orders of magnitude greater than the conductivity of the confining layer, the flow lines are nearly horizontal in the aquifers and vertical through the confining layers (Freeze & Cherry, 1979).

If the water on both sides of the confining layer has the same density, Darcy's Law is formulated in terms of hydraulic head differences across the layer while if the density is different, vertical density gradients are important and Darcy's Law has to formulated in terms of pressure:

$q_l = -\frac{k'}{\mu}\left(\frac{P_a - P_b}{\Delta z} + \rho g\right)$ where q_l is the vertical leakage, positive upwards (LT^{-1}), k' is the vertical permeability of the confining layer (L^2), P_a, P_b is the fluid pressure above and below the confining layer, respectively ($ML^{-1}T^{-2}$), ρ is the fluid density (ML^{-3}), Δz is the thickness of confining layer (L) and g is the gravitational acceleration (LT^{-2}). Using definition of hydraulic head, specific weights γ and freshwater conductivity of the confining layer and approximating the specific weight of the layer γ as an average of the specific weights above the confining layer (γ_a) and below (γ_b) $\gamma \cong \bar{\gamma} = (\gamma_a + \gamma_b)/2$ the general form of the leakage term becomes:

$$q_l = -\frac{K'}{B'}\left[\frac{\gamma_a}{\gamma_f}\Phi_a - \frac{\gamma_b}{\gamma_f}\Phi_b + \frac{(\gamma_b - \gamma_a)}{\gamma_f}\frac{(z_b + z_a)}{2}\right] \tag{6.15}$$

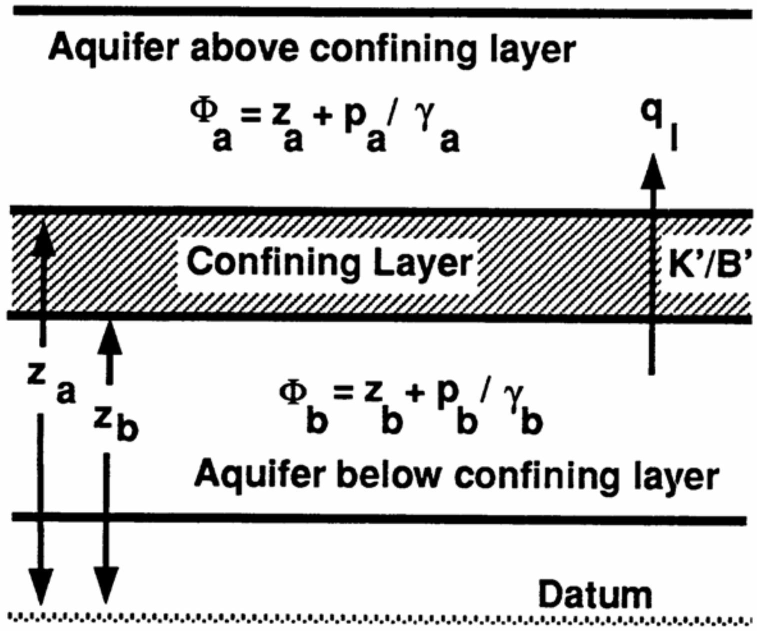

Fig. 6.4. Leakage through a confining layer

6.8 Numerical form of the freshwater and saltwater flow equations

The continuous spatial and temporal derivatives of the freshwater and saltwater flow equations are discretized using finite-difference methods. In particular the spatial discretization is obtained by using a block-centered finite-difference grid that allows for variable grid spacing. The second-order approximation for the space derivative in the x-direction at grid node (i, j, k) and time level n is given by:

$$A\left[\frac{\partial\left(B_\lambda K_{\lambda x}\frac{\partial \Phi_\lambda}{\partial x}\right)}{\partial x}\right]^n \cong T^n_{\lambda x_{j+1/2}}\Delta y(\Phi_{\lambda_{j+1}} - \Phi_\lambda)^n - T^n_{\lambda x_{j-2/2}}\Delta y(\Phi_y - \Phi_{\lambda_{j-1}})^n \tag{6.16}$$

Where f is fro freshwater and s is for saltwater flow, A is the grid block area (A=ΔxΔy).

The transmissivity terms at the block boundaries are given by:

$$T^n_{\lambda x_{j+1/2}} = B^n_{\lambda_{j+1/2}}\left(\frac{K_{\lambda x}}{\Delta x}\right) j+1/2 \tag{6.17}$$

$$T^n_{\lambda x_{j-1/2}} = B^n_{\lambda_{j-1/2}}\left(\frac{K_{\lambda x}}{\Delta x}\right) j-1/2 \tag{6.18}$$

The thickness at the block boundaries re linearly interpolated on the basis of adjacent nodal values, and the conductivity terms are estimated using the harmonic mean of the nodal values. The central difference approximations for the space derivative in the y-direction are made in the same manner and the result is:

$$A\left[\frac{\partial\left(B_\lambda K_{\lambda y}\frac{\partial \Phi_\lambda}{\partial x}\right)}{\partial y}\right]^n \cong T^n_{\lambda y_{j+1/2}}\Delta y(\Phi_{\lambda_{j+1}} - \Phi_\lambda)^n - T^n_{\lambda y_{j-2/2}}\Delta y(\Phi_y - \Phi_{\lambda_{j-1}})^n \tag{6.19}$$

The time derivatives of the freshwater and saltwater potentials are approximated by using a backward difference:

$$\frac{\partial \Phi_\lambda}{\partial t} \cong \frac{\Phi^n_\lambda - \Phi^{n-1}_\lambda}{\Delta t} \tag{6.20}$$

6.9 Sources and sinks

The potential sources (or sinks) of freshwater and saltwater in a block are pumpage (or injection), recharge, and leakage from the overlying or underlying confining layers.

The proportion of freshwater and saltwater extracted from a well depends on the position of the interface relative to the elevation of the screened interval of the well. The rate of freshwater extraction at a node is determined by a linear apportionment of the total extraction from the well based on the proportion of the open interval of the well penetrating the freshwater zone:

$$P^n_f \cong \frac{Th^n_f}{Th_t} P_t \tag{6.21}$$

where P^n_f is the freshwater pumpage from grid block ijk at time level n (L^3/T), Th^n_f is the length of the open interval penetrating the freshwater zone at time level n (L), Th_t is the total open interval of the well (L) and P_t is the total pumpage from the well (L^3/T).

The saltwater pumpage from the well at time level n P^n_s is given by:

$$P^n_s \cong P_t - P^n_f \tag{6.22}$$

Positive values of P_t represent extraction of water from a well while negative values represent injection of water into a well.

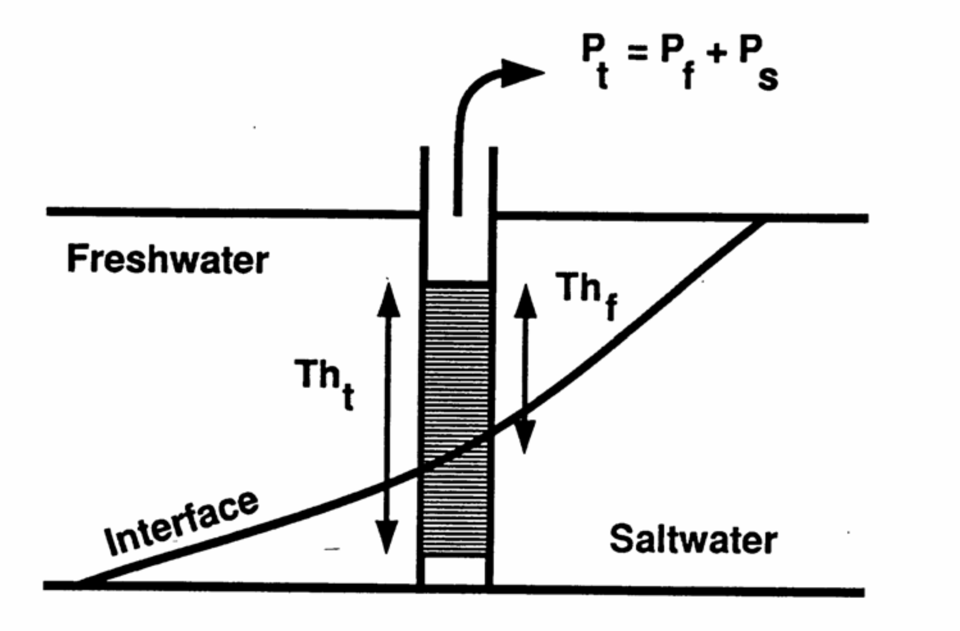

Fig.6.5. A well penetrating freshwater and saltwater in an aquifer (Th_t is the total open interval of the well, Th_f is the length of the open interval penetrating freshwater)

6.10 Modified version of SHARP model-Sharp_sar

The model Sharp (Essaid, 1990), provided by USGS with the source code in FORTRAN 77, has been modified by Santini (2008) leaving it unchanged for the computational part and amending the structure of input and output data in order to homogenize formats to other models ones and make them easily managed through the software package ArcInfo ESRI.

So the original text file was divided into an input file containing some general simulation parameters (criteria of convergence, the grid size, duration and number of pumping wells) and some values of the hydrodynamic aquifer characters. In addition, 12 grids in ArcInfo ASCII format provide spacialized data such as the location of wells, the recharges, the surface piezometric, aquifer thickness and so on for model run. Regarding water extraction, a module (wells) has been implemented in the code to create the list of wells, their positions, and the pumping interval directly from the grids containing this information. The following list of input data is required:

-*iwt.asc*: ASCII grid describing the type of aquifer, whether confined (code 0) or unconfined (code 1) derived from the aquifer map, geological information, water table and so on;
-*zbot.asc*: ASCII grid with aquifer bottom elevation (m.a.s.l.);
-*thck.asc*: ASCII grid about aquifer thickness;
-*bath.asc*: ASCII grid for bathymetry of the seabed in front of the simulated area;
-*rech.asc*: ASCII grid for spatialized recharge from effective infiltration;
-*phif.asc*: ASCII grid for water table;
-*pump.asc*: ASCII with pumping wells location and amounts (data on the wells);
-*wtop.asc*: ASCII with the top elevation of the cracks range thickness in wells coating;
-*wbot.asc*: ASCII with the bottom elevation of the cracks range thickness in wells coating;
-*aql.asc*: ASCII grid spatializing percolation coefficient for confined aquifer (code 0 for an unconfined aquifer everywhere);
-*head.asc*: ASCII grid for static water table over confined layer (code 0 for an unconfined aquifer everywhere).
The model output provides a codified map of the area in ASCII float grid (*Intrusion.asc*) in which:

Ex code	New code	Cell attribute
F	0.5	Fresh water
M	0.75	Interface
S	1	Seawater

Tab. n°6.2 Sharp_sar output codes

6.11 Sharp-sar model implementation for Maremma Laziale aquifer

A seawater wedge simulation model has been implemented for the coastal alluvial aquifer of Maremma Laziale applying Sharp_sar code, modified version of SHARP (Essaid, 1990).
For the study area all the required ASCII grids were elaborated.
Taking into account the aquifer delimitation from geological map and from The Water Resource Management Plan edited by The Latium Regional Basins Authority in 2007, *iwt.asc*, *aql.asc* and *head.asc* were immediately derived.

The aquifer can be delineate as an unconfined layer mainly made of volcanic deposits (Superior Pleistocene, Thyrrenian), conglomerates, recent and actual alluvial deposits (Olocene).

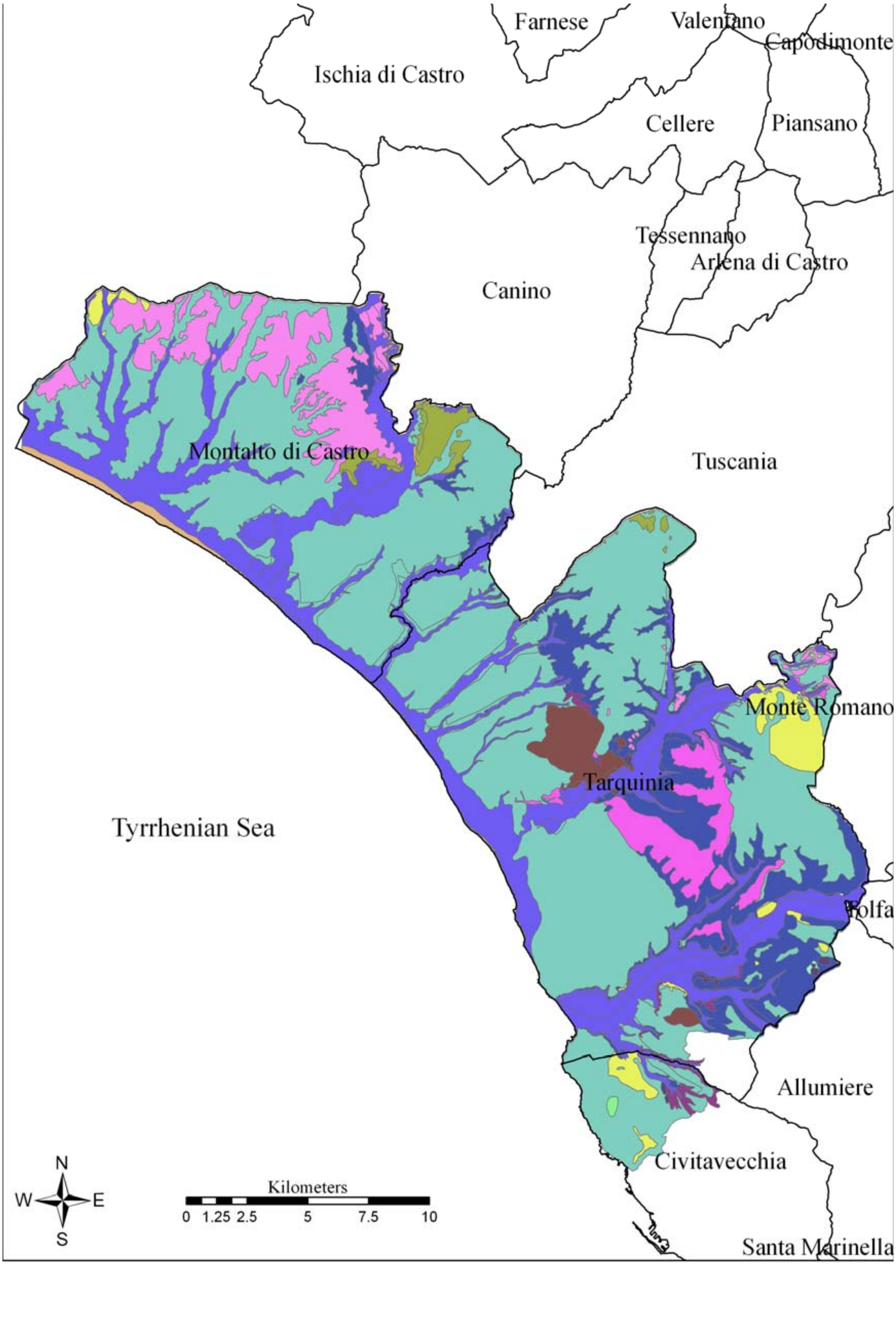

Fig. 6.6 Geological map of the study area

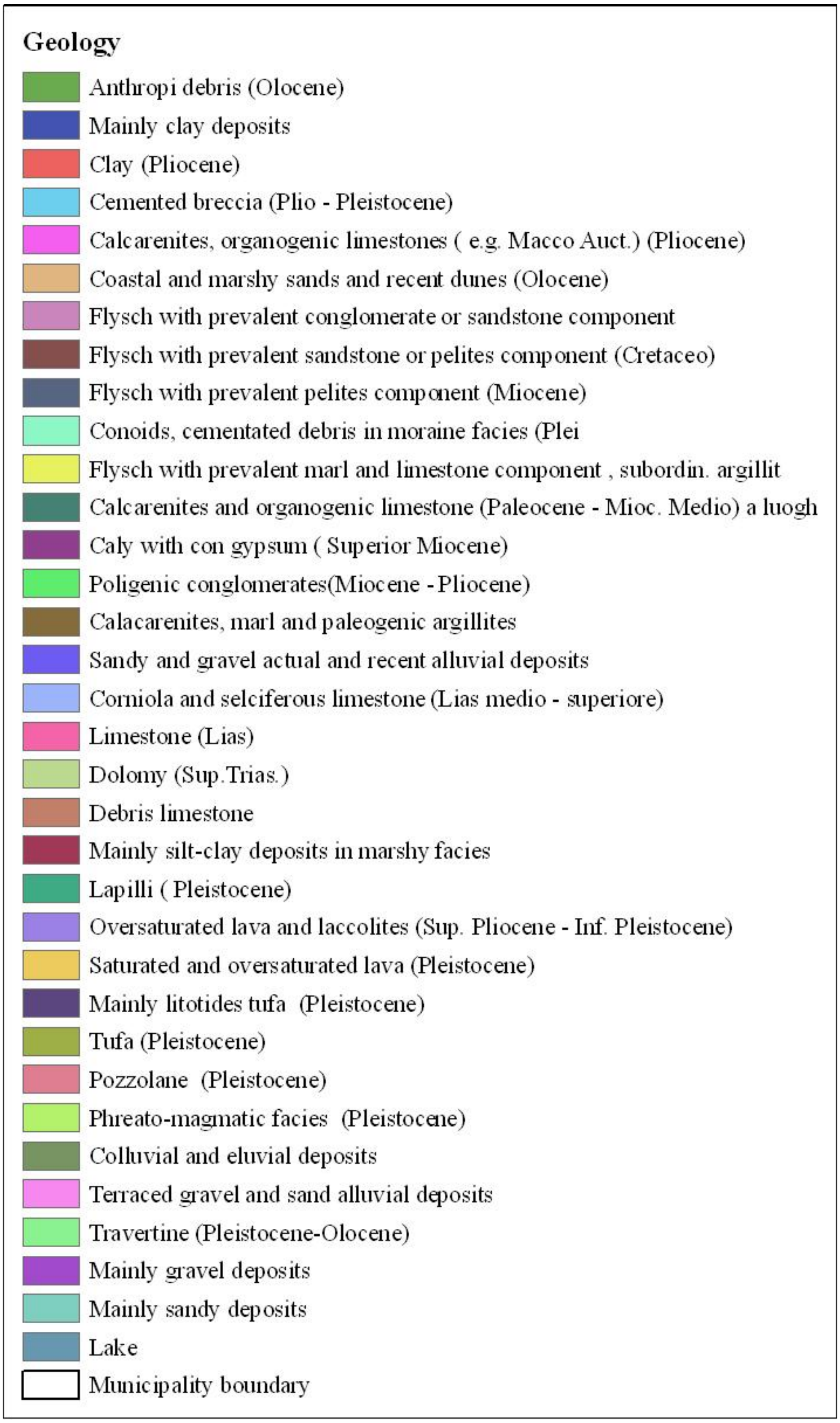

Fig. 6.7 Legend for the geological map of Latium coastal area (Fig.6.8)

Data from wells database provided by APAT (now ISPRA), the Italian National Agency for Environment Protection and Technical Services, have been elaborated using GIS techniques in order to define the aquifer thickness, top and bottom of the unconfined layer (*thck.asc*), top and bottom elevation of the cracks range thickness in wells coating (*wtop.asc*, *wbot.asc*), location of wells (*wells.asc*), pumping information (*pump.asc*) and water table levels (*phif.asc*). The study area covers about 480 km^2 and the aquifer thickness has low value toward the sea as geological sections show and increases reaching 264 m in the inner part.

According to the available database 35 wells insisting on the considered coastal aquifer were found with pumping amounts between 0 and 12 m^3/year.

Recent studies (Capelli & Mazza, 1994, Chiocchini et al., 2007) have been carried out on this area in the few years providing accurate and useful data to define the hydro-geological structure that could be interested by saltwater intrusion phenomena.

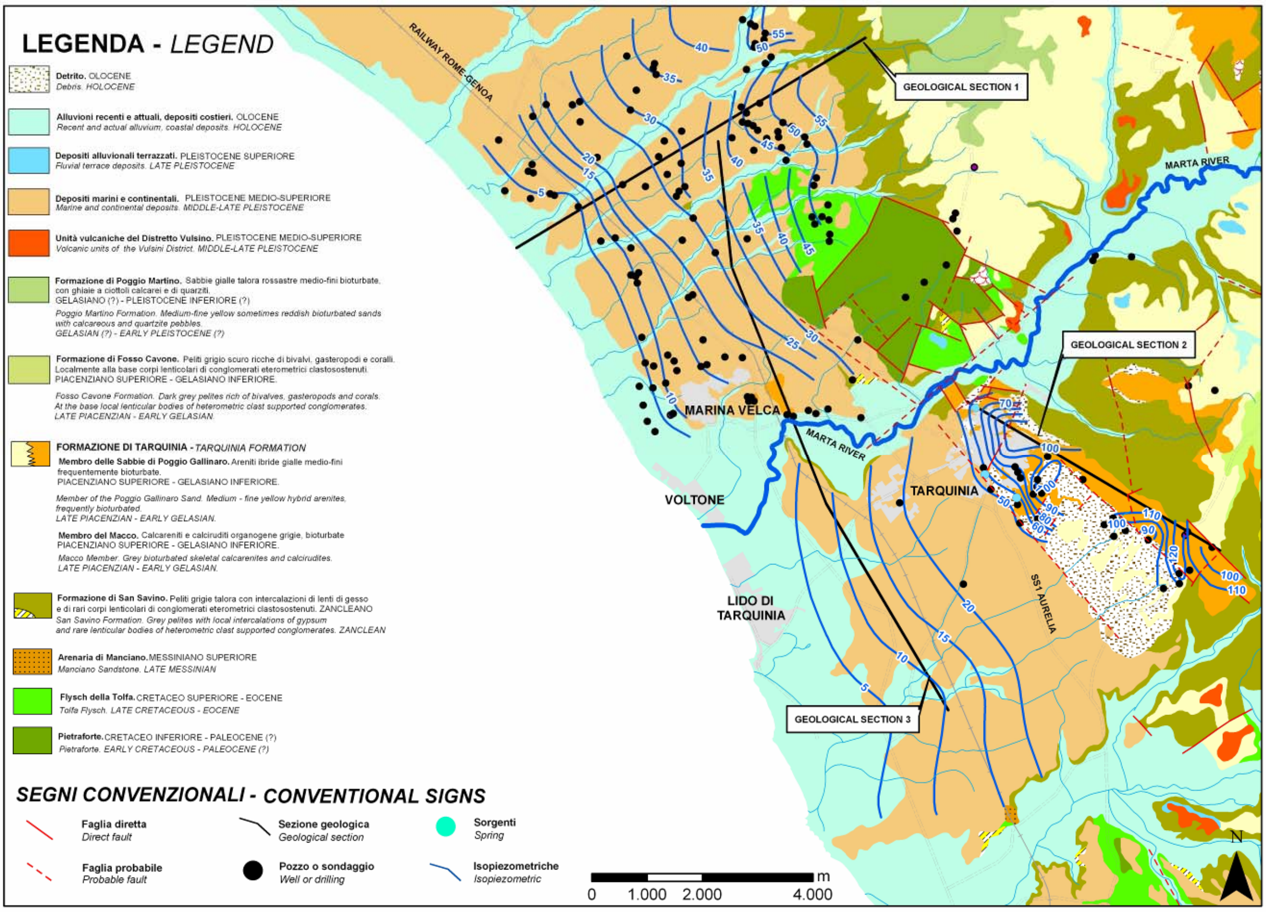

Fig. 6.8 Coastal aquifer geological map from Capelli & Mazza (1994)-modified.

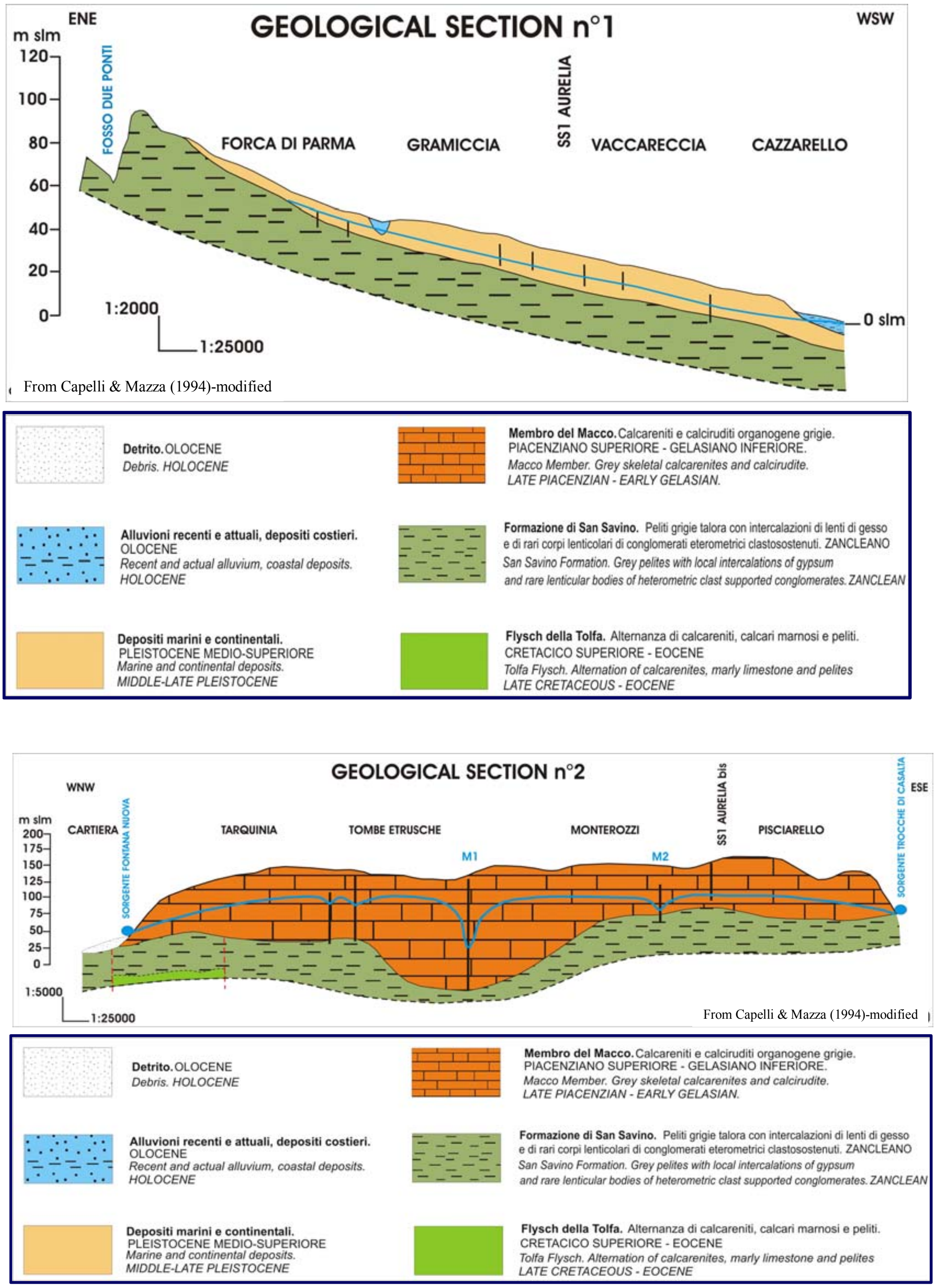

Fig. 6.9 Geological sections of the coastal aquifer: section 1 from inland toward seashore, section 2 inland and parallel to the coastline.

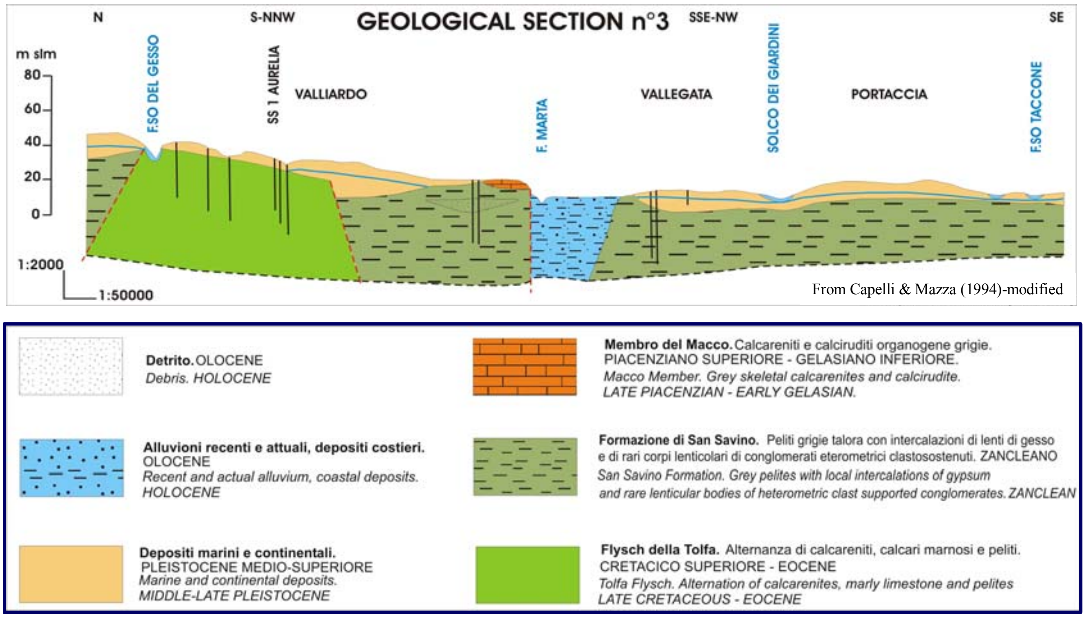

Fig. 6.10 Geological section 3 parallel to the coastline.

On the basis of these geological sections and of the stratigraphic information contained in APAT database on declared wells, the hydro-geologic structure has been reconstructed and the *thck.asc* and *zbot.asc* grids were obtained.

From static water levels in archived wells and digitalizing piezometric contour lines from map elaborations (Capelli & Mazza, 1994) the spatialized value of piezometric level has been derived and the *phif.asc* grid was generated.

Regarding *rech.asc*, recharge has been estimated as effective infiltration starting from Turc formula (1954) and potential infiltration coefficient (p.i.c.) parameterized according to geo-lythology available information:

$$ET = P / \sqrt{\left(0.9 + P^2 / L^2\right)} \tag{6.23}$$

Where P is the mean annual precipitation (mm),

$$L = 300 + 25T + 0.05T^2 \tag{6.24}$$

T is the mean annual temperature (°C) and the effective precipitation amount can be derived as:

$$P_{eff} = P - P / \sqrt{\left(0.9 + \frac{P^2}{L^2}\right)} \quad (6.25)$$

For temperature and rainfall, mean annual values have been computed on the simulation period (10 years) as to take into account an average climatic reference year.

The assigned p.i.c. values are listed below according to geo-lythology literature: the code field represents decreasing permeability with numbers from 1 to 4 while the letters meaning is:

-f = crack permeability;

-c= carsism permeability;

-p= porosity permeability.

Code	Lythologic type	p.i.c.
4f	Argillites, argillo-schists, schists, marls and serpentites	0.15
4p	Clay	0.1
4pf	Marls and schists with arenaceous and calcareous layers	0.2
3p	Morains, lake deposits, clay and sandy clay	0.3
3f	Gneiss, granites, gabbro, quartzite, marl limestone	0.4
3fc	Limestone, Dolomite limestone with marl intercalations	0.5
3pf	Flysch, sandstones, altered granites, sienites	0.5
2p	Fine sand, silt, conglomerates, incoherent molassa, lake deposits	0.6
2f	Volcanites, compact limestones	0.7
2pf	Conglomerates, more or less cemented alluvial deposits, travertine, poor cemented sandstones	0.8
2fc	Dolomy and dolomy limestones	0.8
1p	Alluvial deposits with gravel, sand and silt prevailing, screes, landslides debris, conoids, beach and dunes.	0.9

Tab. n° 6.3 Potential infiltration coefficient used for the effective infiltration estimate and codified on the basis of permeability map.

Other 4 parameters have been defined as representative for water at an average temperature of 15 °C:

-freshwater density 999.175 kg/m3

-freshwater viscosity 1.14E-6 m2/s

-seawater viscosity 1.18E-6 m2/s

Finally a spatialized bathymetry was obtained by digitalizing the nautical map of the area (scale 1:100000) and interpolating it in GIS environment to produce a spatialized information summarized in *bath.asc* grid.

In the input .txt file, INPUT_sar.txt, running the executable in Fortran code, model parameters values such as simulation period, time step, convergence criteria, observation wells, maximum number of iterations have to be defined and information about vertical and horizontal hydraulic conductivity has to be provided. Taking into account the geological characterists of this coastal aquifer and all the available data from literature and from APAT database, vertically and horizontally averaged values have been set with a minimum of 10^{-5} order of magnitude to a maximum of 10^{-3}. The simulation period is 10 years with a time step of 1 day.

6.12 Sharp_sar model results

With a simulation period of 10 years, Sharp_sar model was implemented on Maremma Laziale coastal aquifer and the results show that after of a pumping period of 10 years, saltwater intrusion might occur in the area between Fiora river and Arrone stream.

The initial condition was set using the Badon-Ghyben (1889) e Herzberg (1901) laws to place the initial interface between fresh and salt water so that to ensure the model results after 10 years of simulation.

The interface appears located along the coastline without showing clear signs of intrusive phenomena taking place in the middle and southern part of the coastal aquifer, while a retreat of the fresh water is clear in the northern part of it up to 1.2 km inland, in the area between Fiora river and Arrone stream and then confirming what emerged from the study for the establishment of coastal environmental state "(Chiocchini et al., 2005).

Even with several uncertainties on number of existing wells, since it's not mandatory to declare a private well, on pumping amounts and periods the model results point out a supposed critical area with a particular vulnerability to saltwater intrusion phenomena.

Other smallest areas in southern part of the coastal aquifer seem to be interested by saltwater intrusion phenomena falling in Tarquinia municipality.

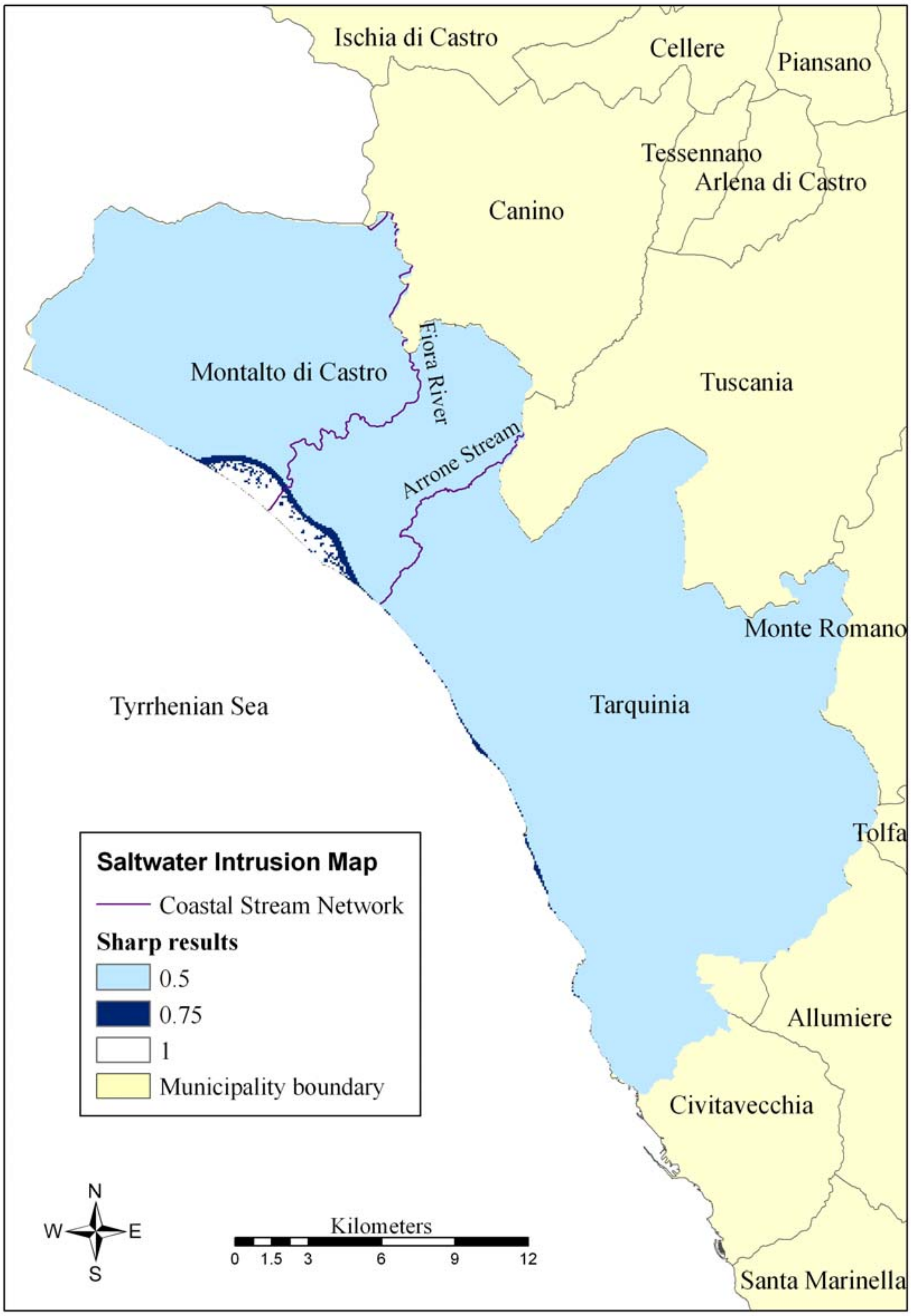

Fig.n° 6.14 Saltwater intrusion map from SHARP_sar model simulations.

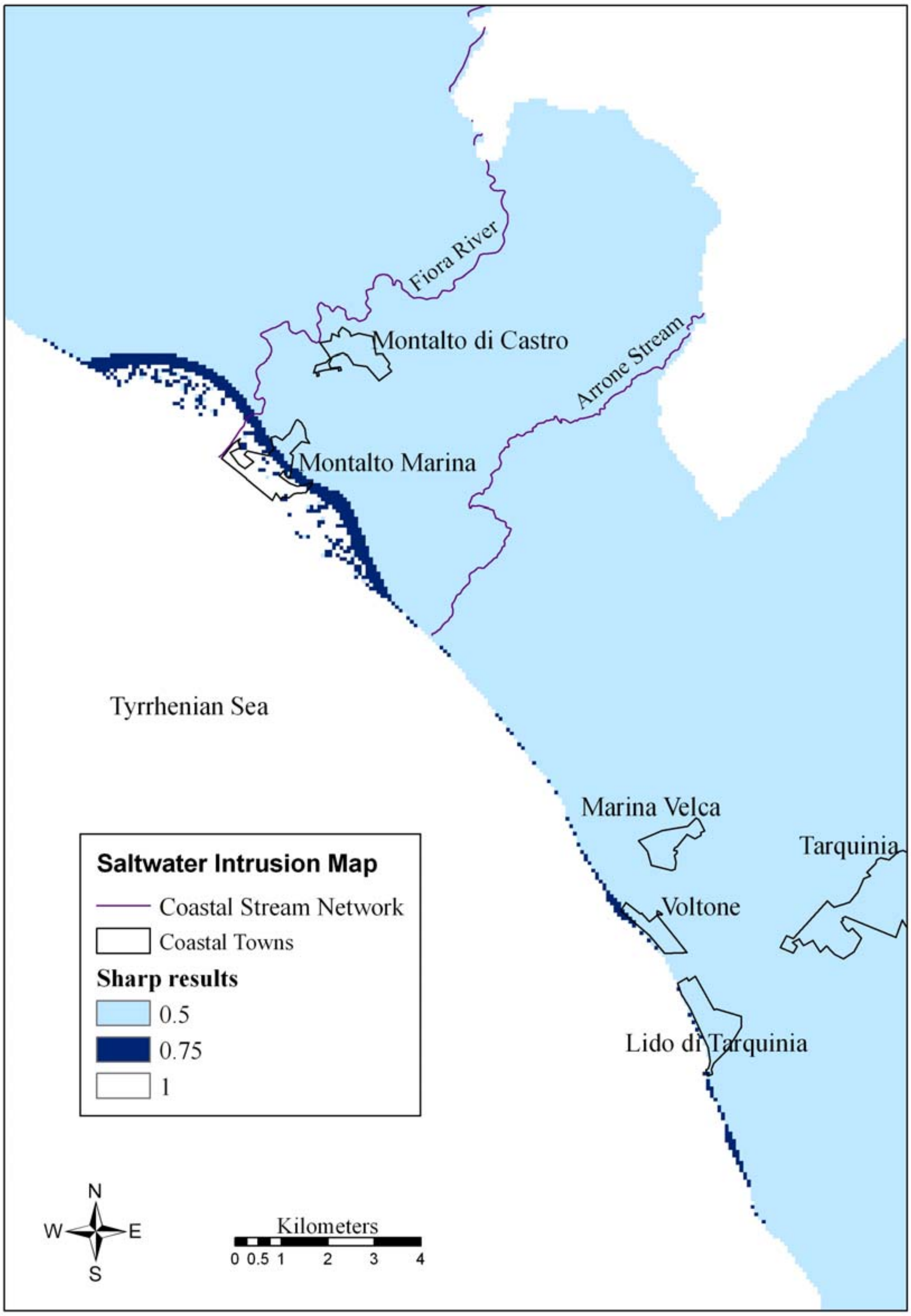

Fig. 6.12 A zoomed map for saltwater intrusion results by SHARP_sar simulations where 0.5 values represent freshwater domain, cell values equal to 1 indicates saltwater domain and 0.75 values stand for sharp interface position.

CHAPTER 7

CONCLUSIONS AND DISCUSSION

Hydrology and water resources are becoming a growing issue in the public debate and according to UNESCO (Andras Szöllösi-Nagy, personal communication) and WMO (Obasi, 1999) water will be a main issue in this century and in this context the conflicts between countries sharing river basins or aquifers have the potential to start new wars in the next future. Growing populations, pollution phenomena, possible future climate change and a generally increasing requirement of water from several sectors are among the challenges for the future water resources management. Integrated approaches are needed bringing together all disciplines and sectors involved. Distributed hydrological models are one of the tools which can be used in this regard and all the information and results from the model can be integrated into some sort of a decision support system. The present work is an attempt to improve the performance of distributed hydrological models in setting-up a planning and management tool for natural resources preservation and should be seen in the above context.

Within the MEDDMAN Project activities, a SWAT model, a physically based model, has been implemented on Marta river basin in the northern part of Latium region for the hydrologic and nutrients transport behavior investigation. All the gathered data, required as input, concerned meteo-climatic variables, soil classes, chemical and physical characteristics, land use, agricultural practices and fertilizer application, water uses, nutrients loads point and non point sources, deviations for hydroelectric power generation, wastewater treatment plant position. These data have been elaborated in a GIS environment in order to create a interactive platform containing useful information describing the Marta watershed capability, vulnerability and risks.

The hydrologic model shows a substantial reliability and accuracy in providing the watershed response in terms of discharge flowing and timing pointing out a rapid rebound on it as a consequence of heavy rainfall events. Statistical tests confirmed the truthfulness of its results.

A good correspondence between observed and simulated values can be obtained also regarding nutrients movement and processes even if the available data were not so complete and comparable in terms of nitrogen and phosphorous, and their compounds, concentrations.

Surely, the nitrate concentrations found in the monitoring campaigns carried out by the Regional Agency for Environmental Protection (ARPA Lazio) are quite well represented by model results.

Such a hydrological and nutrient transport simulation model, can be certainly a powerful and reliable tool for water and natural resources planning in order to achieve a rational and prudent management of them taking into account anthropic needs (water demand, agricultural activities, wastewater treatment plants, hydroelectric power production and so on) but also ecosystems preservation (ichthyic life requirements, river Minimum Flow Requirement, biological communities and so on) and economic aspects allowing to evaluate and compare benefits, disadvantages and consequences for each suggested or hypothesized technical solution on watershed.

For the particular characteristics and past of Marta basin, the implemented SWAT model can provides an overview of its multifaceted response to climatic and human pressures and also an estimation of the future available water resources quantity and quality.

Coupling a SWAT model for hydrologic and nutrients transport simulation and investigation with a saltwater interface simulation model, such as SHARP_sar, for the coastal area of this basin, give the opportunity to take into account the several and different aspects and issues connected with the whole watershed behavior and evolution. A correct planning and management of the available natural resources involve a conscientious water bodies exploitation, with respect to habitats and local animal and plants requirements, avoiding saltwater intrusion phenomena and environmental damage, accomplishing people needs, economic, agricultural and tourist development and income, but, above all, ensuring citizens and buildings safety.

In the local and actual context, regarding past and present events in the study area, an incisive and suddenly action from government is hoped in order to restore equilibrium conditions and environmental health for watershed.

All over the world methods and solutions are continuously suggested, implemented and improved to face these important and necessary issues recurring to hydrological and transport simulation models at catchment scale but also publishing on web interactive modules with the goal to introduce a flexible framework for watershed planning and point out driving factors helping make planning successful and efficient. For example, The Environmental Protection Agency of United States, EPA, created a web site (http://www.epa.gov/watertrain/planning/) on which the user begins taking a look at what's needed for developing a successful watershed plan, with particular regard to kind of stakeholders, citizen groups, local agencies and states to involve in working together on plans for community and environmental improvements. Then all the steps needed to produce a powerful plan are laid out meeting the natural resources requirements, social and economical aspects.

EPA also provided the Know Your Watershed guidance documents developed by the Conservation Technology Information Center (CTIC), with rewrites and additions tailored for broader audiences.

As EPA studies and investigations showed that the degree of success achieved in watershed planning often depends on having people that can devote substantial time to the effort. A wider interest and awareness on water and natural resources management and preservation could help in finding sustainable and safe ways to manage and plan.

An effort in this direction has been begun for Marta watershed with the help of Parrhesia-Stamnos group lead by Aquilio Todini, pursuing the aim of dissemination about local environmental and social issues and methods to achieve a management plan satisfying territorial needs and requirements (www.tutor/fiumemarta.it). Going on in making information and investigation results available to all the stakeholders and people involved, directly or indirectly, in Marta river basin management, could allow an increase in awareness and consciousness and lead to quickening planning actions and works in a shared and advantageous way for all. Especially with regards to Minimum Flow Requirement, in relation with the water amount deviated for hydroelectric power generation, a rational regulation of the sluice-gates located on Marta river at the exit of lake Bolsena, is needed to ensure ichthyic life and ecosystem preservation together with simple turbines volumes required to correctly working.

A multifaceted and integrated approach could certainly be applied in such a complex problem-solving, with the help of hydrologic and nutrients transport simulation models, saltwater intrusion position and movement simulation models and building all the data and results in a GIS platform as to provide a real and concrete Decision System Support.

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Corso di Dottorato di Ricerca in "Scienze e Tecnologie per la Gestione Forestale e Ambientale"
XXI Ciclo
Coordinatore: Prof. Gianluca Piovesan
Tutor: Prof. Antonio Leone

Tesi di Dottorato dal titolo: "Hydrological models for watershed planning and water resources management: a Decision System Support for Marta River Basin (Central Italy)"

Dottorando: Federica Gobattoni

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