GIS based simulation of scenarios for river basin management

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Natural resources management requires an approach that integrates aspects of various natural sciences, socio-economic facts and last not least stakeholder involvement. For these purposes, a huge amount of legal instruments and literature is available that build a framework and ease management activities. In the EU member countries, the Water Framework Directive (WFD), the Soil Directive (SD), Habitat Directive, the Floods Directive (FD) and other important documents play a crucial role in relation to the here described work

As Ukraine aims at implementing the above mentioned directives or at least adapted directive versions the relevant methods have to be oriented at the corresponding guidance documents. [xxxxx]. For the WFD for example, the EU member states have to prepare reports including a whole series of GIS based maps. The GIS guidance document contains the details to be applied to reach seamless continuation of thematic maps all over Europe.

The main aim of the WFD is to reach the “good ecological status” (or “good ecological potential”) of water bodies until the year 2015. For many rivers this requires a management of the river basin to optimize the use of land and water resources respecting the above mentioned directives. Management measures are, nowadays, discussed with the stakeholders including the public as prescribed in article 14 of the WFD and in the Aarhus Convention. Consequences of management variants for the future are often discussed controversially according to the differing interests.
International projects have been launched that will reduce the conflict potential and to work out a common vision for the future (e.g. Geo-4, Harmonica, Scenes). For the Scenes project the Black Sea Region was selected including the Ukraine (Pilot Area Crimea) and stakeholder workshops were held to reach a common vision for the future till the year 2050. [x].

In this framework, GIS based models can help to quantify the effect of influencing factors with respect to water quantity and water quality of rivers. Various land use changes, climate change, water abstraction, discharges of waste waters and many other influences can be simulated and compared for a bigger territory like a river basin and looking forwards to the coming years. The Soil, Habitat and Floods Directive (a.o.) provide further aspects and inputs to be considered. The interrelationship between all these aspects can best be understood and quantified using GIS based models.

Stakeholders often ask how GIS and GIS based models can support landscape management and decision making. GIS target groups work in water management related state administrations, water works and waste water treatment plants, industry, agriculture, tourism, research and education institutes, NGOs or the engaged public. Typical questions are listed in the following table grouped into the three categories: hydrophysic, land management and ecology.

Hydrophysical aspects:

- How does the river network look like under different weather and hydrological conditions (dry reaches, length of streams)?
- From which areas does the river water mainly come from and what are the related shares?
- How big are the slopes, slope lengths and potential flow accumulation in the basin?
- How are the different soil types and land uses distributed in the subbasins?
- Which run-off potential (in terms of curve numbers, CN) can be attributed to the singular subbasins?
- Where are soil erosion risks and where do the suspended solids in the river come from?

Land managements aspects:

- From which subbasins do nutrients mainly come from and which concentration range can be expected?
- Where can be identified erosion risks that can be reduced by land use changes?
- How does land use influence the above mentioned hydrophysical parameters?
- How to optimise irrigated lands allocation and irrigation performance?

Ecological aspects:

- What will be the land use and landscape changes if climate (temperature, precipitation) continues changing?
- What will be the impact of land use changes as for example enlargement of riverbank buffer stripes?
- How can the existing landscapes be reshaped to reach better preconditions for endangered species, biodiversity increase?
- Where are anthropogenic impacts or human stressors located? (density of roads and other impermeable surfaces, vicinity of roads close to streams or rivers)
- How can nature and agricultural landuse be balanced for ecosystem (wetland) protection?

This paper will show some examples of work with GIS and GIS based models. Some of the required inputs are available on the Internet but some other data and information must be prepared manually using existing information sources like maps, atlas, specialized literature or satellite imagery.

Methods overview

The work with GIS was performed using the commercial program ArcView 3.2a (ESRI) and the “open source” program MapWindow. ArcView has been selected because many additional extensions can be linked for a broad spectrum of tasks. These modules are the hydrological simulation model SWAT (AVSWATx), also usable for statistics and graphics; L-THIA NPS GIS and ATtILA are additionally used to generate maps of hydrological parameters, water quality and related landscape assessments. They require similar input data and maps as AVSWATx and broaden the spectrum of attainable results.

SWAT principle

SWAT is a simulation model (Arnold et al. 1998) that requires a big amount of input data related to more than 200 parameters including the optional inputs, (for an overview s. fig. 1). If the input data are insufficient, the model can use default values in some cases, but if too many data is missing, delivered results might be inaccurate or the model will not work at all.

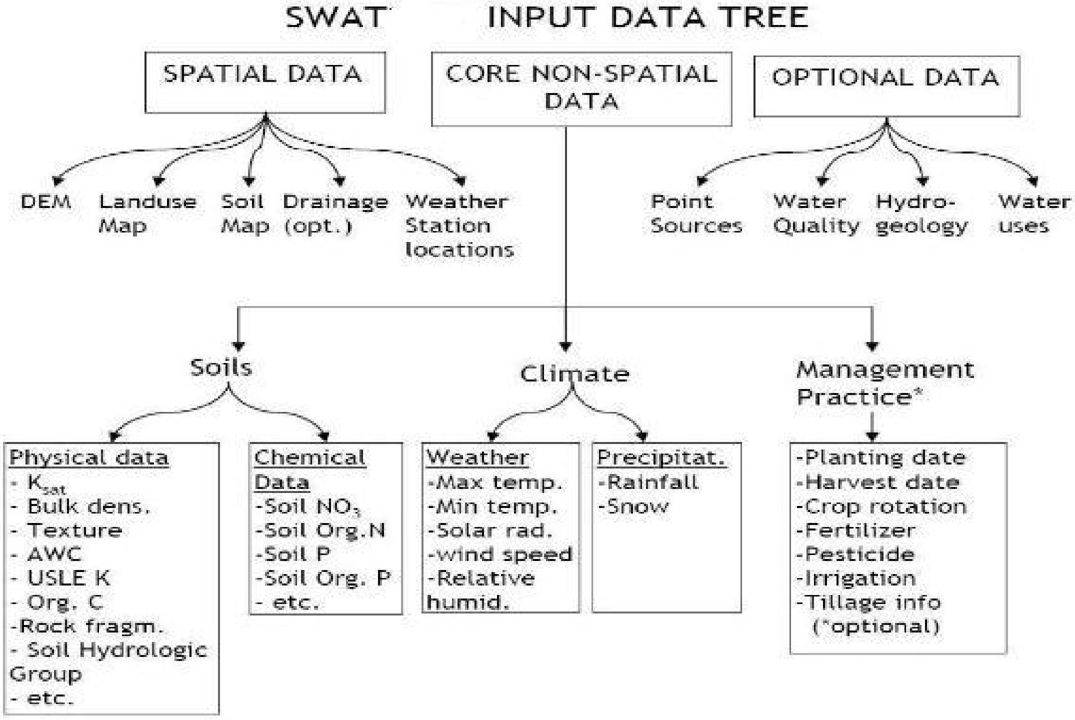

Fig. 1: Overview on required input information for SWAT (from [4])

The model is capable of continuous simulation over long periods. Major model components include weather generator (to fill in missing data and for forecasting), hydrology, various physical soil properties, plant growth parameters, nutrients, pesticides and land management. In SWAT, a watershed is divided into multiple subbasins, which are then further subdivided into hydrologic response units (HRUs) that are homogeneous with respect to land use, soil type and elevation above sea level.

ATtILA2004v.1.0 principle

The program is used to assess landscape diversity, the role of riparian zones, hydrophysical characteristics and human stressors. Correspondingly, the work with ATtILA is subdivided into four “metrics” (Environmental Protection Agency 2007):

1. **landscape characteristics** (main input is a land use grid, soil grid and precipitation grid),
2. **riparian characteristics** (focusing on the buffer stripes along the water courses),
3. **human stresses** (including anthropogenic impacts on rivers by agriculture, settlements and roads)
4. **physical characteristics** (slope, erosion risks)

L-THIA NPS GIS principle

This module also works based on a land use map, soil type map and precipitation time series (Purdue University 2004). It firstly calculates CN (curve numbers) (United States Department of

Agriculture 2009), average and peak flows under different weather conditions as well as a set of inorganic and organic water quality parameters, and then allows for presenting the results in the GIS project.

Preparation of Inputs

It is crucial to prepare the input information very carefully. In many western countries, suitable maps and data on land use, soil types and weather data are available on the Internet in digital form and retrieving them is a matter of a view minutes. In Ukraine, data are more difficult to find, expensive to get and usually they are on paper only. This is why the preparation phase can comprise many months or even years.

The main materials required to work with SWAT in the pilot area (Crimea) are (s. fig. 1):

- Topographical map available from SRTM (Jarvis et al. 2008)
- In special cases (flat landscape): a map of the river network (prepared as shapefile)
- Land use map (prepared as shapefile, updated or edited using Google Earth)
- Map of soil types (and related physical characteristics to be stored in a database); a soil map is available from the *European Commission and the European Soil Bureau Network (2004)*, for editing some details, Ukrainian maps were used (SL-studio 2005, Bagrov and Rudenk 2004. Some of the missing hydrological soil parameters have been estimated using the program *Soil Water Characteristics,* version 6.02.74 (Saxton 2007).
- Weather data time series for precipitation and minimum and maximum temperature; optional: time series of solar radiation, relative humidity and wind speed (CGMS data; European Commission 2009)

Statistics

The results of simulations (SWAT) were compared (main method: calculation of the Nash and Sutcliffe 1970 coefficient) with observed data (using monitoring results as far as available) for model calibration and verification. In order to compare water quality data, more monitoring results still have to be collected and will be reported later.

Investigation program

The investigation area was restricted to several headwaters subbasins of the river Salgir on Crimea, Ukraine. The remaining subbasins are investigated too to provide simulation results for decisions of local stakeholders and for the construction of quantitative water scenarios in the frame of the international "Scenes" project. A third investigation area has the focus on the basin of the Pobeda River (NE Crimea) and the influence of the river water discharge on the Sivash wetlands.

The main work consisted in the search and collection of input data; many of them are available locally but exist on paper only; they have to be copied and stored in databases. Maps of land use and soil characteristics exist but sometimes they must be corrected like land use maps according to recent years. Soil types have to be defined according to the needs for the SWAT model. Each soil area includes about 14 aspects (parameter) that are not mapped and even difficult to find in the literature. Own field trips have to complete the picture in this case as far as possible.

Results and discussion

On the basis of maps (retrieved from the Internet or manually digitised) and input data (weather, soil and land-use data) a series of new thematic maps has been generated with GIS techniques and GIS based models. They can be used to answer such questions as they are listed in the table above. Below two typical examples, out of many others, are described. The river water discharge is a matter of concern for planning of possible and ecologically sustainable water use. Priority has the private water consumption, but bigger amounts of water are required for agriculture and industrial purposes. For sophisticated plannings, one should be aware of the expected river water discharge under different climatic conditions, the water yield in the various tributary subbasins and the effect of planned land use changes.

As a **first example**, the situation in the Simferopol Oblast is considered here. Gaining suitable drinking water for more than 400000 inhabitants of Simferopol has the highest priority. The required water volume is secured through the management of the Simferopol reservoir. The actual river basin management task consists in the aim to select land uses in the upstream catchments in a manner that optimises the available water volume and quality. High concentrations of nitrate and phosphate in the Salgir and the reservoir lead to eutrophication and thus to problems for the drinking water preparation.

A possible scenario could be to decrease (crops dominated) agriculture in a broad stripe along the river and its tributaries and replace it by forestation or pastures or a mixture of both. Additionally, places, which are at risk for erosion are sorted out and forested. This will reduce the transport of phosphorous, which is mainly adsorbed on soil particles, to the reservoir.Figure x shows the sediment yield in the singular subbasins of the upper Salgir reaches. The exact amount of transported sediment will, of course, depend on the actual weather conditions and, besides, calibration with observed data is necessary. Nevertheless, GIS based models can help to show changes in sediment yield under different land use of climatic changes. Additionally, agricultural practice is changed in the sense that soil covering crops, especially those growing in winter, and adapted tillage methods are implemented. Artificial fertilising is replaced by organic fertilisers and it is secured that no fertilising at all is practised from October till end of March. Another measure to be discussed could be to provide canalisation for all settlements in the region. The high costs of this measure can be justified if a positive effect can be demonstrated by model simulation. All these measures can be implemented together or step by step and their effect can be estimated well in advance using GIS and GIS based models.An example of actual nitrate yield in the various subbasins is shown on the map (fig. y).

A **second example** is related to floods that rather often occur in the Pre- and Trans-Carpathian regions but also in the southern part of Crimea. The various above mentioned European directives dispose a broad spectrum of measures and recommendations to reach a sustainable anti-flooding management. A general aim is to reduce peaks of river discharge as far as possible but not more than ecologically acceptable.One measure consists in reducing the surface run-off by selecting the appropriate land cover according to the soil characteristics and slopes and to reduce the impact of different types of roads, including uncovered forest roads. Aim is to increase the infiltration and recharge of groundwater (baseflow). In order to reach a reasonable distribution of discharge all over the year simulation of land use changes can help to balance human needs and natural requirements. The figures below show some related examples of maps. Figure x shows a map indicating erosion risks on agricultural surface situated on fields having a slope of more than 9 % [x]. The water yield of the various subbasins depends, amongst others, on the amount of precedent precipitation. Water yield maps, splitted off in surface run-off, lateral flow and groundwater flow, can be provided for different scenarios like strong short time precipitations, long lasting precipitations or draughts (fig. x,y). Of course, it will be impossible to exclude all risks, especially under changing climate conditions. This is also an important argument for the participation of farmers and other stakeholders who are directly concerned in various ways.

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