River Basin Models to Support

Green Water Credit Assessments

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IFAD

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FutureWater Science for Solutions

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1 Introduction

Green Water Credits (GWC) is a mechanism for transfer of cash to rural people in return for water management activities that determine the supply of green and blue water at source. These activities are presently unrecognized and un-rewarded, but have the potential for rural people to better manage land and water resources in order to improve food security, water security and public health, and to combat and adapt to climatic and related environmental changes.

The International Fund for Agricultural Development (IFAD) and the Swiss Development Cooperation (SDC) support a GWC Proof-of-Concept project. The project aims to demonstrate the viability and feasibility of the offer–and–demand aspects of the GWC concept as a sustainable environmental service mechanism; improve local resilience to external shocks by asset building (green water resource, stable soils, shortening the hunger gap, diversified rural incomes); deliver enhanced blue water resources and to reduce the hazards of flood and landslip downstream.

The GWC Proof-of-Concept will be undertaken in a pilot basin in Africa. In order to undertake the Proof-of-Concept a modeling support tool is required to evaluate GWC options, with a strong focus on upstream—downstream linkages.

The objective of this report is to give a brief overview about modeling tools available that will form the background for the selection of the most suitable tool to be used.

2 Hydrological Modeling

2.1 Application of models

Appropriate water management is one of the challenges faced by mankind since history. Many regions are already water scarce currently and projections on future water resources indicate a worsening of the situation. Important to realize is that agriculture is the dominant consumer of water and any changes in water consumptions patterns in this sector will have a substantial impact on total water resources (Figure 1).

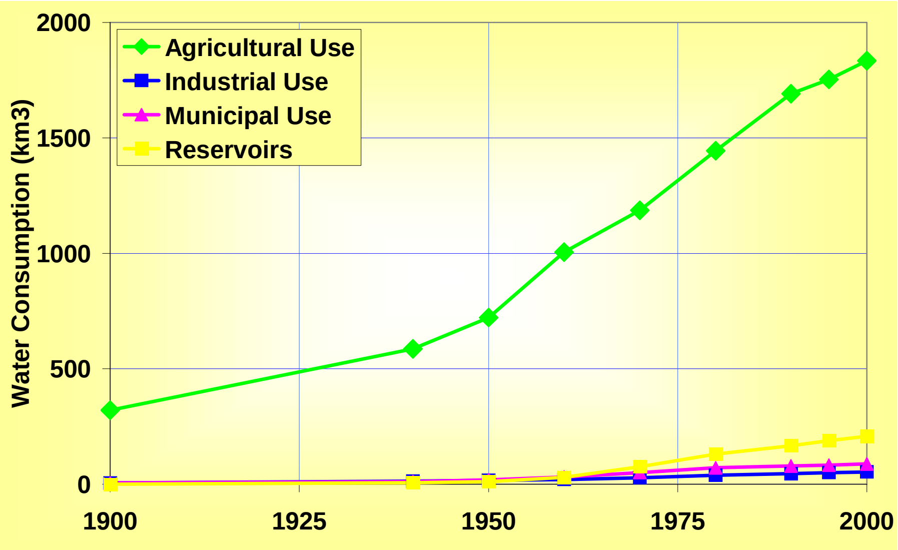

Figure 1. Water consumption for different sectors. (Source Shiklomanov, 2003).

To feed the growing population requires substantial amounts of water. Seckler et al. (1999) estimated that by 2025 cereal production will have to increase by 38% to meet world food demands. The World Water Vision, as outcome from the Second World Water Forum in The Hague in 2000, estimated a similar figure of 40% based on various projections and modeling exercises (Cosgrove and Rijsberman, 2000). Global estimates of water consumption per sector indicate that irrigated agriculture consumes 85% from all the withdrawals and that this consumptive use will increase by 20% in 2025 (Shiklomanov, 1998). Gleick (2000) presented estimates on the amount of water required to produce daily food diets per region. According to his figures large differences can be found between regions ranging from 1,760 liters per day per person for Sub-Saharan Africa to 5,020 for North America. Differences come from the larger number of calories consumed and the higher fraction of water-intensive meat in the diet of a North American.

This increase in food, and therefore water requirements coincide with a growing water scarcity at an alarming rate. Recently, a study by the United Nations (UN, 1997) revealed that one-third of the world's total population of 5.7 billion lives under conditions of relative water scarcity and 450 million people are under severe water stress. This relative water scarcity and severe water scarcity are defined using the Relative Water Demand (RWD) expressed as the fraction water demand over water supply. A

RWD greater then 0.2 is classified as relative water scarce, while a RWD greater then 0.4 as severe water stress. However, these values as mentioned by the UN are based on national-level totals, ignoring the fact that especially in bigger countries, huge spatial differences can occur. Vörösmarty et al. (2000) showed that including these in-country differences 1.8 billion people live in areas with sever water stress. Using their global water model and some projections for climate change, population growth and economic growth, they concluded that the number of people living in sever water stress will have grown to 2.2 billion by the year 2025.

A study published by the International Water Management Institute (Seckler et al., 1999), based on country analysis, indicated that by the year 2025 8 percent of the population of countries studied (India and China where treated separately, because of their extreme variations within the country) will have major water scarcity problems. Most countries, which contain 80% of the study population, need to increase withdrawals to meet future requirements, and only for 12% of the population no actions are required.

References given before are related to the global scale, but it is very clear that at smaller scales, such as basins, extreme variations will occur and many basins with tremendous water problems can be found. This, in combination with the "think globally, act locally" principle, makes the basin the most appropriate scale to focus on. Despite the fact that the basin is the most appropriate scale to analyze water management issues, in terms of food supply the field scale should be added and, in case of irrigated agriculture, the irrigation system scale as intermediate between basin and field.

The most important aspect of applying models however is in the use to explore different scenarios. This can relate to aspects that cannot directly be influenced, such as population growth and climate change. These are often referred to as projections. On the contrary to this are the so-called management scenario's where water managers and policy makers can make decision that will have a direct impact. Examples are changes in reservoir operations, water allocation and agricultural/irrigation practices. In other words: models enable to change focus from a re-active towards a pro-active approach. (Figure 2).

The power of models is in exploring scenarios, such as with aspects that cannot directly be influenced, like population growth and climate change. These are often referred to as projections. Contrary to this are so-called management scenario's where water managers and policy-makers can make decisions that have a direct impact. Examples are changes in reservoir operations, water allocation and agricultural/irrigation practices. In other words: models enable to change focus from a re-active towards a pro-active approach. (Figure 2).

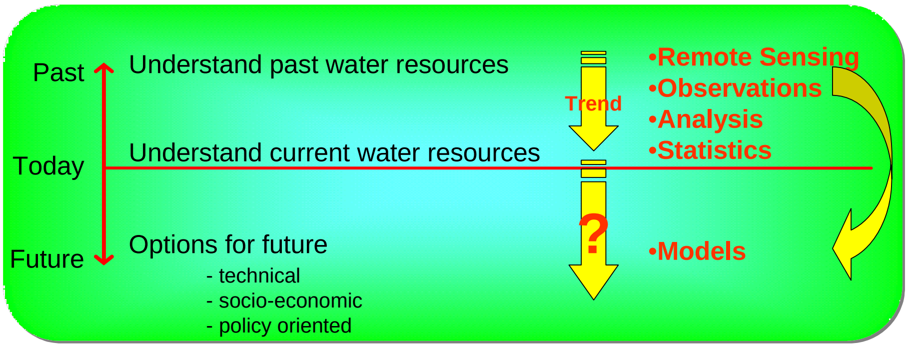

Figure 2. The concept of using simulation models in scenario analysis.

2.2 *Concepts of hydrological modeling*

The term modeling is very broad and includes everything where reality is imitated. The Webster dictionary distinguishes 13 different meanings for the word model where the following definition is most close to the one this study is focusing on: "a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs". However we will restrict our definition here to computer models and that a model should have a certain degree of process oriented approach, excluding statistical, regression oriented models. This leads to the following definition: "a model is a computer based mathematical representation of dynamic processes".

The history of hydrological and agro-hydrological models, based on this somewhat restricted definition, is relatively short. One of the first catchment models is the so-called Stanford Watershed Model (SWM) developed by Crawford and Linsley in 1966, but the main principles are still used in nowadays catchment models to convert rainfall in runoff. This SWM didn't have much physics included as the catchment was just represented by a set of storage reservoirs linked to each other. The value of parameters describing the interaction between these different reservoirs was obtained by trying to optimize the simulated with the observed streamflows. At the other end of the spectrum are the field scale models describing unsaturated flow processes in the soil and root water uptake. One of the first models to be developed was the SWATR model by Feddes et al (1978) based on Richards' equation. Since, these models are based on points and use the concept that unsaturated flow is highly dominated by only vertical transport of water, much more physics could be built in from the beginning.

Hydrological modeling is a powerful technique of hydrologic system investigation for both the research hydrologists and the practising water resources engineers involved in the planning and development of integrated approach for management of water resources. Hydrologic models are symbolic or mathematical representation of known or assumed functions expressing the various components of a hydrologic cycle. However, the term hydrological model is often understood to be and is used more narrowly as a computer based mathematical model. With the current rapid developments within computer technology and hydrology the application of computer based hydrologic models can only continue to increase in the near future.

A huge number of hydrological models exits and applications are growing rapidly. The number of pages on the Internet including "hydrological model" is over 2.7 million (according to Google, March

2006). A relevant question for hydrological model studies is therefore related to appropriate model selection. One of the most important issues to consider is the spatial scale to be incorporated in the study and how much physical detail to be included. In Figure 3 this has been explained where a triangle type of figure exits in terms of feasible options to undertake analysis (e.g. very high physical detail at continental scale is not possible). The figure shows also some models quite commonly applied at several scale levels.

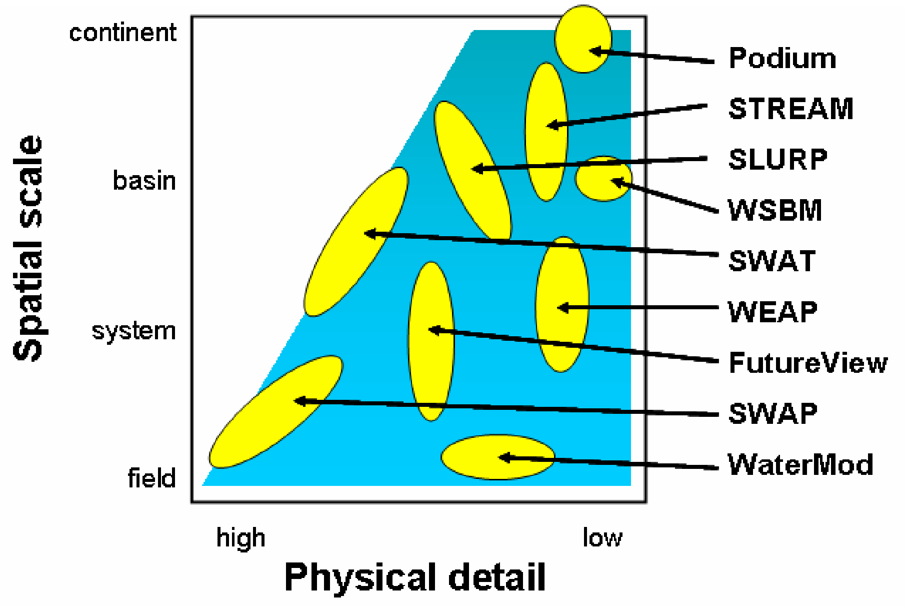

Figure 3. Spatial and physical detail of hydrological models.

2.3 Model classification

Models are analytical tools for schematizing a complex reality. They are attractive tools for studying processes or systems, especially when the actual processes are expensive or difficult to measure. Models, have potential strengths beyond the limits data alone can offer. They can be used for: (i) study of processes and for (ii) scenarios analyses. Mathematical definition of processes or relations between factors we know exist or understand is the starting point for model development. There are many types of models, differing in level of complexity and data requirements. Apart from qualitative or expert models, which are exclusively based on 'reasoned intuitive estimates' (van Diepen *et al.* 1991), we can discriminate between:

1) statistical (empirical) models that relate selected variables and processes on the basis of regression analysis,
2) parametric models (multiplying factors that are considered relevant), which are in fact qualitative of nature. Results can be satisfactory when calibrated for specific conditions,
3) mechanistic or deterministic models that describe fundamental physical and/or chemical processes in mathematical functions.

The number of simulation models developed to deal with water for food issues is unknown, but must be in the order of thousands. Even if we exclude the one-time models developed for a specific study and count only the more generic and more applied models it must exceed thousands. Some existing model overviews, as described later in more detail, include numerous models: IRRISOFT: 105, USBR: 100, CAMASE: 211, and REM: 675, amongst others. Interesting is that there seems to be no standard model or models emerging, as can be seen for example in groundwater modeling where ModFlow is the de-facto standard. Two hypotheses for this lack of standard can be brought forward. The first one is that model development is still in its initial phase, despite the about 25 years of history, and is therefore easy to start developing one's own model in a reasonable amount of time and effort that can compete with similar existing ones. A stimulating factor related to this is that a serious scientist is considered to have his/her own model or has at least developed one during his or her PhD studies. A second reason for the large number of models is a more fundamental one saying that processes in water for food studies are so complex and diverse that each case requires its specific model or set of models.

It is therefore interesting to see how models can be classified and see whether such a classification might be helpful in selecting the appropriate model given a certain question or problem to be solved. Probably the most generally used classification is the spatial scale the model deals with and the amount of physics included (Figure 3). These two characteristics determine other model behavior as data need, expected accuracy, required expertise, user-friendliness amongst others.

2.4 *Existing model overviews*

A substantial number of overviews exist listing available models and a short summary. Most of this information is provided by the developers of the model and tends therefore biased towards the capacities of the model. The most commonly used model overviews are discussed briefly here, keeping in mind that these overviews are changing rapidly, in size and number, since the Internet provides almost unlimited options to start and update such an overview in a automatic or semi-automatic way. A clear example is the Hydrologic Modeling Inventory project from the United States Bureau of Reclamation, where about 100 mainly river basin models are registered by the model developers (USBR, 2002).

An overview of agro-ecosystems models is provided by a consortium named CAMASE (Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment; CAMASE, 2005). The following types of models are distinguished supported: crop science, soil science, crop protection, forestry, farming systems, and land use studies, environmental science, and agricultural economics. A total of 211 models are included and for each model a nice general overwiew is provided. Unfortunately the last update of the register was in 1996 and advancements in model development over the last six years are not taken into account.

The United States Geological Survey (USGS, 2006) provides an overview of all their own models, about 50, divided in four categories: geochemical, ground water, surface water, water quality, and general. Some of the models are somewhat outdated, but some commonly used ones are included too. All the models are in the public domain and can be used without restrictions. For most of the models source code is provided as well.

The United States Department of Agriculture provides also models to be used in crop-water related issues. The National Water and Climate Center of the USDA has an irrigation page (NWCC, 2006) with some water management tools related to field scale irrigation.

United States Environmental Protection Agency is very active in supporting model development. The SWAT model, originating from their research programs, might have the potential to become the de-facto standard in basin scale modeling, and has been included in the BASINS package (BASINS, 2006). More linkages to models and other model overviews are provided too (EPA, 2006).

The USGS, USDA, USACE, and EPA, together with some other models, are brought together by the USGS Surface water quality and flow Modeling Interest Group (SMIG, 2006a). SMIG has setup the most complete link to models archives including links to 40 archives (SMIG, 2006b).

The most up-to-date overview of models used crop growth modeling is the Register of Ecological Models (REM, 2006), with 675 models as per 12-Dec-2005. Besides this overview of models the same website provides general concepts and links to modeling.

2.5 *Existing model reviews*

In the previous section an overview of existing model inventories have been given. Although useful as a catalog it does not provide any independent judgment of model quality. The quality of model output can never be better than that of the basic data and. Uncertainty in model output is determined by several factors in particular the assumptions and generalizations in the models (especially for expert- and parametric models) (Mantel and van Engelen 1997):

1) the method used for spatial aggregation and linking of climate and soil and terrain data;
2) the representativity, completeness and quality of the basic data;
3) the representativity of applied pedo-tranfer functions (PTF's) for filling of data gaps.

As argued before, the best model does not exist and is completely a function of the application and question to be answered. However, within one range of models some studies have been done where a limited amount of models have been tested and reviewed. The majority of these studies focuses on two or three models that are almost similar in nature and conclusions are that models are reasonable comparable.

Texas Natural Resource Conservation Commission evaluated 19 river basin models, referred to as Water Availability Models, in order to select the most suitable model used for management of water resources, including issuing new water right permits (TNRCC, 1998). A total of 26 evaluative criteria were identified as important functions and characteristics for selecting a model that fits the need for the 23 river basins in Texas. Most importantly was the ability of the model to supports water rights simulation. During the evaluation process, each model was assessed and ranked in order of its ability to meet each criterion. The 19 models were in the first phase narrowed down to five: WRAP, MODSIM, STATEMOD, MIKE BASIN, OASIS. Models not selected included WEAP (no appropriation doctrine) and SWAT (not intuitive and user-friendly). The final conclusion was to use the WRAP model with the HEC-PREPRO GUI. As mentioned, the study focused only on models able to assist in water rights questions.

A similar study was performed to select an appropriate river basin model to be used by the Mekong River Commission (MRC, 2000). In fact, it was already decided that considering the requirements of the MRC not one single model could fulfill the needs, but three different types of model were necessary: hydrological (rainfall-runoff), basin water resources, hydrodynamic. Three main criteria were used to select the most appropriate model: technical capability, user friendliness, and sustainability. Considering the hydrological models 11 were evaluated and the SWAT model was considered as the most suitable one. Since water quality and sediment processes were required models like SLURP were not selected. Interesting is that grid based models were not recommended as they were considered as relatively new. The selected basin simulation model was IQQM. ISIS was reviewed as the best model to be used to simulate the hydrodynamic processes.

An actual model comparison, where models are really tested using existing data, is initiated by the Hydrology Laboratory (HL) of the National Weather Service (NWS), USA. The comparison is limited to hydrological models and their ability to reproduce hydrographs, based on detailed radar rainfall data. The intent of the Distributed Model Intercomparison Project (DMIP) is to invite the academic community and other researchers to help guide the NWS's distributed modeling research by participating in a comparison of distributed models applied to test data sets. Results have been published recently, but no distinct conclusions were drawn (Reed et al., 2004).

Sing et al. (2005) evaluated the performance of two popular watershed scale simulation models HSPF and SWAT. Both models were calibrated for a nine-year period and verified using an independent 15-year period by comparing simulated and observed daily, monthly, and annual streamflow. The characteristics of simulated flows from both models were mostly similar to each other and to observed flows, particularly for the calibration results. The final conclusion was SWAT predicts flows slightly better than HSPF for the verification period, with the primary advantage being better simulation of low flows.

3 Summary of Selected Models

Based on the previous chapters a few potential models have been identified that might be used for the Green Water Credits (GWC) Proof-Of-Concept project. The following models will be described briefly:

1. SWAT - Soil and Water Assessment Tool
2. ACRU - Agricultural Catchments Research Unit model
3. WEAP - Water Evaluation and Planning model
4. MIKEBASIN
5. MIKESHE
6. SWAP - Soil, Water, Atmosphere and Plant model
7. WATERGAP
8. WOFOST

3.1 *SWAT - Soil and Water Assessment Tool*

3.1.1 General

The Soil and Water Assessment Tool (SWAT) is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. SWAT is a public domain model actively supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA.

SWAT is a process-based continuous daily time-step model which evaluates land management decisions in large ungauged rural watersheds. A natural subbasin is usually composed of several land uses (or crops) and soil types. In SWAT modeling, a subbasin is required of representing a unique landuse (or crop rotation) and soil type. A straight forward approach is to use predominant landuse (or crop rotation) and soil. SWAT model also allows for non- spatial subdivision of subbasins into smaller sub-units based on landuse and soil variations, a concept of virtual subbasins. Virtual subbasins represent percentages of the larger subbasin area.

Different versions of SWAT are currently being distributed. SWAT2000 is the current version of the SWAT model and the version incorporated into EPA's BASINS 3.0 release.

Grassland, Soil and Water Research Laboratory and Blackland Research Center cosponsor three-day workshops periodically. These workshops are designed to introduce new users to the model, review necessary and optional inputs, and familiarize the user with the ArcView interfaces.

An extension of ArcView GIS entirely has been developed in Avenue - AVSWAT- and works in with the Spatial Analyst and Dialog Designer extensions. AVSWAT is organized in several linked tools grouped in the following eight components: Watershed Delineation, Land Use and Soil Definition, Editing of the model Data Bases, Definition of the Weather Stations, Input Parameterization and Editing, Model Run, Read and Map-Chart Results, Calibration tool.

3.1.2 Input

SWAT requires spatial distributed data for the basin. The most important ones are DEM (Digital Elevation Model), land cover and soils. From the DEM the sub catchment are generated automatically as well as the stream network. These sub catchment and the land cover and soils are then used to obtain the so-called Homogenous Response Units (HRU). Meteorological data at one or more locations in the basin provides sufficient information to run the model. Optional is to include reservoirs and operational rules for these.

Multiple standardized databases are included to parameterize different land use types, crops as well as soils.

3.1.3 Output

The output of SWAT can be distinguished in stream flow output and land based results. Stream flow can include water quality aspects as well for every stream in the basin. The land based results are extensive and include all the components of the hydrological cycle as well as erosion, pollutants, nutrients and crop growth. All this information is available per sub catchment as well as per HRU.

3.1.4 Evaluation

SWAT has been applied in various basins in different countries and has been calibrated and validated for different conditions. It is used for modeling basins and in the USA and is actively supported by the USDA Agricultural Research Service.

SWAT can be considered as the de-facto standard in hydrological basin scale modeling where land use interactions are relevant.

3.1.5 Availability and costs

SWAT can be downloaded from the internet and is free of charge. There is extensive support by the developers as well as a group of active users.

3.2 *ACRU - Agricultural Catchments Research Unit model*

3.2.1 General

The ACRU model has its hydrological origins in a distributed catchment evapotranspiration based study carried out in KwaZulu-Natal Drakensberg of South Africa in the early 1970s (Schulze, 1975). The acronym ACRU is derived from the Agricultural Catchments Research Unit within the Department of Agricultural Engineering of the University of Natal in Pietermaritzburg. The agrohydrological component of ACRU first came to the fore during research on an agrohydrological and agroclimatological atlas for Natal. The model has been verified on data from southern Africa and the USA, and used extensively in decision making in southern Africa. The model has also been applied in research in Botswana, Chile, Germany, Lesotho, Namibia, Swaziland and the USA.

The ACRU Agrohydrological Model - a multi-purpose and multi-level daily soil moisture budgeting model (Schulze, 1990) can be used to determine what the soil water moisture status is for a given catchment area and this model requires inter alia continuous amounts of daily rainfall as input. ACRU can be used to estimate, inter alia, runoff volume, sediment yield, peak discharge, reservoir water budgets, crop yield and irrigation water demand and supply.

The ACRU Agrohydrological Modelling System (Schulze, 1995) uses a programme called the Menubuilder to assist the user in preparing an input dataset, called a menu, to the ACRU model.

ACRU can operate as a point or as a lumped small catchments model. However, for large catchments or in areas of complex land uses and soils ACRU can operate as a distributed cell-type model. In distributed mode individual subcatchments (ideally not exceeding 30 km2) are identified, discretised and flows can take place from "exterior" through "interior" cells according to a predetermined scheme, with each subcatchment able to generate individually requested outputs which may be different to those of other subcatchments or with different levels of input/information. The ACRU model is not integrated in GIS-software. In the catchment or basin mode in ACRU, the basic mapping units - lumped small catchments - are polygons from which the basic data are derived and on which the calculations are based. Results are linked to vector based GIS-files, through polygon attribute files.

3.2.2 Input

Daily rainfall, daily or monthly evaporation, soils and land use parameters.

3.2.3 Output

Simulated streamflows, sediment and crop yield, reservoir yield analysis.

3.2.4 Evaluation

The model has been applied in been applied in different South African basins. Relatively small user-community outside South Africa, althoug several cases of application outside South Afica of ACRU are known (e.g USA and Germany).

3.2.5 Availability and costs

The model can be obtained from the School of Bioresources Engineering and Environmental Hydrology of the University of Natal, Pietermaritzburg and can be downloaded from the internet. User documentation on ACRU was first published in 1984 and updated in 1989 and is also available from the internet.

3.3 *WEAP - Water Evaluation and Planning model*

3.3.1 General

The WEAP model includes a semi-physical, irregular grid, lumped–parameter hydrologic simulation model that can account for hydrologic processes within a water distribution system. WEAP works with nodes and arrows as indicators of water flow and distribution.

While the model can be run on any time-step where routing is not a consideration, the model description assumes a monthly time-step. The time horizon can be set from the user, from as short as a single year to more than 100 years. Scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

WEAP contains built-in models for: rainfall runoff and infiltration, evapotranspiration, crop requirements and yields, surfacewater and groundwater interaction, and instream water quality. It has a GIS-based, graphical "drag and drop" interface. WEAP allows user-defined variables and equations and has a model builing facility. It has dynamic links to spreadsheets and other models. Data structures are flexible and expandable.

3.3.2 Input

Since WEAP primarily goal is to evaluate water allocation options is the major input related to so-called demand and supply sites (nodes) that are connected by links. Examples of required input: urban areas, agricultural areas, groundwater, reservoirs, catchment nodes, rivers, canals. The catchment nodes can be specified to be more hydrological oriented including rainfall-runoff processes.

3.3.3 Output

WEAP operates always in an optimization water allocation mode, based on priorities set for each demand site. This makes WEAP unique in comparison to other water allocation tools such as RIBESRSIM or MIKE-BASIN.

Output of WEAP includes flows for all connection lines (rivers, canals) and met and unmet demands for all the demand sites.

3.3.4 Evaluation

Although the WEAP model comprises both a hydrological component and a water management component, it is more of a water planning model, focused on the water division, infrastructure, and economic evaluation than on the physical water hydrology.

Support of the model in terms of manuals, training and support of developers is excellent.

3.3.5 Availability and costs

Single site license for Accredited academic institution based in an industrialized country $1000 and non-consulting license $2500. Non-profit, governmental or academic organization based in a developing country: free of charge.

3.4 MIKEBASIN

3.4.1 General

MIKE BASIN is a user-friendly water allocation model with a Arc-Gis interface. MIKE BASIN builds on a network model in which branches represent individual stream sections and the nodes represent confluences, diversions, reservoirs, or water users. The ArcGIS interface has been expanded accordingly, e.g., such that the network elements can be edited by simple right-clicking. Technically, MIKE BASIN is a quasi-steady-state mass balance model, however allowing for routed river flows. The water quality solution assumes purely advective transport; decay during transport can be modeled. The groundwater description uses the linear reservoir equation.

Typical areas of application of MIKE BASIN are:

- Water availability analysis: conjunctive surface and groundwater use, optimization
- Infrastructure planning: irrigation potential, reservoir performance, water supply capacity, waste water treatment requirements
- Analysis of multisectoral demands: domestic, industry, agriculture, hydropower, navigation, recreation, ecological, finding equitable trade-offs
- Ecosystem studies: water quality, minimum discharge requirements, sustainable yield, effects of global change. Regulation: water rights, priorities, water quality compliance

3.4.2 Evaluation

MIKE BASIN is a water planning model, focused on the water management, water division, and the infrastructural planning of water division rather than on the physical aspects of hydrology. However, the very user-friendly interface and the ability to built quickly models makes MIKE BASIN suitable for quick policy oriented water resources planning at basin or sub-basin scale.

3.4.3 Availability and costs

Licenses costs are available on request by DHI but are substantial.

3.5 MIKE-SHE

3.5.1 General

MIKE-SHE is a dynamic, user-friendly modeling tool that can simulate the entire land phase of the hydrologic cycle and can be summarized as an integrated modeling environment that allows components to be used independently and customized to local needs

MIKE-SHE includes powerful preprocessing and results presentation tools for making your results understandable and convincing. The developers claim to have a proven track record in hundreds of consultancy and research applications around the world.

3.5.2 Input

The input data requirements and model parameters for the fully integrated MIKE SHE model are comprehensive (such as horizontal and vertical soil hydrologic conductivity). Each component of the model applies a range of input data types and parameters. The parameters may be physically measurable or empirical specific to the equations solved in the model.

3.5.3 Output

Output of MIKE-SHE includes maps and time series graphs of all hydrological processes included in the model.

3.5.4 Evaluation

MIKE-SHE can be considered as a complete package to analyze hydrological processes into detail. Input requirements are therefore substantial. MIKE-SHE requires a high-level of knowledge both on technical aspects as well as on conceptual hydrological and water resources issues.

3.5.5 Availability and costs

Licenses costs are available on request by DHI but are substantial.

3.6 *SWAP - Soil, Water, Atmosphere and Plant model*

3.6.1 General

SWAP (Soil, Water, Atmosphere and Plant) simulates transport of water, solutes and heat in unsaturated/saturated soils. SWAP is the successor of the well known Swatre model which originates from 1978. The department of Water and Environment of the Alterra Institute and the sub-department of Water resources of WUR have developed the computer model SWAP in close co-operation. The program is designed to simulate the transport processes at field scale level and during entire growing seasons. The model offers a wide range of possibilities to address both research and practical questions in the field of agriculture, water management and environmental protection.

Some of the typical applications of SWAP are: field scale water balance, evapotranspiration, plant growth as affected by water and/or salinity stress, improvement of surface water management, soil moisture indicators for natural vegetations.

3.6.2 Input

Physical and hydrological soil properties, crop characteristics (soil cover, leaf areaindex, crop height etc.), daily meteorological data, drainage and irrigation specific data. Flow rate through profile, state variables, crop rate and state variables.

3.6.3 Output

Flow rate through profile, state variables, crop rate and state variables. Time interval of simulation: 1 day. Basic spatial unit: m^2 to field level.

3.6.4 Evaluation

SWAP is a point scale model that includes all unsaturated flow processes including crop growth modeling at several levels of detail. Some semi-2D components exit in terms of drainage and surface water flow. SWAP has been used extensively all over the world to evaluate field scale water and salt management issues.

3.6.5 Availability and costs

SWAP is free of charge and can be downloaded from the internet.

3.7 *WATERGAP - Water Global Assessment and Prognosis model*

3.7.1 General

WaterGAP – the integrated global water model has been developed at the Center for Environmental Systems Research at the University of Kassel in Germany in cooperation with the National Institute of Public Health and the Environment of the Netherlands. WaterGAP computes both water availability (surface runoff, groundwater recharge and river discharge) and water use at a spatial resolution of 0.5 degree (55 x 55 km at the equator). WaterGap is based on many global data sets.

WaterGAP belongs to the class of environmental models which can be classified as 'integrated' because they seek to couple and thus integrate different disciplines within a single integrated framework.
The Global Hydrology Model simulates the characteristic macro-scale behavior of the terrestrial water cycle to estimate water resources, while the Global Water Use Model computes water use for the sectors households, industry, irrigation, and livestock. All calculations cover the entire land surface of the globe (except Antarctica) and are performed on a 0.5° by 0.5° spatial resolution (this is presently the highest feasible resolution for global hydrological models because climatic input is usually not available at higher levels of detail).

The WaterGAP Global Hydrology Model calculates a daily vertical water balance for both the land area and the open water bodies at each of the 0.5° cells. The vertical water balance for the land fraction in a cell consists of a canopy water balance and a soil water balance. These are calculated as functions of land cover, soil water capacity, and monthly climate variables (i.e. temperature, radiation, and precipitation).

3.7.2 Applications

In the course of the development of WaterGAP global datasets were generated that could be of interest for the Green Water Initiative: a global map of irrigated areas, a global drainage direction map and a global lakes and wetlands data set. WaterGap includes a hydrological model.

3.8 *HSPF*

3.8.1 General

HSPF (Hydrological Simulation Program) is a public domain software program distributed by the U.S. EPA's Center for Exposure Assessment Modeling (CEAM). HSPF first version originates from the 1960's and was called Stanford Watershed Model, one of the first hydrological models. In the 1970's, water-quality processes were added as well as improved concepts and computer engineering. In the 1980's, preprocessing and postprocessing software, algorithm enhancements, and use of the USGS WDM data file system were developed. The current release is Version 11.

3.8.2 Input

HSPF requires a substantial amount of data at high spatial and temporal resolution. Meteorologic records of precipitation and estimates of potential evapotranspiration are required for watershed simulation. Air temperature, dewpoint temperature, wind, and solar radiation are required for snowmelt. Air temperature, wind, solar radiation, humidity, cloud cover, tillage practices, point sources, and (or) pesticide applications may be required for water-quality simulation. Physical measurements and related parameters are required to describe the land area, channels, and reservoirs.

3.8.3 Output

The amount of output HSPF can generate is impressive and overwhelming. Output is either printed tables at any time step, a flat file, or the WDM file. The postprocessing software uses data from the WDM file format. Hundreds of computed time series may be selected for the output files.

3.8.4 Evaluation

HSPF can be considered as a classical hydroloigcal rainfall-runoff model with a very long history. The model is not particular user-friendly and requires a high-level of computational as well as hydrological skills.

3.8.5 Availability and costs

HSPF can be obtained free of charge.

3.9 *WOFOST*

3.9.1 General

WOFOST is a dynamic water balance model and is different from other models. Most hydrological flow process based models require saturated and unsaturated soil hydraulic conductivity data of soils, which are lacking for most soils of tropical and subtropical Africa.

The well tested and world-wide used crop growth model WOFOST includes a soil-crop-atmosphere water balance that allows working with a minimum soil dataset that is available in the SOTERSAF database (FAO and ISRIC, 2003).

The crop growth simulation model WOFOST-version 7.1 is a generic model, which simulates potential, water-limited and nutrient-limited production situations (Boogaard et al. 1998). WOFOST calculates on a daily basis crop growth and water balance for varying climate, crop and soil, and management conditions such as of infiltration enhancing practices and crop germination date. It can be used at field level as well as regional level, for example it is used in the European Crop Growth Monitoring System (Van Ittersum et al., 2003).

The WOFOST water balance calculations is based on a daily book-keeping of in- and out-going water flows between the components soil, crop, atmosphere. The soil is divided into two dynamic compartments. Firstly, the variable actual rooting depth, from small at germination till maximum rootable depth at the end of the growing period. Secondly, the deeper subsoil, which is the subsoil below the rooted soil. Rainfall infiltrates and the part that does not infiltrate is considered runoff. The return vapor flow of the water stored in the soil to the atmosphere is calculated through evaporation and transpiration processes. The infiltrated water that exceeds the storage capacity of the two soil compartments percolates downward and contributes to the aquifer and river base flow.

3.9.2 Model data input

Six yield and water balance determining factors are assessed in WOFOST: (i) climate, (ii) soil available water content, (iii) rootable depth, (iv) crop, (v) crop management restricted to germination date, and (vi) soil management restricted to practices of enhanced water infiltration.

Climate

The WOFOST climate file requires 6 parameters: radiation, temperature, relative humidity of the air (or vapor pressure), wind speed, precipitation and number of rain days. The WOFOST rainfall generator facility mimics daily rainfall based on monthly rainfall data and number of rainy days.

Crop

The WOFOST model is operational for a wide range of crops (Van Ittersum et al. 2003). It has some widely cultivated well tested annual crop files

Soil

Soil type determines the soil water storage capacity that is controlled by soil thickness, soil water holding capacity and effective rootable depth.

The WOFOST soil moisture characteristics include water retention and hydraulic conductivity. WOFOST recognizes the option of a soil with free drainage conditions that requires a minimum dataset, which is limited to the Available Water Capacity (AWC) of the soil. For free draining conditions the hydraulic conductivity of the saturated soil and the percolation rate are assumed to be high and kept at a fixed high value at 10.0 cm d^{-1}. Once measured soil conductivity data becomes available, these fixed values can be replaced.

3.9.3 Availability and costs

WOFOST can be obtained free of charge.

4 Conclusions

A wide range of models exists to support decisions to be made regarding water related issues. From the enormous amount of models available nowadays the most relevant to support the Green Water Credits Proof of Concept project have been summarized in this report. The overall question to be answered is which model is the best to support the project. A set of criteria has been defined that will be applied to each model:

A. Ability to evaluate upstream water processes
B. Ability to evaluate upstream erosion processes
C. Ability to evaluate downstream flow benefits
D. Ability to evaluate downstream hydropower benefits
E. Experiences with model
F. External support
G. Transferability
H. Price

In summary it can be concluded that the following models can be used to support the Green Water Credit assessment process:

- SWAT as the base to evaluate the impact of upstream managerial aspects regarding crop-land-soil management
- WEAP to evaluate basin scale issues with a strong focus on economic benefits of hydropower
- WOFOST/SWAP for some detailed field analysis on crop-soil-water management.

Table 1. Evaluation of model suitability to evaluate GWC.

	A	B	C	D	E	F	G	H
SWAT	++	++	++	+	++	+	+	++
ACRU	++	++	++	o	+	+	o	++
WEAP	+	o	++	++	++	++	++	++
MIKEBASIN	o	o	++	+	+	+	+	o
MIKESHE	++	++	+	+	o	+	o	o
SWAP	++	o	o	o	++	++	++	++
WATERGAP	o	o	+	o	o	+	o	+
HSPF								
WOFOST	+	+	o	o	++	++	++	++

++ = strong, + = good, o = weak

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