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Application of SWAT modelling for assessment of ecosystem goods and services in the Azov Sea basin

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Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:

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The current research is devoted to application of SWAT modelling for assessment of ecosystem goods and services (EGS) using the Azov Sea Basin as a case study. The Upper Don River sub-catchment has been chosen for this purpose as a vital Azov ecosystem component, providing a high number of EGS in the region, including water supply for the Tsimlyansk reservoir, the largest freshwater body in the Azov Sea basin.

The SWAT model has been developed for the study area and calibrated using historical meteorological and hydrological data. Then four scenarios of potential regional development including land use and climate changes have been formulated and analyzed using spatial analysis techniques. It was concluded that for all scenarios the important hydrological parameters of the Upper Don River will decrease significantly by 2050. As a result the water inflow into the Tsimlyansk reservoir will be reduced by 28-36% threatening provision of EGS in the region. The developed model can be used for the evaluation of alternative water management strategies and the regional development.

Based on the assessment the recommendations for researchers applying SWAT for EGS assessment and the Azov Sea basin decision-makers have been developed. The developed model and created datasets can be used as a foundation for basin-wide decision-support tool in water management and an incentive for the regional transboundary cross-sectoral cooperation.

The study contributes to the European FP7 Project EnviroGRIDS "Building Capacity for a Black Sea Catchment Observation and Assessment System supporting Sustainable Development" by providing additional case study for data collection, analysis and framework testing.

Keywords: SWAT, environmental modelling, GIS,ecosystem goods and services, Azov Sea, Don River, Tsimlyansk reservoir, water supply, Geographic Information Systems, spatial analysis, ArcGIS

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List of Abbreviations

ANN – Artificial neural network

BSC – Black Sea Catchment

CBD – Convention on Biological Diversity

DEM – Digital Elevation Model

DWSM – Dynamic Watershed Simulation Model

ECA - European Climate Assessment

EGS – Ecosystem goods and services

EPA – Environmental Protection Agency

ET – Evapotranspiration

GEOSS – Global Earth Observation System of Systems

GIS – Global Information System

GSM – Global Climate Models

HRU – Hydrological response unit

HSPF – Hydrologic Simulation Program Fortran

IKI RAN – Institut Kosmicheskih Issledovaniy (Space Research Institute) Rossiyskoy Akademii Nauk (Russian Academy of Science)

IMAGE – Integrated Model to Assess the Global Environment

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC – Intergovernmental Panel on Climate Change

LARS-WG – Long Ashton Research Station Weather Generator

L-THIA – Long-Term Hydrologic Impact Assessment

MEA – Millennium Ecosystem Assessment

MES – Markets for Ecosystem Services

MODIS – Moderate Resolution Imaging Spectroradiometer

NUTS – Nomenclature of Territorial Units for Statistics

PES – Payment for Ecosystem Services

PET – Potential evapotranspiration

RSMNR – Russian State Ministry of Natural Resources

SMIS – Space Monitoring Information Support laboratory

SHETRAN – Syste`me Hydrologique Europe´en TRANsport

SRTM – Shuttle Radar Topography Mission

STEPL – Spreadsheet Tool for Estimating Pollutant Load

SWAT – Soil Water Assessment Tool

UNECE – United Nations Economic Commission for Europe

UNEP – United Nations Environment Programme

WTA – Willingness to Accept

1. INTRODUCTION

The interest in the concept of *ecosystem goods and services* (EGS) is rapidly growing in different sectors of science, management and economy. Water related EGS such as flood control, provision of hydropower, navigation, water supply, have received wide acknowledgement in scientific and practical applications.

Numerous frameworks on measuring EGS have been elaborated during the last decade creating linkages between nature conservation and human well-being, rationalizing conservation and better nature management approaches through the economic and non-economic valuation of ecosystem services (Tallis *et al.* 2008). Upon recognition of the significance of ecosystem goods and services and rapid development of information and communication technologies allowing extensive data collection and processing the need for tools and models that could gather and process data for decision makers has grown tremendously (Vigerstol and Aukema 2011).

1.1. Background

The assessment of the currently available ecosystem goods and services and their future availability is being incorporated as a vital component into policy-making process in last decades.

In 2000 the ecosystem approach as "a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way" (UNEP-CBD 2000) was adopted by the Convention on Biological Diversity.

The Millennium Ecosystem Assessment (MEA 2003) emphasized dependence of human well-being on the ecosystem services with underlying ecosystem processes and functions and became a starting point for different initiatives such as the Stern Review on the Economics of Climate Change Stern 2006 and the project on Economics of Ecosystems and Biodiversity (TEEB 2012).

The establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in 2012 is a recent milestone and highlighted the increasing importance of the ecosystem management approach in managing biodiversity and other natural resources.

One of the main functions that have been assigned to IPBES is performing assessments of knowledge on ecosystem services and their interlinkages and generating knowledge for decision-makers. Simultaneously, the need for application of assessment tools in order to build the knowledge on EGS and deliver this knowledge to decision-makers.

Estimating the present or future supply of EGS requires good quality and adequate data and the analysis of data using various assessment and modelling methods and tools. Different integrated environmental models are available to analyze data, required for the EGS estimates and the development of future EGS projections. Key components of an integrated modelling framework include: finding, processing, and standardizing data from different sources; infrastructure to sequentially execute linked models (that may be written in different programming languages) and to facilitate data exchange between them; uncertainty and sensitivity analysis capabilities; and tools to analyze, summarize, and visualize model outputs (Johnston et al. 2011). Many of the models are able to represent and analyze spatial data related to EGS.

The Soil Water Assessment Tool (SWAT) is one of such integrated modelling frameworks. As SWAT is an integrated model with emphasis on agriculture, the analysis of spatial variations in the quality and quantity of water will provide a good indication of where water may be a critical constraint for specific economic sector in spatially explicit area. This in turn may serve as a basis for studying the impacts of potential changes in land use, agricultural management, and/or the impacts of various climate change scenarios.

Shared by Ukraine and Russian Federation the Azov Basin is unique and important ecosystem providing the densely populated areas with numerous goods and services. However, due to unsustainable management decisions the capacity of the Azov ecosystem to maintain the same level of these goods and services provision has decreased significantly. The problem is exacerbated by the lack of regional cooperation and negligence of the existing threats to the Azov ecosystem. In order to develop the long-term regional strategy on EGS security and sustainable development it is necessary to make an assessment of the water resources availability based on the potential changes in demography, land use and climate condition in the next decades.

1.2. Aim and objectives

The aim of this research is to analyze the potential and limitations of the SWAT modelling in assessment of water-related ecosystem goods and services based on the case study of the Azov Sea Basin.

Through developing the SWAT model and model-based analysis of regional development scenarios the following research question will be answered: *How ecosystem goods and services provided by the Azov Sea Basin will change under different scenarios on land use and climate change?*

The research question will be tackled through the attaining the following objectives:

- Analysis of the Azov ecosystem goods and services in order to define the scope and the study area;
- Development of the SWAT model for the chosen sub-catchment and model calibration based on historical meteorological and hydrological data;
- Formulation of the development scenarios and their analysis using the developed SWAT model;
- Performing EGS assessment and recommendations development for the EGS assessment in the selected Azov region and using the SWAT models during this process

This research will contribute to the project “Building Capacity for a Black Sea Catchment Observation and Assessment System supporting Sustainable Development” (http://www.envirogrids.net).

1.3. Structure of the thesis

The thesis consists of 8 chapters. The first introduction chapter provides the background information on ecosystem goods and services and their assessment tools, presents aims and objectives of the research. The second chapter describes the concept of ecosystem goods and services, providing specific information on water-related EGS and watershed-based approach on defining ecosystem boundaries. Then different frameworks on performing EGS assessment and the role of ecohydrological modelling tools, such as SWAT, are described. The third chapter presents methodology of the conducted research with description of main phases and steps and methods applied. The fourth chapter is dedicated to the Azov Basin Ecosystem with description of main hydrological and economic characteristics of the Basin and water-related activities in the region. The fifth chapter defines the study area and provides analysis of hydrology, climate and land use patterns in the selected sub-catchment. The sixth chapter provides step-by-step description of the model development and application in the selected sub-catchment. The seventh chapter presents scenarios on land use and climate change formulated and tested with SWAT for performing assessment on hydrological processes in the area and provides the EGS assessment based on formulated scenarios. The final, eighth, chapter presents discussion of the research findings, provides recommendation for further assessment of EGS in the area and for improvements of the SWAT model performance. Finally, conclusions of the research are summarized.

2. ECOSYSTEM GOODS AND SERVICES AND HYDROLOGICAL MODELLING

The purpose of this chapter is to review existing literature on the ecosystem goods and services (EGS) concept analyzing the application of environmental modelling in the EGS assessment.

The first section discusses the concept of ecosystem goods and services, more specifically water-related EGS, and different approaches used by different authors and researchers. It also includes review of existing EGS assessment frameworks, based on different metrics.

The second section aims to examine the role of environmental modelling in investigating ecosystem dynamics. It focuses on utilization of the different ecohydrological modelling tools, specifically SWAT model, in the assessment of ecosystem goods and services. Finally it provides an example of application of SWAT modelling tool in the Black Sea Catchment in the framework of EnviroGRIDS project.

2.1. Ecosystem goods and services

The term ecosystem introduced by Tansley in 1935 has found wide theoretical and practical application in different studies and management practices. Starting from the recognition of the set of functions within consideration of the usefulness of these functions for humans (Hector *et al.* 2007) the concept of ecosystem goods and services in 1990s it became a theoretical and practical framework, connecting human well-being with natural ecosystem dynamics (Daily 1997; de Groot *et al.* 2002). Comprehensive overview of the history of EGS concept development is given by Gómez-Baggethun *et al.* 2010 (Gómez-Baggethun *et al.* 2010).

The theoretical framework on ecosystem goods and services originates from the utilitarian approach in valuation of ecosystem functions as services aimed to increase significance of biodiversity conservation (De Groot 1987; Ehrlich and Ehrlich 1981; Westman 1977). After mainstreaming the concept in the literature in 1990s different authors attempted to address the issue on methods of implementation of economic metrics in the EGS assessment (Bockstael *et al.* 2000; Costanza *et al.* 1997). It brought the EGS concept into the policy-making process and economic decision-making through different market-based tools, such as Payments for Ecosystem Services schemes (Engel *et al.* 2008; Immerzeel *et al.* 2008; Quintero *et al.* 2009; Wunder 2005) or Markets for Ecosystem Services (Bayon 2004). Comprehensive overview of the history of EGS concept development is given by Gómez-Baggethun *et al.* 2010 (Gómez-Baggethun *et al.* 2010).

Some examples of existing framework on the EGS assessment will be discussed in the last section of this chapter. Meanwhile, it is necessary to define what are ecosystem goods and services and what water-related EGS can be provided by natural ecosystems. That is important in order to perform EGS assessment. In the next section the choice of definition interpreting ecosystem goods and services in general will be presented.

2.1.1. What are ecosystem goods and services?

Daily (Daily 1997) determines ecosystem services as “the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. They maintain biodiversity and the production of ecosystem goods, such as seafood, forage, timber, biomass fuel, natural fibre, and many pharmaceuticals, industrial products and their precursors.”

Another broadly used definition determine ecosystem goods and services as the benefits human derived directly or indirectly from ecosystem functions (Costanza *et al.* 1997).

The Millennium Ecosystem Assessment (MEA 2003) defined EGS as "benefits people obtain from ecosystems. These include provisioning, regulating, and cultural services that directly affect people and the supporting services needed to maintain other services".

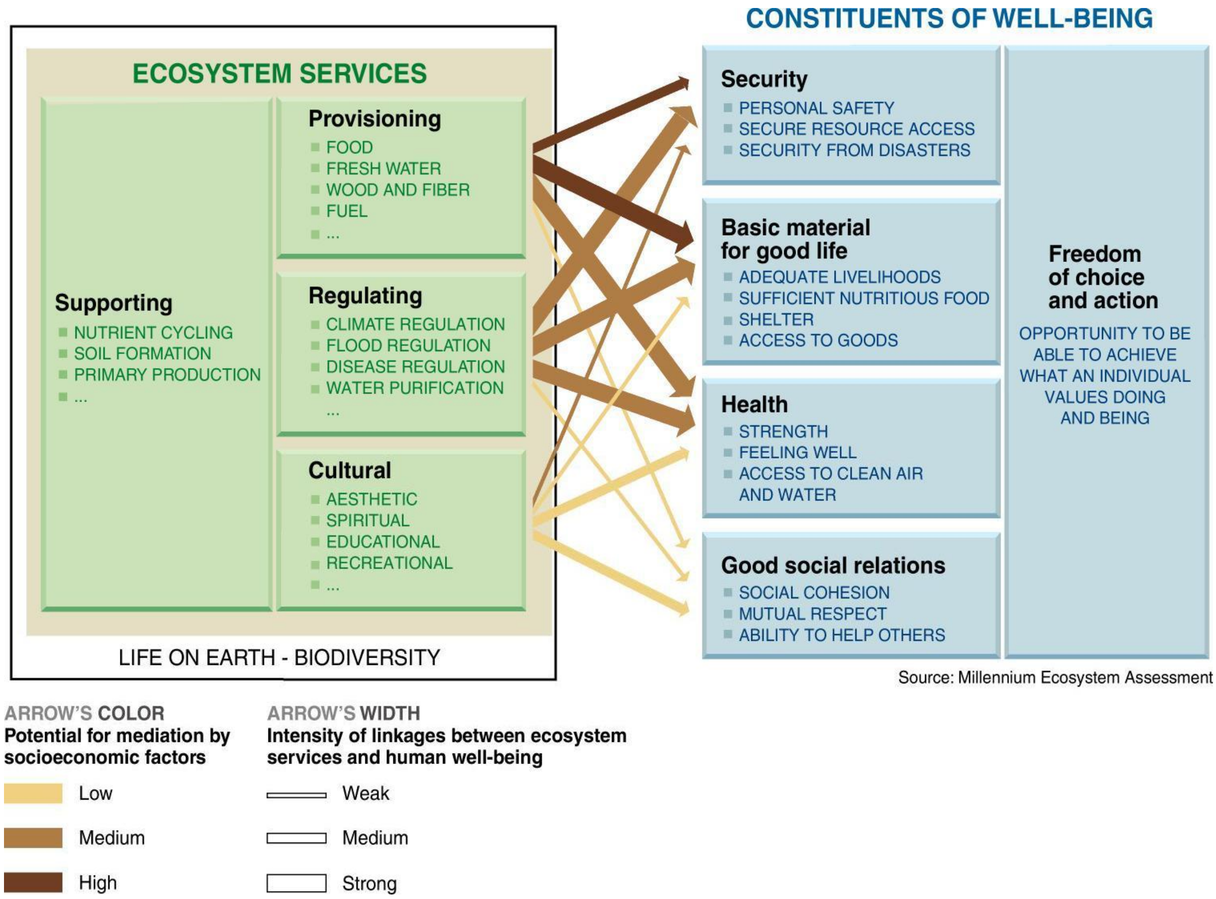

Fig. 1. Linkages between Ecosystem Services and Human Well-being (MEA 2005)

The last definition is widely used in environmental management, integrating ecological processes and the management of natural ecosystems and their services properly (Maes *et al.* 2009).

Many authors attempted to develop classification of the ecosystem goods and services, applying different level of complexity and integrity (Costanza *et al.* 1997; de Groot *et al.* 2002; Fisher and Kerry Turner 2008; Wallace 2007). Mainly all existing classifications aimed to connect ecosystem functions with their associated goods and services. Therefore many assessment frameworks are based on consideration of EGS through the assessment of ecosystem functions.

This thesis also uses the framework developed by the Millennium Ecosystem Assessment. However, the water-related EGS should be defined explicitly, which will be discussed in the next section.

2.1.2. Water related ecosystem goods and services

Many different types of ecosystem goods and services are related to water. Though all ecosystem services are interconnected and valuable, water services and attributes are often considered separately, mostly due to defining watersheds boundaries as ecosystem scale proxy (Post *et al.* 2007; Puth and Wilson 2001; Wiens 2002).

Mostly such ecosystem goods and services like the provision of drinking water, water for irrigated agriculture, hydropower, fishery stocks, flood control and recreation services are directly utilized by people. Such hydrological attributes of quality, quantity, timing and location, determined by ecosystem processes, are in the basis of these EGS (Brauman *et al.* 2007). Therefore in order to provide estimations of EGS it is important to use these attributes while defining hydrological ecosystem services.

Brauman (Brauman *et al.* 2007) defines 5 broad categories of hydrological ecosystem services: improvement of extractive water supply, improvement of in-stream water supply, water damage mitigation, provision of water-related cultural services, and water-associated supporting services (Fig. 2).

Water supply serves as a provisioning service, indicating change of water available within the ecosystem boundaries for extraction and in situ purposes. Extractive water is used for different sectors like industry, municipality and thermal energy, whereas in situ water is used for hydropower, recreation, transportation and fish production. Regulating service on water damage mitigation includes reduce of flood damage, sedimentation processes in water reservoirs, salinization of dryland and intrusion of saltwater into groundwater. There is also substantial number of different water-related supporting services, like creating habitats and supply of water for plant growth, and, finally, cultural hydrological services related to aesthetic valuation of watershed, cultural and religious uses and recreation. All these services have attributes of quantity, quality, location, and timing of flow (Brauman *et al.* 2007).

Vigestrol and Aukema (Vigerstol and Aukema 2011) also defined supporting services that are important hydrological components of the attributes and processes for hydrological EGS: water retention, water yield, natural water filtration and sediment regulation (Vigerstol and Aukema 2011).

Water retention is an important hydrological component, determining water quantity, functioning as a reservoir of water that can be released over time and providing a buffer for water supply shortages, as well as for flooding. Water retention in upper basin ensures water supply in dry season, meanwhile during the flood peaks it can reduce damages. Moreover, water retention facilitates the process of replenishment of groundwater, which is important for watercourses, originated from groundwater.

Water yield is significant indicator of water quantity as well, showing the availability of water for direct consumption, such as for drinking purposes and irrigation. It is also used to indicate in situ water supply, which is important for hydropower and water supply. Land use change is an important factor that can change water yield and determine hydrological state of the ecosystem, for example, increase in water yield due to change of landscape management can reduce the quantity of groundwater. Runoff changes over the seasons also affect the water yield (Vigerstol and Aukema 2011).

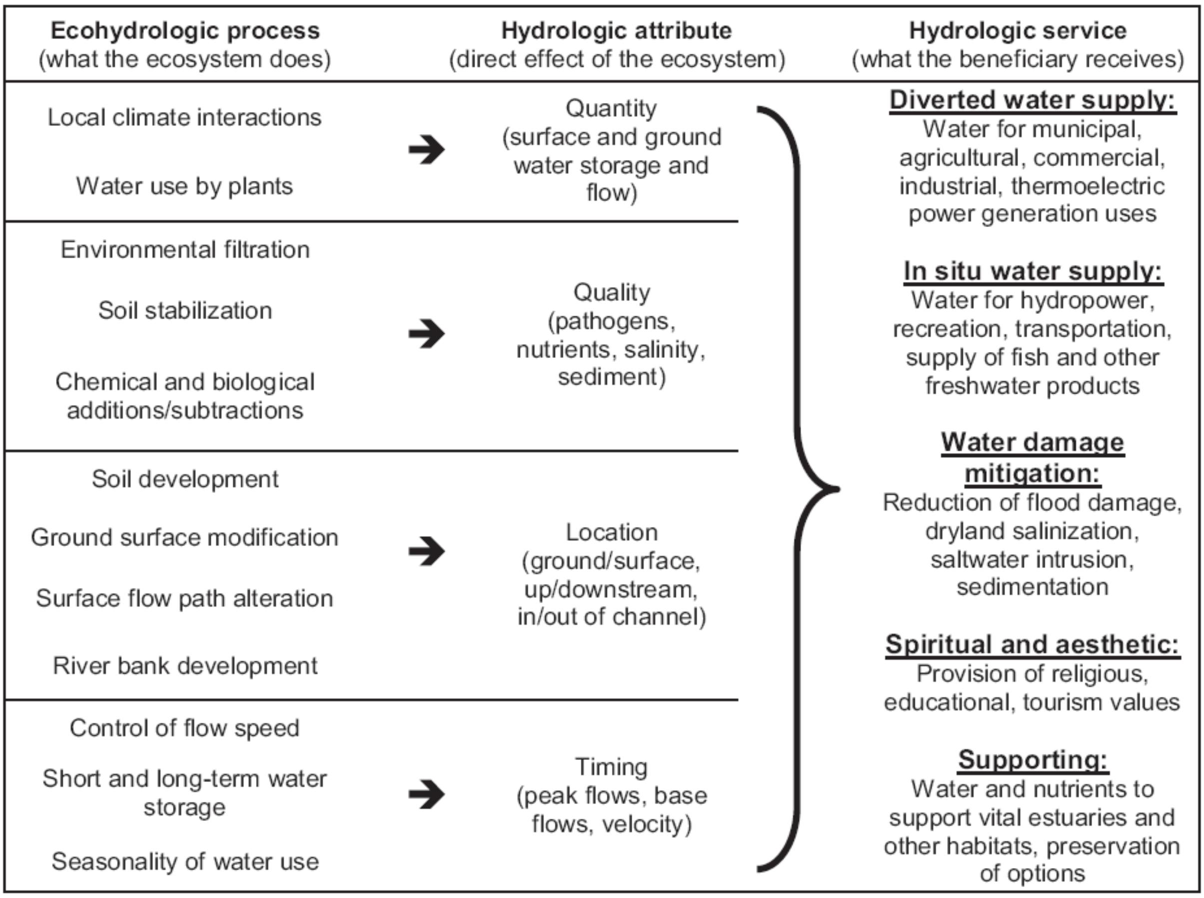

Fig. 2. Relationship of hydrologic ecosystem processes to hydrologic services (Brauman et al. 2007)

Another important attribute determining the quality of water is *natural water filtration,* which is important attribute for such services like water supply, recreation, fisheries and other services. Living organisms may provide natural ecosystems with the filtration, which is important for decreasing level of contamination from agriculture and transport in streams prior reaching the water reservoirs (Vigerstol and Aukema 2011).

Sediment regulation is another important factor in terms of water quality maintenance. It indicates both natural movement of sediments and additional sediment load, caused by soil erosions and inappropriate landscape management. It could determine, for example, durability of hydropower-related equipment, quality of water supply, suitability of habitats, etc. (Vigerstol and Aukema 2011).

All these attributes are important to be considered while valuating hydrological ecosystem goods and services, and therefore should be included in the EGS assessment frameworks. Examples of such frameworks and their main components will be described in the next section.

2.1.3. Existing frameworks for performing EGS assessment

The ecosystem services framework, which includes hydrological goods and services as only one type of EGS, comprises number of methods to perform assessment of the trade-offs of ecosystem change for different beneficiaries at spatial and temporal scales (Brauman *et al.* 2007).

Many authors attempted to develop methods of valuation based on specific ecosystems through the case studies analysis (Dixon and Hufschmidt 1986; Pearce and Turner 1990; Wasike *et al.* 1995). The development of common metric monetary valuation is commonly used as unified proxy for decision-making on a global scale (Kremen 2002).

Based on the frameworks, developed earlier by different researchers (Pearce and Turner 1990;Costanza *et al.* 1997; de Groot *et al.* 2002 and MEA 2003) Hein (Hein *et al.* 2006) proposed the integrated framework for the valuation of ecosystem services, that includes three types of services and four types of value (Fig.3)

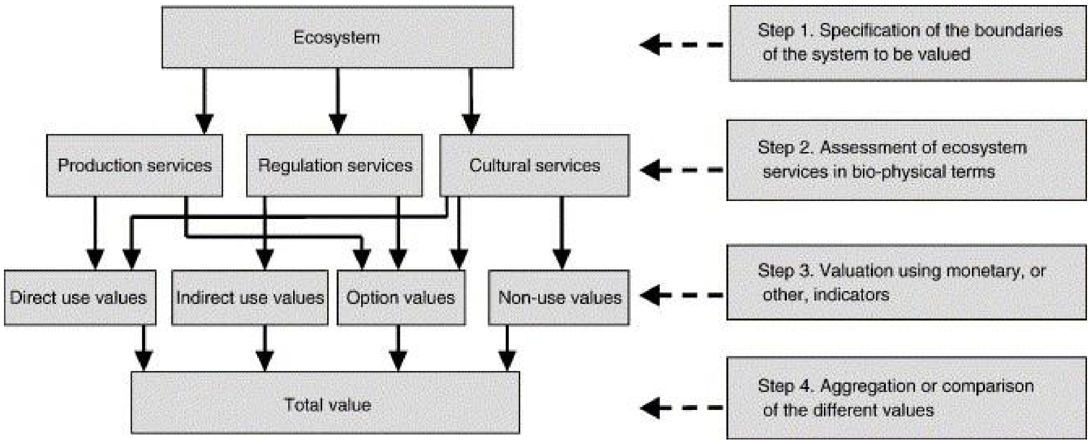

Fig. 3. The ecosystem valuation framework (Hein et al. 2006).

The framework includes important steps of the assessment of ecosystem goods and services. The first two steps (specification of ecosystem boundaries and assessment in biophysical terms) are going to be used in order to perform baseline assessment of EGS in the Azov Sea Basin. Next steps can be applied further to valuate determined ecosystem goods and services using appropriate metrics and aggregate results for final assessment. In order to understand how this framework can be applied, it is important to elaborate more on every step.

Definition of the ecosystem boundaries

Many researchers emphasized the importance of the question of the ecosystem boundaries (Gilmanov 1992; Likens 1992; Post *et al.* 2007) and definition of the spatial scale of the EGS assessment (Hein *et al.* 2006; MEA 2003; Syrbe and Walz 2012; Tacconi 2000).

This is a significant step for valuation of EGS, as it can determine stakeholders that are supplied by EGS and could benefit from it (Vermeulen and Koziell 2002).

Assessment of the ecosystem services in biophysical terms

The issue of double counting of the ecosystem goods and services can be avoided through the definition and classification of the provided services (de Groot *et al.* 2002; MEA 2003). The supply of EGS may vary both in temporal and spatial scales so both actual and potential future supplies should be taken into account for further valuation of EGS (Drepper and Mansson 1993). As it was mentioned in the first section of this chapter, different classifications have been developed. This thesis will apply the classification that has been developed by defined by Brauman, connecting ecosystem goods and services to the related function (Brauman *et al.* 2007). As the research is mainly focused on the water supply, it will also include different supporting services, such as water yield, as it was proposed by Vigerstol and Aukema 2011). In this way hydrological ecosystem goods and services the assessment of the ecosystem services are represented appropriately in biophysical terms, which is prerequisite step for further application of valuation metrics

Valuation of the ecosystem services based on economic and other metrics.

The valuation of the ecosystem goods and services is mainly determined by stakeholders benefiting from these services. Hein (Hein *et al.* 2006) defined stakeholder as "any group or individual who can affect or is affected by the ecosystem's services".

According to de Groot (de Groot *et al.* 2002), there are 3 main types of valuation that can be applied to ecosystem goods and services valuation: socio-cultural, economic and ecological value.

Socio-cultural value, that in some sources also considered as part of non-use values (Hein *et al.* 2006), is based on the perception of the importance of natural ecosystems in terms of health, education, culture, religion, etc. (Norton 1987). This type of value associated with such services as education and scientific information, aesthetic, cultural and artistic inspiration, recreation and (eco)tourism, spiritual and historic information, provided by ecosystems (de Groot *et al.* 2002). Though this type of value is difficult to assess, it is important to recognize them in the EGS assessment framework.

Economic value can be defined in many different ways. Even though many authors challenged the adequacy of economic valuation of ecosystems in general (Bockstael *et al.* 2000; Toman 1998) it still remains quite used type of valuation of EGS, addressing the issue of common metrics for decision-makers.

According to de Groot (de Groot *et al.* 2002) 4 types of economic valuation can be differed:

1) Direct market valuation is applied to ecosystem services that can be referred to certain markets. There are 2 main types market mechanisms exist today (Gómez-Baggethun *et al.* 2010):

- Markets for Ecosystem Services (MES) – market mechanisms, commodifying EGS such as atmospheric sink functions of greenhouse gases (through the Emission trading of greenhouse gases (Bayon 2004) , wetlands and other aquatic EGS (wetland mitigation banking (Powicki 1998).

- Payment for Ecosystem Services (PES) – voluntary and conditional transactions over well-defined ecosystem services between at least one supplier and one user (Wunder 2005), that compensate providers of the ecosystem goods and services by beneficiaries.

In this way such EGS like carbon sequestration (Pagiola 2008), habitat conservation and wildlife services (Asquith *et al.* 2008), agro-environmental services (Dobbs and Pretty 2008);

and hydrological functions of watersheds (for example, freshwater flows from upstream areas to downstream users (Kosoy *et al.* 2007) are subject to the establishment of PES.

2) Indirect market valuation is applied in the absence of market for a service rendered by ecosystem. The value can be revealed through the Willingness To Pay (WTP) or Willingness To Accept compensation (WTA) counting different costs:

- Avoided costs that would be associated with the absence of the EGS, such as flood control and cost associated with potential damages.

- Replacement costs, associated with the need for constructing artificial systems to ensure the service that can be rendered by natural system (like wastewater treatment by marshes that can be replaced by wastewater treatment plant)

- Factor income as many EGS can increase profit in the economic activities

- Travel cost associated with the implied value of the service

- Hedonic prices that people will pay for associated goods

3) Contingent valuation based on the development of alternative scenarios associated with EGS and choice of the alternatives by communities. In such a way numerous studies have been made based on the willingness to pay of the local communities revealed through the social surveys (e.g. Gurluk 2006; Tao *et al.* 2012; Tyrvainen 2001; Tyrvainen and Vaananen 1998).

4) Group valuation is based on principle of deliberative democracy, performing valuation based on open public debate (Kenter *et al.* 2011; Wilson and Howarth 2002). In this way

stakeholders can be involved into a representative assessment of the values of different ecosystem services (O'Neill 2001).

Ecological value is based on sustainability of the ecosystem itself that define capacity to provide stakeholders with required EGS. It can be determined by such ecosystem parameters as complexity, diversity, and rarity. The recognition of the underlying biophysical processes of the ecosystem functions is crucial for valuation of the services (Templet 1998). Different types of metrics could be applied for ecological valuation. For example, some studies have been made, estimating ecosystem goods and services based on the energy fluxes (Costanza and Hannon 1989). The results of such estimations however are not necessarily contradictory to the economic valuation (Costanza *et al.* 1997).

Some authors also highlighted incommensurability of the monetary units as a valuation language (Martinez Alier 2002), and importance of application of the integrated valuation frameworks applying multi-criteria based approach (Munda 2004; Koschke *et al.* 2012). Integrated valuation frameworks allow stakeholders assigning weights for different set of indicators (economic and non-economic), connecting different approaches of valuation of the ecosystem goods and services.

The integrated valuation framework based on ecological valuation will be applied for performing assessment of the hydrological EGS in the Azov Basin. Next chapter will cover use of modelling tools in such frameworks and performing EGS assessments.

2.2. Use of environmental modelling in EGS assessment

In order to better investigate whole complexity of the ecosystem dynamics many underlying processes should be explained and substantial number of data should be derived. One of the effective tools for examining processes and factors that affect the dynamics of the ecosystems is ecological modelling (Bravo de la Parra and Poggiale 2005). It could serve for scientific (e.g. Jorgensen 2001; Watzold *et al.* 2006) or decision-making purposes in the environmental management field (Fath *et al.* 2012; Jorgensen 2001; Watzold *et al.* 2006; Willemen *et al.* 2012). There is also growing role the modelling in forecasting of ecosystem dynamics change and environmental impact assessment (e.g. Krysanova *et al.* 2007). Ecological models play an important role in the understanding interactions between society and the environment, including analysis of ecosystem services dynamics (Willemen *et al.* 2012).

In this chapter existing frameworks for ecohydrological modelling will be discussed, and more specifically modelling with SWAT, reviewing existing researched on pros and cons of this tool. Finally one of the examples of use of modelling with SWAT in the framework of EnviroGRIDS project at the Black Sea Catchment will be presented.

2.2.1. Existing frameworks for ecohydrological modelling

Watersheds are often used as a proxy for ecological modelling, evaluating state of the ecosystem with application of ecohydrology (Davenport *et al.* 1996; UNEP 2004). Ecohydrology is an integrative science studying the relationships between hydrological, biogeochemical and ecological processes in soils, rivers and lakes, and at the catchment scale (Krysanova and Arnold 2008).

Ecohydrological models are based on hydrological factors, defining the dynamics of terrestrial ecosystems in response to natural and anthropogenic factors, and affecting hydrological dynamics and water quality (Krysanova and Arnold 2008).

From 1970s ecohydrological models have been developed substantially and became more complex and realistic in terms of representation and solving different ecohydrological problems, taking into account different physical, biological and economic aspects (Hesse *et al.* 2008).

There are many different classifications of ecohydrological models. Krysanova and Arnold (2008) differentiated them based on the approach or scale of application. In this way models can be classified as physically-based, conceptual, or black-box models; lumped and distributed models; and deterministic and stochastic models. Hesse (Hesse *et al.* 2008) defined existing ecohydrological models into 3 main categories based on the goal of model application:

- *conceptual models* as the simplest ones in terms of input data requirements, aimed to demonstrate statistical relations within the complex landscapes with lack of important physical processes (e.g., Biondi *et al.* 2008; Hersperger 2010; Palmeri *et al.* 2005).

- *physically based models* that are based on physicochemical processes with detailed data, requiring substantial number of measurements and computations in order to derive proper results, mainly used for small scale modelling (e.g., Arhonditsis *et al.* 2007; Vanclooster *et al.* 1995). Such models describe ecosystems through the mathematical representations of physical law and should be fully distributed by accounting for spatial variations in all parameters. However, high requirement to data and complicated mathematic description do not necessarily assure high quality of the model and often include empirical and statistical equations, especially to represent non-hydrological processes (Beven 1996).

- *process-oriented models*, based on physicochemical process, applying some simplification to the certain extent with utilization of the empirical approach (e.g., Bouraoui and Grizzetti 2008; Jackson *et al.* 2007; Pisinaras *et al.* 2010; Xu *et al.* 2010). One of the examples of such type of models could be continuous dynamic models, using mathematical representation of physical, biogeochemical and hydrochemical processes. Such models include elements of both a physical and conceptual semi-empirical nature, and utilize a reasonable spatial disaggregation scheme (Krysanova and Arnold 2008).

Many studies proved that these models are capable represent ecohydrological processes at the catchment scale with satisfactory level of adequacy (Arnold *et al.* 1993; Krysanova *et al.* 1998; Steinhardt and Volk 2003;Borah and Bera 2004; Steinhardt and Volk 2003). More information on application of ecohydrological modelling tools in EGS assessment will be provided in the next section.

2.2.2. Application of ecohydrological modelling tools in the ecosystem goods and services assessment.

Several studies have been conducted on the assessment of better techniques for ecosystem goods and services assessment. Variety of such techniques are developed both for terrestrial and aquatic ecosystem assessments specifically to address the issue on the estimation of EGS. Houdet (Houdet *et al.* 2012) defined 3 types of such models:

Tools for raising awareness on EGS (such as Ecosystem Services Benchmark, Ecosystem Services Review, etc). For example Ecosystem Services Benchmark (Grigg *et al.* 2009) has been developed to assist institutional investors to make sensitivity analysis of the investment project based on the impact on biodiversity and ecosystems services. It was developed for businesses within the agricultural supply chain, focusing on a company's impacts and dependence on biodiversity and ecosystem services.

These tools, however, often oriented on the specific beneficiaries and do not provide assessment in biophysical terms, which can omit many important attributed and processes underlying the EGS.

Tools for mapping EGS at the broad landscape level for scenario analysis purposes (e.g. ARIES — Artificial Intelligence for Ecosystem Services, InVEST — Integrated Valuation of Ecosystem Services and Tradeoffs). For example, InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is a family of tools aimed to map and value the goods and services across the landscape (Tallis *et al.* 2011), to provide the information for decision-makers about general patterns and changes in ecosystem services, based on land use changes or climate change impacts. It can also be applied for analyzing tradeoffs between biodiversity conservation and ecosystem services (Nelson *et al.* 2009).

These tools are useful in terms of providing baseline assessments for decision-makers on the national and regional scale, however being simplified significantly for broad application, these tools are often not effective for site-specific and EGS specific assessments.

Tools used for finer-scale assessments at the land asset level (MEASURES — Model Ecosystem Services Credit Calculator; Wildlife Habitat Benefits Estimation Toolkit). For example, the Wildlife Habitat Benefits Estimation Toolkit generates assessment of economic values of different EGS based on findings of numerous studies on benefits associated with wildlife and habitat (Kroeger et al. 2008). MEASURES Ecosystem Services Credit Calculator allows to private forest land owners assess ecosystem services provided by a forest tract such as nutrient and sediment loads prevented, carbon mass preserved, and habitat and biodiversity protected (CWS 2010).

These tools, however, are not effective for site-specific assessments as they often utilize worldwide aggregated data.

Ecohydrological models themselves may serve for providing assessment of specific hydrological services, quantifying and visualizing water-related EGS. In this case it is important to consider the purpose of modelling, potential and limitations of the tool, spatial and temporal scale of analysis, data requirements and access to it (Vigerstol and Aukema 2011). The advantage of ecohyrological models use, even though they require substantial expertise and data, is that it actually allow understanding and estimating many underlying processes, supporting the ecosystem. Thus, such models provide with objective information on ecological values of the ecosystem, which can be further applied in variety economic and non-economic assessment frameworks and involve different stakeholders. Some ecohydrological modelling tools found quite broad application. For example, Dynamic Watershed Simulation Model (DWSM) allows simulating water runoff, flood dynamics, transport of sediment, nutrients, and pesticides in watersheds (Borah and Bera 2004). Another Syste`me Hydrologique Europe´en TRANsport (SHETRAN) (Ewen *et al.* 2000) - 3D model, providing with detailed information on the flow and transport in the basin, that can be visualized using graphical animation, agricultural Non-Point Source Pollution Model (AnnAGNPS) (Bingner and Theurer 2009), artificial neural network (ANN) which can be applied in various ways to estimate water runoff and sediments load in watersheds (Luk *et al.* 2001; Smith and Eli 1995; Tokar and Johnson 1999).

The development of the integrated hydro-economic assessment frameworks for EGS assessment in last decade encouraged further application of ecohydrological modelling tools in order to increase quality of input-output data within such frameworks (Brouwer and Hofkes 2008; Cai 2008; Johnston *et al.* 2011). For example, U.S. EPA program developed Better

Assessment Science Integrating point & Non-point Sources (BASIN) Package (EPA 2009) – multipurpose environmental analysis system designed for use by regional, state, and local agencies in performing watershed and water quality-based studies. It integrates different tools for processing and visualization of data, integrating different powerful ecohydrological modelling tools, such as Hydrologic Simulation Program Fortran model (HSPF), simulating hydrology and water quality for both conventional and toxic organic pollutants (Donigian 1984); Spreadsheet Tool for Estimating Pollutant Load (STEPL) (EPA 2006) calculating nutrient and sediment loads from different land uses and effects of changing management practices; Long-Term Hydrologic Impact Assessment (L-THIA), which allows estimating changes in water quantity and quality online (Harbor and Grove 1997), an ArcView GIS Tool to Calculate Nonpoint Sources of Pollution in Watershed and Stormwater Projects (PLOAD) (EPA 2001).

Johnston (Johnston *et al.* 2011) defined the following key components of the integrated modelling frameworks: tools for data retrieval and processing; infrastructure to execute linked models and to facilitate data sharing between them; tools for uncertainty and sensitivity analysis; and, finally, tools to analyze, summarize, and visualize model outputs (Fig. 4). Ecohydrological modelling tools play important role in holistic investigation of the ecosystems services and goods and their inherent attributes that determine functioning of the whole system.

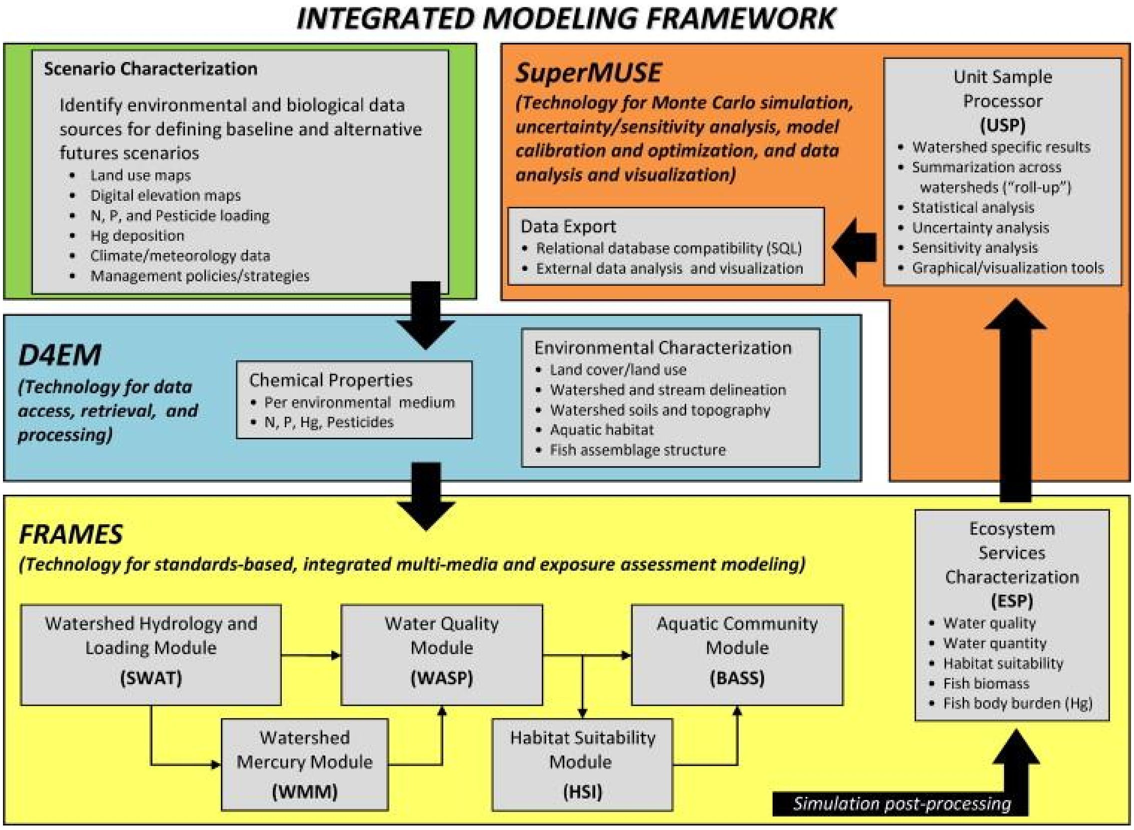

Fig. 4. Conceptual diagram of the integrated modelling framework for hydrological EGS assessment. (Johnston *et al.* 2011)

The Soil Water Assessment Tool (SWAT) may serve as one of the part of such integrated system, providing the basement assessment of hydrological ecosystem goods and services. In this framework it may serve as a tool for data collection and processing, as well as a tool for uncertainty and sensitivity analysis. Brief description of the SWAT modelling tool will be presented in next section.

2.2.3. Soil and Water Assessment Tool (SWAT)

SWAT has been developed by the U.S. Department of Agriculture, Agricultural Research Service (Arnold and Fohrer 2005; Gassman *et al.* 2007). There numerous studies have been conducted applying SWAT for different purposes. Gassman (Gassman *et al.* 2007) has made the comprehensive overview of the tool application.

SWAT is "a basin-scale, continuous-time model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds" (Gassman et al. 2007). Main components of SWAT are hydrology of the watershed, weather parameters, soil properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management.

SWAT modelling tool can be classified as physically based model, though some authors refer to process oriented model (e.g. Bouraoui and Grizzetti 2008; Jackson *et al.* 2007). Simulation in the model is processed for multiple subbasins or sub-catchments, represented by hydrologic response units (HRUs). In order to designate these units, the input data on land use, management, and soil characteristics should be included. Subbasins or sub-watersheds have geographic position in the watershed and spatially related to each other, while the HRU is not identified spatially, it only represents the percentage of the sub-watershed area (Gassman *et al.* 2007).

Nevertheless, linkage of HRUs to the sub-watersheds with specific streamflow and sediment yields allows spatial identification of hydrological services, such as retention of sediments and production of water (Haverkamp *et al.* 2005).

The overall hydrograph continuously simulates daily water budget in each HRU, and includes canopy interception of precipitation, partitioning of precipitation, snowmelt water, and irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers (Gassman *et al.* 2007):

$\Delta SW = P - Q - ET - DP - QR$,

where

ΔSW - daily change in soil water content

P - precipitation

Q - surface runoff

E_T – evapotranspiration

D_P - vertical percolation,

Q_R - return flow to the stream channel.

There is also capacity to simulate crop yields and biomass output with the crop growth submodel. SWAT is capable to simulate planting, harvesting, nutrients and pesticide applications for each cropping system with specific dates or with a heat unit scheduling approach. Sediment, nitrogen, phosphorus, pesticides, and bacteria can be estimated on HRU-level and for in-stream losses. Sediment yield is calculated with the Modified Universal Soil Loss Equation (MUSLE) developed by Williams and Berndt (Williams and Berndt 1977). All these attributes of the SWAT modelling tool allow using it for baseline assessments of hydrological ecosystem goods and services.

In general SWAT is being used for performing wide range of hydrological assessments and pollutant loss studies. Different researchers analyzed different types of hydrological models, and examined limitations and potential improvements of such tools, including SWAT. Some advantages and limitations of SWAT mentioned in literature in comparison with other modelling tools are presented in the Table 1.

Table 1. Advantages and limitations of ecohydrological modelling in SWAT in comparison with other modelling tools

Advantages	**Limitations**	**Compared tools/ Reference**
SWAT is a more suitable for continuous simulations in predominantly agricultural watersheds for predictions of flow volumes, sediment, and nutrient loads on annual and monthly basis (except for months having extreme storm events and hydrologic conditions).	SWAT is not really suitable for daily simulations of extreme flow events. DWSM is more preferable in this case	SWAT DWSM HSPF (Borah and Bera 2003, 2004)
SWAT gives better results on the validation watersheds. Results of this study showed that SWAT performed better in simulation for agricultural watersheds under various climatic conditions, so it's better for examining long-term impacts of climate variability on surface-water resources	SWAT was limited in calibration process, while HSPF performed better	SWAT HSPF (Van Liew 2003)
SWAT is better representing point-source pollution and therefore more suitable for critical source area targeting for watershed planning	SWAT requires substantial number of data available both for running model and for calibration. Non-calibrated SWAT model provides with incorrect estimates of pollutants loads	SWAT STEPL L-THIA PLOAD (Singh 2002)
SWAT performed better on assessment of pollutant loads (phospohorus)	More errors have been derived by SWAT model while simulating total disharges in the basin on a daily basis, so HSPF model performed better	SWAT HSPF SHETRAN (Nasr 2004)
SWAT model has a superior performance in estimating high values of sediment load	SWAT performed not accurately for estimation of low and medium values of sediment load. Prediction interval was bigger for SWAT results. It was explained by relatively big uncertainty of SWAT outputs.	SWAT ANN (Talebizadeh et al. 2010)
Based on results of calibration and validation SWAT performed better in terms of uncertainty of the output data while simulating hydrology, sediment, and total phosphorus loads in separate calibration and validation watersheds		SWAT AnnAGNPS (Parajuli 2009)
SWAT was recommended as a tool for estimation of specific hydrological services, or if there is need for scientific consensus of the underlying processes	SWAT required both data and expertise for conducting substantial and meaningful assessment, while simplified modelling tools such as InVEST and ARIES were more simple for decision-makers	SWAT InVEST ARIES VIC (Vigerstol and Aukema 2011)

Most of these studies emphasized the need for substantial input data for SWAT in order to ensure better performance both on calibration and validation stages. Calibration play important role in final output data adequacy. Some researchers emphasized the need for simplified tools both for dealing with insufficiency of data available for analysis, as well as with delivering of the results of assessment to decision-makers (Singh 2002; Vigerstol and Aukema 2011). Also there is an issue with transfer of variety of parameters for regions out of the U.S.(Steinhardt and Volk 2003). Nevertheless, SWAT remains one of the best available tools for simulation of hydrological processes. The main advantage of SWAT modelling is the possibility to run simulation for watersheds without monitoring data and capacity of quantification of change in quality and quantity of water, applying different scenarios (land use change, climate change, etc) (Quintero *et al.* 2009).

Moreover, nowadays many different tools for use of SWAT and other modelling tools results in the integrated modelling frameworks, where input data can be derived from other models and final information is provided through different other user-friendly tools, addressed to decision-makers (Bouraoui and Grizzetti 2008; Johnston *et al.* 2011). Therefore SWAT itself remains one of the appropriate tools in the assessment of EGS.

However, SWAT found limited application both in performing EGS assessment, as a baseline integrated tool (e.g.: Jujnovsky *et al.* 2012; Schuol *et al.* 2008; Swallow *et al.* 2009), and within the complex hydro-economic modelling frameworks (e.g: Immerzeel *et al.* 2008; Martinez de Anguita *et al.* 2011; Quintero *et al.* 2009) quite recently.

Therefore the need for additional studies on the integration of SWAT tool into best management practices evaluation, different PES schemes has been emphasized (Gassman *et al.* 2007; Krysanova and Arnold 2008).

This thesis is going to provide one more case study of the EGS assessment with SWAT in the framework of the EnviroGRIDS project. Main goal and objectives of the project focusing on the use of ecohydrologial modelling will be discussed in the next section.

2.2.4. Building Capacity for a Black Sea Catchment observation and assessment system supporting sustainable development

One of the examples of using environmental modelling tools aimed to address regional environmental, social and economic problems is the EnviroGRIDS project at the Black Sea Catchment (BSC) launched specifically to address the needs of the Black Sea Commission (BSC) and the International Commission for the Protection of the Danube River (ICPDR) (EnviroGRIDS 2012).

The scientific aim of the EnviroGRIDS project is to assemble an observation system, involving scientific partners, stakeholders and the public, at the BSC to provide solutions for different GEO Societal Benefit Areas within a changing climate framework.

Gathering and processing data with the Global Earth Observation System of Systems (GEOSS) provide opportunities to build models and scenarios, capable to bridge the gap between science and policy and inform decision-makers and the public about environmental changes, which will affect human health, biodiversity and ecosystems integrity on a 50-year time horizon.

Several specific technical objectives have been designed by project, such as gap analysis in the regional data, building spatially explicit scenarios of land cover, climate and demography changes, creating tools to visualize and interpret data and results of integrated models.

One of the innovations of this project is streamlining grid data processing through hydrological modelling with SWAT and scenarios development in function of forecasted climate conditions, land cover and demographic changes.

Basically the EnviroGRIDS project includes many different components of the integrated modelling, which can be successfully utilized to perform water-related EGS assessment.

Firstly, it promotes watersheds based management rather than setting administrative boundaries, using Water Framework Directive as one of the building blocks of the project.

Secondly, it provides extensive analysis of the observation systems key environmental data availability in the region, and improving data acquisition networks, linking, gathering and managing key environmental data in the region.

Then, it utilizes scenario approach to analyze key drivers of changes such as climate, demography and land use. For practical use this scenarios are spatially explicit and represented in a way to be incorporated into hydrological models calibrated and validated, generating outputs for further impact assessments and analysis.

Finally, the impacts of forecasted climatic, demographic, land cover and hydrological changes are presented through different tools to conduct analysis and provide both the expert and non-expert the early warning on the expected risks. It creates opportunities for enhancement of the regional water management based on river catchment analysis, putting the economic value of water use for stakeholders in order to understand the cost effectiveness of alternative policy and technical measures.

These steps can also help to identify vulnerable areas in terms of diminishing water-related ecosystem goods and services and providing solutions to adapt or to decrease negative social, economic and environmental on human and ecosystem well-being.

This thesis partially contributes to work of one of the working groups of the project, which is responsible for developing hydrological model in the BSC, addressing the following objectives:

- To gather and format required data for the application SWAT to model water spatial distribution of water quantity and water quality in the Black Sea Catchment.
- To calibrate and validate hydrological models, and perform uncertainty analysis
- To run land use/cover and climate change scenarios

2.3. Conclusions

Ecosystem goods and services concept found broad application in last few decades. The definition provided by MEA on EGS as benefit directly affecting people, including provisioning, regulating, and cultural services, and indirect benefits - supporting services needed to maintain other EGS. Many of EGS are related to water and can be assessed within the watershed boundaries.

Mostly such ecosystem goods and services like the provision of drinking water, water for irrigated agriculture, hydropower, fishery stocks, flood control and recreation services are directly utilized by people. Such hydrological attributes of quality, quantity, timing and location, determined by ecosystem processes, are in the basis of these EGS. Water supply is the major service provided by water ecosystems. In order to assess these services it is important to examine supporting services, such as water retention, water yield, natural water filtration and sediment regulation.

Variety of integrated frameworks, designed for EGS assessment, can be applied for hydrological goods and services as only one type of EGS. Such framework include number of methods to perform assessment of the trade-offs of ecosystem change for different beneficiaries at spatial and temporal values of ecosystem, which can be further applied in variety economic and non-economic assessment frameworks and involve different stakeholders.

The SWAT model is one of the examples of physically-based basin-scale, continuous-time model, capable to assess water budget within the spatially explicit watershed boundaries based on input data, such as hydrology of the watershed, weather parameters, soil properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. Number of studies has been made, comparing different modelling tools scales. In order to conduct baseline assessment of EGS it is required to define ecosystem boundaries, and to assess EGS.

Both these step can be done through different modelling frameworks. The development of the integrated hydroecological and economic EGS assessment frameworks in last decade encouraged broad application of ecohydrological modelling tools in order to increase quality of input-output data within such frameworks. Such modelling tools can provide assessment of specific hydrological services, quantifying and visualizing water-related EGS. The advantage of ecohyrological models, even though they require substantial expertise and data, is their capacity to quantify and analyze many underlying processes, supporting the ecosystem. Thus, such models provide with objective information on biophysical with SWAT. Limitations of the tool are mainly related to the availability of substantial data and expertise both in modelling and hydrology in order to calibrate and validate the model outputs. The main advantage of SWAT modelling is the possibility to run simulation for watersheds without monitoring data and capacity of quantification of change in hydrological regime and quality of water, applying different scenarios (land use change, climate change, etc). Therefore this toll may serve as a framework for hydrological EGS assessment.

3. METHODOLOGY

This chapter presents both quantitative and qualitative methods that will be applied for study of the ecosystem goods and services, provided by the Azov Sea Basin ecosystem, based on the ecohydrological modelling with SWAT in one of the sub-catchments.

In the first section the outline of the research design is provided, main research stages are defined with the relevant steps and methods. The second section presents the description of methods on analysis of ecosystem goods and services provided by the Azov Basin and defining the scope and study area. The third section describes the SWAT model development and its application. The forth section describes methods on developing scenarios for SWAT analysis. The final section presents methods of the analysis of EGS under formulated scenarios based on the retrieved data.

3.1. Research design

This thesis is going to conduct an analysis of SWAT modelling tool applied in one of the sub-catchments in the Azov Basin and use output data in the assessment of water-related ecosystem goods and services. In order to accomplish this, the research will be made through the four main stages that include different steps and methods (Table 2).

Table 2. Research design

№	Stages of the research	Steps	Methods
1	The analysis of the Azov ecosystem	Understanding of existing water-related EGS in the region	Literature review Spatial analysis with GIS
		Defining study area and scope of the research	
2	SWAT model development and application for the chosen sub-watershed	Developing datasets required for SWAT input data	GIS data collection Statistics analysis Spatial analysis with GIS SWAT modelling
		Creating input data, parameterization and running the SWAT	

№	Stages of the research	Steps	Methods
		Calibration and validation of the SWAT model	
3	Formulating scenarios of land use and climate change and analysis with the SWAT model	Data collection for land use and climate change	GIS data collection Scenario approach SWAT modelling
		Preliminary analysis of formulated scenarios with GIS	
4	Performing EGS assessment in the chosen sub-catchment based on SWAT model outputs	Examining main hydrological parameters derived with the SWAT model under different scenarios	SWAT modelling
		Developing recommendations for decision-makers in the region on sustainable water management	

Various software packages have to be used on the different steps of the research stages. They will be outlined in the following sections. Unless it is stated otherwise all the illustrations have been developed by the author using ESRI ArcGIS 9.3 software package[1].

3.2. Analysis of the Azov Ecosystem

In order to define the ecosystem goods and services in the Azov Sea Basin comprehensive overview of the water related issues should be made. This involves different methods of data collection and analysis.

Main ecological and hydrological characteristics of the Basin will be analyzed to understand environmental situation in the area. This will include both literature review and spatial analysis with GIS.

The required data can be obtained through the extensive review of different available literature sources, such as national statistics reports, regional and international agreements,

[1] ArcGIS Desktop: Version 9.3. Environmental Systems Research Institute Redlands, U.S.A.

international and local books and journal articles, environmental expert assessments, mass media. The information is available both in English and Russian.

Tendencies in decision-making process on water management both in the Ukraine and Russian Federation will be studied in order to define important goods and services of the Azov Ecosystem. As a result, the choice of the study area and ecosystem service will be rationalized.

Different GIS data will be analyzed and presented through maps in order to define spatially explicit ecosystem boundaries, which is the first step of the EGS assessment (section 2.1.3.).

3.3. Model development

Based on the review of EGS the SWAT modelling approach has been chosen to simulate hydrological processes in the study area. Currently the approach has gained worldwide recognition and been tested in many similar studies. In particular, this approach is used by the FP7 EnviroGRIDS project focusing on the modelling of the Black Sea watershed. The main advantages and applications of SWAT have been discussed in Section 2.2.3.

The model will be developed within the ArcSWAT extension (Winchell *et al.* 2010) created by Texas A&M University for ArcGIS 9.3 software package, the leading Geographic Information System (GIS) tool, available at the Central European University. The ArcSWAT extension contains numerous functions needed to create and run the SWAT model such as watershed delineation, input file generator, edit modules and others. This is freely available software which has gained worldwide recognition due to its effectiveness and reliability.

Once the area of interest to be modelled is defined the SWAT model can be created through the following steps:

- Developing datasets required for SWAT input data;
- Creating input files for the SWAT model, setting up and running the model;
- Calibration and validation of the SWAT model.

3.3.1. Developing datasets required for SWAT input data

Many studies emphasized that substantial data availability increases capacity of the SWAT to represent ecohydrological processes at the catchment scale with satisfactory level of adequacy (e.g.: Arnold *et al.* 1993; Krysanova *et al.* 1998; Steinhardt and Volk 2003).

Process-based simulation in general and SWAT modelling in particular requires extensive list of basin characteristics and data on management activities to be collected. The data is required in two categories: geographically explicit (GIS datasets) and basin-wide averaged values uniform for the entire area of interest.

Different data sources are available to run the model, for instance global and national data repositories can be used to prepare required datasets. For this purpose different data sources such as Food and Agriculture Organization (FAO), United States Geological Survey (USGS), National Climate Data Center (NCDC) can be used. Firstly, these datasets should be analyzed in order to find the most appropriate data. For example, digital elevation (DEM) data quality plays significant role in the results of simulation and may ensure satisfactory performance of the SWAT model even without calibration (Srinivasan *et al.* 2010).

The selected study area also benefits from the Black Sea Catchment datasets collected as an outcome of the EnviroGRIDS project.

3.3.2. Creating input files for the SWAT model, setting up and running the model

Collected spatial and non-spatial data should be reprocessed in order to generate datasets suitable for SWAT input files.

In order to connect prepared datasets to the SWAT model, it is necessary to edit SWAT database, which contains default data and parameters for the U.S. It is required to create lookup tables connecting new data to the default SWAT database, incorporating specific climatic, hydrological and other parameters of the study area in the model.

Then it is necessary to set up the model specifying numerous model parameters such as simulation period, methods of rainfall distribution and other parameters based on input data coverage and watershed characteristics. This can be done using ArcSWAT software.

Finally, the SWAT model will be run and output data will be collected and analyzed in order to retrieve the key hydrological parameters such as surface runoff, baseflow, water yield and streamflow.

3.3.3. Calibration and validation of the SWAT model

In order to ensure adequate performance of the SWAT model it is necessary to apply validation and calibration procedures. The validation tools are aimed to prove an adequacy of simulation and identify potential problems that might affect the model performance. Variety of techniques and methods were developed for these purposes. The SWAT CHECK software package will be used for this purpose[2]

[2] SWAT Check. 2012. http://swatmodel.tamu.edu/software/swat-check/

During the consequent calibration process the output hydrological data simulated by the SWAT model will be compared with the observed historical data during multiple model runs. The set of input parameters and coefficients should be adjusted in each model run in order to find the best parameters, providing with simulation close to the corresponding real data. The SWAT-CUP calibration tool (Abbaspour *et al.* 2007) will be applied in the current research. The package interface will be used to edit input data, assess calibration results, conduct sensitivity analysis and perform other relevant calibration procedures.

Adequate observed hydrological data should be collected and pre-formatted in order to achieve appropriate calibration results. To ensure reasonable calibration results the analysis of the observed data should be made in order to conduct reliable uncertainty analysis (Moriasi et al. 2007). Sensitive parameters should be identified and adjusted based on calibration results.

3.4. SWAT scenarios formulation and analysis

In order to make assessment of EGS in the chosen sub-catchment scenarios approach will be applied. The approach plays important role in the environmental science effectively appreciating and addressing global environmental changes (Wilkinson and Esther 2008). Firstly introduced by Kahn (Kahn et al. 1967) as one of the way “to plunge into the unfamiliar and rapidly changing world of the present and the future”.

Scenarios in opposite to predictions and projections are more complex, claim less confidence, being schematic and coming in sets of two or more (Parson 2007). The scenarios represent the frequency and magnitude of changes in ecosystem goods and services and allow decision-makers getting information about the potential futures of ecosystems and effect of the decisions on them. Therefore the scenarios should address the concerns of decision-makers and represent key aspects of the ecosystem dynamics behind those concerns (Bennett et al. 2005).

To apply this approach for the discussed EGS assessment within the study area it is required 1) to identify the parameters influencing the SWAT model behavior; 2) to formulate set of scenarios highlighting the changes in these parameters; 3) run the developed and calibrated SWAT model for each scenario; 4) retrieve the main hydrological parameters and assess the relevant EGS.

Based on the regional literature review and model understanding built through the conducted model development and calibration processes it has been preliminary concluded that the most influential and relevant factors affecting the water availability in the region will be land use and climate changes caused by both various anthropogenic activities and natural factors. Such data will be collected and converted to the format compatible with ArcSWAT model in order to run the scenarios.

Some of the relevant datasets (e.g. land use changes depending on the economic regional development and demography trends) can be collected from the scenarios developed by the EnviroGRIDS project. Other datasets (e.g. time-series weather data for the projected period) can be prepared using other methods. It is planned to use the stochastic weather generator Long Ashton Research Station Weather Generator (LARS-WG) (Racsko *et al.* 1991; Semenov and Barrow 1997) in order to create climate data in correspondence with storylines of the EnviroGRIDS scenarios.

Then preliminary analysis of formulated scenarios in the study area will be conducted, using geospatial analysis methods in order to assess potential implications on the hydrological balance. Finally, the developed SWAT model will be used to retrieve the main hydrological parameters for further assessment of hydrological EGS under different scenarios.

3.5. EGS assessment

The comprehensive output data acquired with the SWAT model can be used as a foundation for both for economic and non-economic valuation of water-related EGS quantifying main hydrological processes and attributes in temporal and spatial scales. The following outputs can be derived from the SWAT model: precipitation, actual evapotranspiration, potential evapotranspiration, surface runoff, baseflow, recharge, total water yield and others. Runoff and water yield are key elements of the water balance that can be considered to be a water provision ecosystem service (Brauman *et al.* 2007). Analysis of these outputs depending on the scenarios of regional development and climate change will provide assessment of ecosystem services, what is a prerequisite step for further application of valuation metrics as it was mentioned in the section 2.1.3.

Finally, the set of recommendations on further work on assessing EGS in the study area will be developed according to the integrated framework described in the section 2.1.3.

4. ECOSYSTEM GOODS AND SERVICES OF THE AZOV BASIN

The following chapter analyzes the Azov Basin ecosystem, its main characteristics and beneficiaries of ecosystem goods and services provided in the Basin.

The first section covers background information on the Azov Sea Basin, covering hydrological, biological and economic characteristics of the watershed and its main rivers. Next also includes information on the use of different good and services of the Azov Ecosystem in different economic activities in Russia and Ukraine. The last section presents conclusions of the analysis in order to understand significant EGS of the region and define the scope and area of study.

4.1. The characteristics of the Azov Basin

The Azov is a sea on the south of Eastern Europe, representing a unique and important ecosystem in the Black Sea catchment. It is bounded in the north and west by Ukraine and in the east by Russia (Fig. 5).

The Sea of Azov is about 340 km long and 135 km wide. It is the shallowest sea in the world, with an average depth of 7 m, and the smallest sea in the world, with an area of 39.1 km^2 and a volume of 290km^3 (Borisov and Kapitonov 1973).

Salinity of the sea varies significantly depending on the region, while average salinity has changed significantly in the second half of the twentieth century, increasing from 10.9 ‰ to 14.0 ‰ with high stratification of salinity level (Lagutov and Lagutov 2010; Russian State Oceanographic Institute 2011). The water residence time is around 10-20 years (Borisov and Kapitonov 1973).

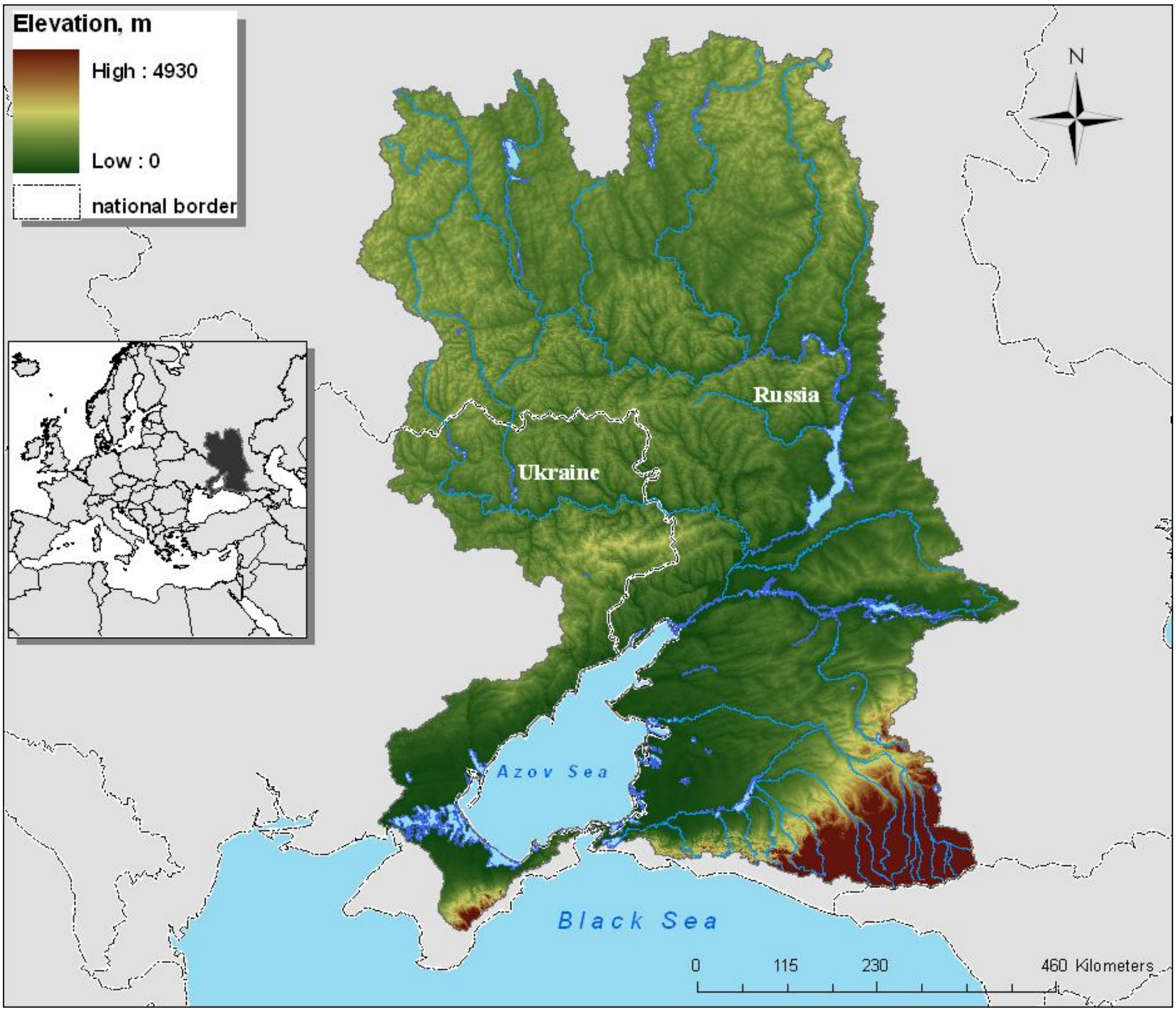

Fig. 5. The Azov Sea Basin

The Sea of Azov is connected with the Black Sea through the Kerch Straight in the south. Two main tributaries, the Don River, which flows from the northeast through the Taganrog Bay, and the Kuban River, which enters from the southeast near the Kerch Straight, bring sand, silt, and shells, forming numerous bays, limans and spits. These rivers play important role in supporting relatively low water salinity, being almost fresh in the Taganrog Gulf, and providing rich nutrient material, which in combination with good mixing and warming of water in the shallow sea ensures abundance of algae and plankton and, in turn, high fish growth (Britannica 2012; Debolskaya *et al.* 2008; Lagutov and Lagutov 2010). Due to such favourable conditions for high biological productivity, historically it was one the most productive seas in the world in terms of fishery rates (more than 85 kg per ha of surface) (Lagutov and Lagutov 2010; Semenov 2010).

Biodiversity in the region is quite rich. Numerous spits of the Azov Sea with total length exceeding 300 km, that is larger than the width of the sea, are important sites for migrating birds (Kostianoy and Kosarev 2007). Distinction in biotic and abiotic conditions of the main tributaries also contributes to the richness of biological diversity of the Sea (Lagutov and Lagutov 2010).

The Azov Sea total drainage area is 586000 km^2 with one of the highest drainage ratio (15km2 of watershed per 1km2 of sea surface), ensuring freshwater runoff through the 3 main catchment areas: the Don catchment, the Kuban catchment and the catchment area of 20 other small tributaries. Annually the rivers provide around 40 km3 of freshwater to the Sea (Lagutov and Lagutov 2010), mainly contributed by the Don river (around 60% of the total freshwater supply), with the rest of delivering freshwater by the Kuban river (around 28%) and another smaller rivers of the basin.

High seasonal and annual variations of the freshwater runoff, mainly depending on weather conditions, cause unstable freshwater supply in the region (Borysova *et al.* 2005). Low precipitation rates and relatively high aridity (Fig. 6) in the entire basin make this area vulnerable to droughts and desertification (Dronin and Kirilenko 2010).

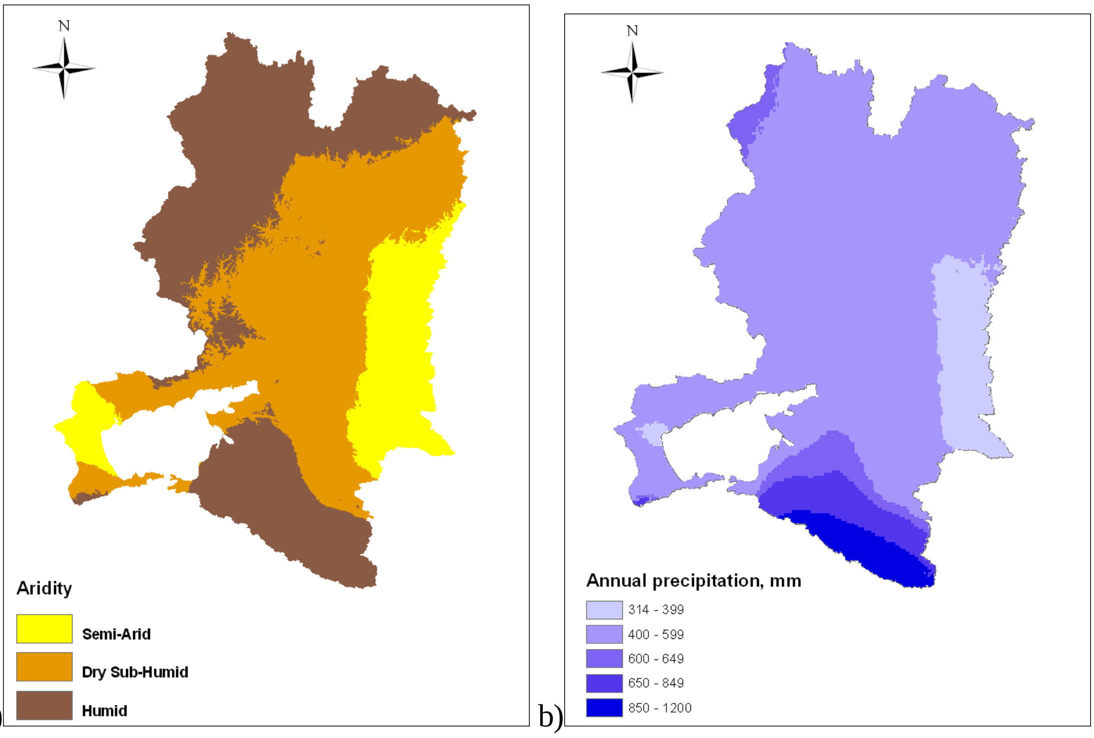

Fig. 6. a) Climate classes according to global aridity values (Based on Trabucco and Zomer 2009) and b) annual precipitation in the Azov Basin (Based on Hijmans *et al.* 2005)

Being one of the most productive areas of Russia and Ukraine with intensive development of agriculture and industry, this area is highly populated by around 30 million people. It includes more than 20 administrative units of Russia and Ukraine.

For better understanding of the Azov ecosystem, it is necessary to describe two main rivers of the Basin: the Don and the Kuban.

4.1.1. The Don River

The Don River is the fourth longest river in Europe, with a length of 1970 km, with the largest catchment area in the basin (442 thousand km[2)] of the Azov Sea). The Don brings the major part of freshwater to the Sea. Simultaneously, this area is characterized by intensively developed industry and agriculture (Lagutov and Lagutov 2010).

The Don is a typical plain river with an extended floodplain. Beginning in the narrow valley, it flows through the large floodplain up to 12-15 km in the lower course (Fashchevsky 2003)

The river is mainly fed by snowmelt (up to 70% of the total flow), which highly varies and determines annual fluctuations in the water flow, distribution and discharge of the river. Water level significantly changes during the flood period in spring, reaching 8-13 m (Sokolov 1952).

The river is regulated by Tsimlyansk dam, forming the Tsimlyansk reservoir that was put into operation in 1952 mainly to secure navigation between the Volga River and Azov Sea through the Volga-Don Canal, which is the major waterway in the region. At the same time it serves many other purposes, mainly for irrigation and hydropower production, and at a lesser degree, to maintenance of the Rostov nuclear power plant and water consumption for municipal needs (Sharvak *et al.* 2010). Being 260 km long, the Tsimlyansk reservoir has full capacity of 23,9 km^3 with maximum depth 36m. (AzovCenter 2010)

4.1.2. The Kuban River

The Kuban, another major tributary of the Azov Sea, originating from the Caucasus Mountains, is a typical mountain river, mainly fed by glaciers and therefore its hydrological and biological properties significantly differ from the Don River. The Kuban has relatively even water distribution. However, occasional intensive precipitation through the year may cause large scale floods, threatening many economic activities in the area.

The Kuban floodplain is relatively narrow although in some places it can reach up to 20 km. The length of the river is 906 km, while the drainage area of the river is 61 thousand km^2 (DEWA 2004). Estuaries, located in the well-developed delta of the Kuban River, are important parts of the river's ecosystems, serving as sites for spawning and breeding of many fish species in the Azov Basin.

The river flow has also been regulated by number of dams for hydropower production, irrigation, fishery and flood control. Krasnodar Reservoir, constructed in 1975, with length of 45 km and maximum depth of 20 m, has full capacity of 2.4 km^3 (Lagutov and Lagutov 2010).

The Don River however remains the main tributary in the Basin, providing with major part of freshwater in the region, which is important for many water-depended economic activities. These activities will be examined in the next section.

4.2. Economic activities and water related challenges

Favourable environmental conditions and access to the international trade routes through the Sea supported intensive economic development of the region. Great Construction Projects of communism, launched by the Soviet Government in the second half of the twentieth century, brought significant changes to the Azov Ecosystem through the construction of dams, irrigation and shipping canals (Lagutov and Lagutov 2010).

Water redistribution and regulation of water flow in the Basin allowed rapid development of different economic activities in the region. However, the Azov Sea Basin is characterized by low water availability, having less then 1% of total water runoff in the Russia. Simultaneously, it is the second most utilized basin from all watersheds of the country after the Caspian Sea (RMNR 2010).

Some major economic activities in the region that are depended on water-related ecosystem goods and services will be considered below.

4.2.1. Agriculture

The Azov Sea Basin is characterized by highly developed agricultural activities. Both favourable climatic conditions and soil fertility stipulated cultivation of various crops.

The percentage of agricultural lands in many provinces reaches 70-80% from the total land (Dronin and Kirilenko 2010).

Some crops are cultivated only in the region, making this area an important at the national scale. For example, one of two rice farming regions in Russia is located at the Kuban area.

Nineteen provinces of Russia, located in the area, collect almost 50% of all grain in the country, and four provinces of Ukraine harvest 15% of all Ukranian grain. Therefore regional economics highly depends on agricultural performance. For example, agriculture contributes to 28% of the total GDP for 19 provinces of Russia, located in the Basin (Dronin and Kirilenko 2010).

However, because some areas of the region, mostly in the eastern part of the Basin, are vulnerable to desertification, there is considerable dependence on the water withdrawal from the rivers for irrigation purposes. Though nowadays irrigated areas occupy only around 3,4% of the agricultural area in the Azov Sea Basin, future changes in temperature and precipitation in the region may lead to further expansion of the irrigation system to ensure food security. Moreover, the extent of further development of irrigation is challenged by already limited water availability in the basin (Dronin and Kirilenko 2008).

Even though the increase of precipitation due to climate change is forecasted for major part of the region, it will not compensate increase of evapotranspiration in a warmer climate. So the water requirement for crops cultivation is going to increase. Overall increase of aridity of the climate in the region is projected under all emission scenarios (Dronin and Kirilenko 2010).

4.2.2. Industrial and municipal water consumption

As it was mentioned above, the Azov Sea Basin is characterized by low water availability and high level of water withdrawal.

High population density and well-developed industry in the area require intensive use of water. As a result a deficit of water is observed, especially in the basin of the Don River, where only from the Tsimlyansk reservoir 30-40 million m^3 water are extracted for supplying surrounding settlements (Sharvak *et al.* 2010).

Sharp deficit of water in the Kuban and the Don basins even in the semi-dry years causes problems for municipal, industrial and agricultural water supply. Simultaneously, the threat of floods for hundreds of settlements is exacerbated by lack of engineer protection means (RMNR 2010).

Majority of population in the region (up to 70%) utilize the treated drinking water from surface reservoirs. However, there are significant problems with quality of water, especially in the lower course of the Don River.

According to the report of the Russian State Ministry of Natural Resources 2,3% of the Rostov region (83 000 citizens) use transported drinking water, and 0,3% (11 100 citizens) utilize untreated water from the surface reservoirs. Water deficit of one of the largest city in the basin, Voronezh, is 150000 m3 per day (RMNR 2010).

In many provinces of Russia and Ukraine in the region wastewater is discharged to the basin rivers without any treatment (RMNR 2010; UNECE 2007, 2011).

Substantial share of water use is allocated to the different types of industries in the region (AzovCenter 2010). Moreover highly industrialized area in the upper streams of the Don River significantly affects the quality of water, diminishing EGS provision for the downstream beneficiaries.

4.2.3. Energy

Significant number of hydropower stations is located on the Don and Kuban river. Though overall hydropower stations in the basin generate relatively small amount of energy (in comparison with Caspian basin, for instance) (Lagutov and Lagutov 2010), still this sector is responsible for use of significant share of water. For example, up to 80% of water in the multipurpose water scheme of the Tsimlyansk reservoir is utilized for hydropower generation (Sharvak *et al.* 2010).

Another way of water use by energy sector in the region is maintenance of thermal and nuclear power plants, located in the basin. Even though the total share of water utilization for this purpose is relatively small, the demand for water supply is relatively stable and there are not many options to decrease water consumption in this sector (Lagutov and Lagutov 2010).

4.2.4. Fishery

The fishery sector in the Azov Sea Basin underwent dramatic changes in the 20th century. Being one of the most prosperous sector in the region, it supplied almost one of the fifth of total fish in the USSR (Borisov and Kapitonov 1973). However during last decades the fishery in the region has collapsed. The sharp decline of the majority of valuable fish species has occurred due to overexploitation of fish stock and river regulation with dams, including construction of the Tsimlyansk reservoir, caused disruption of many fish species migration (Lagutov 2009). Therefore provision of such ecosystem goods as food is drastically decreased in the region.

4.2.5. Transport

In spite of its shallowness, the Azov Sea plays an important role for transport routes connecting major industrial centers of Russia and Ukraine through the canals and rivers of the Basin. Being the only exit to the southern seas for the Russian Federation, it has also strategic role in the national interests of the country.

Volga-Don shipping canal, connecting the Don River and the Volga River, is the only waterway connecting Caspian countries with Europe (Lagutov and Lagutov 2010). Its total carrying capacity is 16,5 million tons of cargo per year (Foster 2010). The forecasted increase in trade volumes in the region will require increase and modernization of transportation facilities (Kozlov and Zbaraschenko 2009).

The Tsimlyansk reservoir plays important role to secure the navigation in the canal. However, increase in water loss due to climate change and siltation of the Priplotinnaya section challenge the future of the navigation in the Volga-Don Canal.

Considering the growing need for transporting goods throughout the region, several more initiatives on developing transportation infrastructure in the Azov Sea Basin have been launched. One of them is Rostov Universal Port construction, connecting Russian industrial sites and the Caspian Sea with Europe and Mediterranean countries. The first terminal has already started functioning, transporting 1 million tons of goods (Russian South 2010).

Due to limited carrying capacity of the Volga-Don shipping canal, 2 alternative projects have been launched in the region: Volga-Don 2 and Eurasia Canals.

The project of Volga-Don 2 canal proposes completion of the suspended Soviet construction, which started in 1980s. The new canal, mainly due to allowing larger vehicles flotation, is supposed to increase annual traffic capacity of both these canals up to 30 million tones or to 60-72 tonnes due to possibility of use of larger vessels (Lagutov and Lagutov 2010).

The Eurasia project proposes the construction of a shorter canal using potential of the natural landscape and existing artificial reservoirs (Foster 2010). Due to absence of final project documentation, different estimations on the transport capacity of the canal exist. Many authors emphasized significant environmental impact of this project on the biodiversity and water resources in the area of construction, which might affect important habitats of migrating species, including Saiga antelope and unique steppe landscapes.

Obviously, both these projects will have significant impact on the Azov Sea Basin, creating additional threats to the ecosystem (AzovCenter 2010), such as:

- shortage of freshwater supply by the rivers due to additional water extraction for supporting new canals;
- habitat fragmentation, including protected areas, located in the project site;
- water pollution, mainly due to oil spills, that could potentially grow with increased intensity of oil transportation;
- salinity increase in the Azov Sea due to inflow of Black Sea water.

4.3. Conclusions

Though the Azov Sea Basin is characterized by low water availability it provides many beneficiaries in the region with numerous water-related ecosystem goods and services. Freshwater supply is one of the major provisional services with the most significant contribution of the Don River. Due to high seasonal and annual variability in freshwater flow depending mainly on climate conditions the water supply in the region can be defined as unstable.

Moreover, intensive economic development in the second half of the twentieth century, brought significant changes to the Azov Ecosystem through the construction of dams, irrigation and shipping canals. In order to secure even water availability and support the various EGS number of reservoirs has been constructed. The Tsimlyansk reservoir, the largest freshwater body in the basin, plays a crucial role in the securing freshwater provision.

An increase of demand for freshwater associated with economic growth and demography changes along with actively promoted projects related to additional water extraction may threaten adequate freshwater supply in the region in the near future. Many water depended economic activities in the area became threatened by diminished capacity of the ecosystem to secure required level of EGS provision. The discussed possibility of climate change in the region causes additional challenges for water managers and regional planners. In particular, possible changes in the Tsimlyansk water inflow will have significant impact on the regional economy and communities well-being.

5. DEFINITION OF THE STUDY AREA

This chapter attempts to define and rationalize the scope and area of study based on review of the Azov Sea ecosystem, provided in the previous chapter.

The first section discusses the role of Tsimlyansk reservoir in the region in EGS provision and its main beneficiaries. The second section describes the Upper Don River sub-catchment that has been chosen for performing SWAT modelling in order to analyze change of water supply in the Tsimlyansk reservoir. The main land use patterns, hydrological and climate conditions are presented. The final section sums up the main conclusions to be taken into consideration while developing the SWAT model.

5.1. Tsimlyansk reservoir

Careful review of the regional activities and water-related problems in the Azov Basin allows concluding that the Tsimlyansk reservoir plays significant role in the Basin, providing the population with several important ecosystem goods and services.

The Tsimlyansk reservoir supplies with fresh water around 457.5 thousand residents in the region, supporting 156.8 thousand hectares of farmlands and 37.2 ha of forests and allowing maintenance of number of important economic objects such as Rostov nuclear power plant, Tsimlyansk hydropower plant, ports, tank farms, fish factories, hunting farms, fishing companies and wildlife reserves (Sharvak *et al.* 2010).

Among many different EGS provided by the Tsimlyansk reservoir water supply is the most important one. Two major categories of water supply according to Baruman (Brauman et al. 2007) can be defined:

1) In-situ water supply:

- navigation – securing navigation in Volga-Don canal with growing traffic intensity (6799 ships in 2007 versus 5022 ships in 200);
- hydropower generation – comprises major part of the multipurpose water scheme if the the Tsimlyansk reservoir (Sharvak *et al.* 2010) with an average annual power output of 663 million kWh (Rasleigh and Lagutov 2010);
- cooling needs for nuclear power generation – water reservoir cooler supplying water for cooling needs (38,78 million m^3 annually)

2) Diverted water supply:

- municipal consumption – annually 30-40 million m^3 of water are extracted for supplying local town and surrounding villages with freshwater (Sharvak) its significant share of the irrecoverable withdrawal (around 3,4%);
- irrigation – about 323 000 ha of the irrigated lands in the Lower Don River supplied by the Tsimlyansk reservoir (around 2 km^3 annually).

Realization of planned projects on construction of the additional shipping canals Volga-Don 2 and Eurasia may dramatically change the Azov Ecosystem, diminishing capacity of different components of this ecosystem, including the Tsimlyansk reservoir, to provide growing population in the area with water-related ecosystem goods and services.

Number of supporting ecosystem services plays important role in the water supply of the Tsimlyansk reservoir. Climatic conditions and total inflow in the reservoir are two key factors, supporting water balance in the reservoir.

Mainly water yield and water retention of the Upper Don River ecosystem determines Tsimlyansk reservoir inflow. Therefore, this thesis is going to focus on the Upper Don River sub-catchment, where the major water flow is generated with an outlet adjacent to entrance of the Tsimlyansk reservoir.

Investigating water flow, generated in this area under different scenarios of land use, climate and demography change will allow assessing water supply required for the Tsimlyansk reservoir functioning and provision of EGS of many beneficiaries in the area.

5.2. The Upper Don River as a vital component of the Azov Sea Basin

The catchment area encompassing upper streams of the Don River with the outlet adjacent to the entrance into the Tsimlyansk reservoir has been chosen for the research. In order to define the borders of this watershed the approximate mask of the study area has been made. Then delineation function in the SWAT has been used to define borders more explicitly based on elevation data (Fig. 7).

The area of study comprises more than 50% of the total Don Basin catchment area. The area is relatively flat, the elevation range of the sub-catchment is 28-354 m a.s.l., with mean elevation 160 m a.s.l.. It includes 15 gorsovet 162 rayons of 8 regions of Russian Federation.

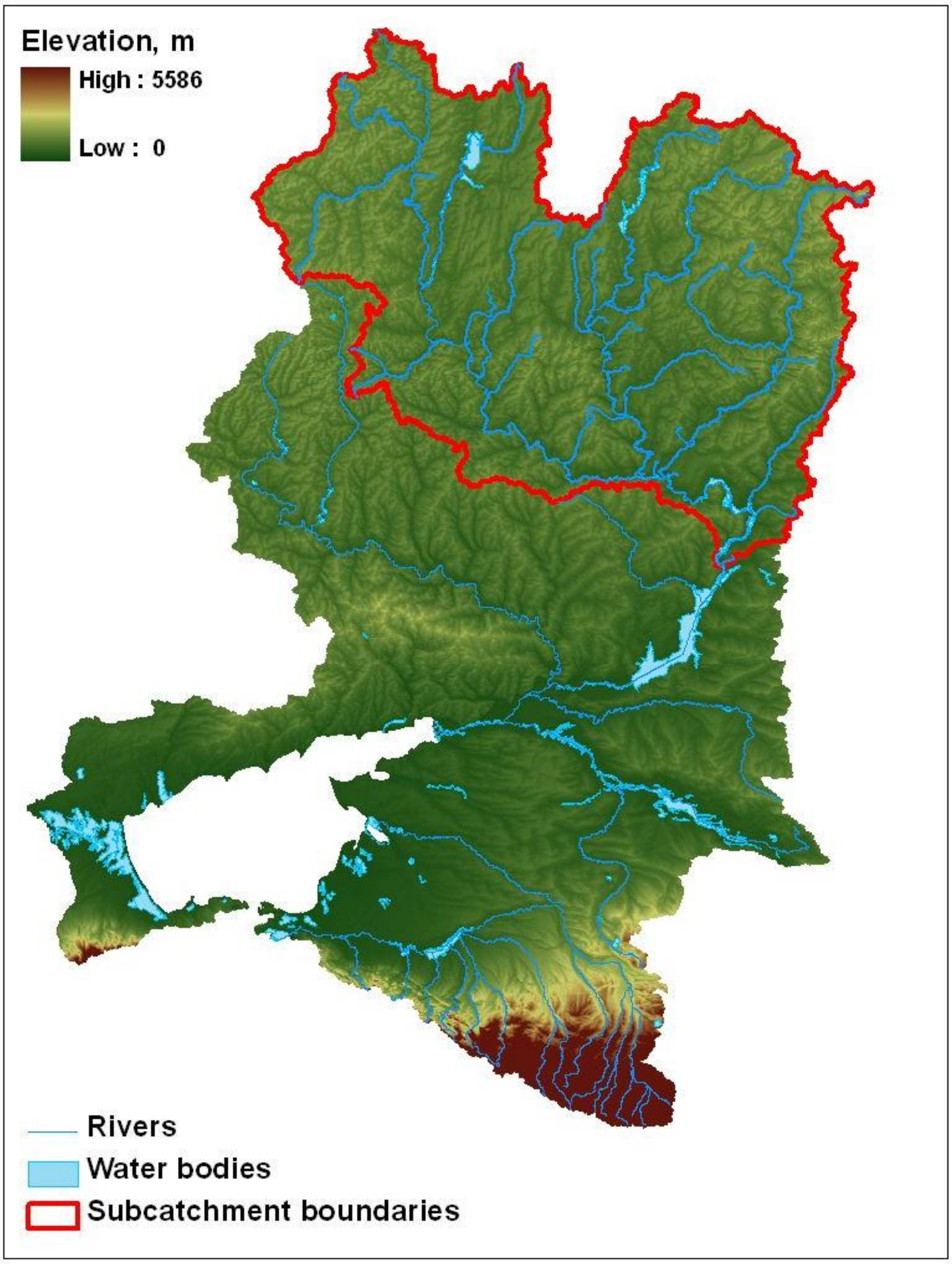

Fig. 7. Defined ecosystem boundaries

5.2.1. Land use patterns of the area

Due to favourable soil and climate properties rainfed crops and mosaic croplands comprises the major part of the basin (47,9% and 39,8% respectively). Other land use types, less presented in the basin, are mosaic vegetation (5,81%), different types of forest (3.45%) and urban areas (0,3%) the land use patterns (Fig. 8).

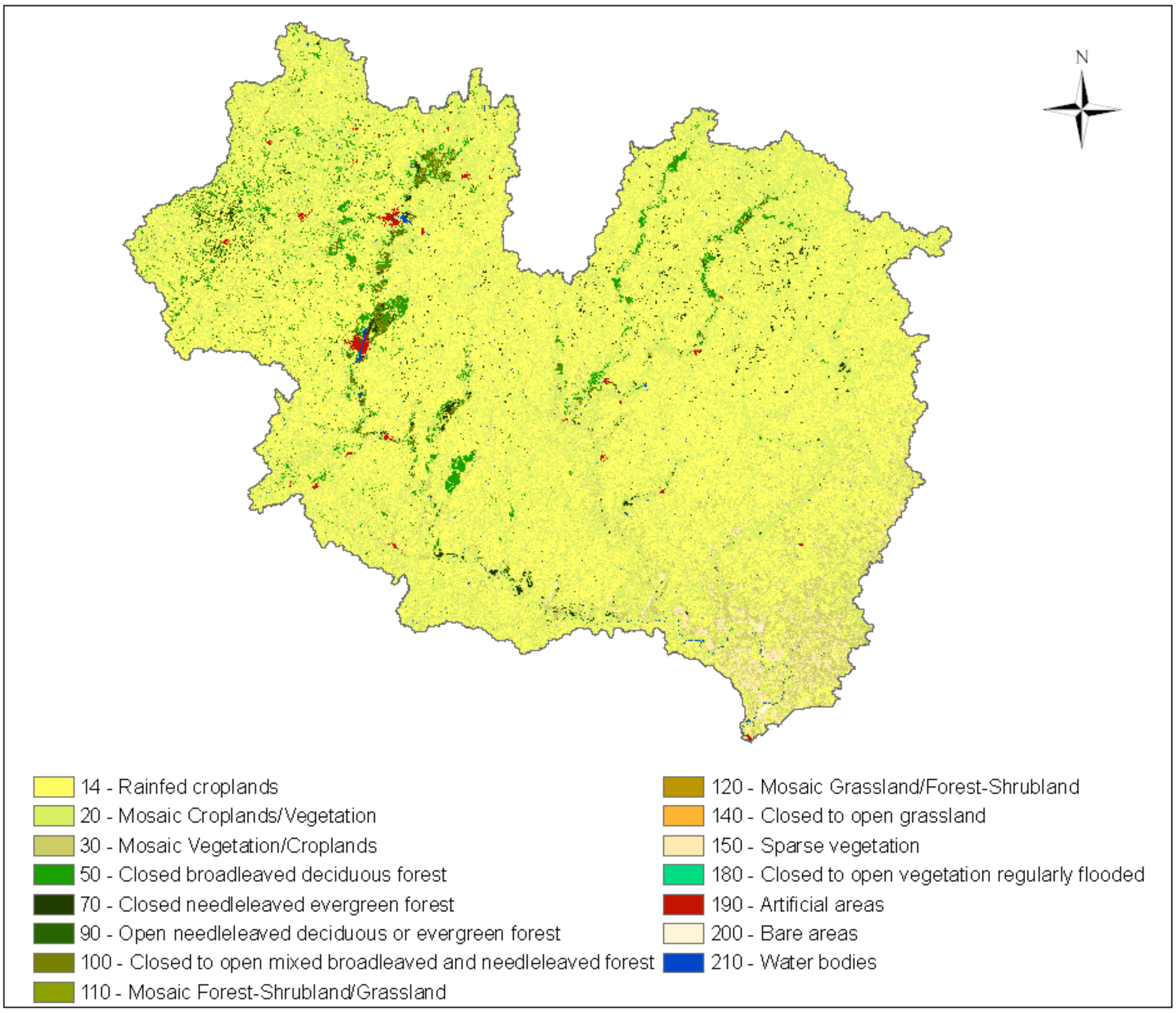

Fig. 8. Land use patterns in the area of study (Based on ESA 2009)

Two large cities, such as Voronej and Lipeck, characterized by intensive industrial development, with population more than 1.3 million residents are located in the area. Predominance of agricultural areas and relatively high urbanization level determines changes in surface runoff and water yields, generated in the sub-catchment.

5.2.2. Climatic and hydrological patterns

Climatic conditions in the area characterized by relatively high humidity and high precipitation rates in comparison with the entire Azov Sea Basin (Fig. 9).

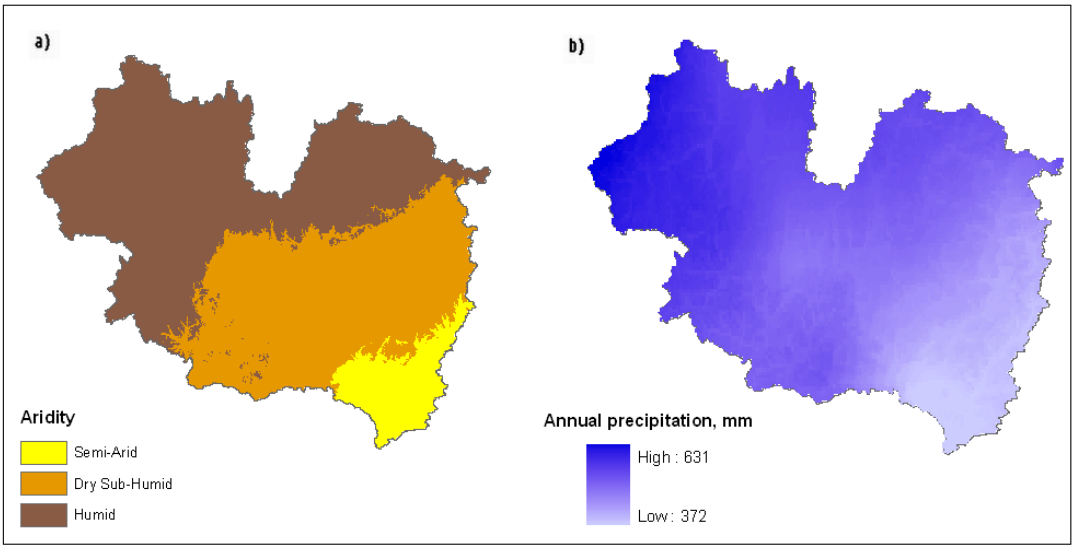

Fig. 9. a) Climate classes according to global aridity values (Based on Trabucco and Zomer 2009) and b) annual precipitation in the Upper Don River (Based on Hijmans et al. 2005)

It was found that there were 8 main tributaries and no significant reservoirs and dams in the sub-catchment (Fig. 10).

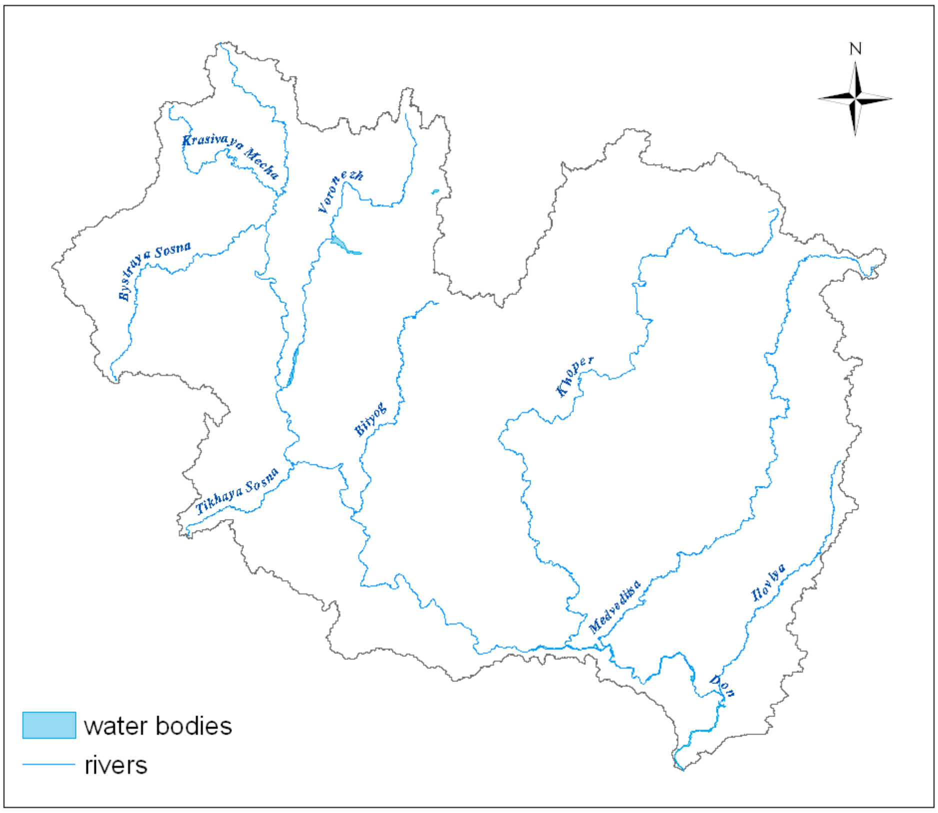

Fig. 10. Rivers and water bodies in the sub-catchment

Rivers are mainly fed by snowmelt, which highly varies and determines annual fluctuations in the water flow, distribution and discharge of the rivers. Water level significantly increases during the flood period in spring. Therefore inflow into the Tsimlyansk reservoir varies through the year (Fig. 11) Average annual inflow in the Tsimlyansk reservoir is 586,9 m3/sec.

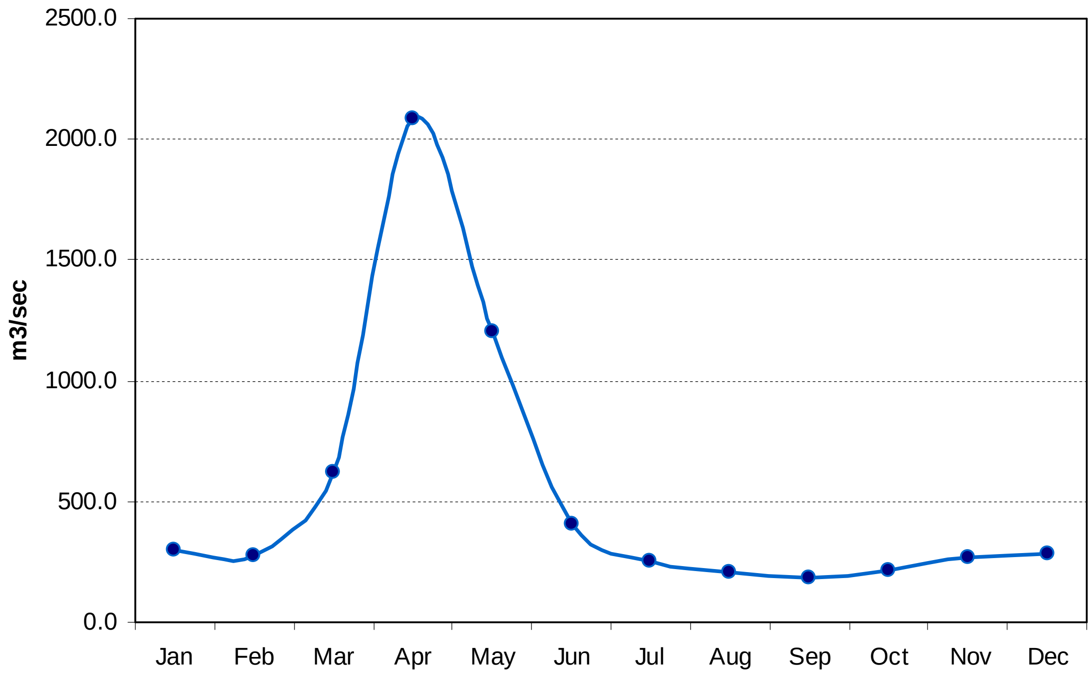

Fig. 11. The average monthly inflow in the Tsimlyansk reservoir (2000-2010) (Based on CRWISWT 2012)

Overall, it's very high seasonal variability is observed in the Upper Don river, which is important to consider while developing and calibrating the SWAT model, especially while simulating extreme events.

5.3. Conclusions

The Upper Don River sub-catchment can be defined as typical agricultural watershed with prevalence of the rainfed crops and mosaic croplands. As it was mentioned earlier in section

2.2.3. the effectiveness of ArcSWAT in ecohydrological modelling in agricultural watersheds is proved by many studies.

While developing the SWAT model for the chosen watershed, it is important to take into account high seasonal change of water availability in the area. Snow accumulation and melting processes play important role in hydrological regimes of rivers in the study area, determining extreme events occurring mostly in spring and total water availability in the area. This might challenge calibration process, while working on appropriate simulation of the extreme events based on observed data. Availability of time-series data for substantial number of hydrological gages in the area is prerequisite for adequate calibration and validation results.

6. DEVELOPMENT OF THE SWAT MODEL

In order to obtain output data from the SWAT model, it is required to pass through different stages, using relevant datasets. The purpose of this chapter is to present step by step process of the SWAT model development using ArcSWAT extension that is presented in the first seven sections. Main assumptions and limitation for the developed model are presented in the final section.

6.1. Watershed delineation

Automatic watershed delineation is the first step of the creating model in SWAT. In this step initial stream network and subbasin outlets are defined based on elevation data. The data on elevation have been derived from the global dataset topography Shuttle Radar Topography Mission (SRTM) (Farr *et al.* 2007). Relatively high resolution of elevation data (90 m) allowed skipping the step on use of predefined streams and watershed.

Then it was possible to add outlets at the points were hydrological gages were located. In order to add this data, it was required to prepare database with locations of the gages. This step is important in order to improve calibration process, based on observed data on streamflow in 8 hydrological posts in the area.

As an output of this step 4 layers were added to the map and displayed over the DEM layer grid: Reach drainage network (created on the basis of elevation data) and Monitoring point (respective stream junction points), Watershed with all sub-basins, outlets (defined by SWAT and added by table) and Basin with full watershed boundary (Fig. 12).

In order to define the border of watershed it was necessary to select the main outlet. The outlet adjacent to the entrance of the Don River to the Tsimlyansk reservoir has been chosen based on outlet, defined by SWAT.

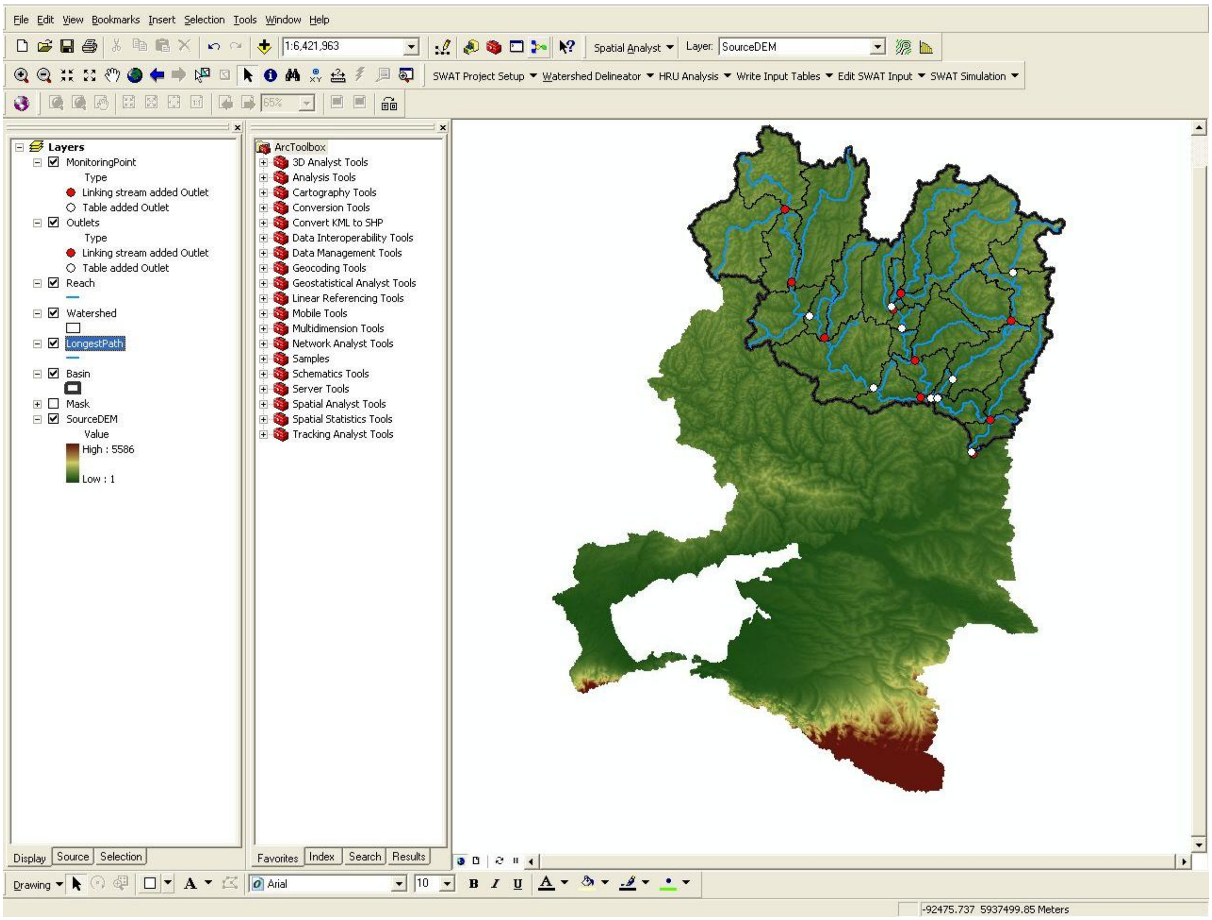

Fig. 12. Automatic watershed delineation in SWAT

As a result, 30 subbasins with 30 outlets respectively have been defined for the watershed. Finally calculation of sub-basin parameters containing elevation data has been derived with information on the stream geometry and longest flow path calculation.

6.2. HRU analysis

After completion of watershed delineation it is required to define unique sub-watersheds, hydrologic response units. The land use and soil layers have been loaded; slope characteristics have been evaluated based upon the DEM input data. This step allowed defining HRUs based on defining and combination of classes of land use, soil and slopes with different thresholds on input data.

The MODIS land cover dataset for 2008 has been used for land cover layer input. However in order to make analysis of the scenarios with SWAT (chapter 7), reclassified datasets, developed by EnviroGRIDS project for Metronamica land use model (Fig. 13) has been used.

	MODIS Land use classes		Metronamica land use classes
0	Water	9	Water
1	Evergreen needleleaf forest	3	Forest
2	Evergreen broadleaf forest		
3	Deciduous needleleaf forest		
4	Deciduous broadleaf forest		
5	Mixed Forests		
6	Closed Shrubland	1	Shrubland
7	Open Shrubland		
8	Woody Savannas		
9	Savannas		
10	Grasslands	4	Grassland
11	Permanent wetlands	7	Permanent wetlands
12	Croplands	5	Croplands
13	Urban and built-up	6	Urban and built-up
14	Crops/natural vegetation	0	Crop/ Natural Vegetation
15	Snow and ice	8	Snow and Ice
16	Barren or sparsely vegetated	2	Barren or sparsely vegetated

Fig. 13. MODIS land use classes and the new classes created to fit the Metronamica land use model (Mancosu *et al.* 2012)

Global soil dataset FAO has been used for soil layers (FAO and IIASA 2012). The soil database with classes used in dataset was incorporated to the SWAT database file.

In order to link this data to the SWAT databases it is necessary to formulate datasets in the required format and create lookup tables that will connect used datasets to the SWAT default databases.

For slope definition 2 classes of slopes have been chosen with threshold in 2%, based on default parameters of HRU definition (Winchell *et al.* 2010). Finally these new reclassified layers have been overlaid in order to define HRU.

HRU definition with unique land use and soil combinations enables the model to simulate evapotranspiration and other hydrologic conditions according to the differences in land cover/crops and soils. Due to insufficient data default crop parameters, included in the SWAT database, has been used.

The recommended thresholds for multiple HRUs on Land Use, Soil and Slope were chosen: 20%, 10% and 20% respectively (Winchell *et al.* 2010). Upon overlaying the reclassified layers, HRUs in 30 subbasins were created using HRU definition function in SWAT (Fig. 14).

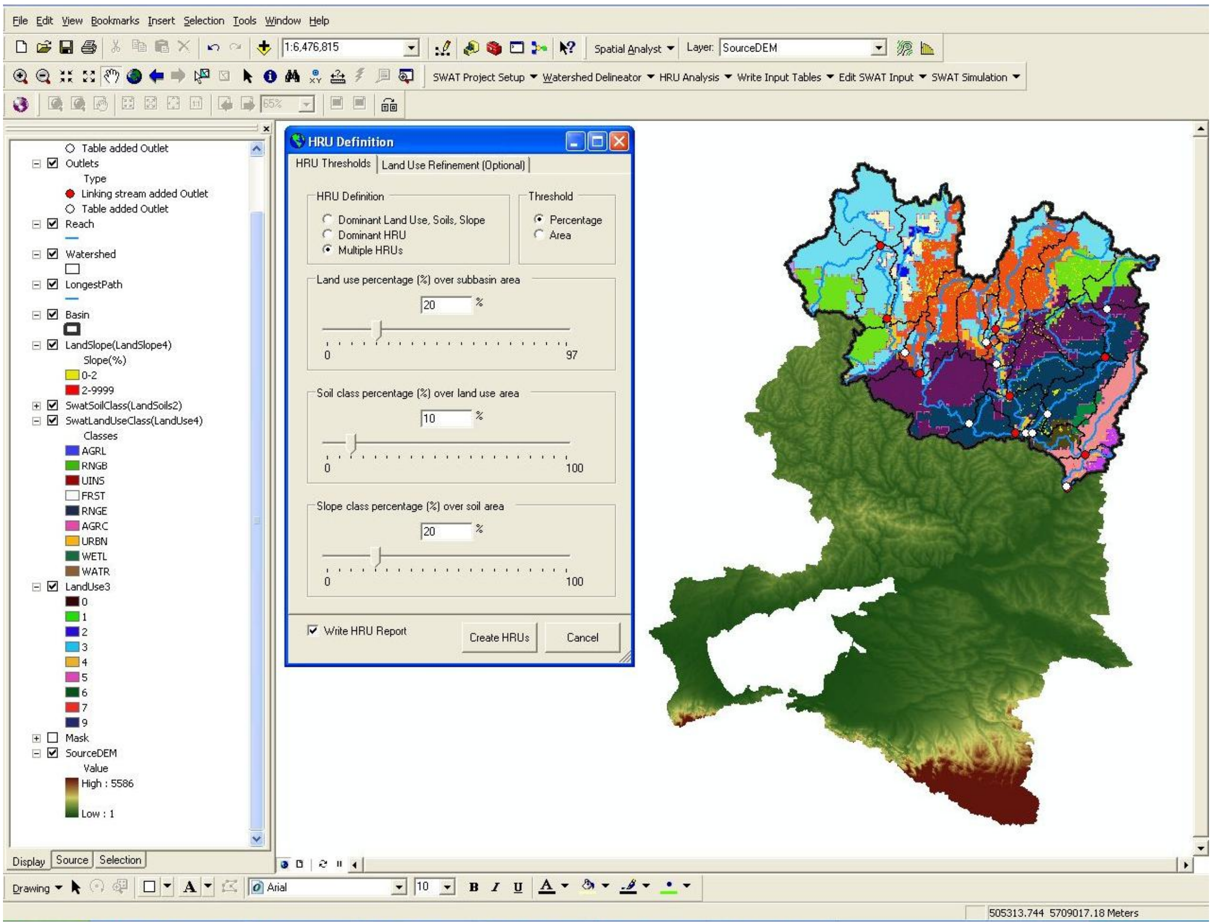

Fig. 14. Definition of the Hydrolical Response Units (HRU)

The report has been created with land use, soil and slope characteristics for the whole watershed and for each sub-watershed.

6.3. Weather data definition

After HRU definition weather data for the watershed should be loaded using Write Input tables command in SWAT. The meteorological stations locations assign climate data to the sub-watersheds, delineated through HRU analysis.

The data is loaded through the Weather Data Definition menu. This menu contains six tabs: Weather Generator Data, which must be set, and five tabs with optional weather parameters, which can be loaded based on measurement from specified stations (Fig. 15).

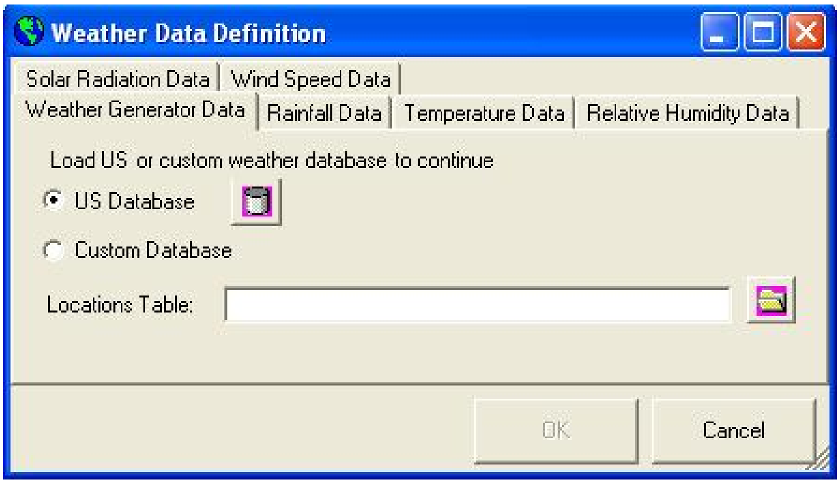

Fig. 15. Weather Data Definition menu in SWAT

In order to fill gaps in the missing records from climatic data on precipitation and temperature, a statistical weather generator - .wgn files were used, based on data derived from 8 meteorological stations within the watershed. It was required to create database with location of the stations used for weather generation and weather generator data. Data on wind speed, humidity and solar radiation has been created for the whole watershed based on the WXGEN parameters.

Then for increasing effectiveness of simulation measured data on maximum and minimum temperature and daily precipitation has been loaded. Coverage of meteorological data plays important role in the SWAT model performance (Abbaspour *et al.* 2007). The data for the period 1998-2008 for the following 5 meteorological stations have been chosen for the model: Urjupinsk, Elec, Frolovo, Voronej and Kamyshin (Fig. 16).

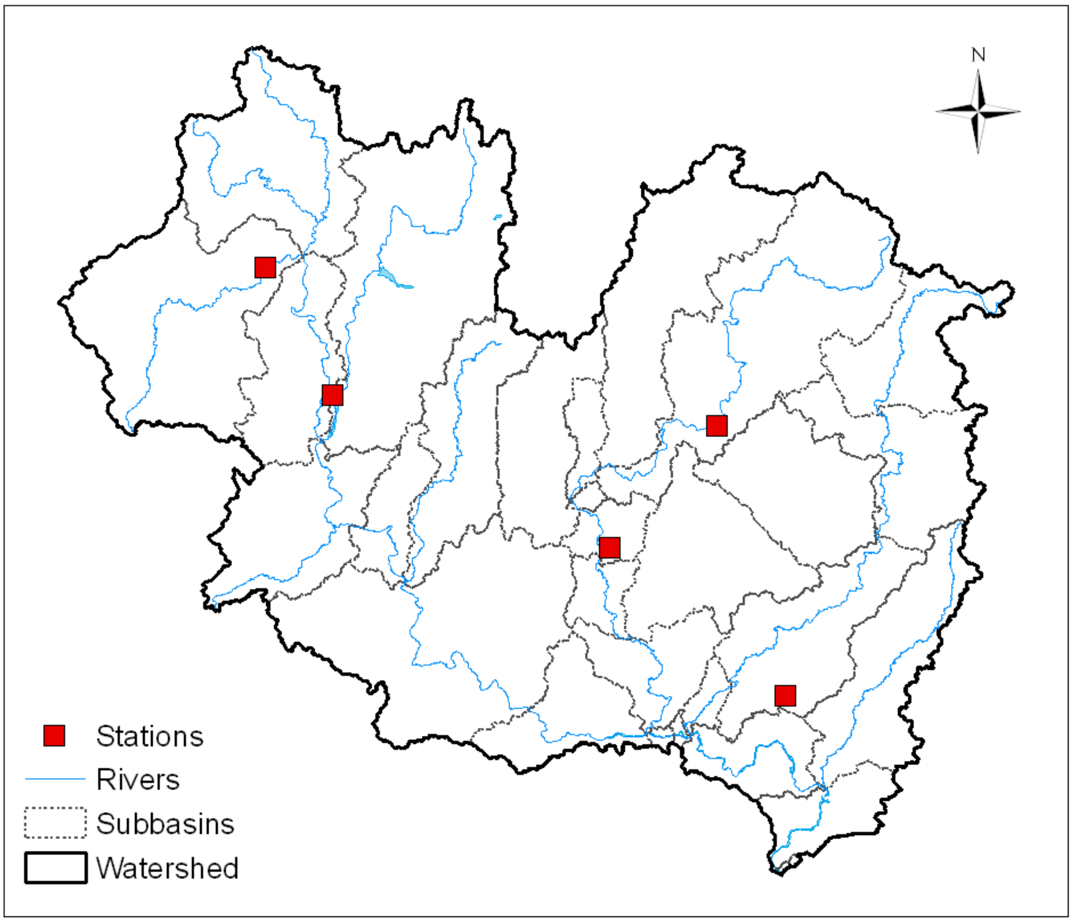

Fig. 16. The Upper Don River watershed and meteorological stations delineated based on DEM data.

It was required to prepare relevant databases with daily precipitation, maximum and minimum temperature for each station that is connected to the stations location database. The datasets have been downloaded from Climate Data Online dataset from National Climate Data Center and Web Server "Russia's Weather" developed by Space Monitoring Information Support laboratory of Space Research Institute of Russian Academy of Science (SMIS IKI RAN), and for some meteorological stations with lack of data for several years data has been downloaded from he Daily dataset of 20th-century surface air temperature and precipitation series for the

European Climate Assessment (ECA) (Klein Tank *et al.* 2002). However, some data required additional processing in order to be read by SWAT program. The minimum and maximum values of daily temperature for years 1998-2000 were computed based on 6 measurements (every 4 hour) as it was presented in original dataset from SMIS IKI RAN. The data from National Climate Data Center had missed dates, which were added and unknown values of temperature and precipitation were assigned for these days.

Many stations did not have data for recent years, partly because of the time that is needed for data quality control and dataset development. Therefore blended datasets from ECA (Klein Tank *et al.* 2002) have been used, which included automated update procedure that relies on the daily data from SYNOP messages that are distributed over the Global Telecommunication System (GTS). In this procedure the gaps in datasets are filled with observations from nearby stations, provided that they are within 12.5km distance and that height differences are less than 25m.

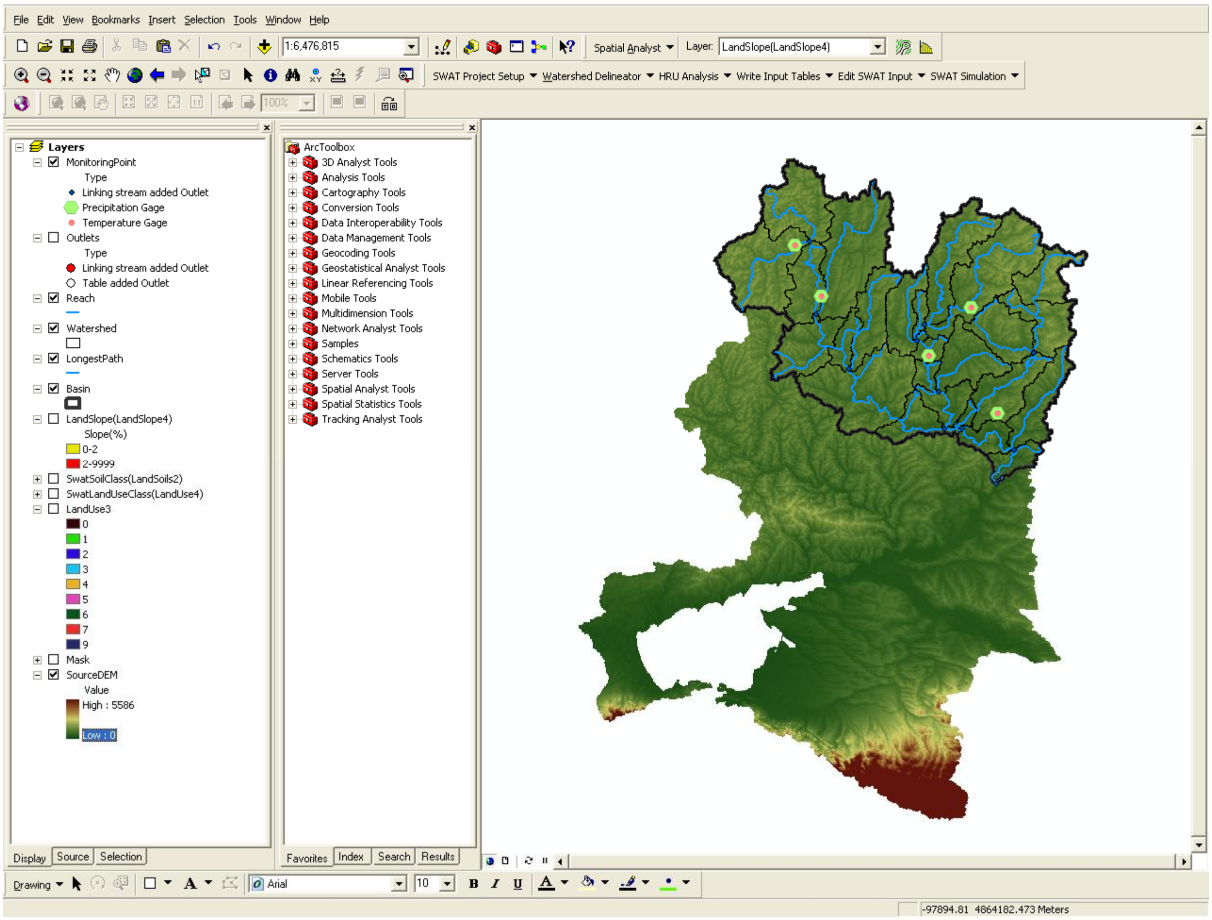

Fig. 17. MonitoringPoint layer with weather stations

After completion of weather database setup the weather gages were added to the MonitoringPoint layer in the map (Fig. 17).

6.4. Creating the SWAT Input datasets

After definition of weather data SWAT allows to build different database files containing he information needed to generate default input for SWAT. There are 2 options on building initial watershed input files, which are required for running the model: it can be done through the Write All command using default database of the SWAT or the individual Write commands. The first option, applying default data has been chosen. It was assumed that default value on Manning's roughness factor (0.014) is appropriate for the respective watershed. Also as the area of study is located in northern hemisphere it was possible to use default data for plant heat units (Winchell *et al.* 2010).

After generating all default input values, it is possible also to start editing default values using the Edit SWAT Input menu. However, it was assumed that there were no significant reservoirs in the watershed, water quality analysis has not been included in the research, and Soil database was included in the default SWAT database, so finally input SWAT data was not edited.

6.5. Model simulation and output data processing

In order to run the model it is required to set up model running parameters using SWAT Simulation menu. The period of simulation for 7 years from 1 January 2001 to 31 December 2008 has been chosen. Two years of warm up period, which is required for better simulation performance, have been set up. Default options with skewed normal distribution of rainfall and monthly printout setting have been selected. Finally, model simulation was run and simulation results were obtained through the Read SWAT output command.

The information on watershed statistic was provided through the output.std text file and MS Access database, where the monthly statistics on HRU, subbasins and reaches within the sub-catchment has been derived. The examples of the output tables, provided by SWAT, can be found in Annex A 1and A 2.

After the subsequent steps of model validation and calibration the simulations results based on these datasets will be used for defining the Baseline for the comparison with scenarios output later in Section 7.3.

6.6. Model validation

In order to check model outputs the SWAT Check tool has been used. This program performs many simple checks to identify potential errors in the SWAT model and validate results comparing. SWAT outputs to nominal ranges, defined based on judgment of model developers. It helps to avoid unnecessary time on calibration process and provides visual representation of various model results. Preliminary validation of the hydrological parameters has been performed successfully (Fig. 18).

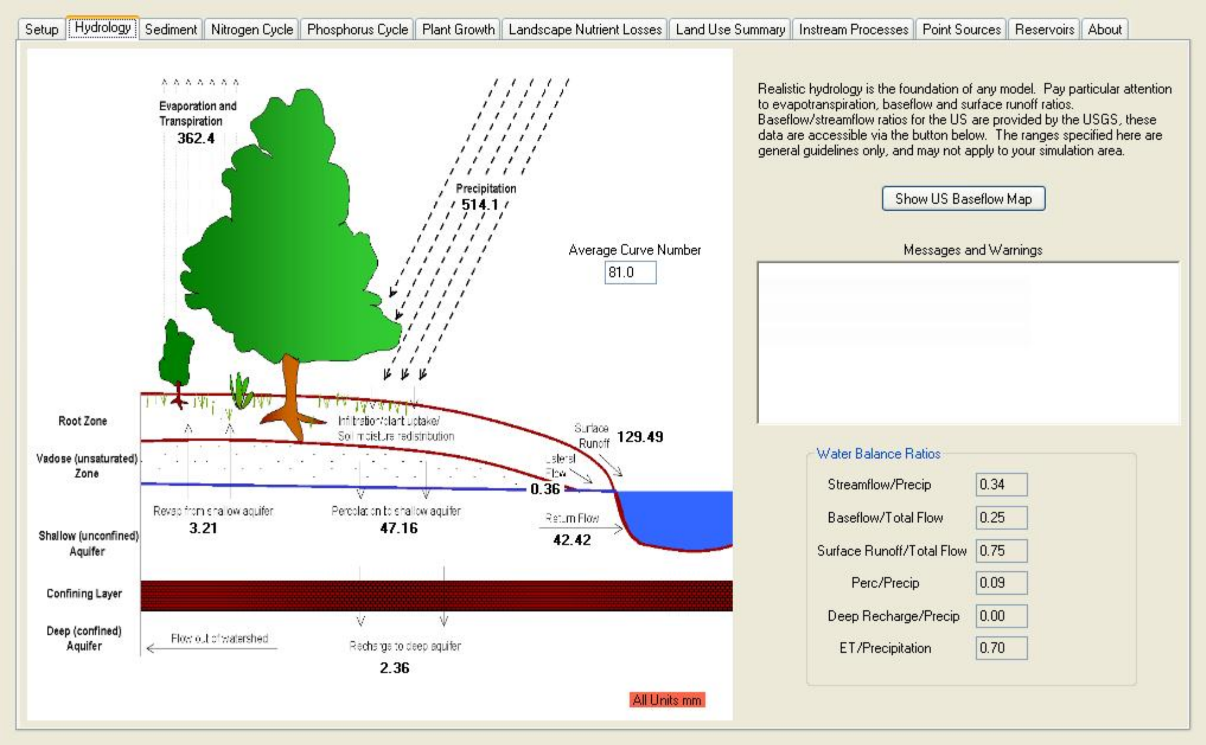

Fig. 18. SWAT-CHECK results

6.7. Model calibration and uncertainty analysis

The SWAT model should be calibrated in order to adjust the calculated and observed data. Therefore it is necessary to acquire the actual flow data of the drainage networks and compare it with the results of flow estimation, simulated by the SWAT model.

The SWAT-CAP application has been used for these purposes. This program is designed for calibration of the SWAT models, linking different procedures to SWAT (Fig. 19). It enables sensitivity analysis, calibration, validation, and uncertainty analysis of the model (Abbaspour 2011).

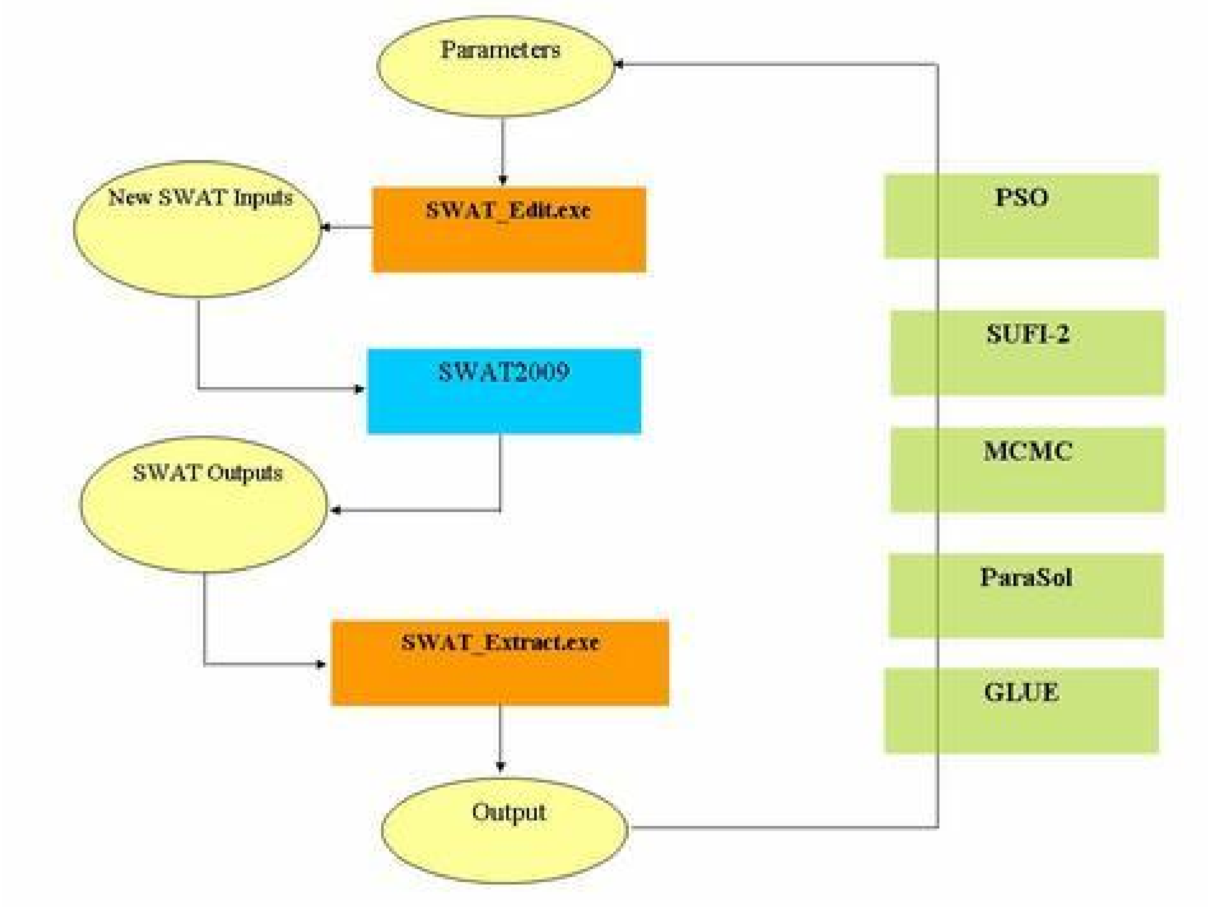

Fig. 19. SWAT-CUP structure (Abbaspour 2011).

Calibrated parameters are based on the objective function, the type, and numbers of data points and the chosen calibration procedure (Abbaspour 2011).

The SUFI2 method has been chosen for calibration. In SUFI-2, uncertainty of input parameters are depicted as uniform distributions, while model output uncertainty is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% and 97.5% levels of the cumulative distribution of output variables obtained through Latin hypercube sampling.

Uncertainty here includes different driving variables (e.g., rainfall), conceptual model, parameters, and measured data.

SWAT-CUP program interface links the input/output of a calibration program and the model. It contains different input parameters of reaches, subbasins, etc that can be edited and optimized by user.

Observed monthly data on the water discharge for 9 outlets, matching existing hydrological gages, covering period 2001-2008, was prepared in required format and loaded in the SWAT-CUP. Thirteen parameters have been included in calibration, 500 simulations have been run with four iterations. Satisfactory calibration results have been achieved for annual waterflow simulation.

6.8. Main assumptions and limitations

The following general assumptions and limitations can be defined for the developed the SWAT model:

- The SWAT model didn't include water quality data therefore output parameters on quality were ignored
- Regionalization of the observed rainfall and temperature data in SWAT may introduce large errors in the SWAT model, so the surface runoff may be simulated incorrectly (Abbaspour et al. 2007)
- Lack of data also prevented calibration of the model based on crop yields.
- The full capabilities of the SWAT model were not realized due to lack of local water and agricultural management information

- Small reservoirs presented in the area were excluded from the analysis, assuming that it will not change significantly water balance in the study area.
- A major limitation to large area hydrologic modelling is the spatial detail required to correctly simulate extreme events, as it may occur with spatial variability of the precipitation data within a watershed.

Overall, considering that the SWAT model was not calibrated properly, mainly due to lack of different data, such as crop yields, agricultural management practices (fertilizers use, tillage, etc.), it still provided results on satisfactory level in order to analyze ecosystem goods and services under different scenarios.

7. SCENARIOS FORMULATION AND ANALYSIS

The purpose of this chapter is formulation of the SWAT scenarios and their analysis using the developed SWAT model.

The first section presents the developed SWAT scenarios till 2050. The second section discusses the results of preliminary analysis of these scenarios in the Upper Don River using the ArcGIS spatial analyst tools. The next section analyzes the outputs of the scenarios-based SWAT model runs. The consequent EGS assessment is provided in the forth section. Finally, the main conclusions from the analysis stage are summarized.

7.1. Land use and climate change scenarios

The scenarios on land use and climate change developed by EnviroGRIDS project, using data for 2050 have been formulated for analysis with SWAT.

The EnviroGRIDS changes scenarios, giving projections for 2050 on 1kmx1km grids land cover dataset have been applied. These scenarios have been developed with the Metronamica modelling framework, which allows developing and testing spatially dynamic land use models enabling the exploration of spatial development in the area of study depending on autonomous developments, external factors and policy measures (RIKS 2005).

Combined method has been used to quantify the land use demand with IMAGE, version 2.2 (Kram and Stehfest 2006), and disaggregation of the global scenarios at a regional scale according to Nomenclature of Territorial Units for Statistics (NUTS2) has been applied. This demand was used to estimate the LU changes in BSC, disaggregating to regional level and used as input to the regional/local LU allocation model (RIKS 2005).

As a result four alternative land use scenarios were derived: BS HOT, BS ALONE, BS COOP and BS COOL (Fig. 20).

The storylines of these scenarios were based on emissions scenarios proposed by IPCC-SRES (Nakicenovic *et al.* 2000), representing different ways of global socio-economic development: more economically oriented and more environmentally and more environmentally and equity oriented ones in the vertical axis. Additionally, different studies on global and European scenarios have been used. More information can be found in deliverables of the EnviroGRIDS project "D3.8 The enviroGRIDS scenarios" (Mancosu *et al.* 2012).

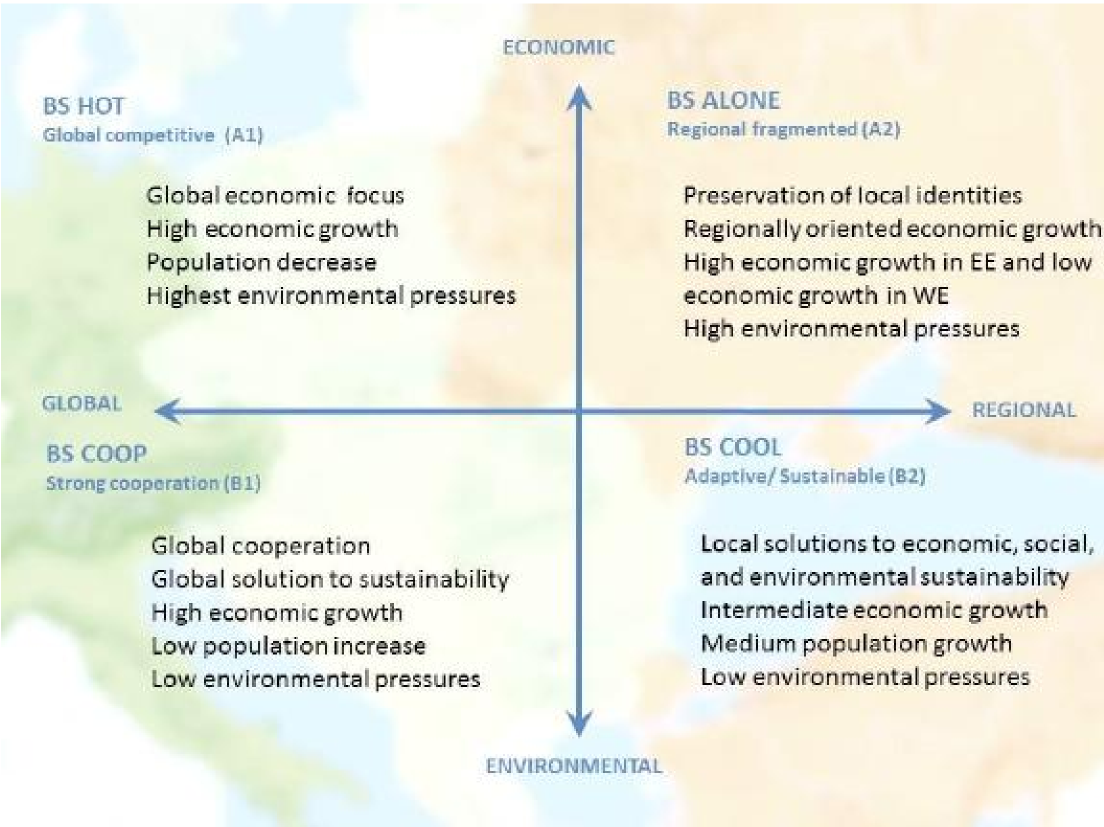

Fig. 20. EnviroGRIDS scenarios: BS HOT, BS COOP, BS ALONE and BS COOL (Mancosu *et al.* 2012)

BS HOT corresponds to the IPCC's A1FI scenarios (fossil intensive), with environmental issues are not the main concern. BS COOP refers to the B1 climate scenarios, with strong cooperation and high environmental concerns. The BS ALONE corresponds to A2 scenario with high economic growth and high environmental pressure, and BS COOL corresponds to B2 scenario with strengthening of the local bodies implementing strategies to promote local sustainable development.

The following land use changes patterns will occur according to the EnviroGRIDS scenarios:

- The largest area of agriculture and grassland in the BSC is observed in the economic/regional scenario: BS ALONE;
- The smallest area of agriculture in the BSC is observed in the environmental/global scenario: BS COOP;
- The largest area of forest in the BSC is observed in the environmental/regional scenario: BS COOL;
- The smallest area of forest in the BSC is observed in the economic/global scenario: BS HOT.

For generating time-series of climatic conditions, corresponding to the land use change scenarios the stochastic weather generator Long Ashton Research Station Weather Generator (LARS-WG) (Racsko *et al.* 1991; Semenov and Barrow 1997) has been applied. The generator simulates time-series of daily weather at a single site. One of the main purposes of use of this tool is generating long time-series suitable for the assessment of agricultural and hydrological risks and produce daily site-specific climate scenarios for impact assessments of climate change. It has been applied successfully in previous studies with SWAT modelling tool (e.g Obuobie 2008), showing satisfactory level of weather data simulation.

The LARS-WG model version 5.0 (Semenov and Stratonovitch 2010) is based on fourteen Global Climate Models (GSMs) used for various emission scenarios in the IPCC 4th Assessment Report. Table 3 shows the scenarios of climate change used for weather data generation in correspondence to EnviroGRIDS land use change scenarios. Green areas indicate correspondence between land use scenarios proposed by EnviroGRIDS and emission scenarios, used for generating weather time-series data.

Table 3. Correspondence of LARS-WG climate scenarios to EnviroGRIDS land use change scenarios

	BS HOT	BS COOL	BS COOP	BS ALONE
SRA1B				
SRA2				
SRB1				

The LARS-WG model version 5.0 doesn't generate weather data on SRB2 scenario, therefore it was assumed that data on SRB1 scenario will be the most relevant, as it also implies low environmental pressure and relatively low economic and population growth (Semenov and Stratonovitch 2010).

The time-series temperature and precipitation input data for 5 stations, used for baseline model development has been generated.

7.2. Preliminary analysis

In order to understand potential implications of the land use changes on the regional hydrological balance the preliminary analysis of the formulated scenarios has been conducted by the author using various spatial analysis techniques using the analysis tools provided by the ArcGIS 9.3 package .

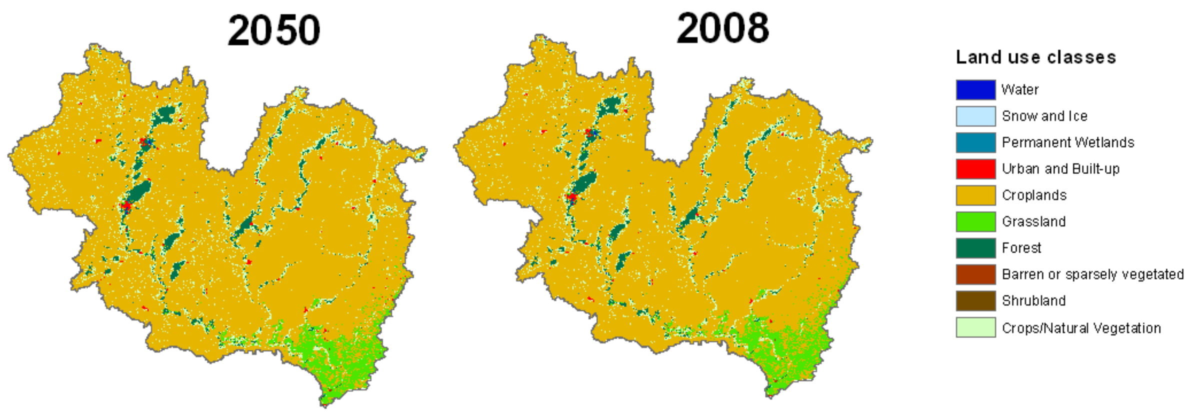

Fig. 21. The current land use in the Upper Don river catchment compared with the EnviroGRIDS BS HOT land use scenario

It was found that according to the EnviroGRIDS scenarios different land use patterns are projected based on different scenarios:

1) BS_ALONE – Almost 40% of increase of barren and sparsely vegetation will occur according to this scenario in the area;

2) BS_COOL – Urban and barren areas are going to decrease on 35 and 12% accordingly, while forests, shrubland and natural vegetation are going to increase (4, 7 and 24 % accordingly);

3) BS_COOP – Natural vegetation is going to decrease twice and shrublands will expand on 25%, while urban areas will decrease almost 25%;

4) BS_HOT – The largest increase of urban area will occur according to this scenario (more than 26%). Simultaneously shrubland area is going to decrease more than 60%.

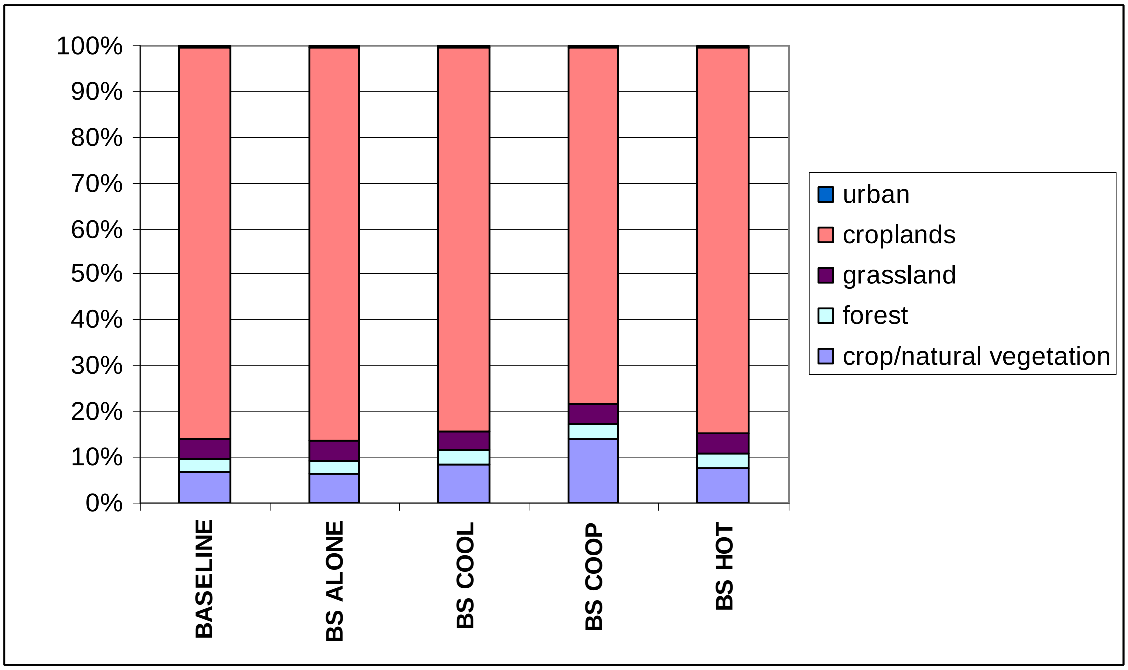

Fig. 22. Change of major land use categories in 2050 according to different scenarios in the Upper Don River Watershed comparing to the baseline (2008). Based on statistics retrieved with ArcMAP

It can be concluded that the significant change in land use patterns the area will occur under all scenarios. Therefore further investigation of the water balance in the Upper Don River catchment under these conditions might reveal substantial change of the water-related ecosystem goods and services.

7.3. SWAT-based EGS assessment

The sets of SWAT input files highlighting land use and weather conditions corresponding to four different scenarios have been prepared. Based on these datasets the developed SWAT model have been used to generate the main hydrological characteristics of the Upper Don River until the year 2050. The main hydrological parameters at the primary subwatershed outlet next to the Upper Don River inflow to the Tsimlyansk reservoir are presented in Table 4. Baseline (2001-2008) and projected (2050) annual average hydrological parameters for the Upper Don RiverThe baseline (column 1) shows the average annual values obtained from the calibrated SWAT model for the period 2001-2008 (chapter 6). The last row ("streamflow") presents the values of the annual average inflow into the Tsimlyansk reservoir (cubic meters per second).

Table 4. Baseline (2001-2008) and projected (2050) annual average hydrological parameters for the Upper Don River

	BASELINE	BS HOT	BS COOP	BS ALONE	BS COOL
Water yield	177.64 mm	139.78 mm	141.07 mm	143.04 mm	140.36 mm
Precipitation	546.2 mm	528.40 mm	535.39 mm	541.19 mm	535.39 mm
Surface runoff	136.25 mm	116.89 mm	117.81 mm	120.11 mm	118.25 mm
Baseflow (groundwater)	53.47 mm	33.32 mm	35.16 mm	34.85 mm	34.33 mm
Evapotranspiration	368.5 mm	407.52 mm	390.70 mm	390.79 mm	393.90 mm
Potential Evapotranspiration	834.8 mm	915.29 mm	908.89 mm	888.90 mm	908.89 mm
Streamflow	1254.91 cms	879.22 cms	799.27 cms	892.20 cms	799.27 cms

As it can be seen from the comparative table all the scenarios formulated for the Azov Sea basin exhibits the same general trend for the decrease in water availability in the region in general and in the Tsimlyansk in particular. At the same time some minor changes among these scenarios can be outlined:

BS HOT. Under this scenario the water yield is going to decrease almost by 22%, which greater than under all other scenarios with the highest decrease of precipitation. The baseflow is going to decrease as well, while evapotranspiration and potential evapotranspiration will increase by 4% and 6% correspondingly. As a result the average annual inflow into the Tsimlyansk reservoir will decrease by 30% in 2050.

BS COOL. Under this scenario the water yield will decrease by 20%, however baseflow will not decrease as much as under other scenarios. Surface runoff will decrease by 13%, less than in BS HOT that can be explained by increase of forests and shrublands area according to the land use change scenario. Nevertheless, higher ET rates and relatively lower precipitation rates will lead to decrease in the average annual inflow into the Tsimlyansk reservoir by 36% in 2050.

BS ALONE. Under this scenario runoff will decrease, but less than under other scenarios (12%), which can be explained not only by relatively high precipitation rates, but also by increase of barren and sparsely vegetation according to the land use change scenario. As a result average annual the inflow into the Tsimlyansk reservoir will decrease by 28% in 2050, which is less than for all other scenarios.

BS COOP. Under this scenario which can be explained by increase of barren and sparsely vegetation. However baseflow will decrease less than in other scenarios that can be explained by increase of forests and shrublands in 2050 according to the land use change scenario. In this case water content in soil may increase, while surface runoff will decrease (14%). As a result average annual inflow into the Tsimlyansk reservoir will decrease by 36% in 2050.

The similar trend for water availability decrease has been observed for all 30 outlets where the hydrological parameters were calculated with the SWAT model . The even outlets distribution through the sub-catchment area allows to conclude that water yield decrease is characteristic for the entire Upper Don River sub-catchment.

7.4. Implications for the regional EGS

The analysis of the obtained changes in waterflow and other hydrological parameters reveals substantial decrease in water supply through the Upper Don River watershed and indicates substantial drop in the water inflow to the Tsimlyansk reservoir, the most significant provider of the EGS in the region. This will challenge provision of many water-related ecosystem goods and services in the area.

Considering high economic growth and high environmental pressure in the region proposed by scenarios BS ALONE and BS HOT, together with high population increase under scenarios BS COOL and BS COOP it may be concluded that demand for water supply will increase under all scenarios, while capacity of the ecosystem to provide it will be diminished according to the results of analysis with SWAT model.

Finally, it was found that the inflow into the Tsimlyansk reservoir from the Upper Don River sub-catchment will decrease from 28 to 36% under different scenarios, what means that the ability of the Tsimlyansk reservoir to provide the various currently available ecosystem goods and services will be hindered. As it was indicated in the previous sections the reservoir is a crucial component of the basin multipurpose water management scheme in the Lower Don river as well. Many EGS such as navigation, water supply for consumptive use depend on the existing annual water flow redistribution scheme. Moreover, attempts to maintain the required reservoir inflow should impose limitations on the EGS provision for the upstream beneficiaries. In this way, the occurred changes in the water supply to the reservoir compromise the EGS provision for the entire basin.

As it was indicated in the previous sections there are numerous plans for the regional development relying on the currently available EGS provided by the existing multipurpose water management scheme, including increase of navigation capacity, construction of new Volga-Don canal, water dependent industry. The Tsimlyansk reservoir plays a crucial role in this scheme and possible changes in water availability under different scenarios should be taken into account in the regional policy-making process in order to secure sustainable development.

7.5. Conclusions

The set of scenarios outlining possible land use and climate changes in 2050 has been developed using the findings of the EnviroGRIDS project. Based on preliminary analysis of these scenarios with ArcGIS spatial analysis tools it was found that proposed changes in the land use might lead to notable change in the hydrological balance. Then, scenarios datasets have been converted into the format required for creating the input data for the SWAT model and analysis of the output data has been conducted.

As it was found all scenarios of the land use and climate change will result in significant decrease of water supply in the Upper Don River sub-catchment and, correspondingly, changes in the Tsimlyansk reservoir inflow. This may significantly undermine provision of the hydrological EGS in the region that should be taken into account while developing regional development strategies.

8. DISCUSSION AND CONCLUSIONS

This chapter presents the discussion of the research findings and outlines recommendations for ecosystem goods and services assessment in the Azov basin and further improvements of use of ArcSWAT for this purpose. The first section provides the discussion of the research outlining the mains steps completed and the outcomes obtained with the SWAT model. The second section discusses the further avenues for the assessment of water related ecosystem goods and services in the Azov region. Next, the limitations of the application of ArcSWAT modelling tool in the EGS assessment as well steps for the possible model improvements are formulated. Final section sums up conclusions of the study.

8.1. Research discussion

The aim of the research was to analyze the potential and limitations of the SWAT tool in assessment of water-related ecosystem goods and services based on the case study of the Azov Sea Basin.

In accordance with the specified research objectives and the formulated research stages the analysis of the current EGS in the Azov basin was carried out.

Firstly, it was necessary to determine the ecosystem boundaries, which is the primary step in the ecosystem goods and services assessment framework. Based on extensive literature review and data analysis of the Azov Basin ecosystem the area and scope of study have been defined. Based on that it was concluded that the Tsimlyansk reservoir plays the key role in the provision of the water related EGS in the region. Correspondingly, it was decided to assess the possible changes in the water inflow to the reservoir as a basis for EGS assessment. Using the ArcSWAT watershed delineation function the sub-catchment encompassing the Upper

Don River the main outlet adjacent to the outflow of the Don River into the Tsimlyansk reservoir has been defined.

The SWAT model for the Upper Don River, the primary source of water for the Tsimlyansk reservoir, has been developed and used for the analysis of the possible changes in the factors influencing the water formation. The model was constructed using ArcGIS software.

The SWAT model requires variety of data including both averaged basin-wide parameters and spatially-explicit GIS datasets. The datasets needed have been collected from various sources. In order to prepare the SWAT input files many datasets have been reprocessed into the SWAT compatible format.

The developed model was successfully validated and calibrated using historical hydrological and meteorological observation records. The obtained hydrological characteristics have been used later for performing baseline assessment of ecosystem goods and services. Nevertheless, the quality of the model and the precision of simulations have been undermined by lack of various specific parameters, such as crop yields, agricultural management practices (fertilizers use, tillage, etc.) and can be further improved.

Based on the scenarios proposed by the EnviroGRIDS project focusing on land use and climate changes the model allows assessing of the prospective water supply in the Tsimlyansk reservoir by 2050.

The preliminary analysis of the change scenarios and their potential impact on the EGS has been firstly conducted using various techniques such as spatial analysis and statistical methods.

The climate scenarios, corresponding to the EnviroGRIDS land use change storylines, are based on the emissions scenarios proposed by IPCC-SRES. They were used in order to generate time-series weather data with the well established weather generator LARS-WG.

Finally, the developed four SWAT model scenarios (BS HOT, BS COOL, BS COOP and BS ALONE) were tested with ArcSWAT in order to estimate the change of inflow into the Tsimlyansk reservoir under different climate and land use conditions. It was found that according to all scenarios annual water yield, baseflow and surface runoff in the Upper Don River sub-catchment will decrease, and as a result the streamflow supplying the Tsimlyansk reservoir will be reduced by 28-36% under different scenarios in 2050 with the largest change under the BS HOT scenario.

Considering high economic growth and high environmental pressure in the region projected under scenarios BS ALONE and BS HOT, together with high population increase under scenarios BS COOL and BS COOP, it may be concluded that the demand for water supply will increase under all scenarios, while the capacity of the Azov basin ecosystem to provide it will be gradually decreasing.

8.2. Further assessment for ecosystem goods and services in the study area

Taking into account the discovered implications of the land use and climate changes on the water balance in the Upper Don River sub-catchment and corresponding decrease of inflow into the Tsimlyansk reservoir hindering EGS provision in the near future, further more detailed assessment of the ecosystem goods and services in the region is required for both in-situ and diverted water supply in the Tsimlyansk reservoir and Upper Don River.

The following measures can be undertaken in order to further improve the EGS assessment in the region:

- identify main beneficiaries of water provision services and their explicit location both in the Upper Don River and at the Tsimlyansk reservoir;
- determine the demand for water supply by different stakeholders in the Upper Don River sub-catchment in order to perform weighted valuation of the water provision;
- define the value of water supply through variety of economic, non-economic or integrated valuation frameworks;
- conduct trade-off analysis based on the valuation and develop strategy on securing water provisioning services such as in-situ and diverted water supply for different stakeholders.

8.3. Recommendations on SWAT modelling for EGS assessment

Overall, it can be concluded that the application of the process-based hydrological model (i.e. SWAT) is an effective tool for the ecosystem goods and services assessment successfully due to its ability to realistically simulate hydrological ecosystem processes depending on number of variable input parameters.

However, it should be emphasized that the model has several limitations and assumptions that should be considered for enhancement of the assessment results. All environmental models, including SWAT, are simplified representations of reality with the level of uncertainty defined by available data sets and their relevance.

The following steps are proposed by the author to improve the performance of the SWAT model:

- inclusion of water quality data as one of the main attribute of hydrological services with main point sources may contribute to the final assessment of hydrological EGS in the area;
- data on the regional agricultural practices and crop rotations is required for better SWAT model calibration;
- expanding the measured meteorological data records (temperature and precipitation) both in spatial and temporal scale might significantly improve performance of the model;
- considering the weather data quality issues. It relates to both historical datasets and stochastic weather generators used for climate scenarios input data, it is highly advisable to validate the datasets generated for the research;
- analysis of adequacy of the observed data should be performed in order to avoid errors in simulation and calibration processes.
- thorough sensitivity analysis of the parameters, affecting the flow discharge for the developed SWAT model, may improve calibration and validation.

8.4. Conclusions

As it was indicated in the previous sections there are numerous plans for the regional development relying on the currently available EGS provided by the existing multipurpose water management scheme, including increase of navigation capacity, construction of new Volga-Don canal, water dependent industry. The Tsimlyansk reservoir plays a crucial role in this scheme and possible changes in water supply under different scenarios should be taken into account while developing the regional management strategies to secure sustainable development.

Data collection, analysis of adequacy of input data, careful data processing and reasonable calibration and validation are prerequisite measures for adequate performance of the SWAT model. Recognizing both the potential and the limitations of hydrological models and critically evaluating the modelling results, it can be concluded that ArcSWAT modelling tool is powerful framework for hydrological processes simulation with evaluation of hydrological EGS, that serves as an effective baseline for further hydrological ecosystem goods and services assessment.

The GIS database describing the Upper Don River, which has been developed in the current research, can be used for further analysis of this important region using alternative methods and techniques. The recommendations on possible improvement and further research avenues have been formulated.

Overall, it can be concluded that though having some shortcomings and limitations (e.g. required data availability) SWAT modelling tool can be considered as a useful tool in EGS assessment.

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10. ANNEXES

A 1 Example of the watershed annual summary created by SWAT for 2015

SWAT Aug 23 2011 VER 2009/Rev. 488

General Input/Output section (file.cio):
7/24/2012 12:00:00 AM ARCGIS-SWAT interface AV

Annual Summary for Watershed in year 3 of simulation

UNIT TIME	PREC	SURQ	LATQ	GWQ	PERCO	TILE Q	SW	ET	PET	WATER YIELD	SED YIELD	NO3 SURQ	NO3 LATQ	NO3 PERC	NO3 CROP	N ORGANIC	P SOLUBLE	P ORGANIC
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(t/ha)	-----------------(kg nutrient/ha)------------------						
1	68.77	35.31	0.02	1.04	0.33	0.00	141.00	10.92	16.05	33.30	0.16	0.83	0.00	0.12	0.06	1.23	0.02	0.13
2	44.24	20.54	0.01	1.69	0.14	0.00	155.01	2.87	5.25	20.01	0.08	0.16	0.00	0.05	0.08	0.66	0.01	0.07
3	32.07	29.19	0.01	2.44	1.05	0.00	141.10	41.47	82.79	29.05	0.12	0.31	0.00	0.35	0.11	0.92	0.02	0.10
4	43.73	3.63	0.02	2.52	0.60	0.00	144.09	37.32	107.12	5.54	0.01	0.05	0.00	0.22	0.10	0.07	0.00	0.01
5	39.87	2.73	0.03	1.78	0.39	0.00	127.58	53.54	91.58	3.99	0.02	0.08	0.00	0.08	151.05	0.10	0.00	0.01
6	73.55	8.30	0.03	1.10	0.18	0.00	110.39	81.06	103.55	8.23	0.03	0.22	0.00	0.03	132.78	0.23	0.00	0.03
7	34.15	1.60	0.03	1.04	0.15	0.00	75.65	68.52	124.88	2.36	0.00	0.01	0.00	0.01	4.67	0.02	0.00	0.00
8	42.20	2.78	0.03	0.77	0.00	0.00	96.51	18.37	114.13	2.91	0.01	0.01	0.00	0.00	0.44	0.07	0.00	0.01
9	26.22	0.27	0.03	0.53	0.14	0.00	103.79	18.69	82.01	0.78	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00
10	24.82	0.27	0.03	0.34	0.27	0.00	112.33	15.68	73.46	0.57	0.00	0.03	0.00	0.05	0.00	0.00	0.00	0.00
11	89.53	6.82	0.05	0.95	7.98	0.00	166.23	17.10	31.27	5.95	0.02	0.23	0.00	3.35	0.00	0.16	0.01	0.02
12	53.75	14.78	0.06	5.77	5.91	0.00	165.69	14.73	24.67	19.06	0.06	0.48	0.01	2.64	0.01	0.49	0.01	0.05
2015	572.89	126.22	0.37	19.96	17.13	0.00	165.69	380.28	856.76	131.76	0.52	2.43	0.03	6.90	289.30	3.95	0.08	0.43

A 2. Example of the daily output data retrieved with SWAT for the outlets. FLOW_OUT represents Streamflow values

SUB	YEAR	MON	AREAkm2	FLOW_INcms	FLOW_OUTcms	EVAPcms
1	2015	1	12980	121.1	121.2	0
2	2015	1	17190	153.7	148.7	0.000343
3	2015	1	7258	130	130	0
4	2015	1	37960	404.1	391.3	2.374
5	2015	1	21190	281.3	269.5	0
6	2015	1	13390	178	167.1	0
7	2015	1	19680	299.1	271.5	0
8	2015	1	34780	450.2	449.5	0.3352
9	2015	1	35120	452.5	452.4	0.05927
10	2015	1	7571	51.32	51.18	0.05861
11	2015	1	68640	820.8	808.8	1.942
12	2015	1	8909	137.9	138	0
13	2015	1	15380	275.1	268.5	0
14	2015	1	44820	520.7	518.2	0.5673
15	2015	1	72110	869.2	862.7	1.186
16	2015	1	8816	120.2	118.3	0.5058
17	2015	1	46900	535.4	526.3	0.7779
18	2015	1	9508	69.46	70.13	0.2704
19	2015	1	34040	520.4	509.5	1.695
20	2015	1	101600	1149	1120	3.49
21	2015	1	61190	632.4	616.6	1.4
22	2015	1	35060	521.4	520.8	0.515
23	2015	1	168800	1769	1769	0.03648
24	2015	1	168600	1767	1767	0.4588
25	2015	1	168800	1769	1769	0.3977
26	2015	1	107200	1165	1148	2.026
27	2015	1	9430	137.2	137.1	0.003119
28	2015	1	208200	2349	2285	4.786
29	2015	1	221400	2471	2441	2.547
30	2015	1	221500	2442	2442	0.09834