Soil and Water Assessment Tool, Kitui – Kenya

WatManSup project

WatManSup Report No 3

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FutureWater Science for Solutions

Report No 3
SWAT Kenya

WatManSup project

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Preface

This report is written in the context of the WatManSup project (Integrated Water Management Support Methodologies). The project is executed in three countries: The Netherlands, Kenya and Turkey. Financial support is provided by Partners for Water. For more information on the WatManSup project see the project website: http://www.futurewater.nl/watmansup.

The Dutch consortium:

- FutureWater (Wageningen)
- Institute for Environmental Studies (Amsterdam)
- Water Board Hunze en Aa's (Veendam)

Foreign clients:

- SASOL Foundation (Kitui, Kenya)
- Soil and Water Resources Research Institute of the Turkish Ministry of Agricultural and Rural Affairs (Menemen, Turkey)
- SUMER (Izmir, Turkey)

Additional technical support:

- the University of Nairobi (Kenya)
- EA-TEK (Izmir, Turkey)

Reports so far:

Report No.1: Water Management Support Methodologies: State of the Art
Report No.2: Water Evaluation and Planning System, Kitui - Kenya
Report No.3: Soil and Water Assessment Tool, Kitui - Kenya

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1 Introduction

The challenge to manage our water resources in a sustainable and appropriate manner is growing. Water related disasters are not accepted anymore and societies expect more and more that water is always available at the right moment and at the desired quantity and quality. Current water management practices are still focused on reacting to events occurred in the past: the re-active approach. At many international high level ministerial and scientific meetings a call for more strategic oriented water management, the pro-active approach, has been advocated. Despite these calls such a pro-active approach is hardly adopted by water managers and policy makers.

Water managers and decisions makers are aware of the necessity of this paradigm shift: from a re-active towards a pro-active approach, but are confronted with the lack of appropriate methodologies.
To be prepared for the paradigm shift Integrated Water Management Support Methodologies (IWMSM) are needed that go beyond the traditional operational support tools. Note that these IWMSM are more than only tools, but include conceptual issues, theories, combining technical and socio-economic aspects. To demonstrate and promote this new way of thinking the WatManSup (Water Management Support Tools) has been initiated. The IWMSM approach comprises three different components: a water allocation component, a physical based component and a decision support component. This report describes the physical based component for one of the study areas included in the project: Kitui in Kenya.

The overall objective of this report is to demonstrate how the physical based component of IWMSM, the SWAT tool, can be used to support water managers and policy makers on relatively small reservoirs in a developing country.

2 Background

2.1 *The SWAT model*

SWAT is the acronym for Soil and Water Assessment Tool, a river basin model developed originally by the USDA Agricultural Research Service (ARS) and Texas A&M University that is currently one of the worlds leading spatially distributed hydrological models.

A distributed rainfall-runoff model – such as SWAT – divides a catchment into smaller discrete calculation units for which the spatial variation of the major physical properties are limited, and hydrological processes can be treated as being homogeneous. The total catchment behaviour is a net result of manifold small sub-basins. The soil map and land cover map within sub-basin boundaries are used to generate unique combinations, and each combination will be considered as a homogeneous physical property, i.e. Hydrological Response Unit (HRU). The water balance for HRU's is computed on a daily time step. Hence, SWAT will distribute the river basin into units that have similar characteristics in soil, land cover and that are located in the same sub-basin.

Irrigation in SWAT can be scheduled by the user or automatically determined by the model depending on a set of criteria. In addition to specifying the timing and application amount, the source of irrigation water must be specified, which can be: canal water, reservoir, shallow aquifer, deep aquifer, or a source outside the basin.

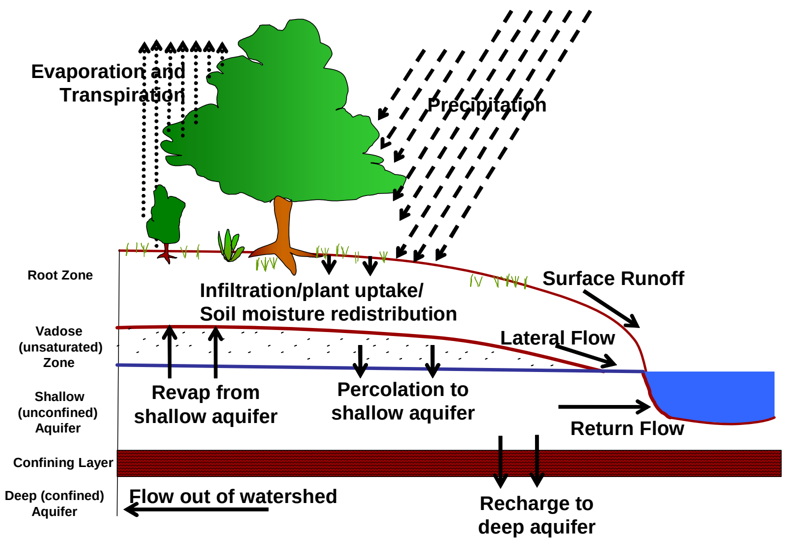

Figure 1. Main land phase processes as implemented within SWAT

SWAT can deal with standard groundwater processes (Figure 1). Water enters groundwater storage primarily by infiltration/percolation, although recharge by seepage from surface water bodies is also included. Water leaves groundwater storage primarily by discharge into rivers or lakes, but it is also possible for water to move upward from the water table into the capillary fringe, i.e. capillary rise. As mentioned before, water can also be extracted by mankind for irrigation purposes. SWAT distinguishes recharge and discharge zones.

Recharge to unconfined aquifers occurs via percolation of excessively wet root zones. Recharge to confined aquifers by percolation from the surface occurs only at the upstream end of the confined aquifer, where the geologic formation containing the aquifer is exposed at the earth's surface, flow is not confined, and a water table is present. Irrigation and link canals can be connected to the groundwater system; this can be an effluent as well as an influent stream.

After water is infiltrated into the soil, it can basically leave the ground again as lateral flow from the upper soil layer – which mimics a 2D flow domain in the unsaturated zone – or as return flow that leaves the shallow aquifer and drains into a nearby river (Figure 2). The remaining part of the soil moisture can feed into the deep aquifer, from which it can be pumped back. The total return flow thus consists of surface runoff, lateral outflow from root zone and aquifer drainage to river.

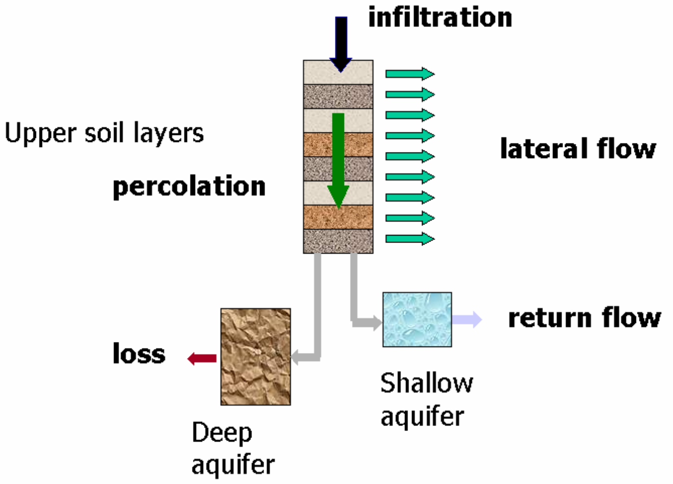

Figure 2. Schematic diagram of the sub-surface water fluxes

For each day of simulation, potential plant growth, i.e. plant growth under ideal growing conditions is calculated. Ideal growing conditions consist of adequate water and nutrient supply and a favourable climate. The biomass production functions are to a large extend similar to SEBAL. First the Absorbed Photosynthetical Radiation (APAR) is computed from intercepted solar radiation, followed by a Light Use Efficiency (LUE) that is in SWAT essentially a function of carbon dioxide concentrations and vapour pressure deficits. The crop yield is computed as the harvestable fraction of the accumulated biomass production across the growing season (Figure 3).

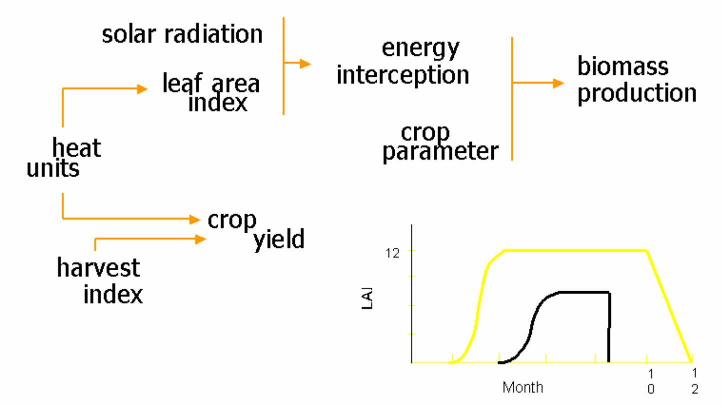

Figure 3. Parameterisation of crop production.

2.2 Kitui – Kenya

2.2.1 Regional setting

The WatManSup project aims at testing and demonstrating the IWMSM components in contrasting settings. The Kitui area is selected as it presents a typical case for a developing country with alternating wet and dry periods within one year and small-scale local human interventions on the water resource.

The Kitui District in the Easter Province of Kenya is a semi-arid region situated 150 km East of Nairobi (Figure 2). The total land area is approximately 20.000 km², including 6.400 km² of the uninhabited Tsavo National Park. The elevation of the district is between 400 and 1800 metres. The central part of the district is characterised by hilly ridges, separated by low lying areas between 600 and 900 metres above sea level. Approximately 555.000 people inhabit the district and the growth rate is 2.2 percent a year (Districts Development Plan 2002).

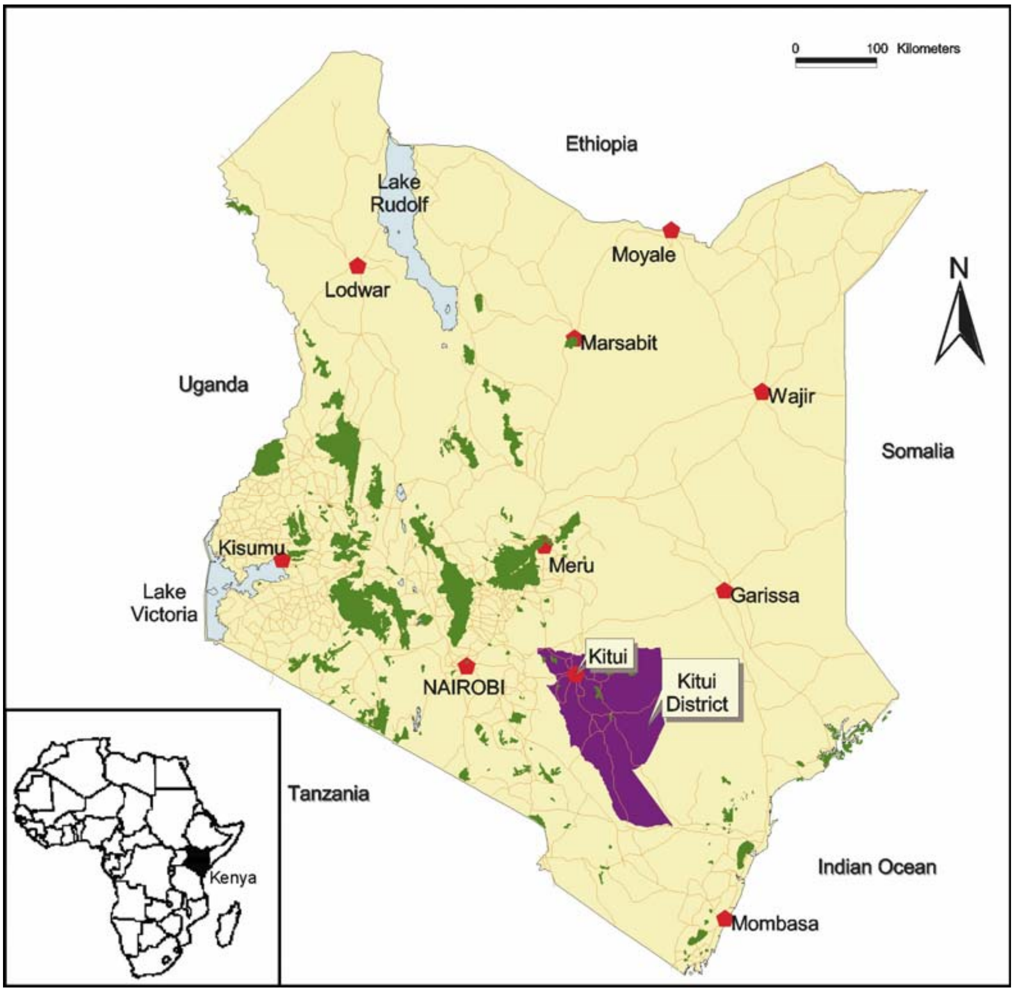

Figure 4. Map of Kenya, with the Kitui district in dark.

2.2.2 Geography and climate

The area is characterised by rainy periods that are highly erratic and unreliable. The rain usually falls in a few intensive storms (Nissen-Petersen, 1982). There are two rainy seasons, one from April to June, these are the so-called 'long rains' and one from October to December, these are the 'short rains'. On average the precipitation in the Kitui District is around 900 mm a year, but there are large local differences in amount of precipitation due to topography and other influences. The potential evaporation is high, 1800 to 2000 millimetre a year.

Virtually all of Kitui District's total area belongs to the Tana River drainage basin. Only a narrow strip along the south and southwest border drains to the Athi River. These two rivers form the northern, western and southern boundaries of the district. The Tana river is Kenya's largest river and drains the Eastern flank of the Aberdares and the Southern slopes of Mount Kenya. Both of the rivers discharge to the Indian Ocean (Figure 5).

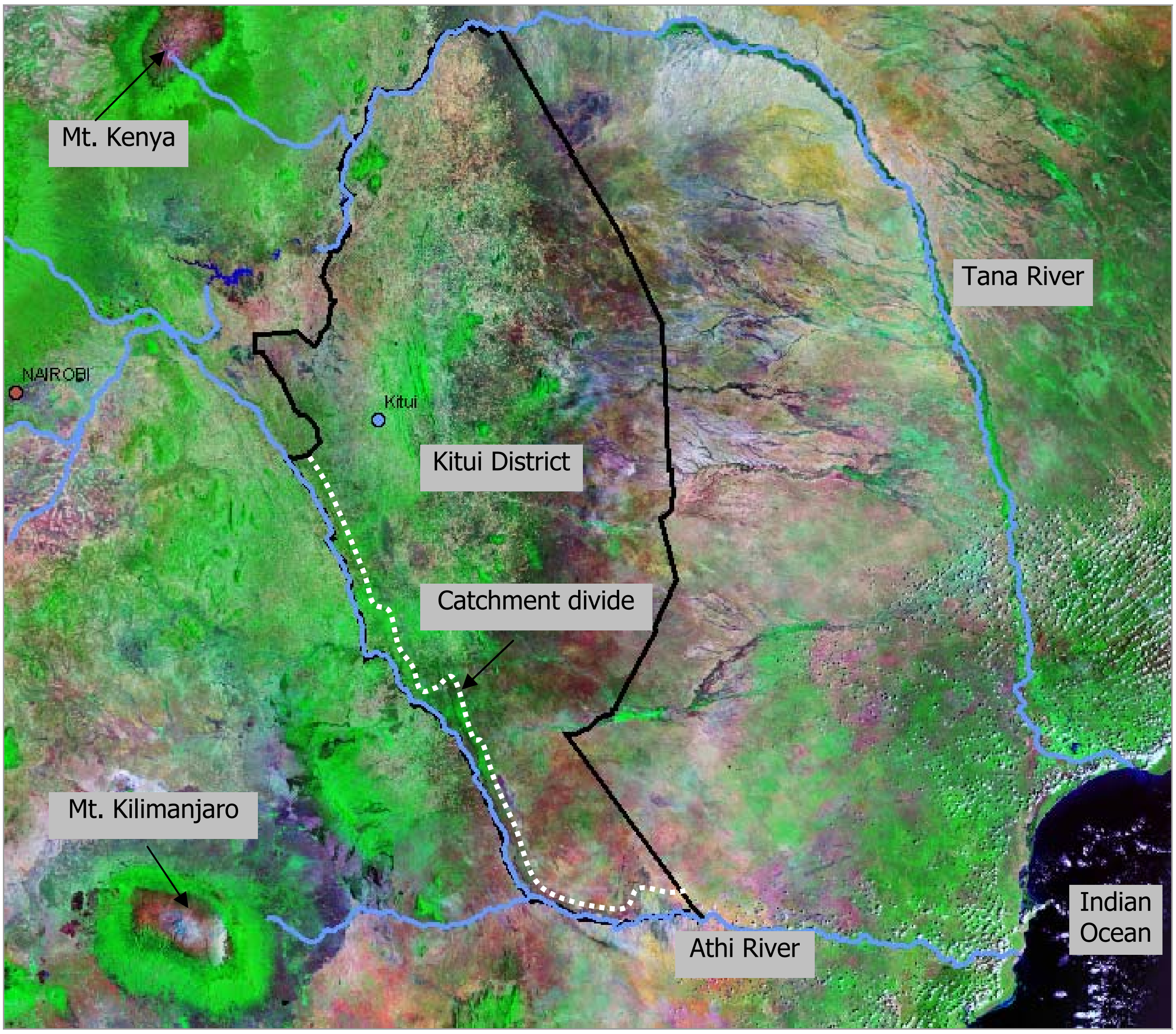

Figure 5. False colour composite satellite image of the Southern part of Kenya (source: USGS and NASA).

There are no perennial rivers in the District except the Tana River. In spite of perennial headwaters, the Athi often runs dry due to evaporation and infiltration losses. All of Kitui's rivers, including the Tana River, are strongly characterized with high flows in April-May and November-December and very low (or nil) flows in the intervening dry periods. Most of the ephemeral streams that drain into the Tana River generally become dry within one month after the rainy season. (Borst and De Haas, 2006)

2.2.3 Socio-economical data

In 1997 the income of 58 percent of the eastern districts was beneath the poverty line of 2 dollars a day (PRSP, 2001). This is one of the poorest regions of Kenya. The main economic activity is rainfed agriculture (1999 census Kitui). Irrigated agriculture only takes place on small plots on the river banks. During prolonged dry periods the farmers are dependent on relief food from donors. In 2004 and

spring 2005 up to 50 percent of the inhabitants of Kitui received food aid (FEWS-NET). Besides farming the main economic activities are charcoal burning, brick making and basket breading.
Only 45 percent of Kenyans have access to clean water for domestic use and even fewer have access to water that is fit to drink. In the Kitui district these numbers are even lower: only 6 percent of the inhabitants has access to potable water (DDP, 2002). Water is the most essential development commodity in this area, the major sources are the ephemeral rivers. Water scarcity forces women and girls to walk up 20 kilometres in dry periods to water sources such as springs and scoopholes.

2.2.4 The Kitui sand dams

One of the successful examples of a rural water conservation programme is the construction of sand storage dams in the Kitui district in Kenya (Figure 6). This programme is a cooperation between the community and the Sahelian Solution Foundation (SASOL). SASOL, founded in 1992, assists Kitui communities to address household and production water scarcity through the sand storage dam technology.

The planning objective was to shorten the distances to water sources to below two kilometres whilst making water available for productive use. Typically, women walk 10-15 km to water sources in the district. To date, almost 500 dams have been constructed in central Kitui. The key success factors of the Kitui sand storage dams are firstly the high degree of community participation in the planning and construction and secondly the concept of cascades (many dams constructed in one riverbed), creating a substantial volume of storage in a small area and hence reaching a larger part of the population.

Sand storage dams are being built in the river bed, perpendicular to the flow direction. Behind these dams the river bed fills up with sand, enlarging the natural aquifer(Figure 4). During the dry season water will be stored in the area for a longer period. More water can be harvested from scoopholes and wells, providing water to the people for a longer period. (Borst and De Haas, 2006)

Figure 6. SASOL sand storage dams in Kitui (pictures field visit July 2006, P. Droogers & A. van Loon).

2.2.5 Water management and institutional aspects

The institutional framework surrounding the sand dam project in Kitui comprises several actors on various institutional levels. By means of interviews with representatives, information was gathered concerning i.e. the responsibilities, the level of cooperation and the coordination structure of the different actors. The results are presented according to the three institutional levels: NGO level, community level and government level.

In the bottom-up approach practiced by SASOL, community participation plays an important role. The organization only facilitates construction materials, knowledge and the required funding, keeping the total costs as low as possible. The 8-step methodology includes formal meetings, selection of the site and site-confirmation by SASOL. At the end of the pre-constructive phase, the community selects a dam committee who is responsible for the organization of the site and for the long-term utilization of the dam. During construction and in the post-constructive phase several trainings are given. These sub-locational training sessions cover subjects like project management, natural resource management and catchment development. In some cases, Ex-change (a Dutch NGO) cooperates with SASOL, by providing student teams to help the community with the construction of the sand dam.

At community level, the village elder and the newly formed dam committee fulfil the most important roles. Being the official spokesperson for the community, the village elder is approached first by SASOL to discuss the Sand Dam Project and its impacts. The responsibilities of the village elder are overall supervision of the site, the participants and the materials and the protection and utilization of the dam. The dam committee has very similar responsibilities, including supervision of the site, organizing the community, and managing and maintaining the sand dam. In cooperation with SASOL, the committee also sets up rules and regulations for the construction period and for utilization and maintenance of the sand dam after construction.

The highest institutional level is the Kenyan government. The various levels of government (ranging from national to district) are not only regulatory institutions, but are also active in setting up projects in sectors as agriculture, irrigation and health. This is mostly done through extension officers who visit communities and give advice on various topics. For this reason, the ministries could play a major factor in making the Sand Dam Project a success.

The Ministry of Water and Irrigation is responsible for the development of water resources, and therefore closely connected to SASOL. Although the Ministry is aware of SASOL's activities, there is little cooperation between the two parties; making the outcome of the project less effective due to insufficient support and follow-up services from the Ministry. The Water Act 2002 is a new policy concerning the management of the water resources. The act supports a minimal role of the government and greater community participation. In the near future, water user groups may become an important entity on district level and it is recommendable that these groups work together with the dam committees.

Another important actor is the District Development Committee. Since 2002 the Kitui Sand Dam Project is incorporated into the Districts Development Plan (DDP for 2002-2008). Because of an increased awareness of SASOL's activities at the government, it is expected that extension services to sand dam-communities will be better matched to their situation (proper utilisation of the resources).

3 Setting up SWAT Model

3.1 Data

SWAT requires detailed spatial and temporal input data, as it is a highly detailed, physical model. The most important spatial information needed are a Digital Elevation Model (DEM), a land use map and a soil map. As for temporal data, daily meteorological data is essential. Additionally, data on reservoirs, point inlets or discharges, water use, irrigation, etc. can be included in SWAT.

3.1.1 River Basin

For the Partners for Water project in Kitui the catchment of the Tiva river was selected because it contains most sand dams of SASOL. In the catchment to the East of Tiva, the Thua catchment, also many sand dams of SASOL are located. However, this catchment drains into a completely different part of Tana river and will therefore not be considered in this study. The Tiva river basin (Figure 7) has an area of 2865.764 km2 and contains 273 sand storage dams.

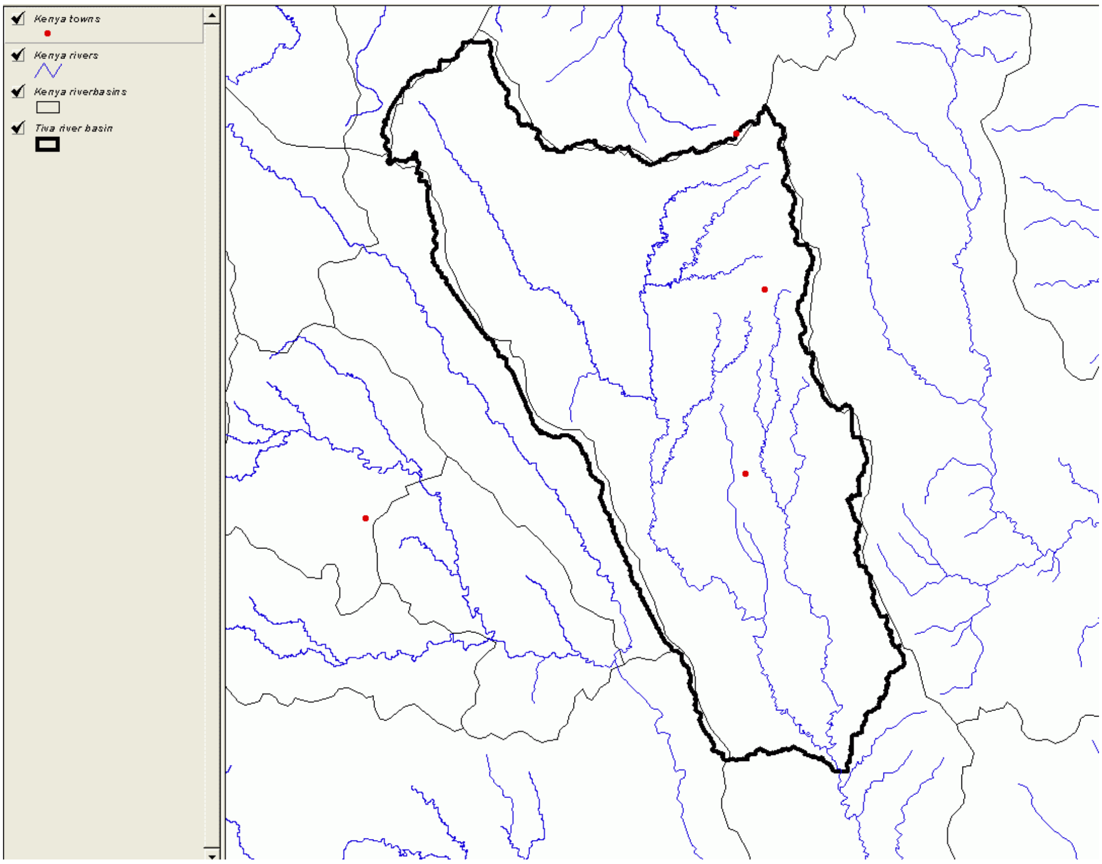

Figure 7. Tiva river basin.

3.1.2 DEM

Digital Elevation data was obtained from the Shuttle Radar Data Topography Mission (SRTM). Data was collected during NASA's Space Shuttle Endeavour flight on 11-22 February 2000, and was collected using a radar device. SRTM data were processed from raw radar echoes into digital elevation models at the Jet Propulsion Laboratory (JPL) in Pasadena, CA. These original data files had samples spaced ("posted") at intervals of 1 arc-second of latitude and longitude (about 30 meters at the equator).

For the United States SRTM data are available at a resolution of 1 arc second (about 30 meter). SRTM data at 3 arc-second (90 meters) is currently available for global coverage between 60 degrees North and 56 degrees South latitude. The product consists of seamless raster data and is available in geographic coordinates (latitude/longitude) and is horizontally and vertically referenced to the EGM96 Geoid.

SRTM-DEM data have been obtained using the USGS Seamless Data Distribution (http://seamless.usgs.gov/) and are reclassified. The SRTM-DEM data have a resolution of 90 m (Figure 8).

The DEM forms the base to delineate the catchment boundary, stream network (Figure 9) and create subbasins. This is performed by the pre-processing module of the SWAT but requires a so-called minimum catchment area size. For a couple of sizes this has been done. After some trials a threshold area of 340 ha provided a nice balance between sufficient detail and at the same time a number of subbasins that can be handled. As outlet point a point in the river was selected downstream of the tributaries with reservoirs. The final Tiva basin was having an area of 28,7555 ha and a total of 380 subbasins was delineated (Figure 10, Figure 11, Figure 12). Note that these 380 units will be divided in smaller units, the Hydrological Response Units (HRU), after overlaying land use and soil maps.

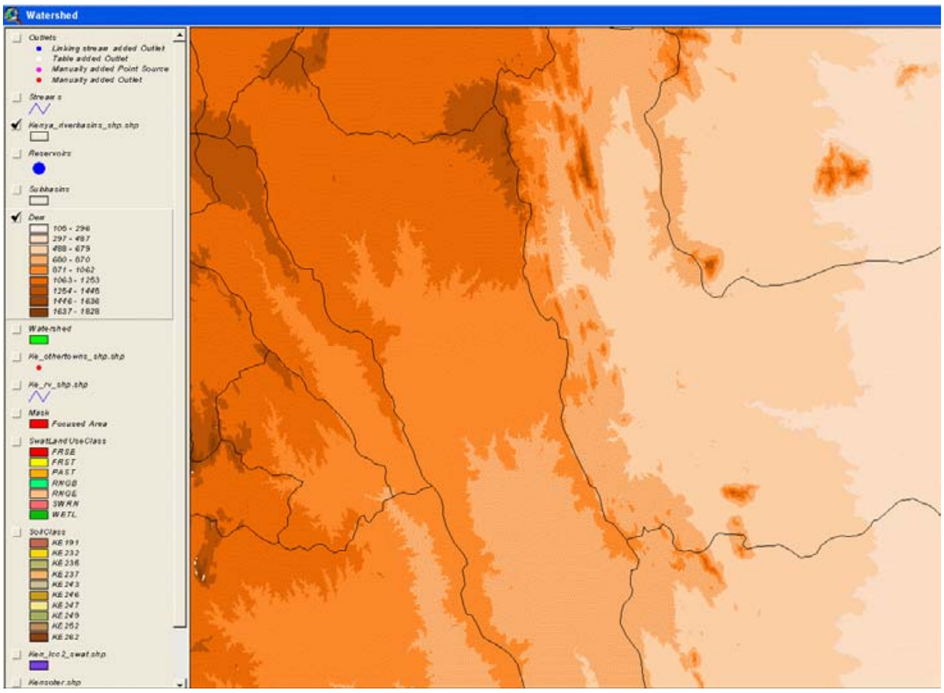

Figure 8. SRTM Digital Elevation Model at 90 m resolution.

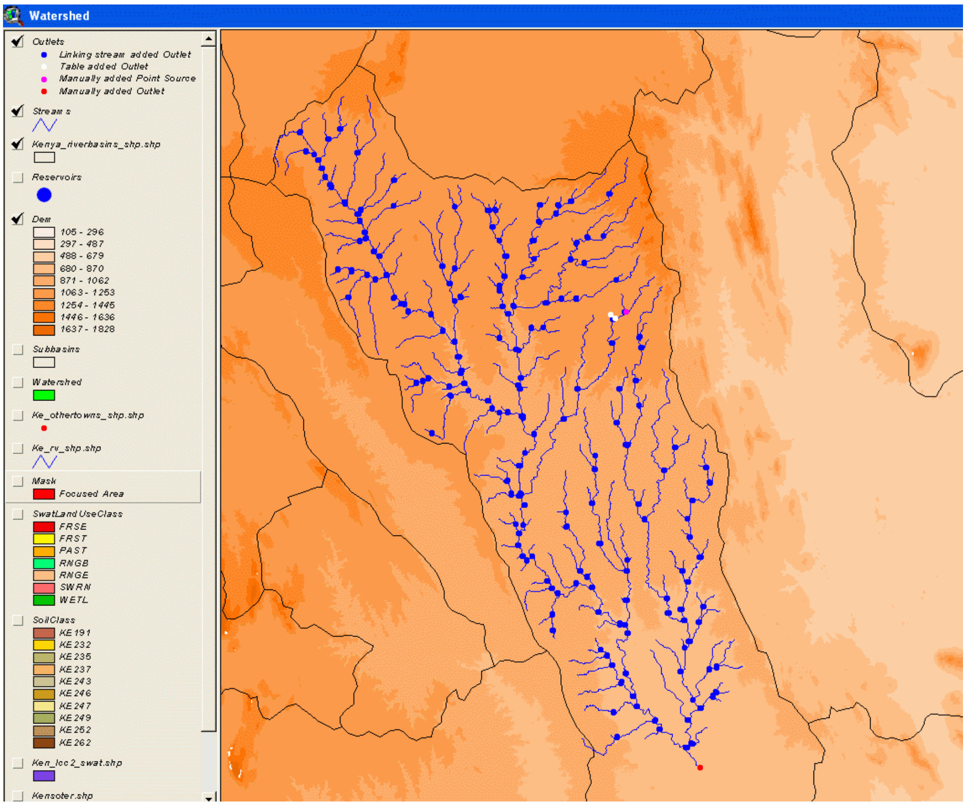

Figure 9. Stream flow network as derived from DEM.

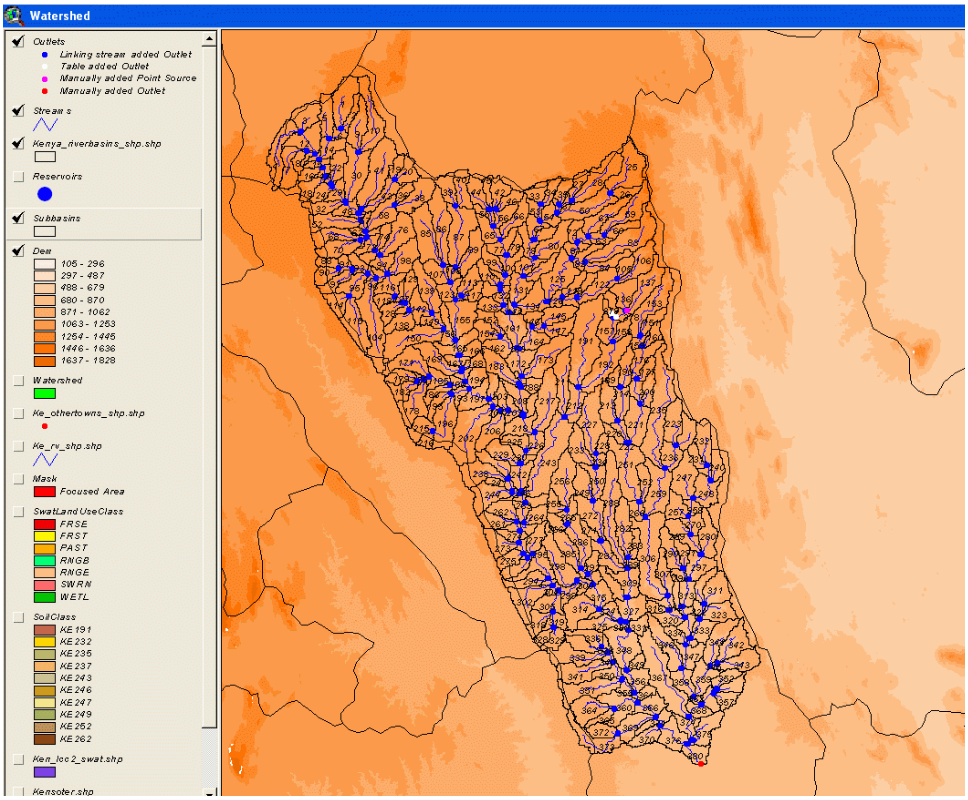

Figure 10. Subbasins as derived from DEM.

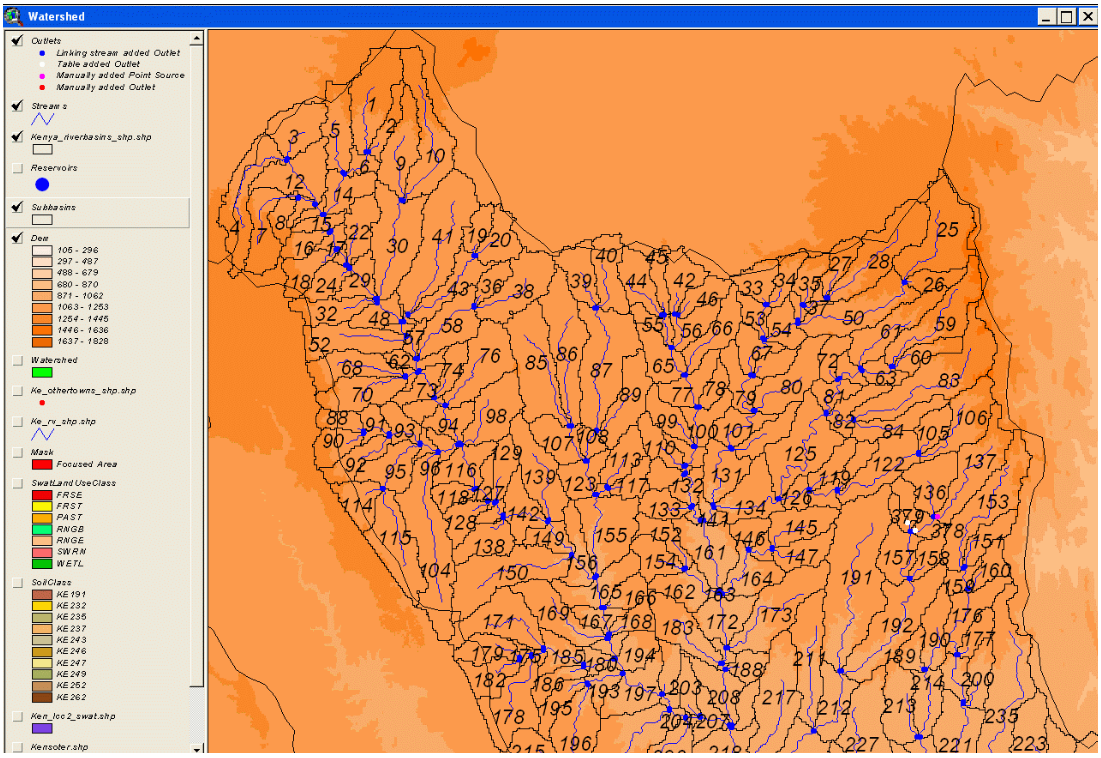

Figure 11. Zoom in on subbasins.

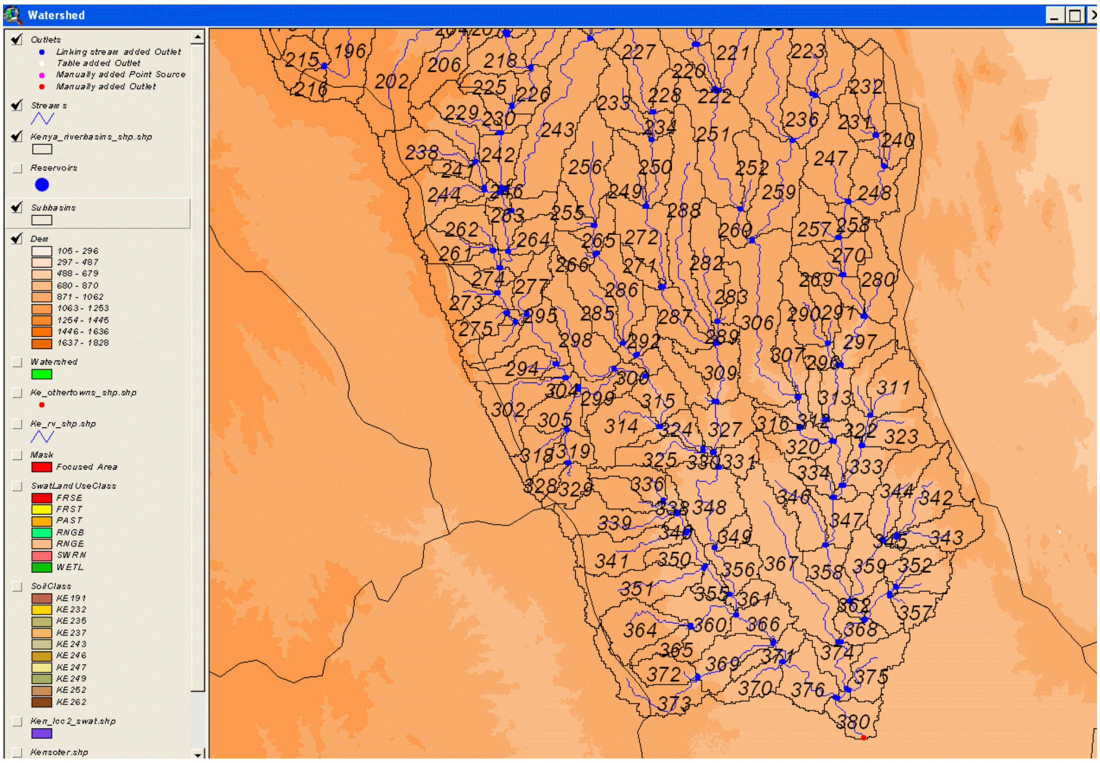

Figure 12. Zoom in on subbasins.

3.1.3 Reservoirs

In SWAT you have to put in reservoirs at the beginning of the set up of the model. The advantage is that the reservoirs are included in the base structure of the model, so that SWAT results can be analysed for the reservoirs and the river reaches at the location of the reservoirs. The disadvantage is that scenarios with changes in reservoir locations are hard to examine. If such a scenario is required a new model has to be set up.

The sand dams of SASOL can not be included in SWAT separately. The model would become highly cluttered and unworkable. Besides, the scale of the sand dams is to small to be included in SWAT and in every subbasin only one reservoir can be located. Therefore we clustered the sand dams in 12 Representative Reservoir Notes (RRNs) of 6 to 63 dams per RRN (Figure 13 and Table 1).

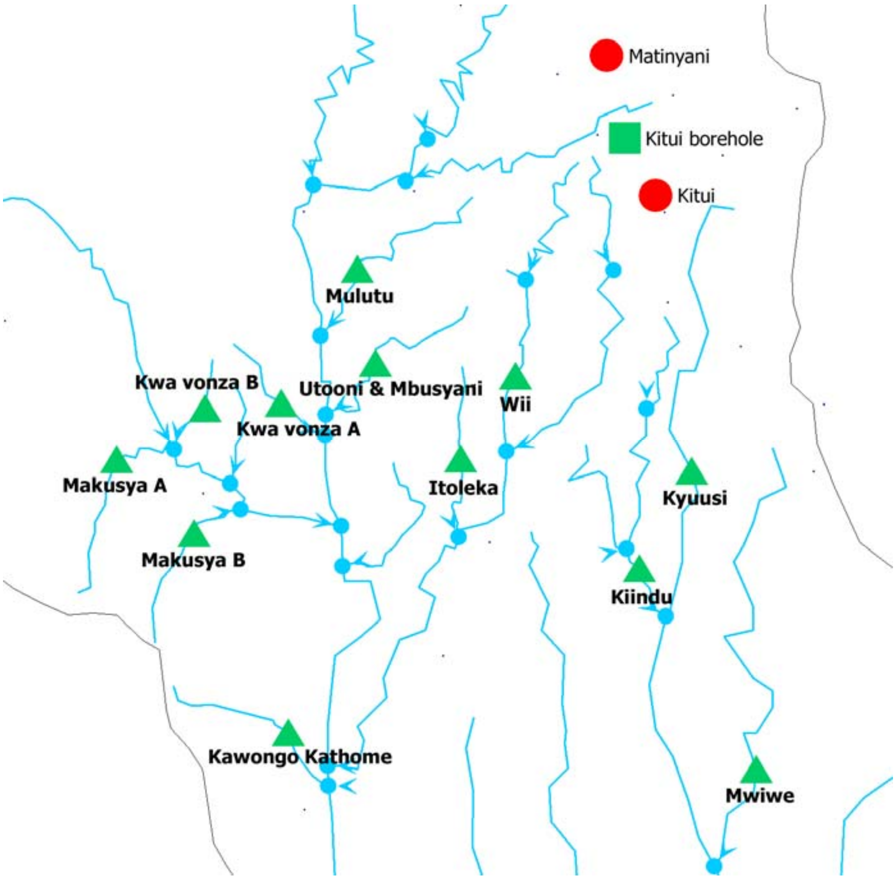

Figure 13. Schematic part of the WEAP model with names of the RRNs (sourse: WatManSup Report No.2).

Table 1. Reservoirs combined from sand storage dams (sourse: WatManSup Report No.2).

Subbasin	Name	No of SASOL sand dams
235	Mwiwe	34
199	Kyuusi	9
219	Kiindu	41
191	Wii	13

211	Itoleka	6
164	Mulutu	18
173	Utooni & Mbusyani	63
183	Kwa Vonza A	11.5
168	Kwa Vonza B	11.5
193	Makusya A	14.5
202	Makusya B	14.5
245	Kawongo Kathome	37

In SWAT the reservoir locations are displayed at the end of a tributary (Figure 14). It looks as if they are located in the main river, but they are not.

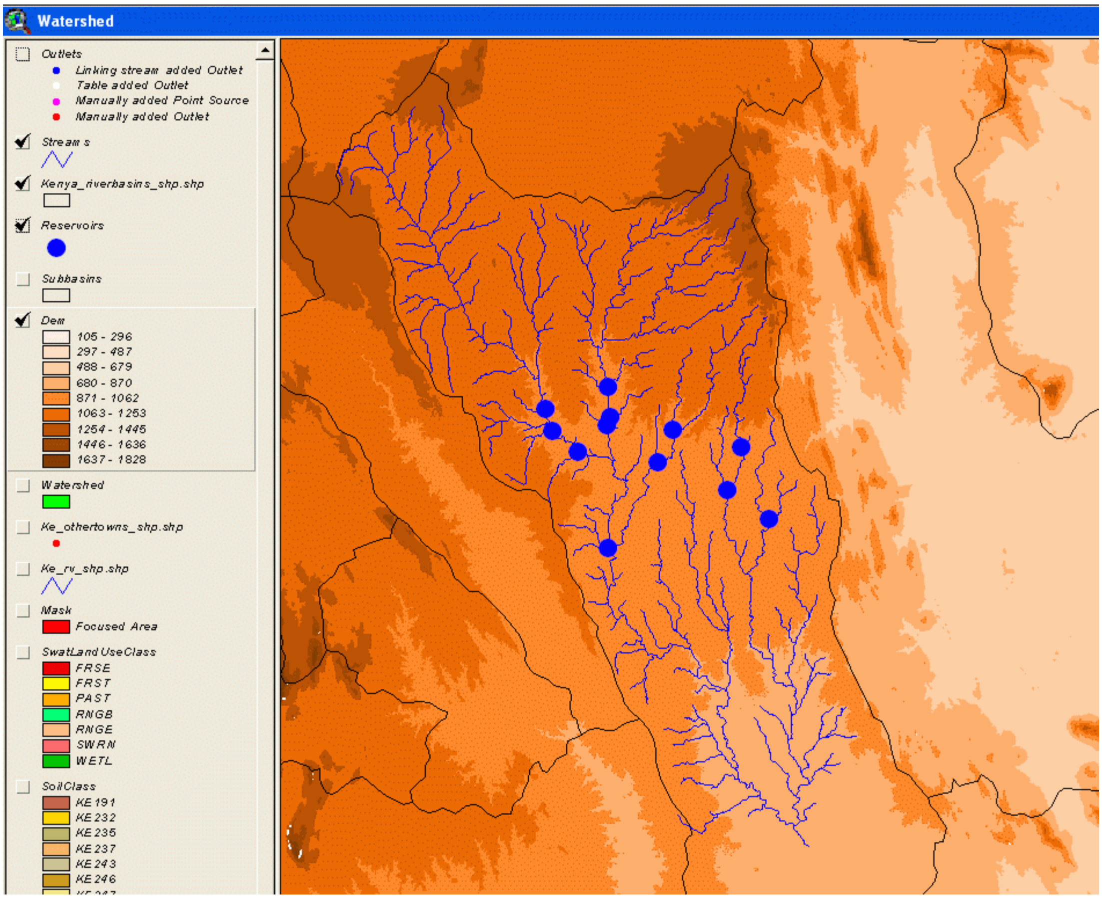

Figure 14. Reservoirs in SWAT.

3.1.4 Land use

Land use is one of the dominant aspects in SWAT. However, it is at the same time one of the most difficult data set to assess and multiple efforts have been undertaken to generate these data. One overview of available datasets is given by the Land Cover Institute (LCI). LCI is established within the United States Geophysical Service (USGS) and has the mission to function as a focal point for coordinating applications and knowledge of land use and land cover information (LCI, 2006).

LCI has identified 19 land cover datasets covering Africa. A major drawback of all these land covers is that they were created for larger scale levels resulting in low spatial detail and non-specific classes. This makes these land cover data sets less suitable for the WatManSup project.

A higher resolution land cover map has been published by the International Livestock Research Institute which is located in Nairobi. This map is derived from a study in 1987 by JICA (Japan International Co-operation Agency), in the context of developing a National Water Master Plan for the country. This map was derived from Landsat 1980 satellite data and has 14 classes: (1) Forest, (2) Woodland, (3) Bush land (dense), (4) Bush land (sparse), (5) Grassland, (6) Barren land (SG), (7) Barren land (R), (8) Swamp, (9) Water body, (10) Water (artificial), (11) Agriculture (dense), (12) Agriculture (sparse), (13) Plantation, and (14) Town. The map clipped to the Tiva River Basin can be seen in Figure 15 and areas per class in Table 2.

The JICA landuse map might be somewhat outdated, and besides that it is also clear that the resolution of the map is still too course and might not provide sufficient details for WatManSup project.

Table 2. Land use areas as shown in Figure 15.

Land use	Area (ha)	%
bushland (dense)	12,499.5	47.1
agriculture (sparse)	11,493.1	43.3
agriculture (dense)	0.0	0
bushland (sparse)	1,704.2	6.4
forest	36.1	0.1
plantation	0.0	0
woodland	38.9	0.1
barren land (R)	648.6	2.4
grassland	97.6	0.4
water (artificial)	0.0	0
swamp	0.0	0
town	0.0	0
Total	26,518	100

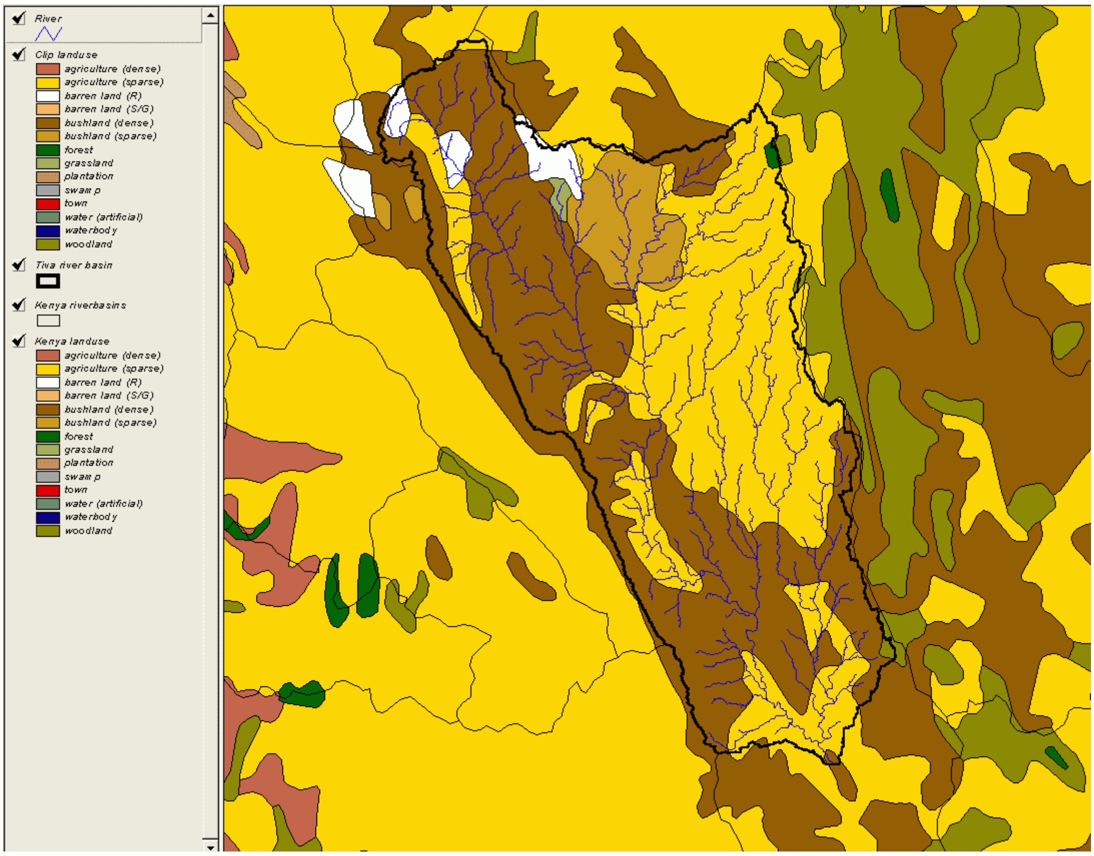

Figure 15. Land use map based on a JICA study (ILRI, 2006).

Another data set is available from the Kenya Department of Resource Surveys and Remote Sensing (DRSRS) survey that was conducted to define land use and land cover for medium and high potential areas (http://www.africover.org). The DRSRS survey resulted in land use/land cover designations for points spaced on an approximate 2400 x 4800 m irregular grid. At each point, the percentage of each land use/land cover was defined. This dataset is known as the AFRICOVER and has a high spatial resolution and an impressive number of 101 land covers are distinguished in Kenya.

In Tiva Basin the dominant AFRICOVER land use classes are:

- Herbaceous - Small Fields - Maize, Rainfed
- Open shrubs with closed to open herbaceous and sparse trees.

The AFRICOVER classes have been converted to SWAT classes resulting in 8 classes for the Tiva basin (Table 3 and Figure 16). The dominant land use class is Corn (CORN), which is a broad group and consists out of the following classes according to the original AFRICOVER data set:

- Herbaceous - Medium Fields -Maize, Rainfed
- Large-Medium Fields - Maize, Rainfed
- Rainfed Herbaceous - Clustered Medium Fields, Maize Rainfed
- Rainfed Herbaceous - Isolated Medium Fields, Maize
- Herbaceous - Small Fields - Maize, Rainfed
- Herbaceous - Clustered Small Fields - Maize, Rainfed
- Herbaceous - Isolated Small Fields - Maize, Rainfed

The SWAT class Agricultural Land-Generic (AGRL) covers 17% of the area and is a combination of the following AfriCover original classes:

- Continuos Rainfed Small fields [cereal]
- Closed to very open herbaceous with sparse shrubs
- Closed to very open herbaceous
- Rainfed Herbaceous - Medium Fields
- Others

The SWAT class Range-Grasses (RNGE) covers 16% of the area and is a combination of the following AfriCover original classes:

- Very open shrubs with closed to open herbaceous and sparse trees
- Open general woody with herbaceous
- Open shrubs with closed to open herbaceous and sparse trees
- Open general shrubs with closed to open herbaceous

Irrigated areas cover a very small portion of the basin (660.5 ha) and is limited the land cover class:

- AGRI: Agriculture general irrigated

Table 3. Land use areas according to the AFRICOVER land use dataset converted to SWAT classes.

SWATLCC	**Name**	**ha**	**%**
CORN	Corn	15806	57
AGRL	Agricultural Land-Generic	4724	17
RNGE	Range-Grasses	4391	16
FRST	Forest-Mixed	1848	7
AGRI	Agriculture general irrigated	660	2
WETL	Wetlands-Mixed	218	1
URML	Residential-Med/Low Density	7	0
RNGB	Range-Brush	3	0
Total		**27,657**	**100**

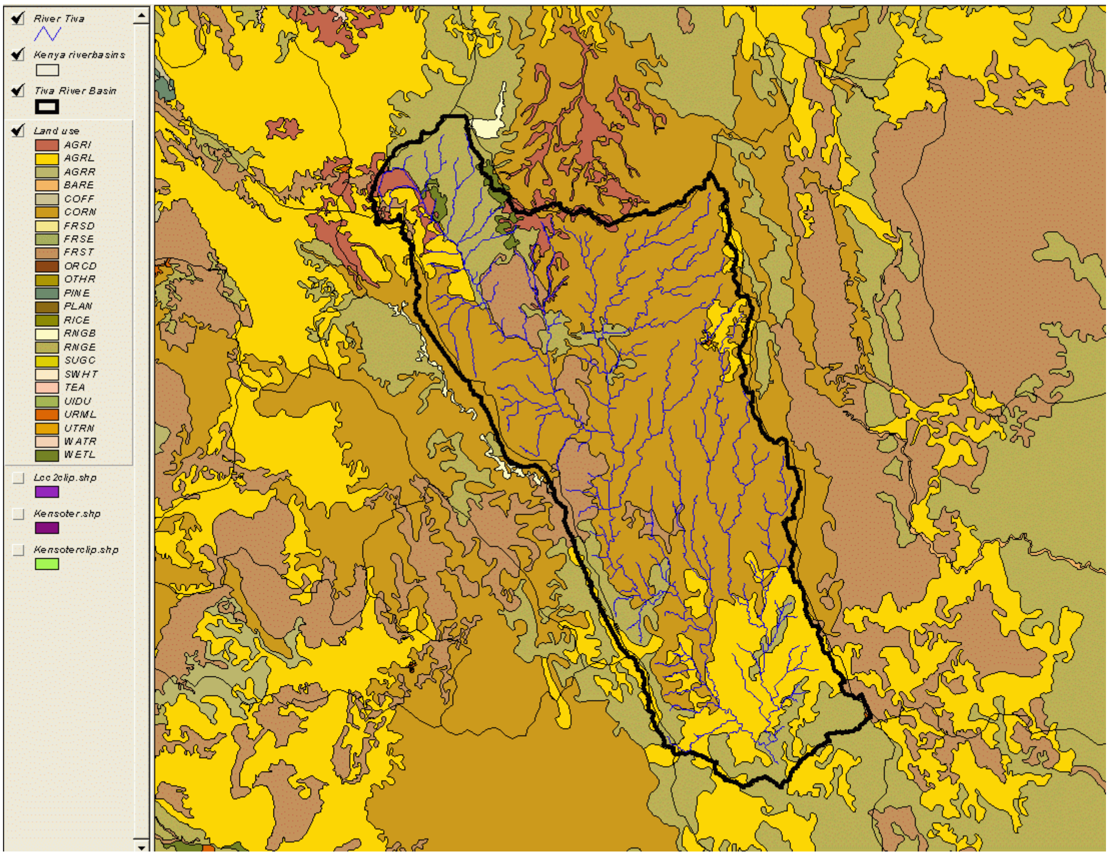

Figure 16. AfriCover land use converted to SWAT units.

3.1.5 Crop Characteristics

In order to simulate crop growth in SWAT crop specific characteristics have to be included in the model. Important is to emphasize that actual crop growth and the actual evapotranspiration is calculated by SWAT. So less optimal growth conditions can occur due to several conditions: water shortage, nutrient deficit, heat stress, less-optimal solar radiation, cold stress.

In Figure 17 an example of Corn is shown required to simulate crop growth. Besides these more or less generic crop characteristics, management information of the crop should be provided. These management data includes planting data, fertilizer application, irrigation if applicated etc.

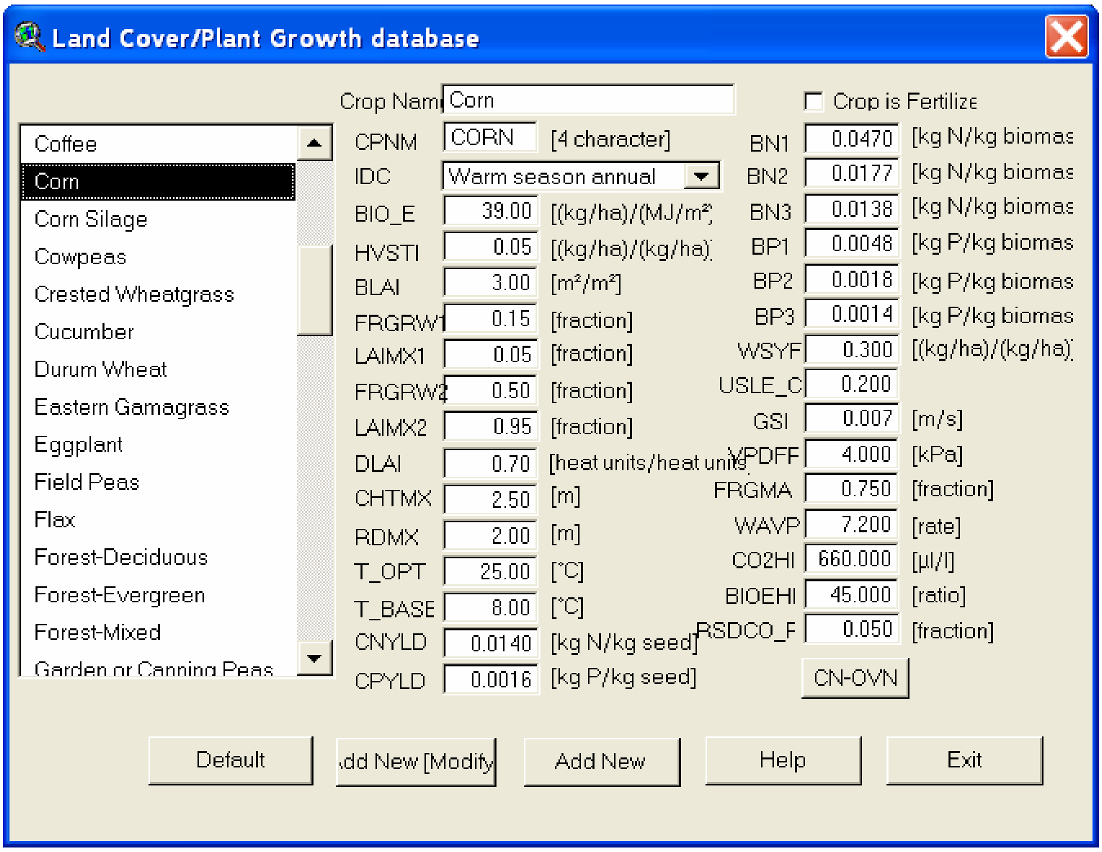

Figure 17. Required crop characteristics for the SWAT analysis. Example of Corn is shown.

3.1.6 Soils information

Soils information was obtained from the KenSOTER database. KenSOTER is the Soil and Terrain Database for Kenya and was completed in 1995 at a 1:1,000,000 scale. KenSOTER is developed in accordance to the SOTER methodology developed for national and local agricultural planning purposes (Van Engelen and Wen, 1995).

SOTER's objective is to characterize all soils from all corners of the world under a single set of rules requires. As the FAO-Unesco Soil Map of the World was designed for this purpose, SOTER has adopted the recently Revised Legend (FAO, 1988) as the main tool for differentiating and characterizing its soil components. As there is no universally accepted system for world-wide classification of terrain, SOTER has designed its own system.

The input of soil and terrain data into the SOTER database is contingent upon the availability of sufficiently detailed information. Although some additional information gathering may be required when preparing existing data for acceptance by the database, the SOTER approach is not intended to replace traditional soil surveys.

The SOTER mapping approach in many respects resembles physiographic soil mapping. Its main difference lies in the stronger emphasis SOTER puts on the terrain-soil relationship as compared to what is commonly done in traditional soil mapping. This will be true particularly at smaller mapping scales. At the same time SOTER adheres to rigorous data entry formats necessary for the construction of a universal terrain and soil database. As a result of this approach the data accepted by the database will be standardized and will have the highest achievable degree of reliability.

The soil map for Tiva basin is shown in Figure 18 and the area of the various soil units is given in Table 4. The required parameters for the SWAT model are displayed in Table 5.

Table 4. SOTER units as shown in Figure 18.

NEWSUID	Area (ha)	%
KE235	16202	58.6
KE252	4276	15.5
KE232	2695	9.7
KE246	2223	8.0
KE237	1704	6.2
KE243	208	0.8
KE262	162	0.6
KE191	87	0.3
KE249	76	0.3
KE247	27	0.1

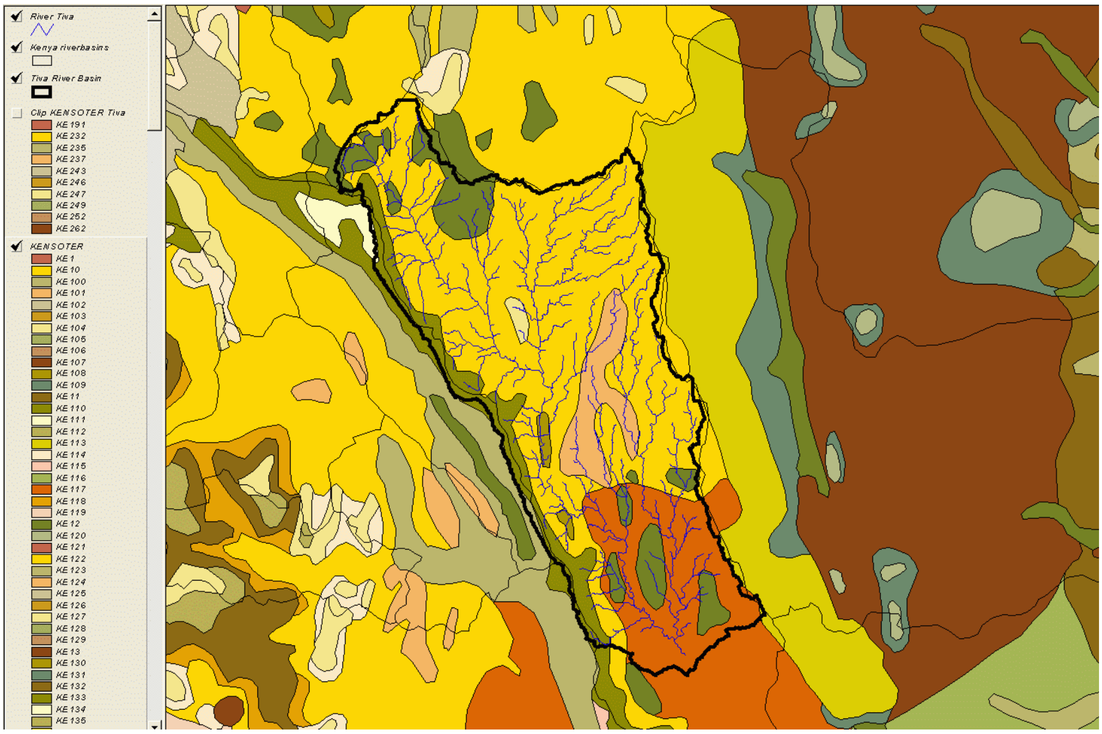

Figure 18. Soil map indicating different soil classes (Batjes and Gicheru, 2004).

Table 5. Required parameters for the SWAT model.

Code	Definition	MIN	MAX
SNAM	Soil name	0.00000	0.00000
HYDGRP	Soil Hydrologic Group	0.00000	0.00000
SOL_ZMX	Maximum rooting depth of soil profile.	0.00000	3500.00000
ANION_EXCL	Fraction of porosity (void space) from which anions are excluded.	0.01000	1.00000
SOL_CRK	[OPTIONAL] Crack volume potential of soil.	0.00000	1.00000
TEXTURE	[OPTIONAL] Texture of soil layer.	0.00000	0.00000
SOL_Z	Depth from soil surface to bottom of layer.	0.00000	3500.00000
SOL_BD	Moist bulk density.	1.10000	2.50000
SOL_AWC	Available water capacity of the soil layer.	0.00000	1.00000
SOL_K	Saturated hydraulic conductivity.	0.00000	2000.00000
SOL_CBN	Organic carbon content .	0.05000	10.00000
CLAY	Clay content.	0.00000	100.00000
SILT	Silt content.	0.00000	100.00000
SAND	Sand content.	0.00000	100.00000
ROCK	Rock fragment content.	0.00000	100.00000
SOL_ALB	Moist soil albedo.	0.00000	0.25000
USLE_K	USLE equation soil erodibility (K) factor.	0.00000	0.65000
NLAYERS	Number of layers in the soil.	1.00000	10.00000
NUMLAYER	The layer being displayed.	1.00000	10.00000

An important characteristic not provided in KenSOTER is the saturated hydraulic conductivity. A well-developed technique to overcome this problem is to use so-called pedo-transfer functions (PTF). A wide range of pedo-transfer functions have been developed and applied successfully over the last decades over various scales (e.g. field scale in Droogers et al. 2001; basin scale in Droogers and Kite, 2001).

Of the many existing PTF the one based on Campbell is used frequently (Lee, 2005):

$K_{sat} = 54 \times \exp(-0.07(sa)-0.167(cl))$

K_{sat} is saturated hydraulic condictivity (mm h^{-1})
sa is sand content (%)
cl is clay content (%)

However, Sobieraj et al. (2001) concluded from a detailed analysis that most PTFs were not very reliable and the impact on runoff estimates could be considerable. One PTF that generated conductivity values close to measured ones was the Jabro (1992) equation:
$Ksat = \exp(9.56 - 0.81 \log(st) - 1.09 \log(cl) - 4.64 BD)$

Ksat is saturated hydraulic condictivity (cm h-1)
st is silt content (%)
cl is clay content (%)

In SWAT mm h-1 is required leading to:
Ksat = exp(11.86 – 0.81 log(st) – 1.09 log(cl) – 4.64 BD)

This one is used to derive Ksat values from the KenSOTER database (Droogers et al., 2007).

3.1.7 Hydrological Response Units

As introduced before, SWAT uses a concept of Hydrological Response Units (HRU): portions of a subbasin that possess unique landuse/management/soil attributes. An HRU is not synonymous to a field. Rather it is the total area in the subbasin with a particular landuse, management and soil. While individual fields with a specific landuse, management and soil may be scattered throughout a subbasin, these areas are lumped together to form one HRU. HRUs are used in most SWAT runs since they simplify a run by lumping all similar soil and land use areas into a single response unit. It is often not practical to simulate individual fields in cases where the focus lies on entire basins.

Implicit in the concept of the HRU is the assumption that there is no interaction between HRUs in one subbasin. Loadings (runoff with sediment, nutrients, etc. transported by the runoff) from each HRU are calculated separately and then summed together to determine the total loadings from the subbasin. If the interaction of one landuse area with another is important, rather than defining those landuse areas as HRUs they should be defined as subbasins. It is only at the subbasin level that spatial relationships can be specified. The benefit of HRUs is the increase in accuracy it adds to the prediction of loadings from the subbasin. The growth and development of plants can differ greatly among species. When the diversity in plant cover within a subbasin is accounted for, the net amount of runoff entering the main channel from the subbasin will be much more accurate.

In practice the HRUs are defined by overlaying three data layers: (i) subbasins, (ii) land cover, and (iii) soils. In the Tiva model the threshold is set to 5% for both land cover and soils. From the 380 subbasins a total of 870 HRUs has been derived for Tiva basin.

3.1.8 Meteorological data

Accurate meteorological data for this initial analysis was not available at a high spatial resolution. Therefore the high-resolution CRU data set was used. The CRU TS 2.0 dataset of the University of East Anglia comprises 1200 monthly grids for the period 1901-2000, and covers the global land surface at 0.5° × 0.5° resolution (Mitchell et al., 2003). The dataset comprises: cloud cover, diurnal temperature range, precipitation, temperature and vapor pressure. The CRU dataset is based on raw station data, which are scarce in some regions and periods. A method called 'relaxation to the climatology' was used to create continuous grids. This implies that, for some areas or regions, data are less accurate. For Tiva the location of the meteo station near Kitui-town was used as CRU point (Figure 19).

1

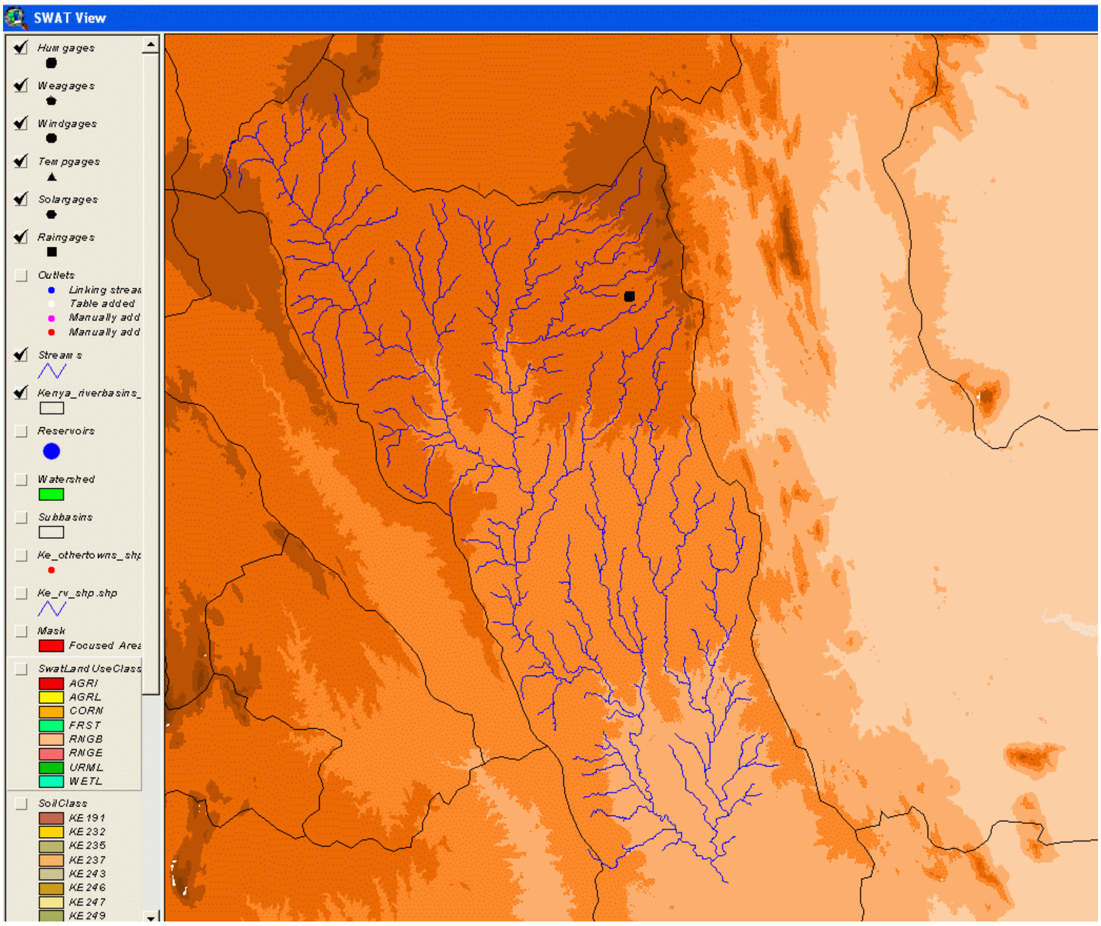

Figure 19. Location of the CRU meteorological data point near Kitui.

For Masinga, a reservoir with a climate comparable to that of the Tiva basin located 70 km north of Kitui, the annual and monthly average precipitation amounts are plotted in Figure 20 and Figure 21. Precipitation over the last 15 years indicates that mean annual precipitation over this period is 983 mm (Table 6). A relatively wet year is 1995, and 2000 can be considered as dry.

It was decided to perform the initial SWAT analysis on this period, 1990 to 2002.

Table 6. Annual precipitation for Kitui based on CRU.

1990	1254	mm
1991	799	mm
1992	684	mm
1993	1050	mm
1994	876	mm
1995	1480	mm
1996	689	mm
1997	1210	mm
1998	1306	mm
1999	818	mm

2000	631	mm
2001	719	mm
2002	1259	mm
average	**983**	mm

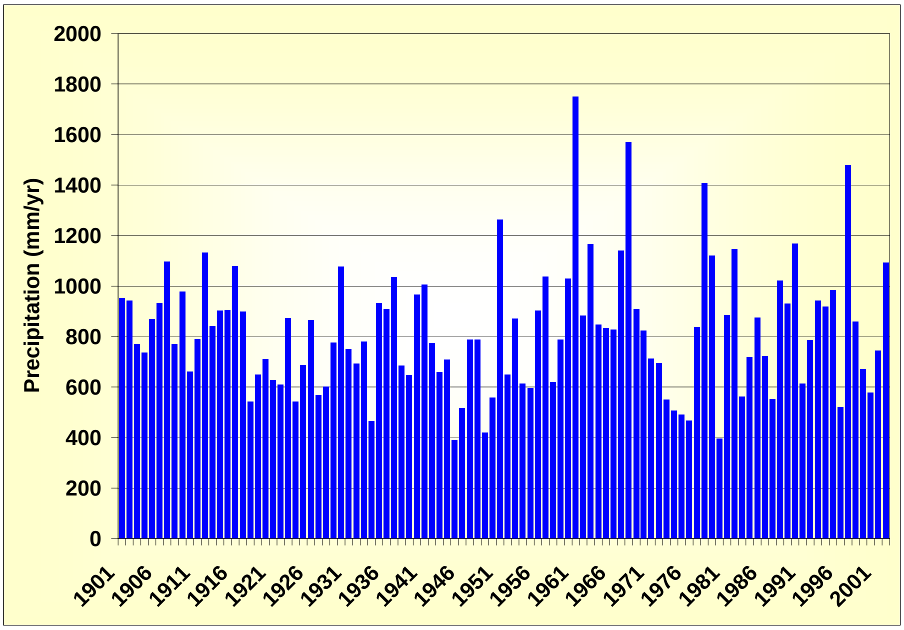

Figure 20. Annual precipitation for the CRU meteorological data point at Masinga.

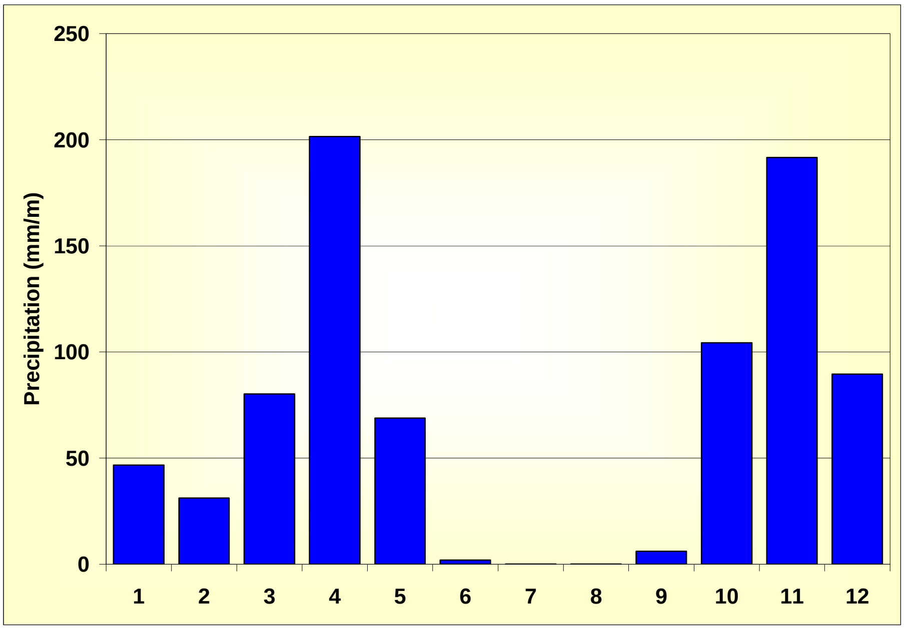

Figure 21. Average monthly precipitation (1901-2002) for the CRU meteorological data point at Masinga.

3.1.9 Reservoir characteristics

In SWAT a reservoir is considered as an impoundment located on the main channel network of a watershed. No distinction is made between naturally-occurring and man-made structures. The features of an impoundment are shown in Figure 22.

SWAT is keeping track of the water balance for a reservoir as follows:

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

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

The sand storage dams in Kitui are small unoperated reservoirs that do not fit the reservoir definition of SWAT. The sand storage dams can not be included in SWAT individually. Therefore, the 273 SASOL sand dams in the Tiva catchment are clustered into 12 representative reservoirs nodes (RRNs) with 6 to 63 dams per RRN (see WatManSup Report No.2). The location of the RRNs within the catchment and the amount of sand dams per RRN are obtained from SASOL (pers.comm. Mr. Julius).

Outflow of the reservoirs can be specified by four different operational rules

- measured daily outflow
- measured monthly outflow
- average annual release rate (for uncontrolled reservoir)
- controlled outflow with target release

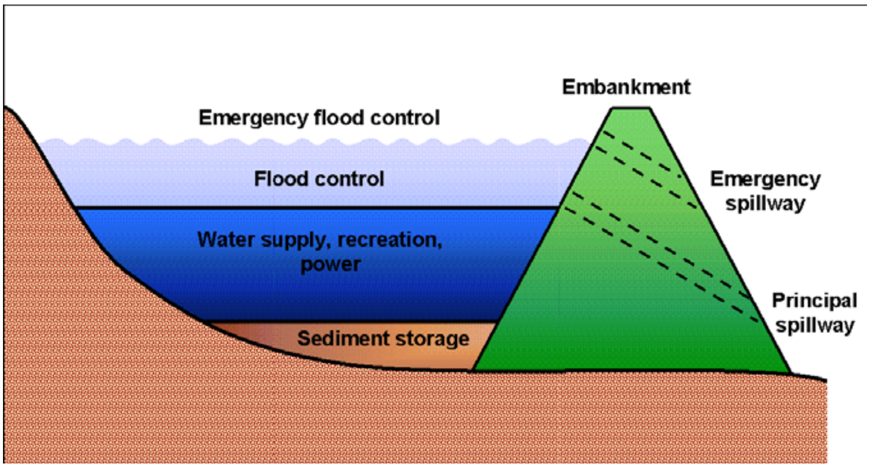

Figure 22. Terminology of reservoirs in SWAT.

The third option is used for this study, as this represents the most realistic practice for the reservoirs in Kitui. When the average annual release rate (IRESCO = 0) is chosen as the method to calculate reservoir outflow, the reservoir releases water whenever the reservoir volume exceeds the principal spillway volume, *Vpr*. If the reservoir volume is greater than the principal spillway volume but less than the emergency spillway volume, the amount of reservoir outflow is calculated:

$$V_{flowout} = V - V_{pr} \qquad if\ V - V_{pr} < q_{rel} \bullet 86400 \qquad (0.1)$$

$$V_{flowout} = q_{rel} \bullet 86400 \qquad if\ V - V_{pr} > q_{rel} \bullet 86400 \qquad (0.2)$$

If the reservoir volume exceeds the emergency spillway volume, the amount of outflow is calculated:

$$V_{flowout} = (V - V_{em}) + (V_{em} - V_{pr}) \qquad if\ V_{em} - V_{pr} < q_{rel} \bullet 86400 \qquad (0.3)$$

$$V_{flowout} = (V - V_{em}) + q_{rel} \bullet 86400 \qquad if\ V_{em} - V_{pr} > q_{rel} \bullet 86400 \qquad (0.4)$$

where *Vflowout* is the volume of water flowing out of the water body during the day (m3 H2O), *V* is the volume of water stored in the reservoir (m3 H2O), *Vpr* is the volume of water held in the reservoir when filled to the principal spillway (m3 H2O), *Vem* is the volume of water held in the reservoir when filled to the emergency spillway (m3 H2O), and *qrel* is the average daily principal spillway release rate (m3/s).

In this model for Kitui *qrel* is set to 0, so if *Vpr* < *V* < *Vem* equation 0.2 is used, and if *V* > *Vem* equation 0.4 is used. *Vpr* is set to 0, so up to *Vem* *Vflowout* is zero. If the volume of the reservoir exceeds *Vem* *Vflowout* is equal to *V* - *Vpr*, which is the excess volume.

The following reservoir characteristics and operational rules are required:

- surface area emergency spillway (RES_ESA) = unit area (ha) * no of dams
- volume emergency spillway (RES_EVOL) = unit storage capacity (m^3) * no of dams
- surface area principal spillway (RES_PSA) = surface area emergency spillway
- volume principal spillway (RES_PVOL) = 0.0
- initial volume (RES_VOL) = unit initial storage (m^3) * no of dams
- RES_RR: 0.0

The characteristics of the individual sand dams need to be clustered and added to be included in SWAT. The storage capacity of one dam is estimated from its dimensions. In average, a SASOL sand dam is about 6 m wide and 2 m high. The slope of the original river is 0.2 to 4% (Ertsen and Biesbrouck, 2004) with an average of around 1%. Consequently, dams of 2 m high have an impact on sand accumulation 200 m upstream. As the distance between consecutive dams in a river stretch is 500 to 1000 m, the dams have the space to fully establish. (pers.comm. Mr. Munyoki) Calculation of the amount of sand accumulated behind a dam results in a figure of 1200 m^3, assuming a triangular shape of the sand accumulation upstream. As coarse sand has a porosity of 45% (Ertsen and Biesbrouck, 2004) the water stored behind a single dam is 540 m^3. Additional to storage directly behind the sand dam, water will also be stored in the banks of the river. The strip of land directly influenced by a sand dam on one site is about half of the width of the dam. Consequently, the additional storage is estimated to be equal to the amount of water stored behind the dam, 540 m^3. The total storage then comes to 1080 m^3 per dam (see WatManSup Report No.2).
The unit initial storage is set at 800 m^3 per dam to represent the situation in January, when just after the rainy season of November and December the storage in the reservoir behind a dam is still high.
The unit area for a single sand storage dam is estimated at 0.1 ha.

The resulting surface area, storage capacity and initial storage for the RRNs are given in Table 7.

The following initial conditions are required as well

- sediment concentration (mg l^{-1})
- normal sediment concentration (mg l^{-1})

In this model these parameters are not considered and set to zero.

Table 7. Key characteristics of the 12 RRNs in Kitui.

Subbasin	Name	No of dams	Surface area	Storage	Initial storage
			ha	m^3	m^3
235	Mwiwe	34	3.4	36720	2720
199	Kyuusi	9	0.9	9720	720
219	Kiindu	41	4.1	44280	3280
191	Wii	13	1.3	14040	1040
211	Itoleka	6	0.6	6480	480
164	Mulutu	18	1.8	19440	1440
173	Utooni & Mbusyani	63	6.3	68040	5040
183	Kwa Vonza A	11.5	1.15	12420	920
168	Kwa Vonza B	11.5	1.15	12420	920
193	Makusya A	14.5	1.45	15660	1160
202	Makusya B	14.5	1.45	15660	1160
245	Kawongo	37	3.7	39960	2960

The values in Table 7 are so small that to include the values in SWAT the source code of the model had to be adjusted. The unit of the storage capacity of the reservoir has been changed from 10^4 m^3 to m^3. Additionally, the ranges for these parameters had to be adapted. The following changes have been made:

Table 8. Ranges reservoir parameters.

name	code	MIN	MAX
surface area emergency spillway	RES_ESA	1.0 > 0.0	
volume emergency spillway	RES_EVOL	15 > 0.0	3000 > 200,000
surface area principal spillway	RES_PSA	1.0 > 0.0	
volume principal spillway	RES_PVOL	10 > 0.0	100 > 200,000
initial volume	RES_VOL	10 > 0.0	100 > 200,000
RES_RR	RES_RR	0.0	

In Figure 23 the location of the RRNs in the Tiva basin is again displayed. SWAT allows having only one reservoir per sub basin and places the reservoir at the outflow point of the tributary into a larger river.

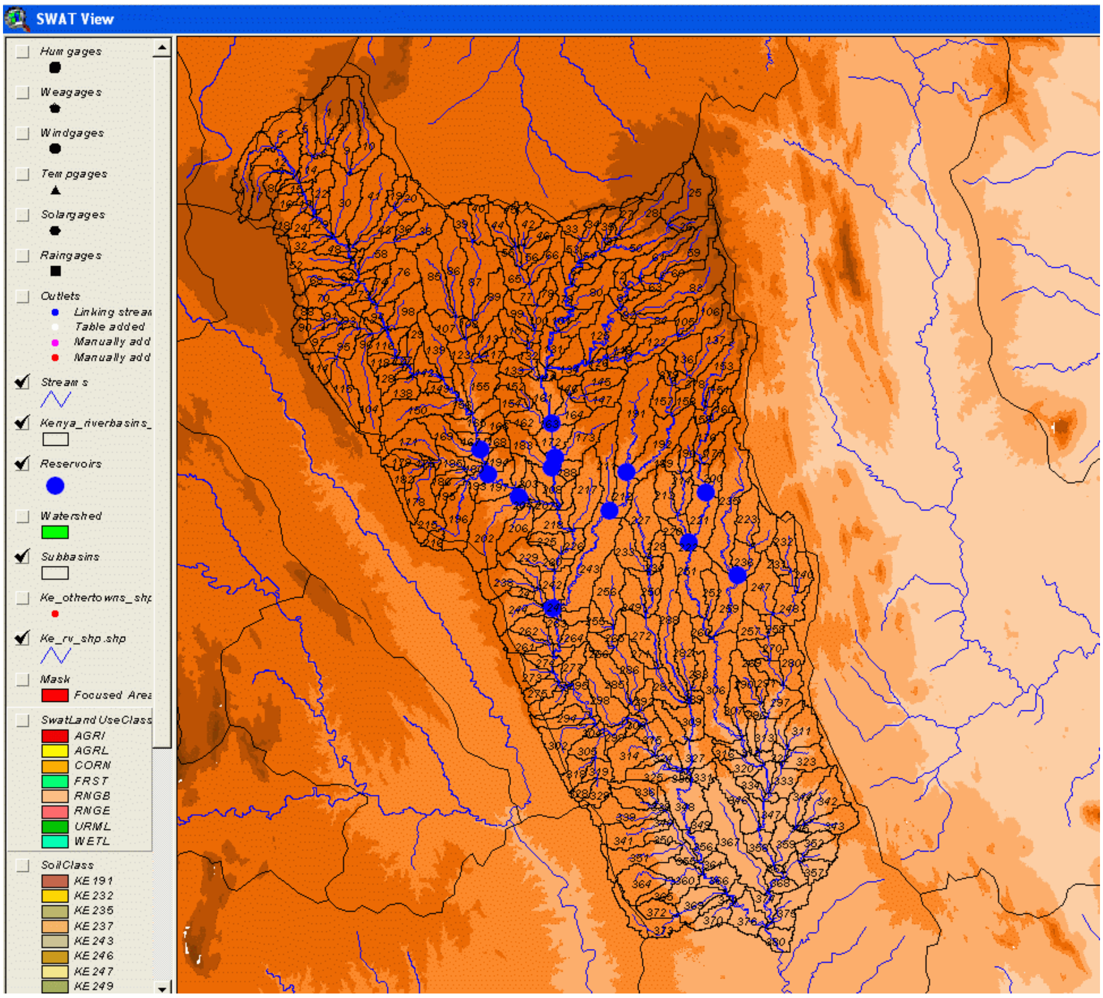

Figure 23. Location of the 12 RRNs in Tiva basin.

3.1.10 Point source

One point source of water is included in the SWAT-model for the Tiva basin. The sewage of Kitui-town enters the Kalundu river in the north-eastern part of the basin. The discharge is 15000 m3/month or 500 m3/day (WatManSup Report No.2).

3.1.11 Water demand

The water demand from the RRNs is calculated from domestic, livestock, agricultural and other use. The same numbers are used as in the WEAP model for the Tiva basin (see WatManSup Report No.2). The results are summarised in Table 9 and an overview of the total daily water demand per month is given in Figure 24.

Table 9. Water demand from RRNs in Tiva basin in m^3 per day.

		January	February	March	April	May	June	July	August	September	October	November	December
RRN	**subbasin**												
Mulutu	164	291	321	254	163	214	371	268	292	313	299	107	185

Kwa Vonza B	168	186	205	162	104	137	237	171	186	200	191	68	118
Utooni & Mbusyani	173	1017	1124	890	569	750	1300	937	1022	1095	1047	373	646
Kwa Vonza A	183	186	205	162	104	137	237	171	186	200	191	68	118
Wii	191	210	232	184	117	155	268	193	211	226	216	77	133
Makusya A	193	234	259	205	131	173	299	216	235	252	241	86	149
Kyuusi	199	145	161	127	81	107	186	134	146	156	150	53	92
Makusya B	202	234	259	205	131	173	299	216	235	252	241	86	149
Itoleka	211	97	107	85	54	71	124	89	97	104	100	36	62
Kiindu	219	662	732	579	370	488	846	610	665	713	681	243	420
Mwiwe	235	549	607	480	307	405	702	506	551	591	565	201	349
Kawongo	245	597	660	523	334	440	763	550	600	643	615	219	379

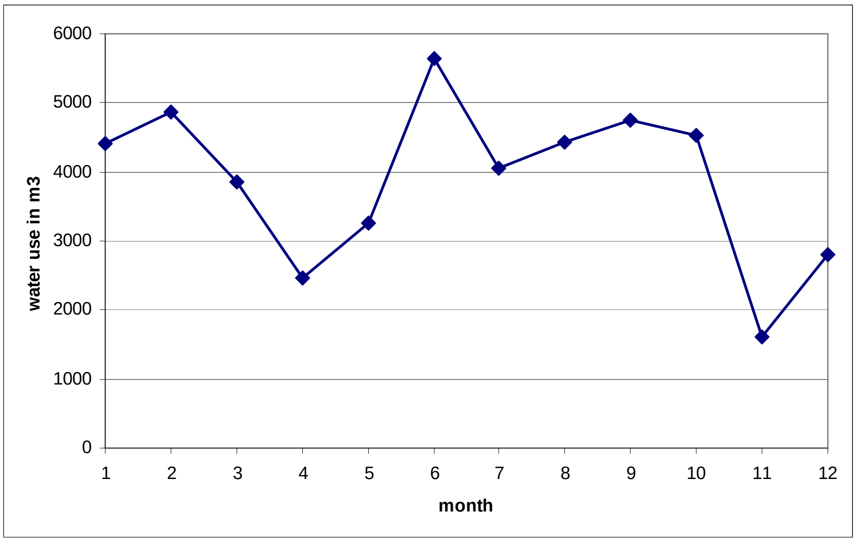

Figure 24. Total daily water demand per month in m^3/day summarised for all RRNs in Tiva basin.

In SWAT water demand can only be included as a single value for all water uses combined. Specification according to different water uses is not possible in SWAT. As indicated in WatManSup Report No.2 the application of WEAP might be beneficial to focus in detail on reservoir water use.

4 Calibration

When the model has been set up and the essential data has been imported the default databases can be edited. For example soil parameters and land use management can be changed (Figure 25).

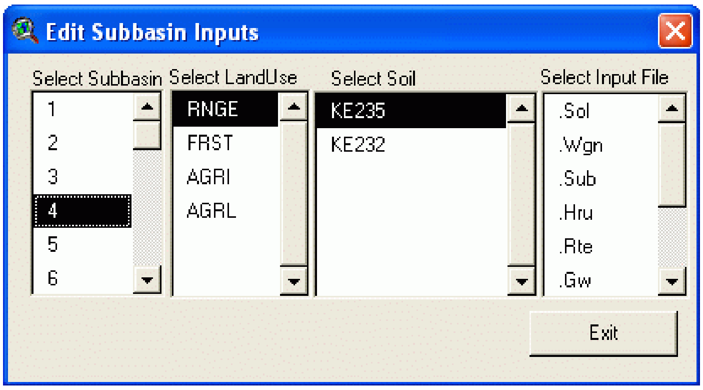

Figure 25. SWAT screen for editing subbasin inputs.

This is needed to improve the results of the model. The default databases are based on the situation in the USA. As the situation in other countries, especially in tropical regions, can be considerably different, the databases should be adapted. Calibration is an essential step in setting up a SWAT model for a region. Without (proper) calibration SWAT will give results, but these will be highly unrealistic and if they are used in management errors will be made. Measurement data of for example streamflow can be used to verify the results of the model and to test the adaptations. Unfortunately, no measurement data are available for the Kitui area, so the calibration of the SWAT model can only be shown based on expert judgement and qualitative data.

4.1 *Evapotranspiration*

The first run of SWAT for Tiva basin showed an unrealistically low evapotranspiration. For example in 1990 the ET was only 20% of the precipitation (Table 10), while in tropical regions it should be at least half of the precipitation.

Table 10. Water balance of HRU 450 for the year 1990.

HRU	MON	YEAR	AREAkm2	PRECIPmm	PETmm	ETmm
450	1	1990	1.98E+01	75	55	22
450	2	1990	1.98E+01	62	66	30
450	3	1990	1.98E+01	221	100	29
450	4	1990	1.98E+01	324	106	44
450	5	1990	1.98E+01	194	107	46
450	6	1990	1.98E+01	8	93	14
450	7	1990	1.98E+01	5	99	6
450	8	1990	1.98E+01	5	100	6

450	9	1990	1.98E+01	7	85	6
450	10	1990	1.98E+01	56	78	21
450	11	1990	1.98E+01	155	67	30
450	12	1990	1.98E+01	142	54	29

Also the spatial distribution was not according to the expectations. In Figure 26 and Figure 27 the spatial distribution of the evapotranspiration is displayed for 1995 and 2000. The evapotranspiration pattern is mainly determined by land use. The part with land use Forest Mixed (FRST) show the lowest evapotranspiration (compare Figure 16), while in reality forests have a higher evapotranspiration than the other land uses, like corn and range-bush.

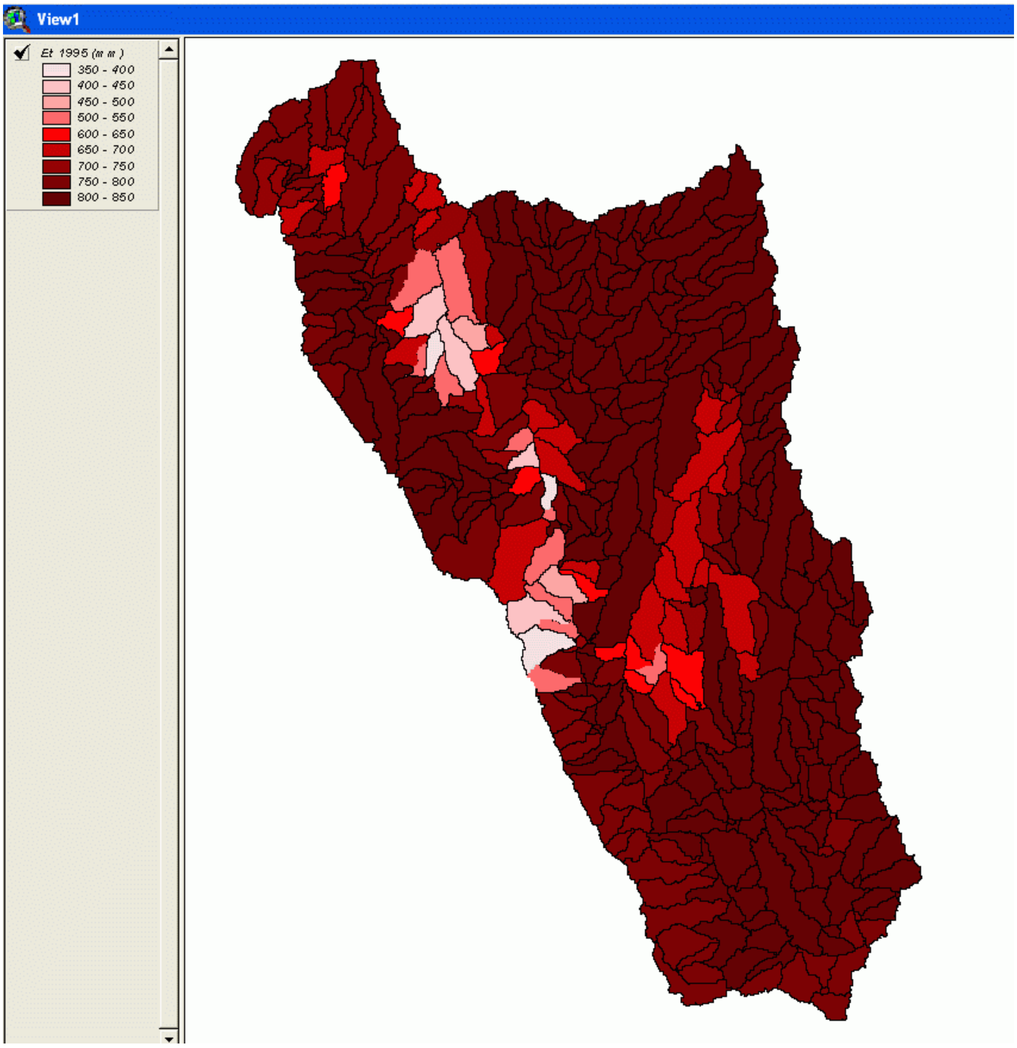

Figure 26. Annual evapotranspiration 1995.

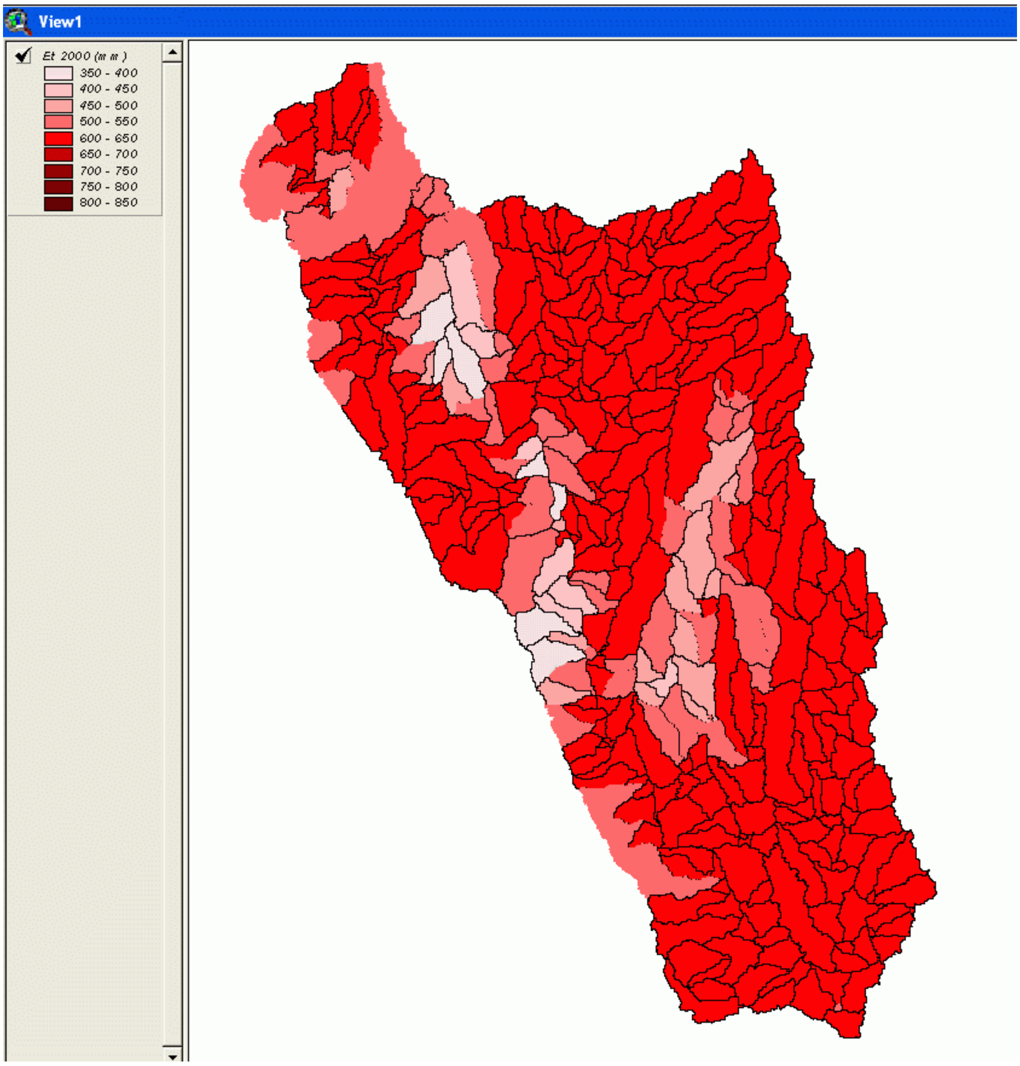

Figure 27. Annual evapotranspiration 2000.

To come to higher, more realistic values of evapotranspiration a number of parameters can be adjusted. In this section adjustments in the management file, the soil file, the groundwater file and the HRU file are discussed. The other files in the SWAT database are left unchanged in the Tiva model.

4.1.1 Management file (.mgt)

For the Tiva model the most important file that has to be changed is the management file (.mgt). Default the management for the land uses is based on the Unites States. In a temperate climate like in the USA the development of vegetation and the presence of crops on the field are only determined by temperature, while in tropical countries like Kenya, with a constant temperature throughout the year, these are principally determined by precipitation. In Kenya two distinct rainy seasons are present, resulting in two peaks in vegetation growth.

In the default management file of for example the land use class CORN the growing season is scheduled by heat units (Figure 28). This means that the growing season starts if the temperatures are above a minimum value for a specified number of days and ends if temperatures drop below a minimum value for a specified number of days. For Tiva basin we choose for a crop management scheduled by date (Figure 29). In that option a number of operations can be defined throughout the year. For the land use CORN two rotations of corn are assumed in the two rainy seasons. The growing period is taken from Puttemans et al. (2004) as is shown in Appendix A. This crop management results in an LAI curve with two peaks per year (Figure 30).

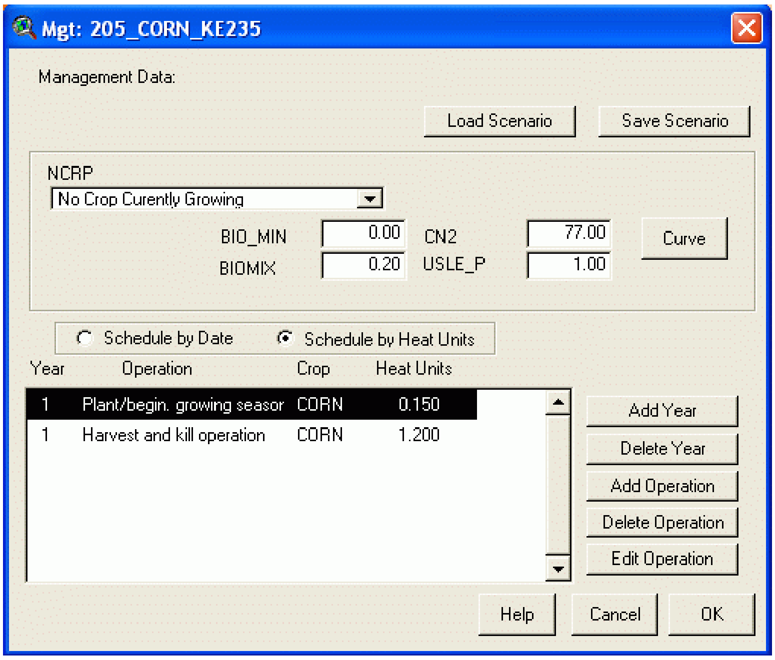

Figure 28. Default management data of land use class CORN.

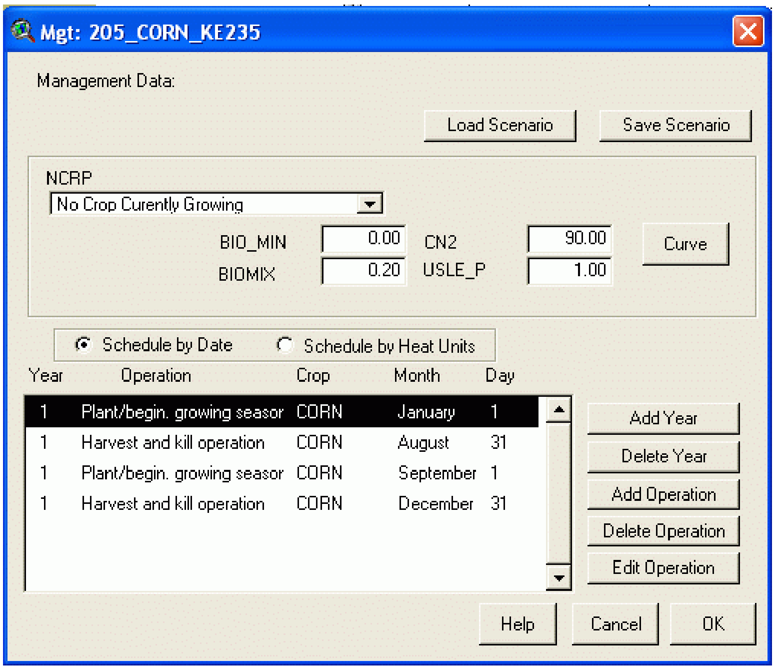

Figure 29. Edited management data for land use class CORN for Tiva basin.

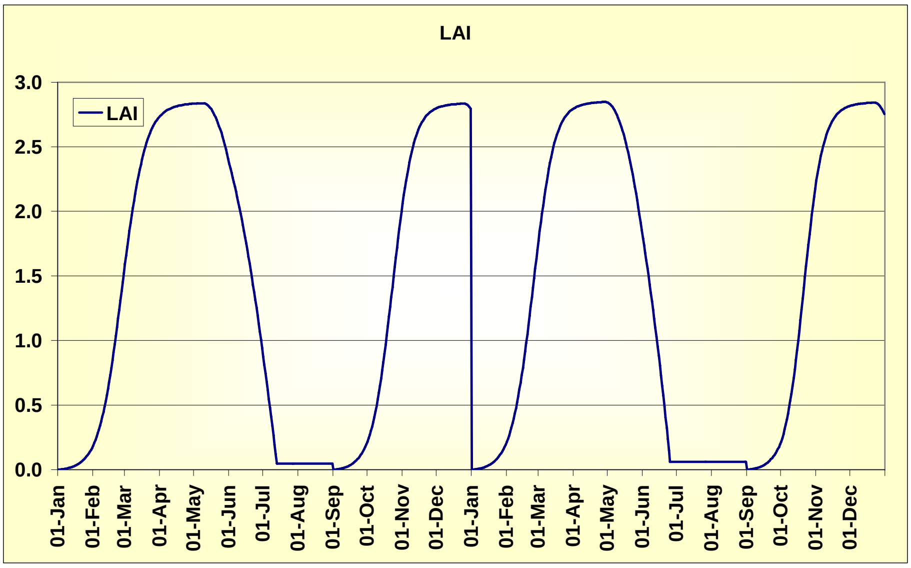

Figure 30. LAI curve for land use class CORN for Tiva basin.

For the land use classes AGRL (Agricultural Land-Generic), FRST (Forest-Mixed) and RNGE (Range-Grasses) the two growing periods are defined from January-June and July-December. Especially the LAI curve of FRST is hard to model with SWAT because the LAI stays on a certain base level, even in the dry season. To mimic that effect in SWAT the initial LAI is set to 1. The result is displayed in Figure 31.

The management of the land use class AGRI (Agriculture general irrigated) is the most complex one, because besides beginning and end of the growing season also the application of irrigation water needs to be defined (Figure 32). The periods that irrigated crops are growing are February and June-July. In Tiva basin the amount of water used for irrigation daily is approximately 0.3 mm (pers.obs. July 2006). In the management file an amount of 1.5 mm is applied each 5 days.

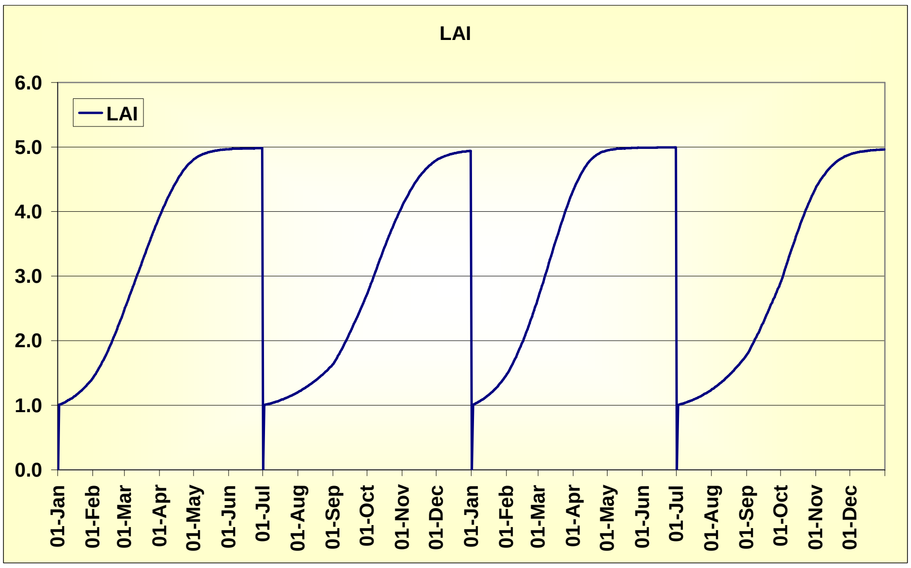

Figure 31. LAI curve for land use class FRST for Tiva basin.

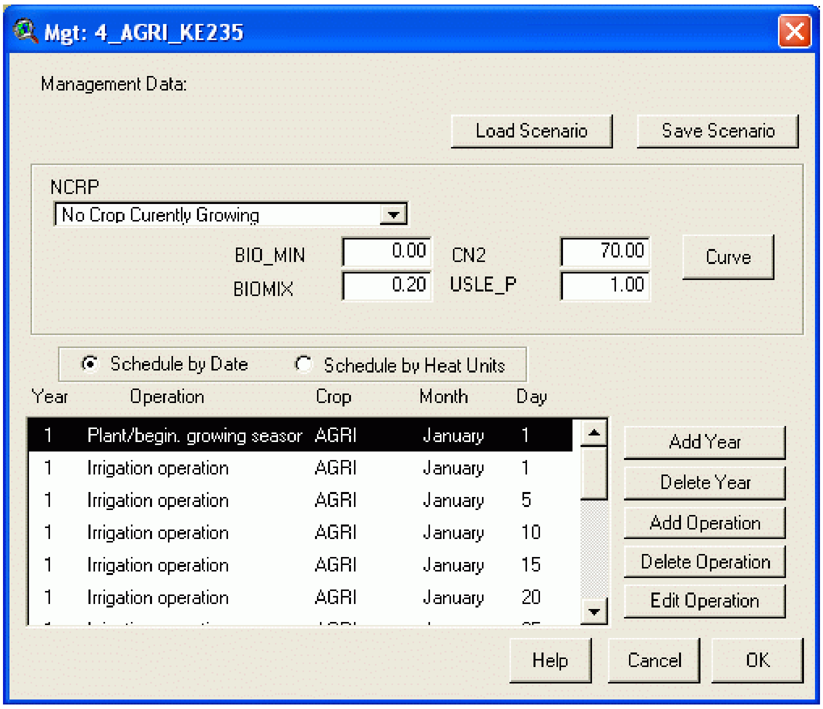

Figure 32. Edited management data for land use class AGRI for Tiva basin (January).

4.1.2 Soil file (.sol)

In the soil file the parameter SOL_AWC defines the available water capacity of the soil layer. Default this parameter is set to a value between 0.02 and 0.19 dependent on the properties of the specific soil layer. The average SOL_AWC value for sand is low (around 0.05) and the average SOL_AWC value for clay is high (around 0.25). A higher SOL_AWC results in more water kept in the upper part of the soil and consequently in more evaporation from the soil. For the Tiva basin the SOL_AWC values are raised to increase the evaporation. Table 11 shows the resulting values for different soil types in Tiva basin. Figure 33 shows the interface of the total .sol file for a specific soil type.

Table 11. Value for parameter SOL_AWC for different soil types.

Soil type	SOL_AWC
KE191	0.2
KE232	0.2
KE235	0.2
KE237	0.1
KE243	0.2
KE246	0.15
KE247	0.2
KE249	0.25
KE252	0.2
KE262	0.2

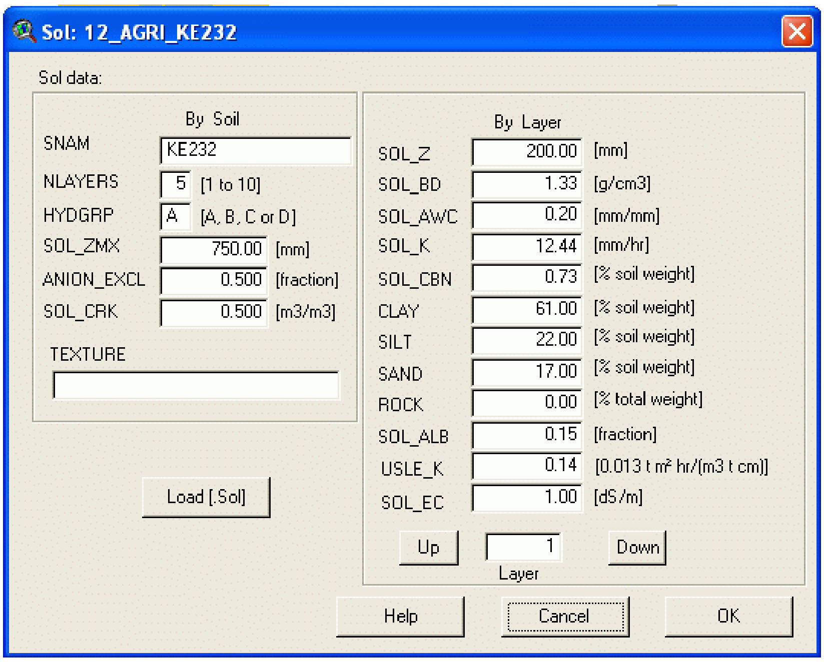

Figure 33. Edited soil data for soil class KE232 for Tiva basin.

4.1.3 Groundwater file (.gw)

The groundwater file is identical for all HRU's, so changes made in this file apply to the entire basin. The evaporation can be influenced by changing two parameters in the groundwater file: SHALLST and GW_REVAP (Figure 34). SHALLST is short for "shallow groundwater storage" and defines the amount of water that can be stored in the shallow groundwater. The default value for this parameter is 0.5 mm. This is unrealistically low. For Tiva basin we estimated a value of 500 mm.

The parameter GW_REVAP defines the capillary rise from the groundwater. The default value is 0.02, but a more realistic value is 0.15.

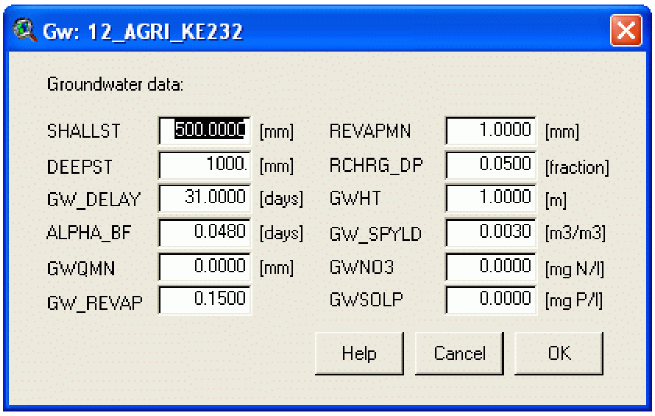

Figure 34. Edited groundwater data for Tiva basin.

4.1.4 HRU file (.hru)

Another file that can be adjusted is the HRU file. An important parameter in that file is ESCO, the "soil evaporation compensation factor". This coefficient has been incorporated to allow the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks. ESCO must be between 0.01 and 1.0. As the value for ESCO is reduced, the model is able to extract more of the evaporative demand from lower levels. The change in depth distribution resulting from different values of *esco* are graphed in Figure 35. If no value for ESCO is entered, the model will set ESCO = 0.95. The value for ESCO may be set at the watershed or HRU level (ESCO in .bsn) (SWAT User Manual, 2000). After some trial and error the best value for ESCO in Tiva basin seems to be 0.4 (Figure 36).

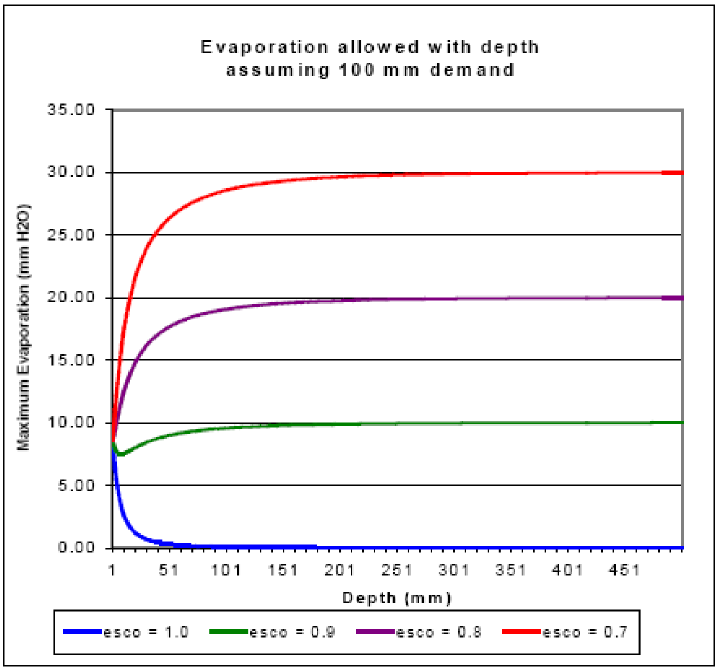

Figure 35. Soil evaporative demand distribution with depth (SWAT User Manual 2000).

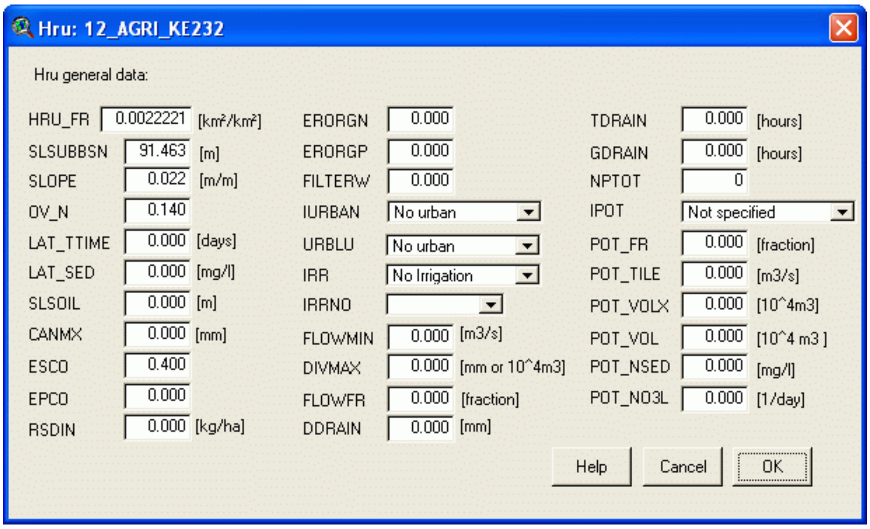

Figure 36. Edited HRU data for Tiva basin.

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4.1.5 Result

The adjustments in the management file, the soil file, the groundwater file and the HRU file resulted in a higher evaporation. For HRU 450 the evapotranspiration is now 50% of the precipitation (Table 12).

Table 12. Water balance of HRU 450 for the year 1990 after adaptations.

HRU	MON	YEAR	AREAkm2	PRECIPmm	PETmm	ETmm
450	1	1990	1.98E+01	75	55	45
450	2	1990	1.98E+01	62	66	55
450	3	1990	1.98E+01	221	100	87
450	4	1990	1.98E+01	324	106	104
450	5	1990	1.98E+01	194	107	107
450	6	1990	1.98E+01	8	93	60
450	7	1990	1.98E+01	5	99	24
450	8	1990	1.98E+01	5	100	12
450	9	1990	1.98E+01	7	85	5
450	10	1990	1.98E+01	56	78	27
450	11	1990	1.98E+01	155	67	57
450	12	1990	1.98E+01	142	54	53

4.2 Reservoirs

Another important aspect in the calibration of the Tiva model is the performance of the sand storage dams, the RRNs. In the basic model the RRNs showed a constant storage volume throughout the year, even in the dry months the dams were full of water (Figure 37).

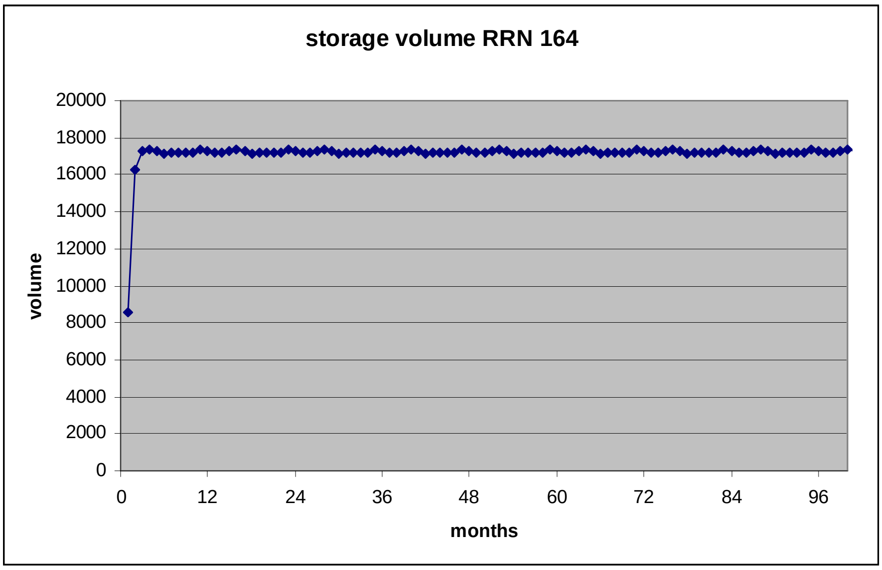

Figure 37. Storage volume in m^3 of RRN No 164, Mulutu, during 8 years.

The water balance of the same RRN for the year 1991 (Figure 38) shows that the net flow into the RRN is still very high in the dry season. Normally, no water flows in the river during the months January and June, July, and August. The inflow into a river reach consists of a number of components: surface flow, lateral flow and inflow from groundwater. During the wet months the inflow from groundwater has the highest contribution (Figure 39), while in the dry season only lateral flow occurs (Figure 40). So, to decrease the inflow in the dry season, the lateral flow should be diminished.

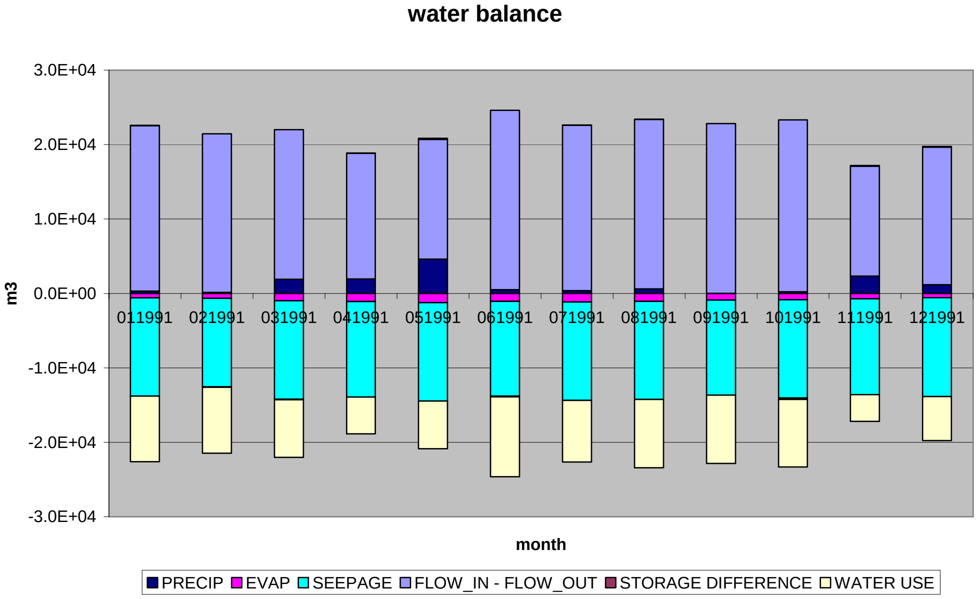

Figure 38. Water balance of RRN No 164, Mulutu, for the year 164: PRECIP = precipitation on the area of the RRN, EVAP = evaporation, SEEPAGE = seepage from the bottom of the RRN, FLOW_IN – FLOW_out = net flow through the RRN, STORAGE DIFFERENCE = the difference in storage in the RRN, WATER USE = the residual of the water balance.

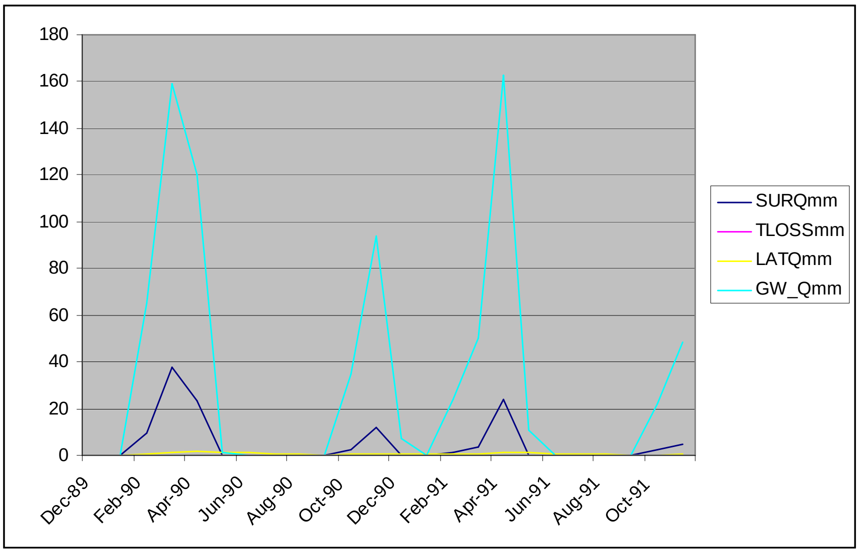

Figure 39. Inflow into HRU 10 for 1990 and 1991 from various sources: SURQmm = surface flow in mm, TLOSSmm = the total loss in mm, LATQmm = lateral flow in mm, GW_Qmm = inflow from groundwater in mm.

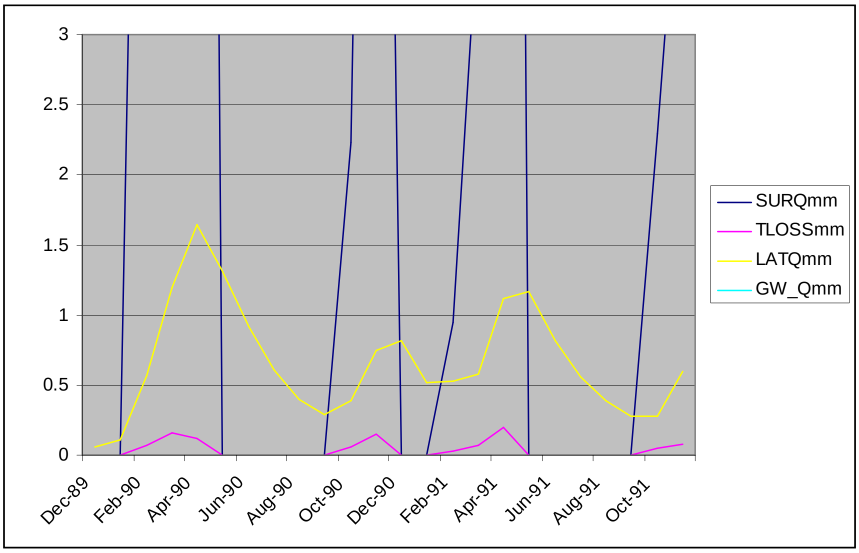

Figure 40. Detail of Figure 39.

4.2.1 Groundwater file (.gw)

The base flow in the river is too a high groundwater delay time (GW_DELAY) and low baseflow alpha factor (ALPHA_BF). The GW_DELAY is the time lag between the time that water exits the soil profile and enters the shallow aquifer (SWAT User Manual, 2000). In Kenya this process is quite fast, so the GW_DELAY should be two days, in stead of the default 31 days.

The ALPHA_BF is the baseflow recession constant, αgw, is a direct index of groundwater flow response to changes in recharge. Values vary from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with a rapid response (SWAT User Manual, 2000). The default value was set to 0.048 days, but a value of 0.9 days is more appropriate for the Kitui area.

4.2.2 Main channel input file (.rte)

Another option to decrease the base flow is to increase the seepage from the riverbed. The riverbed in the Tiva river and its tributaries is sandy and the seepage therefore is quite high. The seepage is determined by the parameter CH_K, which is the effective hydraulic conductivity in the main channel alluvium in mm/h. Default this CH_K is set to 0, but for a sandy river bed a value of 100 mm/h is more realistic.

4.2.3 Reservoir file (.res)

Seepage not only occurs in the river, but also in the reservoirs. To increase the seepage from the reservoirs the hydraulic conductivity of the reservoir bottom should be increased. This parameter (RES_K in the reservoir file) is set to 0.5 mm/h for the RRNs in the Tiva basin.

4.2.4 Soil file (.sol)

In the soil file the parameter SOL_AWC defines the available water capacity of the soil layer. In Section 4.1.2 the SOL_AWC was increased to values between 0.1 and 0.25 to raise the evaporation. However, a further increase of this parameter is needed to increase the storage in the soil and decrease the base flow. SOL_AWC is set to 0.4 for all soil types.

A decrease in the saturated hydraulic conductivity of the soil (SOL_K) results in a slower water movement through the soil. Precipitation will be kept within the soil profile and will not flow to the river by lateral flow. A realistic value for SOL_K is 1 mm/h.

4.2.5 Result

The adjustments in the groundwater file, the main channel input file, the reservoir file and the soil file resulted in a lower base flow (Figure 41) and more variation in the storage volume of the RRNs (Figure 42), which is far more realistic.

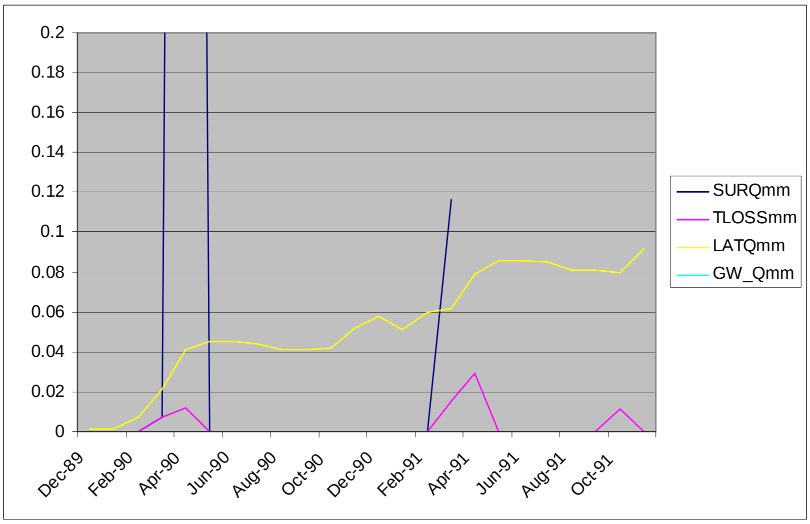

Figure 41. Adapted inflow into HRU 10 for 1990 and 1991 from various sources: SURQmm = surface flow in mm, TLOSSmm = the total loss in mm, LATQmm = lateral flow in mm, GW_Qmm = inflow from groundwater in mm.

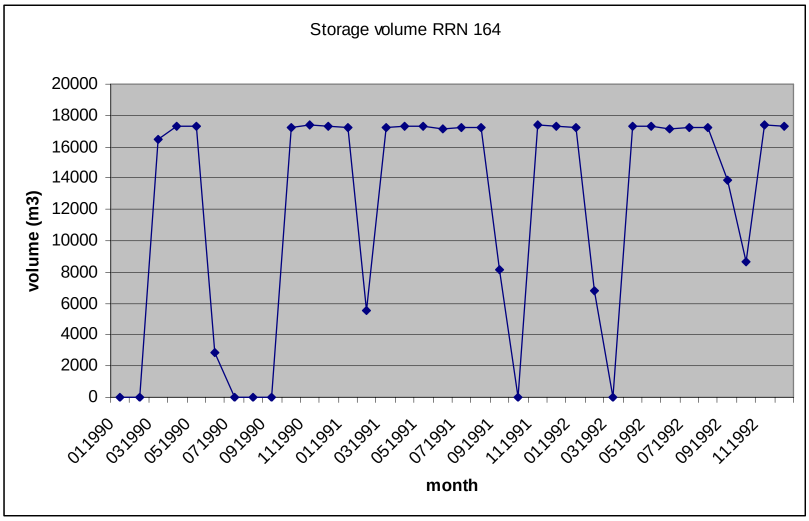

Figure 42. Adapted storage volume in m^3 of RRN No 164, Mulutu, during 8 years.

4.3 Flow

When we have a closer look at the components of the inflow into the river, we see that in the rainy season the surface flow is only a very small percentage of total flow. Due to the heavy rain showers in the rainy season this percentage should be at least 25 %.

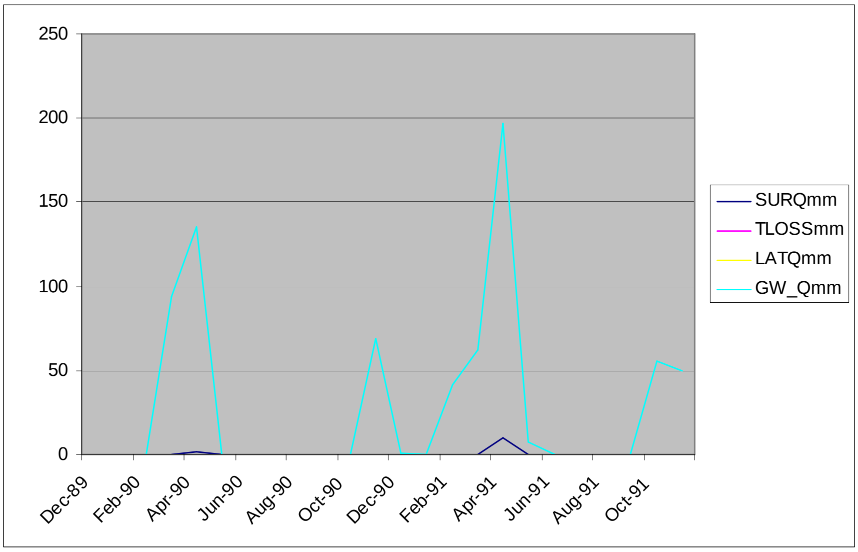

Figure 43. Inflow into HRU 10 for 1990 and 1991 from various sources: SURQmm = surface flow in mm, TLOSSmm = the total loss in mm, LATQmm = lateral flow in mm, GW_Qmm = inflow from groundwater in mm.

4.3.1 Management file (.mgt)

The parameter CN2 in the management file defines the initial SCS runoff curve number for moisture condition II. The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. Typical curve numbers for moisture condition II are between 30 for woodland or bruch with a good hydraulic condition, and 94 for bare soil. In Figure 44 the effect of a number of SCS curve number on the relationship between rainfall and runoff is displayed: the higher the curve number, the more linear the relationship. The original curve numbers of Tiva basin (Table 13) have been increased to increase the runoff during heavy rain showers.

Table 13. SCS curve number (CN) for various land uses in Tiva basin.

land use	original CN	adapted CN
FRST	36	50
AGRL	77	80
AGRI	62	70
CORN	77	90
RNGE	36	50
URH	62	70

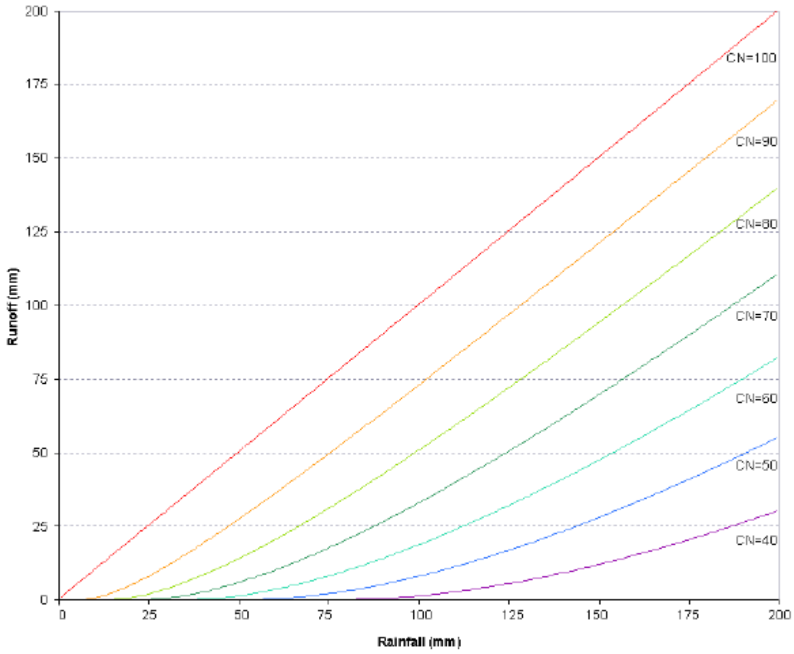

Figure 44. Relationship of runoff to rainfall in SCS curve number method.

4.3.2 Result

The adjustments of the SCS curve number resulted in a higher percentage of the surface runoff (Figure 45). It is now 15 % of the total inflow. The more realistic 25 % can be reached by changing other parameters in the model.

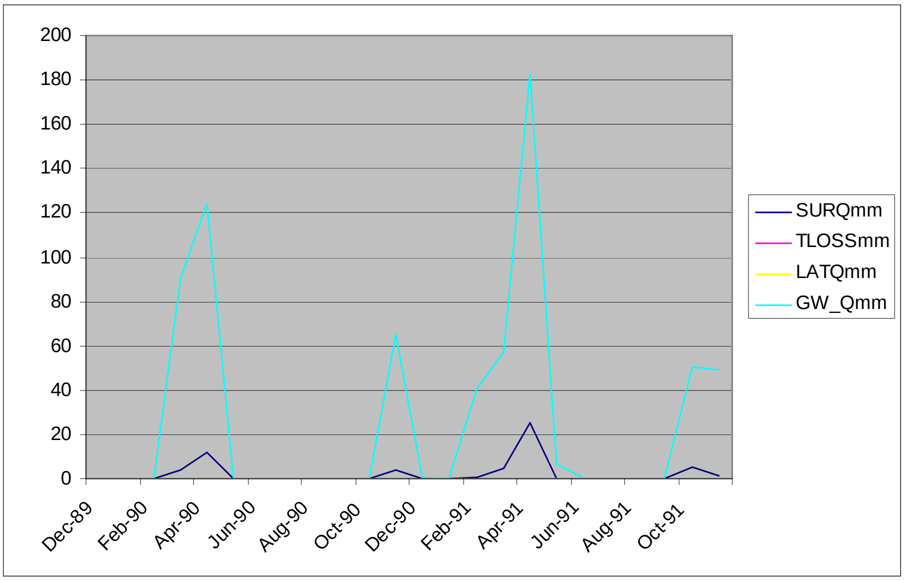

Figure 45. Adapted inflow into HRU 10 for 1990 and 1991 from various sources: SURQmm = surface flow in mm, TLOSSmm = the total loss in mm, LATQmm = lateral flow in mm, GW_Qmm = inflow from groundwater in mm.

5 Results

The results of a SWAT model consist of a number of *txt* and *dbf*-files that can be viewed and analysed manually or within the SWAT interface. The advantage of a manual analysis is that there are much more options for making user defined graphs and maps of the results. Tools like Excel and ArcGIS can be used to do analyses and display the results graphically. In this section we will show some examples of how the results of SWAT can be displayed and analysed.

5.1 Water balance

First, we look at the water balance calculated with the SWAT model. The water balance is an accounting of the inputs and outputs of water. The water balance of a place, whether it be an agricultural field, watershed, or continent, can be determined by calculating the input, output, and storage changes of water at the surface.

5.1.1 Yearly water balance

In Appendix A.2 Table 14 all parameters of the water balance are given for each year in the simulation period. Figure 46 displays the average yearly water balance of the soil surface. The main ingoing flux is the precipitation, while the outflow constitutes of evapotranspiration, surface runoff and percolation to the groundwater. In wet years like 1995 the runoff is relatively the largest outgoing flux.

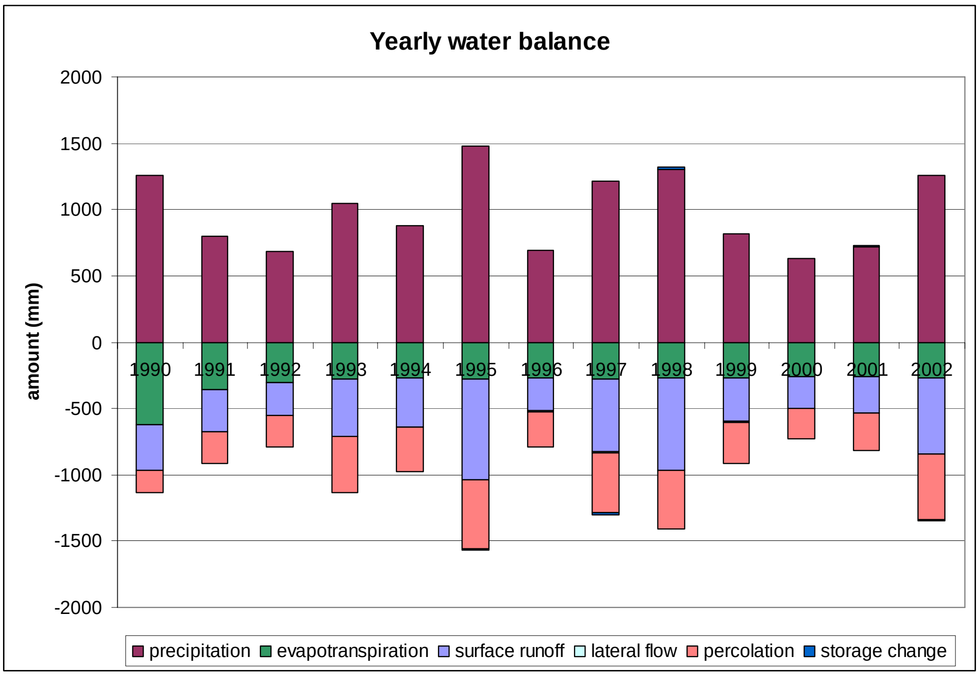

Figure 46. Yearly water balance for the soil profile in Tiva basin.

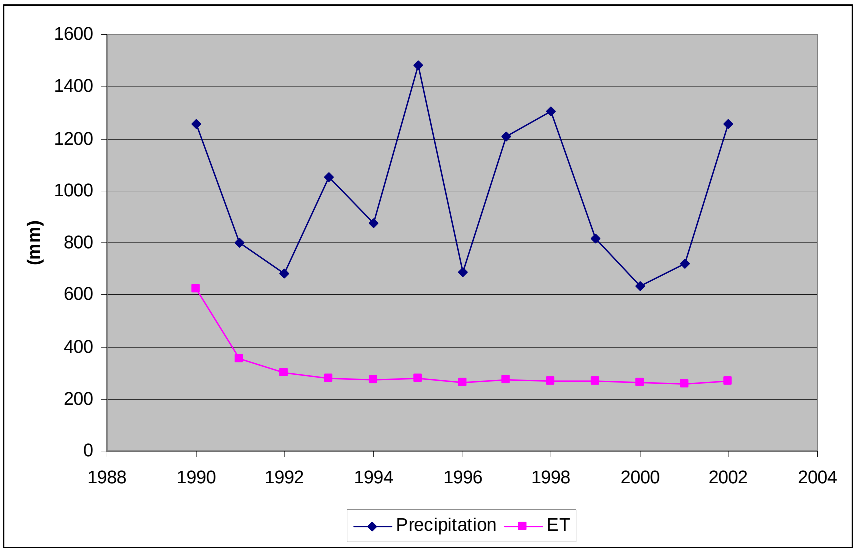

Figure 47. Annual precipitation and evapotranspiration 1990-2002.

Precipitation and evapotranspiration are the most important parameters of the water balance. The yearly fluctuations in precipitation are much larger than the variations in evapotranspiration (Figure 47), resulting in large differences in available water (precipitation minus evapotranspiration) between years. In 1995 and 1998 1000-1200 mm water is available, while in 1992, 1996 and 2000 the difference between precipitation and evapotranspiration is only 300 mm.

The components of the water balance can be displayed spatially. The inflow into the river system mainly consists of groundwater flow (Figure 48) and surface runoff (Figure 49). The balance between these components is mainly determined by the slope of the surface. A steep slope will result in more surface runoff and a flat surface will lead to more groundwater flow. The total storage of water in the soil profile on a specific day is shown in Figure 50. This parameter is mainly determined by the soil type and the soil parameters. The soil water storage can be plotted daily to monitor changes.

In this SWAT model the precipitation is equal for the entire basin because we chose only one meteorological station to be representative for the Tiva basin (see Section 3.1.8). The actual evapotranspitation (Figure 51), however, does have a geographical distribution, because it is determined by a combination of land use, vegetation, soil properties and water availability. With a GIS analysis of these maps more conclusions can be drawn on relationships between different parameters.

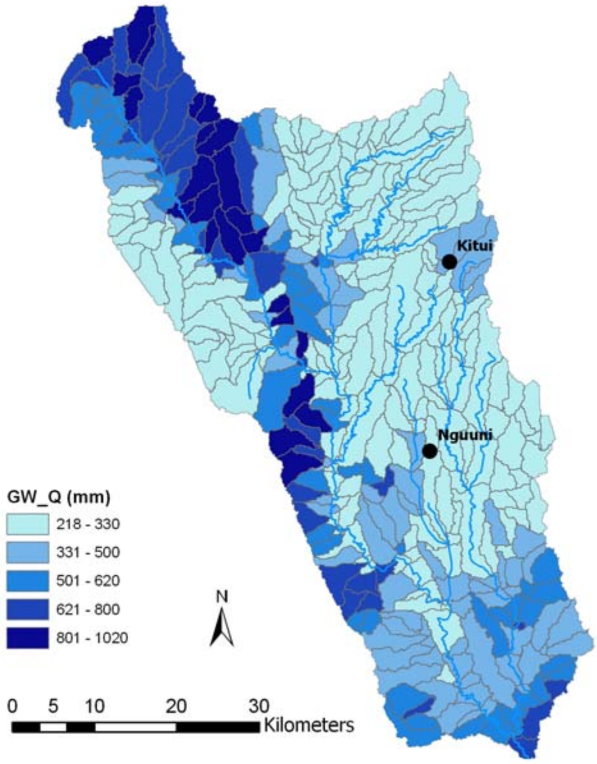

Figure 48. Yearly flow from the groundwater into the river system for 1995.

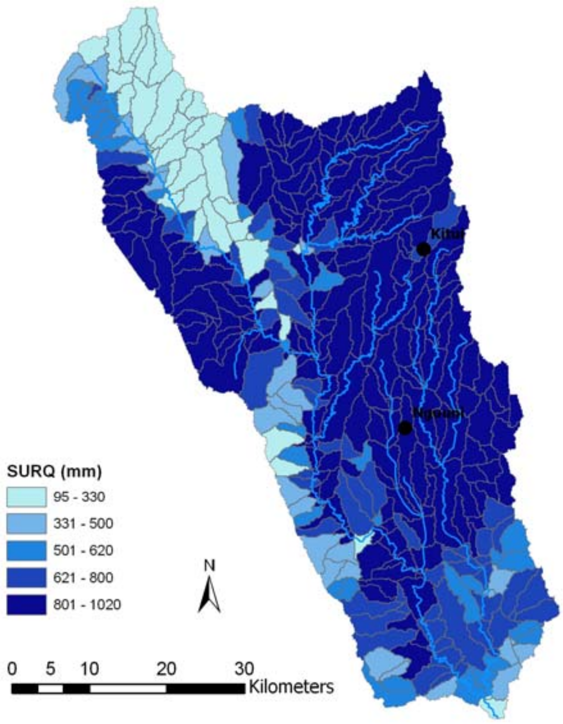

Figure 49. Yearly surface runoff into the river system for 1995.

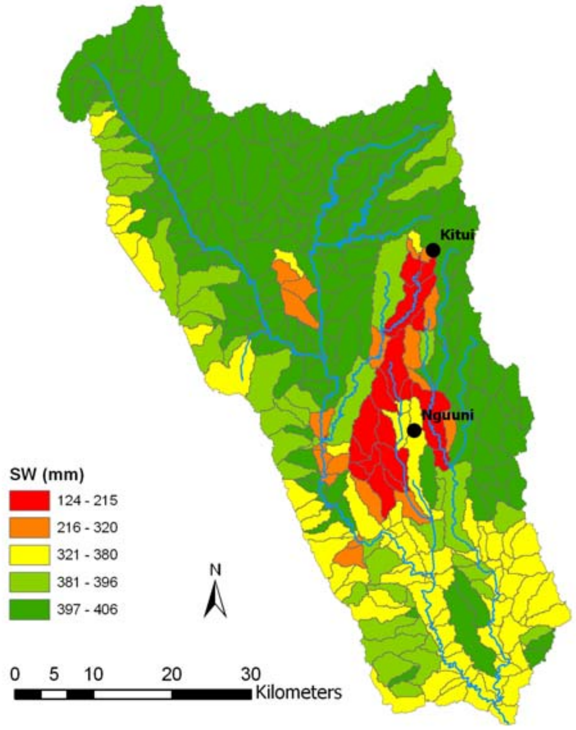

Figure 50. Storage of water in the soil profile on 31 December 1995.

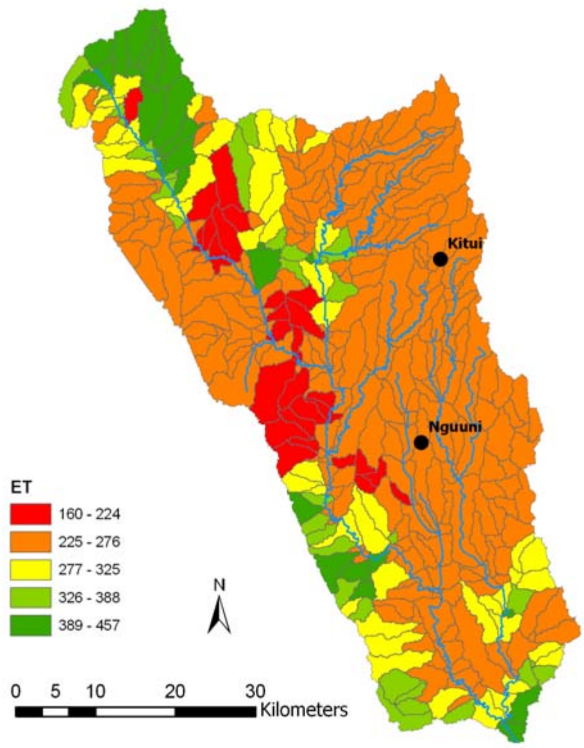

Figure 51. Yearly total evapotranspiration for 1995.

5.1.2 Monthly water balance

To examine at the monthly water balance of the Tiva basin (Appendix A.2 Table 15) we zoom in to two years in the simulation period. 1995 was a very wet year and 2000 was a very dry year (Table 6).

In the year 1995 the high annual precipitation amount is mainly caused by a high rainfall peak in April (Figure 52). The evapotranspiration is relatively constant throughout the year, so in April the water surplus is very high. However, the rainfall is concentrated in a short period and the high surface runoff (65 % of the precipitation) leads to less recharge of the groundwater and consequently to less water availability. The water will drain directly into the Tiva river.

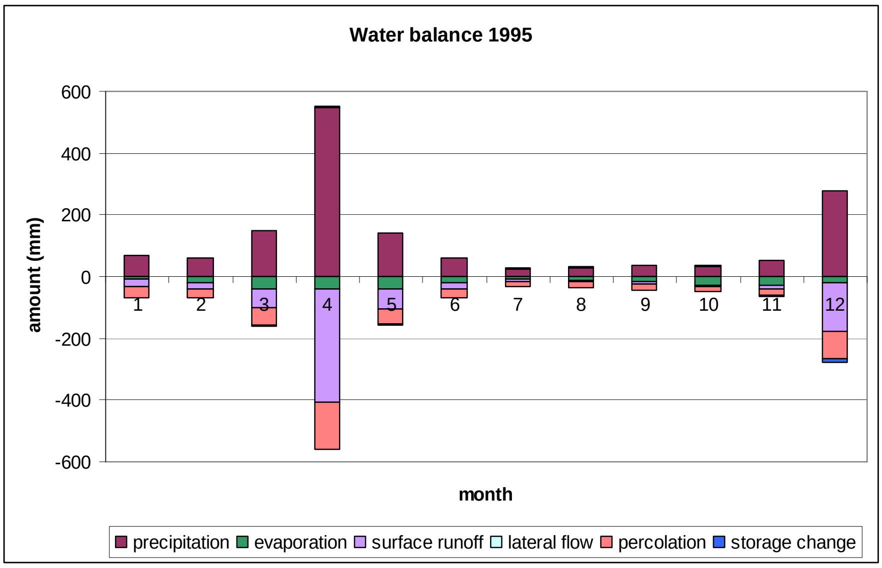

Figure 52. Monthly precipitation and evapotranspiration 1995.

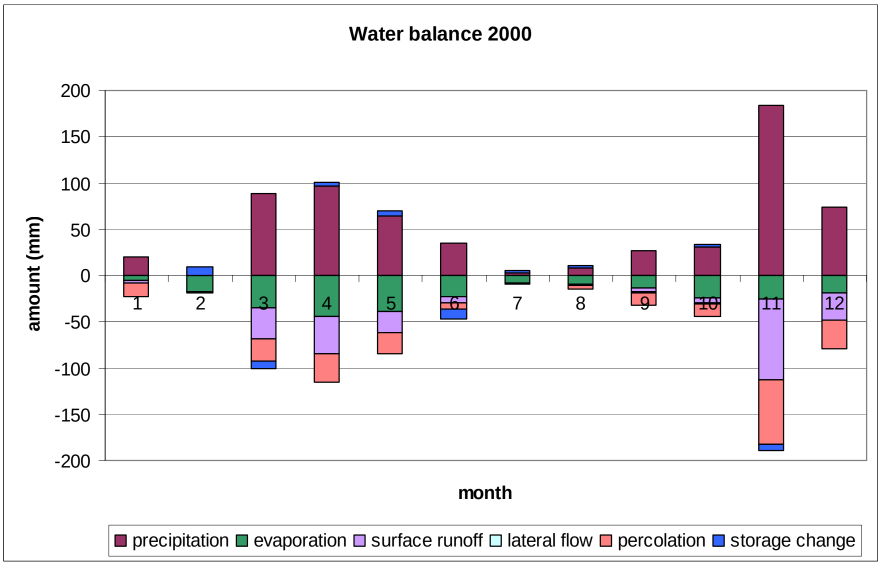

Figure 53. Monthly precipitation and evapotranspiration 2000.

In the year 2000 the peak precipitation in the rainy seasons is less than in 1995 (especially in April), the rainfall is distributed more evenly throughout the year (Figure 53). Furthermore, the evapotranspiration is relatively high, up to 40 % of the precipitation (in 1995 this is only 7 %).

More detailed analysis is possible with the results of SWAT. The water balance can be monitored daily for each subbasin and even for each HRU. However, for the purpose of this study such a detailed analysis is not necessary.

5.2 Discharge

Another important output parameter of SWAT is the river discharge. The discharge at the outlet of Tiva basin is very low, especially in the dry months.

5.2.1 Annual average discharge

The fluctuations in yearly precipitation (Figure 47) are reflected in the annual average discharge (Figure 54). For example, the discharge in 1995 is more than two times as much as in 1996, while the precipitation in 1995 is also about twice as much as in 1996.

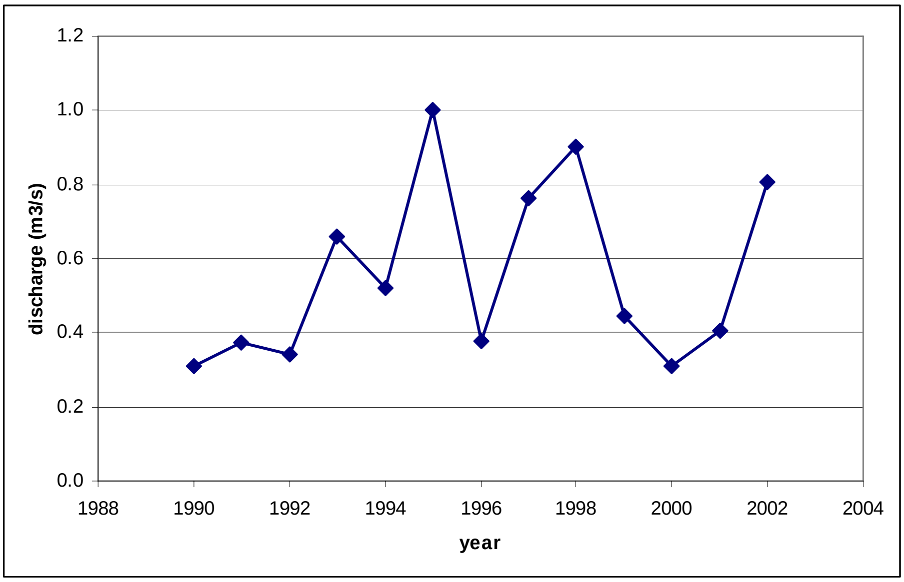

Figure 54. Annual average discharge at the outlet of Tiva river basin.

5.2.2 Monthly average discharge

The monthly average discharge also follows the precipitation pattern. In the months that the water surplus is large (the difference between precipitation and evapotranspiration is large) the discharge is large as well. The normal pattern is two discharge peaks in the rainy seasons and almost no discharge in the dry seasons. However, the differences years are very large. For example, 1995 showed one very large peak in April with discharge up to 5 m^3/s and a smaller one in December (Figure 55), while 2000 did not show a distinctive peak in April (Figure 56) and only a small one of 1.4 m^3/s in January. These differences in discharge pattern can also be explained by the differences in the soil water balance (Figure 52 and Figure 53).

In this example we only considered the outlet of Tiva basin. However, the discharge of all the tributaries and all the subbasins can be evaluated. Unfortunately, no measurement data is available for Tiva river to validate the results.

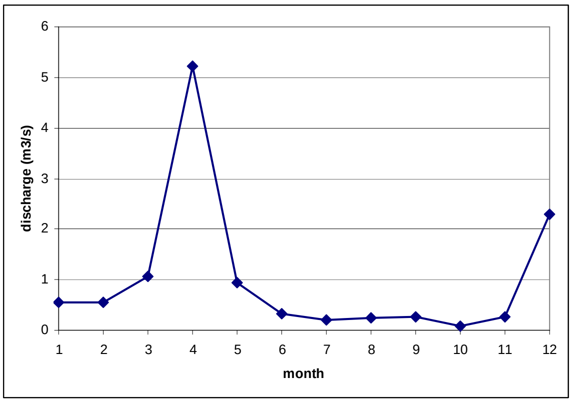

Figure 55. Monthly average discharge at the outlet of Tiva river basin in 1995.

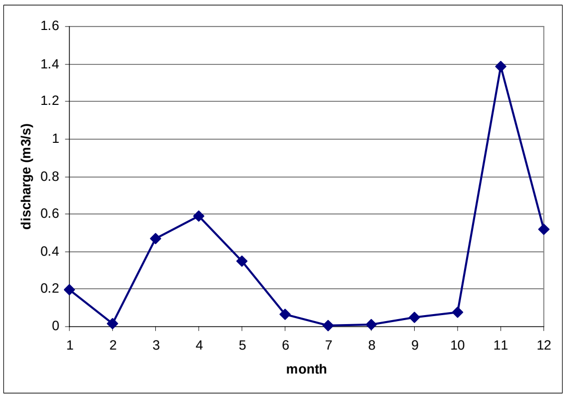

Figure 56. Monthly average discharge at the outlet of Tiva river basin in 2000.

5.3 Reservoirs

In the Tiva basin the sand storage dams are the main source of drinking water and irrigation. Therefore, it is important that the model can give results on the water storage in these dams.

5.3.1 Storage

The maximum volume of water stored in the RRNs (Representative Reservoir Nodes) (Figure 57) is equal to their storage capacity (Table 7), because in the rainy season the sand dams are full. However in the dry season the storage volume of the RRNs decreases below the storage capacity. This decrease is dependent on the water balance of the RRN, which will be discussed in the following section.

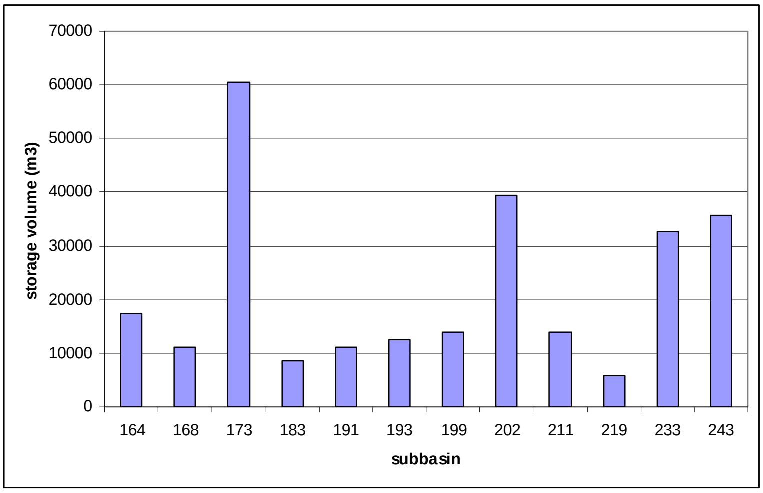

Figure 57. Storage volume of RRN's in Tiva basin.

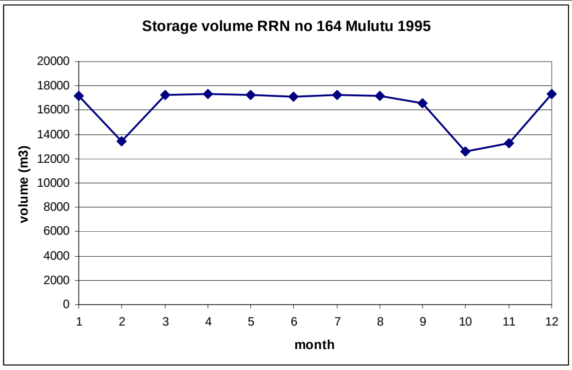

Figure 58. Storage volume of RRN in subbasin No.164 Mulutu in the year 1995.

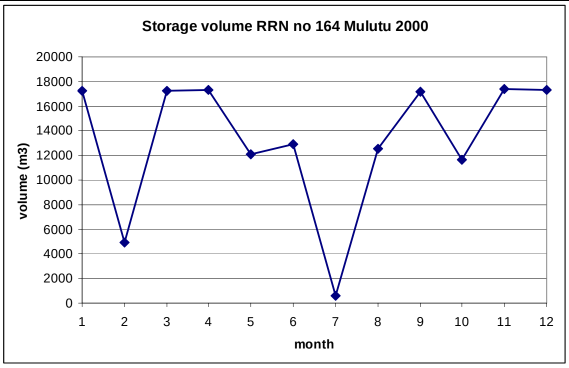

Figure 59. Storage volume of RRN in subbasin No.164 Mulutu in the year 2000.

Figure 58 and Figure 59 show the monthly average storage volume of a representative RRN, Mulutu in subbasin No.164. In 1995 the storage volume decreases with 30% and in 2000 even with maximally 97%. However, even in 2000, the driest year of the simulation period, water was still available in the RRN. Observations in the Kitui area confirm this result, at the end of the dry season the scoopholes in the river bed are very deep and wells in the sand dams in Tiva basin are almost dry.

5.3.2 Water balance

We can get more information on the reservoirs if we look at the detailed water balance. In this example we only consider the monthly water balance, but from the SWAT results it is also possible to analyse the daily water balance.

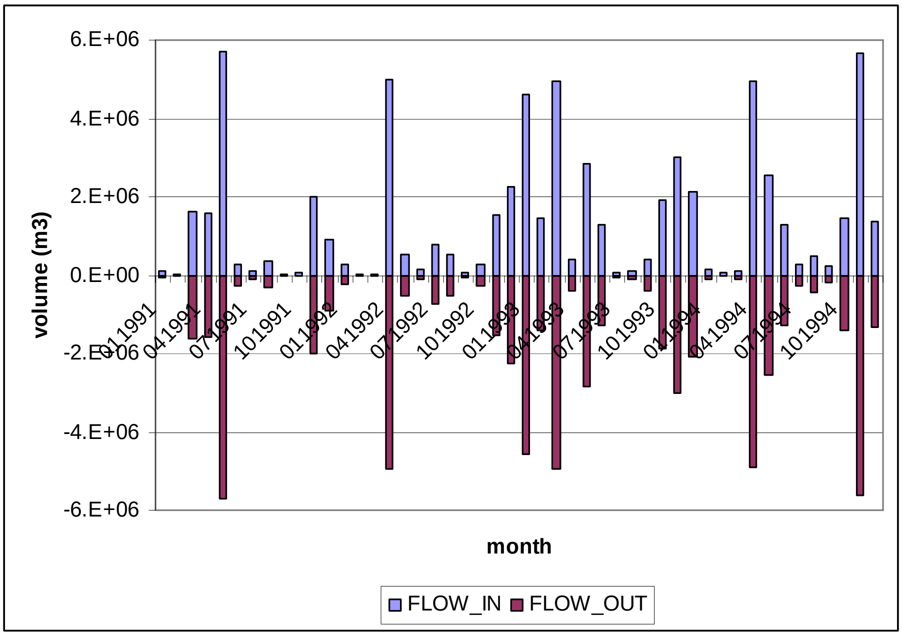

Figure 60. In and outflow of RRN 164 for the years 1991-1994.

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Table 17 and Table 18 give the monthly water balance for the year 1995 and 2000 respectively. The inflow to and outflow from the RRN are very large compared to the precipitation into and the evaporation from the reservoir (Figure 60). This is due to the small surface area of the RRN. However, the evaporation is still higher than in reality because SWAT considers an open reservoir and no reduction of evaporation due to storage in the sand can be included in SWAT.

During the dry seasons of 2000, February and July/August, the seepage from the dams to the groundwater is less than in the wet seasons (Figure 62). The high water use during that months results in a decrease in storage in the RRN.

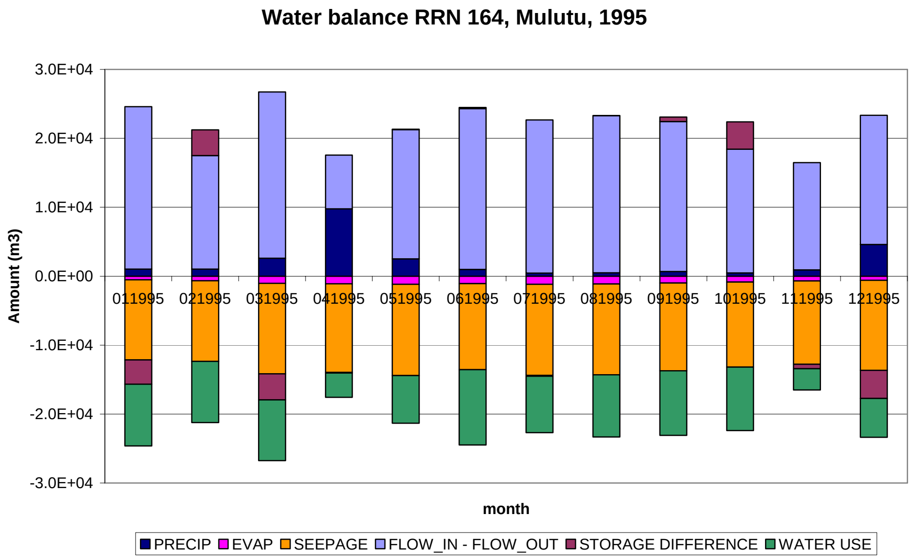

Figure 61. Water balance of the RRN 164 for the year 1995.

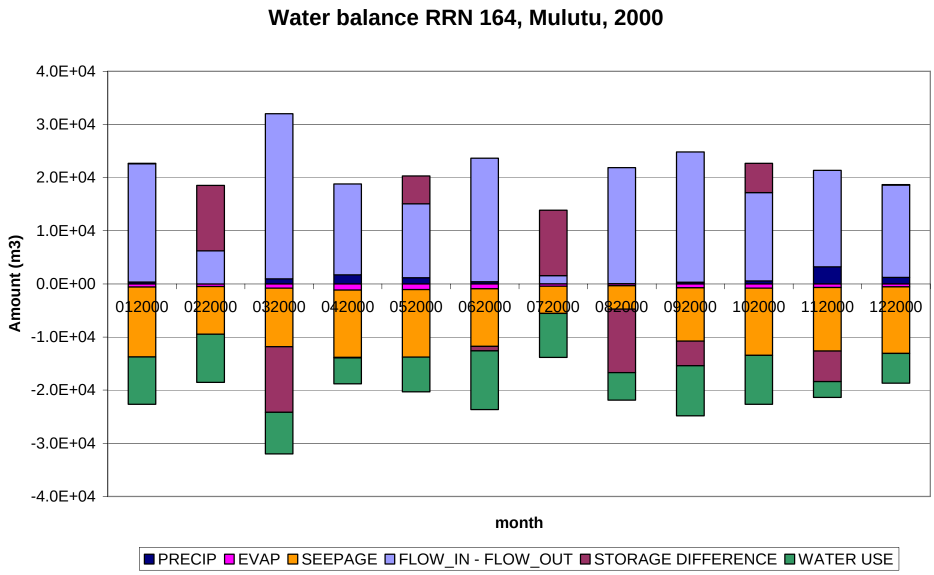

Figure 62. Water balance of the RRN 164 for the year 2000.

6 Conclusions and Recommendations

The overall objective of the WatManSup project is to demonstrate that Integrated Water Management Support Methodologies (IWMSM) can be used to support water managers and policy makers. This report describes one component of IWMSM. The aim is to demonstrate the application of the detailed physical simulation model SWAT in a setting with relatively low human interaction emphasising management of small reservoirs. This report should be considered in the context of the other two components of IWMSM for the same region in Kenya: the water allocation tool WEAP (described in WatManSup Report No.2) and the multi-criteria analysis (described in WatManSup Report No.4).

In the context of WatManSup no specific objectives were included regarding problem solving, only demonstration of tools and methods were considered. Scenario analysis has therefore not been included in this report.

The SWAT model as used as the physical component of IWMSM has been applied successfully to support water managers and policy makers recently. Some examples of applications of SWAT undertaken by FutureWater are:

- Hai Basin, China. Exploring evaporation reduction options in the Hai Basin (http://www.futurewater.nl/uk/projects/hai-china).
- Rio Bravo / Rio Grande, Mexico. Remote Sensing and Hydrological Modelling of the Rio Bravo. (http://www.futurewater.nl/riobravo/).
- Tibet. The Water Tower Function of the Tibetan Autonomous Region. (http://www.futurewater.nl/uk/projects/Tibet).
- Upper Bihma, India. Remotely Sensed Based Hydrological Model Calibration for Basin Scale Water Resources Planning. (http://www.futurewater.nl/krishna/index.html)
- Upper Tana, Kenya. Project to be completed end 2007 to evaluate water and erosion in the context of Green Water Credits (http://www.isric.org/).

The case for the Kitui area as demonstrated here has some specific characteristics:

- A relatively low human interaction in the water cycle.
- A very strong seasonal precipitation pattern.
- Very small reservoirs.
- Strong seasonal vegetation pattern.
- Lack of data and information.

Conclusions regarding the demonstration of SWAT for the Kitui area can be drawn:

- The sand storage dams were too small to be included in SWAT individually. Even when they were clustered to Representative Reservoir Nodes (RRNs), the source code had to be adjusted to be able to put in the storage volume of these RRNs.
- The set up of the SWAT model can be done as complex as required. A simple SWAT model can be build relatively easily and fast by making use of the default databases in SWAT. The model can then be adapted and improved to better represent reality.

- Calibration is essential in SWAT to get realistic results. For Kitui area hardly any calibration data were available resulting in inaccurate results, such as too high storage volume of dams and too high discharge in rivers in the dry season.
- It was demonstrated that SWAT has sufficient physical detail to calibrate the model to reality provided calibration data would be available.
- New tools have been developed to support a more thorough analysis of evapotranspiration and the role of vegetation therein, and to provide a more detailed spatial output in the form of HRU maps.

The first conclusion of this demonstration case is that the strength of the SWAT model lies in its completeness and the high physical detail of the model. All components of the water balance are modelled in detail and the results can be analysed at all temporal and spatial scales from day to year and from HRU to the entire basin. This is very important because knowledge on the hydrological system, for example water storage in different components of the system, the fluxes between these components and the available water for human use, are the basis of proper water management.

Second conclusion is that the high physical detail included in SWAT has also some disadvantages. A modelling study with SWAT requires experienced modellers. A SWAT study therefore has to be performed by modelling experts and stakeholders can not be involved in an early phase of the modelling. This reduces transparency of the method and increases costs.

Third conclusion is that scenario analysis might take a lot of time and is not straightforward for each scenario. Some scenarios require a change in model structure (new reservoirs, change in land cover). However, other scenarios can be included swift (climate change, change in storage capacity of reservoirs, change in crops).

Overall, it can be concluded that SWAT is a very strong tool to support water managers and policy makers as physical processes and human interventions can be analysed in great detail. The only requirement to an actual implementation of SWAT for Kitui (and other areas) is sufficient data and time to setup the model. If this can be achieved SWAT is a key component of Integrated Water Management Support Methodologies.

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A Appendix Data

A.1 Crop coefficient

(From Puttemans et al. 2004)

Mais:

Growing period within the year:

Sowing time: October (short rain season) and March (long rain season)
Harvest time (fresh): January (short rain season) and June (long rain season)
Harvest time (dry): February (short rain season) and July (long rain season)

Crop coefficient and rooting depth per growth stage:

	Initial	*Development*	*Mid*	*Late*	*Total*
Length, fresh (days)	20	35	40	5	100
Length, dry (days)	20	35	40	30	125
K_c-factor (fresh)*	0.30	>>	1.20	0.60	-
K_c-factor (dry)*	0.30	>>	1.20	0.35	-

* Modified values for maize (grain) (FAO irrigation and drainage papers)

Sukuma Wiki:

Growing period within the year:

Sowing time: May-June or January
Harvest time: After 3 months continuously for 1 year

Crop coefficient and rooting depth per growth stage:

	Initial	*Development*	*Mid*	*Late*	*Total*
Length (days)	20	35	25	10-270	90-360
K_c-factor*	0.70	>>	1.05	0.95	-

* Modified values for cabbage, Brassica oleracea var. capitata (FAO irrigation and drainage papers)

A.2 Tables results

Table 14. Yearly water balance 1990 – 2002.

UNIT					PERCO	TILE				WATER
TIME	**PREC**	**SURQ**	**LATQ**	**GWQ**	**LATE**	**Q**	**SW**	**ET**	**PET**	**YIELD**
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(t/ha)
1990	1254	346.74	0.57	61.69	171.03	0	371.52	620.47	1012.68	408.11
1991	799	320.47	1.01	90.61	231.72	0	371.46	356.64	1010.85	411.34
1992	684	251.53	1.07	110.39	231.86	0	371.49	301.65	1021.62	362.18
1993	1050	428.53	1.48	324.69	427.23	0	372.34	279.94	992.61	753.5
1994	876	364.48	1.49	234.55	332.26	0	370.35	273.52	1025.02	599.65
1995	1480	756.27	1.95	411.76	523.29	0	375.37	276.96	1042.43	1168.94
1996	689	253.66	1.85	185.17	271.33	0	368.34	265.55	1034.84	439.83
1997	1210	554.17	1.67	331.74	458.05	0	377.64	275.12	1051.35	886.62
1998	1306	693.03	2.14	370.36	441.51	0	366.53	269.75	1027.77	1064.44
1999	818	330.95	1.62	185.38	309.92	0	372.15	268.84	1046.68	516.92
2000	631	232.04	1.43	126.84	233.96	0	371.27	263.84	1018.04	359.6
2001	719	274.93	1.44	197.4	283.79	0	365.9	258.48	1026.7	473.02
2002	1259	570.32	1.57	376.81	494.59	0	375.4	269.99	1074.18	947.62

Table 15. Monthly water balance 1995.

UNIT					PERCO	TILE				WATER
TIME	**PREC**	**SURQ**	**LATQ**	**GWQ**	**LATE**	**Q**	**SW**	**ET**	**PET**	**YIELD**
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(t/ha)
1	67	25.41	0.14	27.39	34.91	0	370.66	7	56.7	52.88
2	59	19.63	0.13	26.52	29.21	0	367.91	19.69	63.32	46.24
3	150	62.76	0.15	38.35	57.32	0	370.68	38.55	96.07	101.05
4	548	364.19	0.17	142.66	152.55	0	365.89	41.96	102.16	506.88
5	142	63.76	0.19	33.45	49.1	0	368.51	40.5	109.06	97.28
6	59	18.11	0.18	17.61	26.96	0	370.57	21.78	102.69	35.82
7	26	5.09	0.18	13	15.8	0	369.94	9.2	110.56	18.24
8	29	6.38	0.18	14.46	16.94	0	368.27	11.3	104.02	20.95
9	38	10.35	0.16	14.63	18.4	0	368.16	14.96	91.57	25.09
10	32	6.71	0.16	4.95	12.63	0	365.13	27.05	83.93	11.8
11	54	15.68	0.15	8.09	19.59	0	366.31	26.21	67.07	23.87
12	276	158.2	0.17	70.64	89.89	0	375.37	18.77	55.29	228.83
1995	**1480**	**756.27**	**1.95**	**411.76**	**523.29**	**0**	**375.37**	**276.96**	**1042.43**	**1168.94**

Table 16. Monthly water balance 2000.

UNIT					PERCO	TILE				WATER
TIME	**PREC**	**SURQ**	**LATQ**	**GWQ**	**LATE**	**Q**	**SW**	**ET**	**PET**	**YIELD**
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(t/ha)
1	20	1.87	0.14	14.87	15.63	0	371.02	5.56	55.22	16.83
2	0	0	0.12	0.41	0.1	0	361.81	18.01	66.41	0.54
3	89	32.53	0.13	9.29	23.84	0	370.58	35.49	89.45	41.86
4	96	40.22	0.13	16.85	31.28	0	365.45	44.12	109.93	57.11
5	64	22.82	0.13	12.51	22.56	0	359.64	39.05	107.29	35.41
6	35	6.63	0.12	1.44	7.1	0	370.45	22.24	99.28	8.14
7	3	0	0.12	0.04	1.84	0	367.95	7.86	103.98	0.16
8	8	0.48	0.11	0.06	5.1	0	365.24	9.48	99.87	0.63
9	27	4.55	0.1	0.53	13.68	0	366.06	13.48	88.9	5.12
10	31	6.32	0.11	4.91	13.88	0	363.03	23.83	77.63	11.31
11	184	87.32	0.11	41.94	69.06	0	370.36	25.39	66.05	129.21
12	74	29.3	0.12	23.98	29.88	0	371.27	19.33	54.03	53.3
2000	**631**	**232.04**	**1.43**	**126.84**	**233.96**	**0**	**371.27**	**263.84**	**1018.04**	**359.6**

Table 17. Water balance in RRN No.164 Mulutu for the year 1995.

month	FLOW_IN	FLOW_OUT	PRECIP	EVAP	SEEPAGE	water use	storage
	m3	*m3*	*m3*	*m3*	*m3*	*m3*	*m3*
1	1635699	1612129	1042	535	11600	8727	17210
2	1387895	1371444	1039	660	11670	8940	13460
3	3058733	3034627	2633	1018	13120	12691	17240
4	15409440	15401664	9781	1095	12850	3562	17330
5	2868566	2849818	2517	1165	13240	6701	17280
6	1163549	1140221	998	1069	12480	10887	17120
7	626478	604247	462	1178	13210	8274	17230
8	698795	676028	514	1108	13190	8343	17200
9	882576	860803	673	973	12750	4752	16560
10	413009	395064	490	836	12340	5919	12590
11	700618	685066	932	676	12080	7788	13250
12	7012051	6993302	4616	583	13070	9612	17310

Table 18. Water balance in RRN No.164 Mulutu for the year 2000.

month	FLOW_IN	FLOW_OUT	PRECIP	EVAP	SEEPAGE	water use	storage
	m3	*m3*	*m3*	*m3*	*m3*	*m3*	*m3*
1	537823	515592	354	587	13170	-3489	17210
2	16838	10620	0	504	8950	9111	4893
3	1239028	1207958	950	802	11020	20287	17240
4	1652400	1635293	1690	1164	12690	-307	17330

5	999579	985651	1135	1100	12700	2123	12080
6	276048	252798	411	899	10850	-419	12940
7	1500	0	23	431	5129	7904	609
8	21829	0	46	351	4418	21737	12550
9	189346	164851	320	745	10040	8489	17180
10	376047	359441	545	795	12660	9445	11640
11	4012416	3994272	3215	657	11980	8642	17390
12	1567935	1550526	1195	547	12530	5428	17310