Katholieke Universiteit Leuven

Faculteit Landbouwkundige en
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Modelleren van de regionale waterbalans van een bekken in het semi-aride Zuid Kitui, Kenia

Regional water balance modelling of a semi-arid catchment in South Kitui District, Kenya

Promotoren:

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Departement Landbeheer
Laboratorium voor Bodem- en Waterbeheer

Eindwerk voorgedragen
tot het behalen van de graad van
Bio-Ingenieur in de Milieutechnologie

Dirk Neesen

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Acknowledgements

First, I would like to state my thanks to my promotor Jos Van Orshoven and co-promotor Jan Feyen for their interest in this thesis and for giving me the opportunity to explore a magnificent country, Kenya. Thanks to Prof. G.C.M. Mutiso, chairman of the SASOL board, for his supervision during the field study in Kenya and for the general coordination of this project. I would like to express my gratitude to Bernard Biesbrouck who guided me through this thesis and who was always ready to explain, clarify and encourage.
Thanks to the VLIR for assigning an IRO-scholarship.

I would like to say many thanks to Sam Mutiso, field manager of SASOL, for familiarizing us with the administrative procedures of SASOL and for the available facilities. Thanks to all the staff of SASOL with a special thanks to Joseph Muinde Munyoki who guided me inexhaustible, who was always there with good advice and friendship. Ni muvea mono! Thanks to the fathers of the technical school in Nairobi and all the people in Kisayani who made the stay in Kenya pleasant and unforgettable. Thanks to Jan-Kees Bossenbroek and Teun Timmermans for their pleasant company and fruitful cooperation during our stay in Kisayani. I cannot forget to thank Sam Puttemans for his good company in Kenya and the cooperation in Kenya and in Leuven. Thanks for your friendship and for sharing for all those memorable experiences with me.

Of course I would also like to thank my parents who supported me constantly during these past five years of study. Finally, a word of thank to all my dear friends for their comforting words and their support during the sometimes hard and stressing times.

Samenvatting

Studieachtergrond

Waterschaarste en waterarmoede

Waterschaarste is een wereldwijd probleem. Waterschaarste is het gebrek aan rechtstreeks beschikbaar zoet, en dus bruikbaar/drinkbaar water. Omwille van de ongelijke verdeling van zoet water, kan waterschaarste gezien worden als een lokaal en/of regionaal probleem. Dit is zeker het geval als kwaliteits- en duurzaamheidsparameters worden beschouwd.

Waterschaarste kan opgedeeld worden in fysische waterschaarste en economische waterschaarste. Bij *fysische* waterschaarste zal een land, zelfs met de hoogst mogelijke efficiëntie en productiviteit bij het ontginnen van waterbronnen, niet kunnen voldoen aan zijn landbouwkundige, huishoudelijke en industriële waterbehoeften.

Bij *economische* waterschaarste zijn er voldoende natuurlijke waterbronnen voorradig, maar zal de financiële capaciteit van de landen te beperkt zijn om deze uit te baten.

Vaak zijn waterschaarste en armoede met elkaar verbonden. Om dit probleem te identificeren is het concept *waterarmoede* ontwikkeld. Waterarmoede kan omschreven worden als een situatie waarin een land of regio het zich niet kan veroorloven om op elk tijdstip op een duurzame manier drinkbaar water aan de volledige bevolking te voorzien.

Zuiver, zoet water moet aan alle lagen van de bevolking voorzien worden en de tijdelijke periodes van waterschaarste moeten overbrugd worden. Dit kan met behulp van verschillende opslagtechnieken. Het is bovendien essentieel dat dit water voor alle lagen van de bevolking betaalbaar blijft.

Verschillende manieren zijn voorhanden om op een economische manier de waterbeschikbaarheid te verbeteren in ontwikkelingslanden. Eén van deze veelbelovende technieken is het ‘oogsten’ van regenwater. Dit kan door opslag van regenwater in afwateringsreservoirs van rotsen en daken of door opslag van grondwater in ondergrondse reservoirs. Deze methoden leveren relatief goedkoop water van goede kwaliteit.

Regio’s die met waterarmoede geconfronteerd worden, zijn vooral gelegen in arme aride en semi-aride gebieden. Sub-saharisch Afrika, behoort tot deze gebieden en wordt sterk door waterarmoede getroffen.

Het REAL-project

Het onderzoek is een deel van het REAL-project (Rehydrating Arid Lands) dat wordt gesponsord door de Europese Commissie en International Cooperation with Developing Countries (INCO-DEV). Andere partners zijn de Technische Universiteit van Delft (TUDelft) (Nederland), het International Water and Sanitation Centre (IRC) (Nederland), Katholieke Universiteit Leuven (België), Sahelian Solutions (SASOL) (Kenia), University of Nairobi, (Kenia), University of Dar Es Salaam (Tanzania), Westerfeld Conservation Trust (Kenia/Nederland) en Protos (België).

Het REAL-project concentreert zich op semi-aride en aride gebieden in Kenia en Tanzania. Uitgaande van de natuurlijke omstandigheden, de groeiende druk op natuurlijke rijkdommen en een moeilijke economische toestand probeert men de watertoestand van landelijke en licht verstedelijkte gebieden te verbeteren. Het algemeen doel van dit project is om een relatie tussen de lokale kennis en theoretische kennis te onderzoeken en zich te concentreren op het ontwerp, onderhoud en efficiëntie van kleinschalige, grondwater weerhoudende structuren. Dit moet resulteren in een handleiding voor het ontwerp, gebruik en onderhoud van kleinschalige grondwater weerhoudende structuren.

Kenia is een Afrikaans land dat voor 88% van zijn oppervlakte geklasseerd wordt als aride en semi-aride gebied. Neerslag kent een sterke ruimtelijke variatie in Kenia. Daarom varieert de waterbeschikbaarheid sterk in het land. Grote oppervlaktes van het Keniaans grondgebeid worden geconfronteerd met waterarmoede.

Deze studie vond plaats in het Kitui district in het Zuidelijk deel van Kenia. Dit district wordt geklasseerd als een van de aride en semi-aride gebieden van Kenia. Watergebrek in droge periodes is een probleem in de meeste gebieden van dit district.

SASOL, de lokale partner in het REAL-project, bouwt “sand-storage dams” en waterputten in het Kitui district.

“Sand-storage dams” worden gebouwd als betonnen of gemetselde barrières in efemere rivieren. De barrière wordt tot op de ondoorlaatbare rots gebouwd om wegsijpeling te beperken en komt boven het grondoppervlak uit. Het stroomopwaarts gelegen reservoir van de “sand-storage dam” wordt opgevuld met grof zand. De artificieel gecreëerde aquifer wordt aangevuld door de afstroming van het gebied. Dit soort dammen zijn makkelijk te ontwerpen en te construeren met lokaal beschikbare materialen. Dichtslibben van de dam vormt geen probleem zoals bij conventionele dammen, het water wordt immers ondergronds vastgehouden. Dit beperkt de evaporatie van het opgeslagen water sterk en door de afwezigheid van vrije wateroppervlakten zal het aantal parasieten (waaronder muskieten en bilharzia parasieten) afnemen en is het water minder gevoelig voor vervuiling. De stijging van de watertafel zorgt voor een verhoogde groei van de vegetatie langsheen de rivierbanken. Deze planten zorgen op hun beurt voor een verhoogde stabiliteit van de banken.

De capaciteit en performantie van een "sand-storage dam" hangen van verschillende parameters af. Deze parameters zijn ondermeer de lokatie van de dam (smalle en steile rivier, brede rivier, bodem- en landgebruikkarakteristieken,..), de constructie van de dam (hoogte van de overloop, gebruikte materialen,…), de aanwezigheid van andere dammen in de rivier, de porositeit van het zand in het reservoir en het beschikbare budget van de gemeenschap die instaat voor de bouw van de dam.

Hypothese en objectieven

In de zomer van 2004 zal SASOL een "sand-storage dam" bouwen in het dorpje Kisayani in het Kitui district. Het doel van dit eindwerk is om de waterbalans op te stellen van het stroombekken van de Ngunga rivier tot aan de plaats waar de dam gebouwd zal worden. Om de simulatie uit te voeren, zal het AVSWAT model gebruikt worden. Hierbij wordt aangenomen dat AVSWAT een geschikt hydrologisch model is om de waterbalans van een semi-arid stroombekken te bepalen (Conan *et al.,* 2003) en dat er met een beperkte hoeveelheid data een aanvaardbaar model kan worden opgezet.

Het effect van landgebruik op waterbeschikbaarheid zal eveneens onderzocht worden. Verschillende landgebruikscenario's zullen worden opgesteld en het effect hiervan op de simulatieresultaten van het AVSWAT model zal worden nagegaan. De belangrijkste hydrologische processen van het semi-aride stroombekken zullen worden onderzocht.

Een lokale waterbalans zal worden opgesteld voor het zandreservoir van de "sand-storage dam". Hierdoor zal een schatting kunnen gemaakt worden van de hoeveelheid water die door de dam weerhouden wordt en zal een inzicht verkregen worden over de dynamiek van de wateropslag.

Datacollectie in Kisayani was niet voor de hand liggend omwille van de grootte van het te onderzoeken gebied en de daarbij horende transportproblemen. De omgeving rond Kisayani is erg landelijk. Zo goed als geen onderzoek werd tot op heden verricht in deze regio. Omwille van de beperkte hoeveelheid experimentele data kan er geen kwantitatieve kalibratie verricht worden. Daarom zal dit onderzoek methodologisch en kwalitatief van aard zijn.

Materiaal en methoden

Voor de modellering wordt AVSWAT (ArcView 'Soil and Water Assessment Tool') gebruikt. Dit programma gebruikt ArcView GIS als grafische user interface om de ruimtelijke invoerdata te bewerken. SWAT is een modelleringsprogramma voor stroomgebieden ontwikkeld door Dr. Jeff Arnold van het USDA Agricultural Research Service (ARS). Het werd ontwikkeld om de impact van landgebruiksveranderingen op de waterkwaliteit en kwantiteit en op het transport van sediment en agrochemicaliën na te gaan.

Om het AVSWAT model op te stellen moeten bepaalde gegevens verzameld worden. Deze gegevens werden gedeeltelijk gedurende een veldstudie van twee maanden verzameld. De experimentele gegevens werden aangevuld met literatuurwaarden.

De verzamelde gegevens kunnen worden ingedeeld in de invoergegevens voor de pre-processing fase en de data voor de kalibratie van het AVSWAT model.

De pre-processing is de fase waarbij berekeningen worden verricht in de ArcView GIS 3.2a omgeving. De gegevens van deze fase bestaan uit ArcView lagen en database bestanden. Een digitaal terreinmodel werd geïnterpoleerd vanaf een gedigitaliseerde kaart met hoogtelijnen. Op basis hiervan lijnt AVSWAT het stroomgebied af. De verschillende landgebruikseenheden werden ter plaatse geïdentificeerd vanaf de hoger gelegen gebieden en werden ingetekend op een kaart van het gebied. Dit werd geverifieerd met behulp van transecten en raadpleging van lokale kennis. De manueel getekende kaart werd gedigitaliseerd en ingevoerd in het AVSWAT model.

Ter plaatse werden bodemstalen verzameld van de meest voorkomende bodems in het gebied (Lixisol, Vertisol en Planosol). Deze werden in het labo geanalyseerd op verzadigde hydraulische conductiviteit, textuur, bulkdensiteit en watergehalte op veldcapaciteit en op verwelkingspunt. Op basis van de verzamelde gegevens en bestaande bodemkaarten werd een bodemkaart van het gebied gemaakt en ingevoerd in het AVSWAT model. Eveneens werd een database bestand gemaakt met de belangrijkste bodemkarakteristieken van de drie geïdentificeerde bodems van het stroombekken.

Ter plaatse, in de lagere school van Kisayani en in de middelbare school van Mbitini werden twee nieuwe weerstations opgezet. Daar deze zich nog in een beginstadium bevinden zijn hiervan nog een te beperkte hoeveelheid data verkrijgbaar. Daarom werden klimatologische gegevens van bestaande weerstations gebruikt. De neerslaggegevens werden verkregen van het "Mutomo agricultural station" op ongeveer 15 km ten zuiden van de rand van het stroombekken gelegen. Andere klimatologische parameters (dagelijkse minimum en maximum temperatuur, gemiddelde dagelijkse windsnelheid per maand, gemiddeld dagelijks dauwpunt per maand, gemiddelde dagelijkse zonneradiatie per maand) werden verkregen van "Kitui agricultural office" gelegen op ongeveer 30 km ten noorden van de rand van het stroombekken. Op basis van deze gegevens werd een database bestand met statische klimaatparameters gemaakt. Om de simulaties uit te voeren werd een hybride weerstation in Mutomo geplaatst. Omdat van Mutomo enkel neerslaggegevens verkrijgbaar waren, werden de gegevens van dit weerstation aangevuld met andere klimatologische parameters van Kitui.

De simulatie met één pluviometer leverde echter extreme resultaten op, daarom werden er zes fictieve pluviometers in het stroombekken geplaatst. Hierbij werden de neerslaggegevens van zes opeenvolgende jaren van Mutomo in een andere jaarvolgorde ingevoerd. Dit is een theoretisch modellering die echter wel de ruimtelijke variatie van de neerslag in het gebied weergeeft. Indien slechts één pluviometer wordt gebruikt in het model zal de neerslag worden veralgemeend voor het hele stroombekken van 66 km² groot. Dit is echter niet realistisch in een semi-arid stroombekken waar neerslag een grillig en plaatselijk karakter heeft.

De simulaties werden uitgevoerd van juni 1980 tot mei 1986.

Om het model te kalibreren was voorzien om debietmetingen uit te voeren. De veldstudie vond echter plaats in het droge seizoen. De efemere rivier stroomde op dat moment niet en het was dus onmogelijk om debietmetingen uit te voeren. In samenwerking met de TUDelft werden er ter plaatse piëzometers geïnstalleerd om de grondwaterstand op te volgen. De piëzometers en rivierbanken werden opgemeten met een theodoliet en ingevoerd in AUTOCAD waarna een overzichtskaart van de rivier werd gemaakt in ArcView. Omwille van praktische problemen met de piëzometers, zoals schade door rondlopend vee en nieuwsgierige mensen, was het merendeel van de piëzometers onmeetbaar geworden voor het begin van het regenseizoen. Te weinig accurate metingen waren voorhanden om de piëzometers te gebruiken voor de kalibratie van de lokale waterbalans.

Voor de waterbalans van het zandreservoir moeten zes parameters worden bepaald: actuele evaporatie, wegsijpeling, irrigatie en huishoudelijke behoeften, lokale neerslag, debiet en het volume van het zandreservoir.

Het volume van het zandreservoir werd bepaald door een trapezoïdaal reservoir te veronderstellen met een gemiddelde diepte waarop de ondoorlaatbare rots voorkomt. Deze gemiddelde waarde werd bepaald op basis van bodemboringen. Door rekening te houden met de porositeit van het zand, werd er geschat dat het reservoir 4381,75 m^3 water kan bevatten. Actuele evaporatie werd geschat op basis van een modellering met HYDRUS 1-D. Op deze manier werd de actuele evaporatie van het zandoppervlak geschat in functie van de diepte van de watertafel. De dam wordt verondersteld perfect te werken, zodat geen wegsijpeling in rekening werd gebracht. In realiteit is dit vermoedelijk niet zo, maar hier werd nog geen wetenschappelijk onderzoek op verricht. Voor de lokale waterbalans werden de neerslaggegevens van Mutomo gebruikt en het debiet dat toekomt bij de ”sand-storage dam” werd gesimuleerd met AVSWAT.

Resultaten en discussie

Bij de simulatie van de waterbalans van het stroombekken met slechts één pluviometer werden extreme debieten bekomen. Het maximale gesimuleerde debiet was 5620320 m^3/dag. Deze extreem hoge waarde werd bekomen doordat een intensieve neerslagbui van 200 mm die plaatsvond één dag voor dit debiet bereikt werd, veralgemeend werd naar het volledige stroombekken. Aangezien neerslag in semi-aride gebieden zeer plaatselijk is en zowel ruimtelijk als temporeel een sterke variatie vertoont, kan deze intensieve neerslag van 200 mm niet veralgemeend worden naar het hele stroombekken.

Om de ruimtelijke verspreiding van neerslag te modelleren met de beperkte gegevens werden er zes fictieve pluviometers in het stroombekken geplaatst. Van de neerslaggegevens van het beschikbare weerstation “Mutomo agricultural station” werden de jaren in een andere volgorde geplaatst voor elke pluviometer. Op deze manier zullen intensieve neerslagbuien plaatsvinden over een kleiner oppervlak. De extreme

debietwaarden werden verminderd, zo is het maximaal gesimuleerde debiet viermaal kleiner in vergelijking met de vorige simulatie.
Er werd een zeer regelmatig verloop bekomen waarbij in de debietsgrafiek duidelijk twee regenseizoenen te herkennen zijn per jaar. Er zijn echter sterke vermoedens dat dit een te continu verloop geeft in vergelijking met de werkelijkheid, daar in de realiteit een regenseizoen regelmatig uitblijft. Door het mixen van dezelfde neerslaggegevens en deze te spreiden over het gebied komen echter steeds dezelfde neerslagbuien voor. Dit resulteert in een regelmatig verloop. AVSWAT modelleert op deze manier de onregelmatigheid in neerslag en lange periodes van droogte onvoldoende.

Omdat een kwantitatieve kalibratie niet mogelijk was bij gebrek aan geobserveerde data, werd een kwalitatieve kalibratie uitgevoerd. Hierbij werd nagegaan of het verloop van de debietsgrafiek, de gesimuleerde evapotranspiratie en de respons van de snelle afvoer op de regenval een verloop kennen, analoog aan afvoer curves, typisch voor semi-aride streken. Indien het verloop van het debiet wordt vergeleken met andere debietsgrafieken van semi-aride gebieden, kan worden geconcludeerd worden dat dit verloop gelijkaardig is. Hoge debietspieken in periodes met hoge neerslag worden afgewisseld met periodes zonder debiet tijdens het droge seizoen. Het debiet in functie van de tijd heeft een exponentieel verloop omdat infiltratie afneemt in functie van de tijd. Dit werd echter niet waargenomen in de ongekalibreerde output. Daarom werd er gekalibreerd op diepe percolatie, “channel routing” en effectieve hydraulische conductiviteit van het kanaal. Hierdoor werd een typisch verloop verkregen van het debiet in functie van de tijd.
Een sterke correlatie werd waargenomen tussen de neerslag en het gesimuleerde debiet. Bovendien is er in periodes van droogte geen of nauwelijks debiet. Dit suggereert dat het debiet nagenoeg volledig bepaald wordt door snelle afvoer en trage afvoer niet bijdraagt tot het debiet. Efemere rivieren zijn boven de watertafel gelegen die meestal op een zeer grote diepte ligt. Stroming in de verzadigde zone draagt daarom niet bij aan het debiet van de rivier.

Om het effect op het debiet aan het uiteinde van het stroombekken door een verandering van landgebruik na te gaan werden er buiten het basisscenario twee andere scenario’s onderzocht. Bij het eerste scenario werd er aangenomen dat het volledige stroombekken met maïs en "cowpeas" werd bebouwd, in het tweede scenario werd verondersteld dat het volledige stroombekken begroeid is met gras, als gevolg van een gedegradeerde vegetatie en ontbossing. Bij beide scenario's werd vastgesteld dat het debiet aan de uitlaat van het stroombekken steeg. De invloed van het landgebruik is echter beperkt. Aangezien de beide onderzochte scenario's extreme situaties zijn (het volledige stroombekken onder maïs en "cowpeas" of gras vegetatie) kan worden gesteld dat het landgebruik een beperkte invloed heeft op het debiet.

Bij het opstellen van de lokale waterbalans voor het zandreservoir werd geconstateerd dat volgens het model het reservoir altijd volledig opgevuld met water zal zijn, behalve in het begin van de simulatie als er nog geen neerslag is gevallen. Dit correspondeert echter niet met wat gekend is uit lokale kennis. In realiteit neemt de hoeveelheid water in het zandreservoir af in het droge seizoen en wordt de zandreservoir nagenoeg volledig opgevuld bij de eerste hevige regens van het regenseizoen. Er kan dus gesteld worden dat dit model een overschatting geeft. Dit kan verklaard worden doordat het balansmodel zeer sterk afhankelijk is van het resultaat van de AVSWAT output. Het zandreservoir wordt aangevuld door de snelle afvoer van een groot stroombekken. Lokale neerslag en evaporatie dragen dus beperkt bij tot de waterbalans in tegenstelling tot snelle afvoer die het grootste deel van de wateraanvoer vertegenwoordigt. Zoals reeds eerder werd gezegd geeft AVSWAT te continue resultaten waardoor het reservoir te frequent aangevuld wordt en de lange droge periodes waarin het watervolume in het reservoir afneemt te kort zijn. Bij de opstelling van de lokale waterbalans is er ook geen rekening gehouden met wegsijpeling en gebruik van water voor irrigatie en huishoudelijke doeleinden. Aangezien hiervan geen gegevens bestaan is het moeilijk om hierover een schatting te maken, toch kan worden aangenomen dat dit een belangrijke bijdrage kan leveren tot de leegloop van het damreservoir.

Er werd een schatting gemaakt van de leegloop van het reservoir indien de verdwijning van water enkel door evaporatie zou gebeuren. Hierbij zou na twee jaar nog steeds 39% van het reservoir gevuld zijn met water. Dit toont aan dat het water opgeslagen in een "sand-storage dam" die goed gebouwd is een lange tijd beschikbaar is en dus tijdelijke droogten kan overbruggen.

Conclusies en aanbevelingen

AVSWAT is een budgetvriendelijk model met uitgebreide mogelijkheden. In vergelijking met het modelleringsprogramma MIKE BASIN, heeft AVSWAT minder gegevens nodig om een model op te zetten. AVSWAT is een volledig geïntegreerd pakket in tegenstelling tot MIKE BASIN dat uit verschillende, apart aan te kopen modules bestaat. Een groot voordeel is dat AVSWAT geen klimaatstijdsreeksen nodig heeft om een simulatie uit te voeren. Indien het weathergeneration bestand gecreëerd is, kan AVSWAT zijn eigen klimatologische tijdsreeksen simuleren. Deze eigenschappen zijn vooral belangrijk voor ontwikkelingslanden waar data vaak schaars zijn en onderzoek dikwijls aan banden wordt gelegd door financiële beperkingen. Omwille van de volledigheid van AVSWAT, de beperkte aankoopprijs en de gelimiteerde hoeveelheid invoerdata om een model op te zetten kan AVSWAT als hydrologisch modelleringsprogramma in ontwikkelingslanden worden ingezet. Toch moet deze conclusie genuanceerd worden omwille van problemen met de gebruiksvriendelijkheid van de software. Eerst en vooral is het zeer tijdrovend om een simulatie op te starten. Er kunnen veel fouten gemaakt worden bij het invoeren van de gegevens. Indien er een kleine fout gebeurt bij deze invoer zal het programma geen simulatie kunnen uitvoeren. Het is moeilijk en tijdrovend om deze kleine fouten uit het model te halen. Een ander nadeel bij AVSWAT is de hoeveelheid harde schijfruimte door een project ingenomen. In dit specifiek geval, kan een project drie gigabyte beslaan. Dit maakt het zeer moeilijk om reservekopieën te maken of om aan twee scenario's tegelijkertijd te werken. Sommige berekeningen kunnen zeer lang duren. En zelfs een goede computer (Pentium IV processor: 2,26 GHz; 512 Mb RAM geheugen) kan hierbij vastlopen. Goede hardware voor het gebruiken van AVSWAT is dus uiterst noodzakelijk. Ook ArcView draagt bij tot de gebruiksonvriendelijkheid van AVSWAT. Een project kan niet zomaar op een andere computer verder gezet worden, aangezien het project moet worden geopend op dezelfde lokatie als waar het werd gecreëerd. Indien niet, dan moet de directory van alle bestanden in het project geherdefinieerd worden (dit kunnen meer dan 3000 bestanden zijn).

Eens een AVSWAT project opgezet is, kan een simulatie snel worden uitgevoerd. Dit maakt het mogelijk om vanaf een reeds opgestart model, op relatief korte termijn snel resultaten te verkrijgen. De voornoemde praktische problemen kunnen de introductie van AVSWAT in ontwikkelingslanden bemoeilijken of zelfs onmogelijk maken.

Hoewel het model niet gekalibreerd is, kunnen toch een aantal conclusies gemaakt worden. Er is de duidelijke neerslag-snelle afvoer relatie en de periodes zonder debiet. Dit duidt op de minimale bijdrage van trage afvoer aan het debiet. Om tot een volwaardig model te komen is het van belang dat voldoende neerslaggegevens beschikbaar zijn uit het stroombekken. Daarom is het van cruciaal belang dat de opgezette weerstations in stand worden gehouden. Deze zouden nog kunnen aangevuld worden met neerslagmeters in het centrum van het stroombekken. In semi-aride gebieden is het belang van neerslagdata nog groter dan in gematigde klimaten omwille van de ruimtelijke variatie en de variatie in de tijd van de neerslag. Modelleren in een semi-arid gebied is en blijft geen makkelijke zaak daar periodes van droogte veranderingen in de vegetatie en bodemstructuur teweegbrengen. Hierdoor zal de snelle afvoer beïnvloed worden. Het verdelen van neerslaggegevens over verschillende meetstations geeft de ruimtelijke variabiliteit weer, maar niet de temporele variabiliteit. Een te regelmatig verloop van neerslag wordt verkregen doordat dezelfde neerslagbuien elk jaar terugkomen. Een kwantitatieve uitspraak over de modellering kan niet gedaan worden omdat het model ongekalibreerd blijft.

Landgebruiksveranderingen hebben een beperkte invloed op het debiet aan de uitlaat van het stroombekken. Hieruit kan geconcludeerd worden dat bij een toekomstig onderzoek meer aandacht gericht kan worden op het verzamelen van neerslagdata en minder in het opvolgen van landgebruiksveranderingen.

Het opgezette waterbalansmodel is sterk afhankelijk van de resultaten van AVSWAT. Ook hier is het van groot belang dat AVSWAT gekalibreerd wordt. Ook de verwaarlozing van wegsijpeling en watergebruik voor huishoudelijke- en irrigatiedoeleinden draagt bij tot de overschatting van het vastgehouden watervolume. Bij verder onderzoek zal er aandacht besteed moeten worden aan deze parameters.

Om de schatting van het volume van de dam accurater te maken moet er op verschillende plaatsen in het reservoir informatie bekomen worden over de diepte van de ondoorlaatbare laag. Hiervoor kan een terrameter gebruikt worden.

Abstract

Water scarcity is a severe problem in arid and semi-arid areas of sub-Sahara Africa. Kenya, a country with 88% of its land being arid and semi-arid deals with severe water scarcity. Several solutions can be found to address this problem in a sustainable and economical way. In Kitui, a semi-arid region of Kenya, SASOL (Sahelian Solutions) builds sand-storage dams in the ephemeral rivers. These dams obstruct the natural ground water flow and the sandy reservoir is replenished by the runoff of the catchment. These dams are easy to design and can be build with local materials. The water is retained in the sub-surface; this restricts the evaporation. Because of the absence of free water surfaces, breeding of parasites is reduced and the stored water is less prone to pollution. The capacity and performance of the dam is determined by the location, the construction, the presence of other dams in the river, the budget of the community building the dam and the porosity of the sand stored in the reservoir. However scientific research on these topics is rare.

SASOL will build a sand-storage dam in the Ngunga river near the village Kisayani in the summer of 2004. The primary objective of this thesis is to model the water balance of the Ngunga watershed. A simulation with AVSWAT (ArcView Soil and Water Assesment Tool) will be performed to simulate the discharge at the outlet of the watershed. The effect of different land use scenarios will be investigated and the main hydrological processes in a semi-arid watershed will be examined. A local water balance for the sandy reservoir will be set up to estimate the volume of water retained by the dam. Data collection was difficult, because of the extent of the area and the difficult transportation in the region. A quantitative calibration could not be performed because of the shortage of experimental data. Therefore, this research will be methodological and qualitative.

It is concluded that AVSWAT is a budget friendly software package with extensive capabilities. In comparison with the similar MIKE BASIN software, less data are necessary to run a simulation. The main advantage is that AVSWAT does not need climate time series to perform a simulation. Once a database file with statistical climate parameters is produced, AVSWAT can simulate its own time series. However practical inconveniences can occur while using AVSWAT. AVSWAT needs a good computer with enough disk space to run the program. Calculations can take a lot of time. A lot of difficult retraceable input errors can occur. AVSWAT projects cannot be simple copied to other computers or other directories. This will complicate or even prevent the introduction of AVSWAT in developing countries.

Two different simulation models have been made. In the first simulation with one rain gauge accounting for the whole catchment, extreme discharges have been obtained. This simulation did not represent the spatial and temporal distribution of semi-arid watersheds. In the second simulation, six fictive rain gauges have been placed in the catchment and the precipitation data of one weather station has been scrambled over the rain gauges. After a visual calibration, these results are comparable with the discharge of other semi-arid watersheds. The spatial distribution has been accounted for through the distribution of the rain gauges over the catchment. The temporal distribution of rainfall however is not accounted for because rainfall data of one weather station have been used, so the same rainstorms return. The high discharge peaks have been diminished, however, the discharge display is too regular. In reality, periods of drought are longer because rain seasons regularly fail to come. To set up a reliable model, more rainfall data of the studied area should be available. It is therefore indispensable that the recently installed weather stations are maintained and if possible extended.

The effect of land use on the discharge at the outlet of the catchment is small. Because extreme situations have been examined, it is expected that discharge changes because of land use changes will be negligible. More efforts should therefore go to rainfall data collection than in monitoring the land use changes.

In the water balance model an overestimation of the stored water is observed. According to this model, the sandy reservoir will be filled with water continuously except at the start of the simulation when no rainfall occurred. This however does not correspond with experience on the field. In these dams, the water volume diminishes in the dry season and the sand-storage dam is replenished in the rainy season. The overestimation can be explained through the strong dependency of the model on the AVSWAT output because of the size of the catchment. The evaporation of the sand surface and local precipitation is only a minor contributor to the model. As already stated, the AVSWAT output is too regular and the model remains uncalibrated. Seepage and water use for irrigation and domestic purposes are not taken into account in the model and contribute to the overestimation. More research on these topics should be performed to make valid estimations of these parameters. A more detailed estimation of the volume of the reservoir can be performed through the estimation of the underlying rock in more points in the reservoir. A terrameter can be used for this purpose in further research.

List of abbreviations

ArcView 'Soil and Water Assessment Tool'	AVSWAT
Available Water Content	AWC
Danish Hydraulic Institute	DHI
Delft University of Technology	DUT
Digital Elevation Model	DEM
El Niño Southern Oscillation	ENSO
Food and Agriculture Organization of the United Nations	FAO
Geographic Information Systems	GIS
Global Positioning System	GPS
Gross National Product	GNP
Hydrological Response Unit	HRU
Institute for Meteorological Training & Research	IMTR
International Cooperation with Developing Countries	INCO-DEV
International Water and Sanitation Centre	IRC
International Water Management Institute	IWMI
Inter-Tropical Convergence Zone	ITCZ
Katholieke Universiteit Leuven	K.U.Leuven
Policy Interactive Dialogue Model	PODIUM
Rehydrating Arid Lands	REAL
Sahelian Solutions	SASOL
Semi-arid and arid areas	ASALs
Soil Conservation Service Curve Number	SCS CN
United States Department of Agriculture Agricultural Research Service	USDA - ARS
Water content at Field Capacity	FC
Water content at Wilting Point	WP

List of symbols

Accumulated runoff or rainfall excess (mm H_2O)	Q_{surf}
Amount of base flow on day i (mm)	$Q_{gw,i}$
Amount of evapotranspiration on day i (mm)	$E_{a,i}$
Amount of percolation on day i (mm)	$w_{seep,i}$
Amount of precipitation on day i (mm)	R_i
Amount of surface runoff on day i (mm)	$Q_{surf,i}$
Average width of the river	W_{riv}
Bulk density	ρ_b
Discharge (AVSWAT output) (m^3d^{-1})	Q
Evaporation (md^{-1})	E
Final soil water content (mm H_2O)	SW_t
Initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O)	I_a
Initial water content on day i (mm H_2O)	SW_0
Irrigation and domestic withdrawal (m^3d^{-1})	I
Length of the river	L
Maximum depth of the sand reservoir	D
Particle density	ρ_{part}
Perimeter	P
Porosity	n
Precipitation ($m\ d^{-1}$)	P
Rainfall depth for the day (mm H_2O)	R_{day}
Retention parameter (mm H_2O)	S
Sand-storage surface (m^2)	A_s
Saturated hydraulic conductivity	K_{sat}
Seepage (m^3d^{-1})	S
Surface area of the river (calculated in ArcView)	A
Time (days)	t
Water volume in the sand reservoir (m^3)	V
Width of the river at the “proposed dam site”	$W_{prop.dam}$
Width of the river at the natural barrier	$W_{nat.barrier}$

List of figures

1 Introduction

Arid and semi-arid areas of sub-Sahara Africa are facing problems related to water scarcity. In these areas water conservation is a major aspect for sustainable development. Several techniques can be used to store water during the rainy season, so it can be used in the dry season. In order to be successful, these approaches should be economical and should take the local conditions (material and immaterial) into account. In Kitui, a semi-arid region of Kenya, SASOL (Sahelian Solutions) builds sand-storage dams in the ephemeral rivers. These dams obstruct the natural ground water flow, so that the sandy reservoir is replenished, each rainy season, by the runoff of the catchment. These dams are fairly easy to design and it is possible to build them with local materials. Scientific research about this kind of dams is however scarce. The REAL-project (Rehydrating Arid Lands) tries to clarify the relations between theoretical approaches and local practices.

In chapter 2, a general background of the study will be discussed. The terms “water scarcity” and water poverty” will be situated at a world scale and more specific for sub-Sahara Africa and Kenya. Possible methods to address water problems in developing countries will be discussed. Ground water retaining structures will be discussed more thoroughly. REAL-project will be situated.

In chapter 3, the general problem statement will be sketched and the hypothesis and objectives of this thesis will be clarified.

In chapter 4, the study area will be described and the material and used methods for the experimental work in Kenya and Belgium will be explained. A comparison between the used AVSWAT-model and an alternative hydrological modelling tool (MIKE BASIN) will be made.

In chapter 5 the results of the AVSWAT-model and the water balance will be described and critically discussed.

General conclusions will be made in chapter 6.

2 Background of the study

(authors: Dirk Neesen and Sam Puttemans)

Water is the basis of life on earth. It is the main resource on the planet and it is indispensable for human life. Water insufficiency and decrease in water quality has therefore a disastrous impact on health, environment and agriculture. Water is also essential for sustaining economic and social development. The most affected by water scarcity are the world's poorest, what could lead to global conflicts. This is not a problem that will solve itself but that needs a change in policy and scientifically based solutions. The awareness of water shortage and water pollution should rise, so that these problems can be treated effectively.

2.1 Water scarcity

Globally seen, water is not a scarce resource. It is abundantly present in the hydrosphere in liquid, solid or gaseous form. Fresh water would be abundant if it was evenly distributed. However it is not. The major part of the fresh water supplies, about 68.7 percent, is captured in ice and permanent snow in Antarctica and mountainous regions. Fresh groundwater forms 29.9 percent of fresh waters. Only 0.26 percent of the fresh water is present as readily available surface water in lakes and rivers. It is the latter that is most accessible for economic needs and is very important for water ecosystems. For this reason they are also the most vulnerable water sources. Also, available water resources do not coincide with population spread and economic development (Shiklomanov, 2000).

The main reason for water scarcity is availability. Water scarcity is in essence the lack of readily available fresh water. Because of the uneven distribution of the available fresh global water, water scarcity can be seen as a local or regional problem, especially if the parameters quality and sustainability are included in the assessment (Feitelson and Chenoweth, 2002,).

When talking about water scarcity one has to make a difference between two categories; physical and economic water scarcity.

If there is *physical water scarcity* even with the highest feasible efficiency and productivity of water use, countries cannot meet their agricultural, domestic, industrial and environmental needs for water. In a country suffering of *economic water scarcity* sufficient water resources are present, but there will be a necessity to increase water supplies through additional storage, conveyance and regulation systems by 25 percent or more over 1995 levels to meet the country's 2025 needs. Many of these countries face severe financial and development capacity problems in meeting their water needs (IWMI, 2000).

In 2000 the International Water Management Institute (IWMI) has developed the Policy Interactive Dialogue Model (PODIUM) to estimate the world's 'water supply and demand' situation from 1995 to 2025. The water situation in 1995 of 45 countries (representing 83% of the world population) was extrapolated to the situation in 2025. Population growth was calculated as an average between the United Nations low and medium demographic projection. The low projection forecasts a 28 percent world population growth and the medium projection a 38 percent world population growth between 1995 and 2025.

The model predicts that in 2025 countries with 33 percent of world's population will have to deal with physical water scarcity. Countries with 45 percent of the population will live in a situation with economic water scarcity and countries with 22 percent of the world's population will have little or no water scarcity. Of course this does not mean that all inhabitants of a country confronted with water scarcity will experience problems. Especially societies' poorest will be most affected. They will have to deal with lack of water and the associated hygiene/health problems and food insufficiency.

In addition to PODIUM, a less detailed analysis of 80 countries has been made. Results of this analysis are displayed in Figure 2.1. According to the model's results, also Kenya will be suffering economic water scarcity in the future.

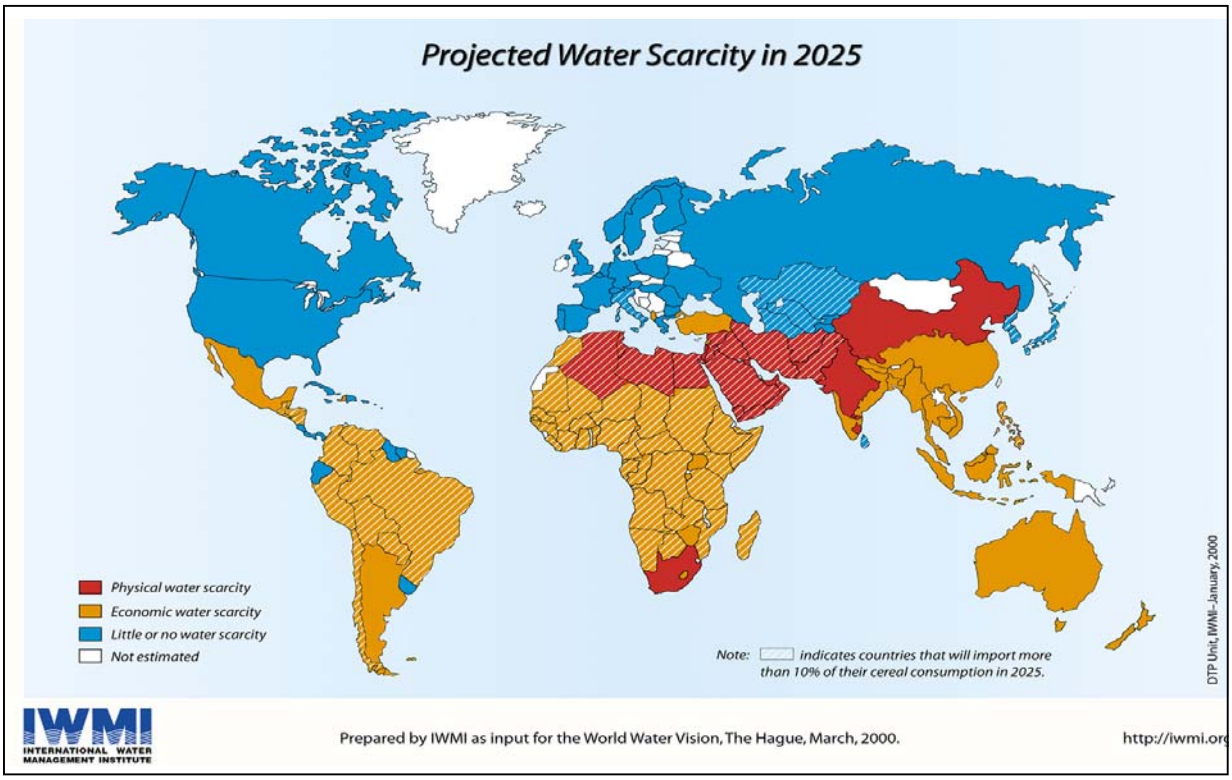

Figure 2.1: Projected Water Scarcity in 2025 Source: (IWMI, 2000)

Although a great deal of uncertainty is involved in these models, they do give an idea of the magnitude of the world's water problem.

2.2 Water poverty index

Often water scarcity and poverty are linked together. To characterize this fact, the water poverty index has been developed. This indicator of water scarcity tries to capture the complex characteristics that bind water and poverty together (Feitelson and Chenoweth, 2002).

> Water poverty can be defined as a situation where a nation or region cannot afford the cost of sustainable clean water *to all people at all times* (Feitelson and Chenoweth, 2002).

In this definition cost and affordability are the main elements. Water should be available for the future generations.

This means that the *cost* factor should include the price of the treatment of polluted water so that sewage water does not pose any danger to contaminate other water supplies.

The term *"to all people"* implies that the cost should supply clean water to all sectors of society. *"At all times"* means that the cost should also be associated with overcoming the temporal variability of water supply by for instance building multi-storage facilities.

The term *affordability* is not so straightforward. It is suggested that affordability can be defined as the potential to pay the cost of sustainable clean water to all. The way to measure this potential is as a percent of the Gross National Product (GNP). But then the question rises what percentage of the GNP is reasonable to spend on water. In some regions of developing countries people spend less than 1 percent of their income on water, while in some other regions people spend more than 10 percent of their income on water of much lower quality.

Important is that the water poverty index focuses the attention on water quality. Clean water should be available. This is especially important for domestic use of water.

The economical approach of water scarcity is also very important because water scarcity is reflected in water prices. The water poverty index includes the economic capacities of countries to develop their water resources.

This implies that the countries that are struck the hardest by water poverty are the poor countries in arid and semi-arid regions in Africa as can be seen from Figure 2.2. These countries do not only have limited water supplies and a highly irregular precipitation, also their inhabitants cannot support the costs of sustainable clean water. These countries have a limited ability to pay for water resources development (Feitelson and Chenoweth, 2002).

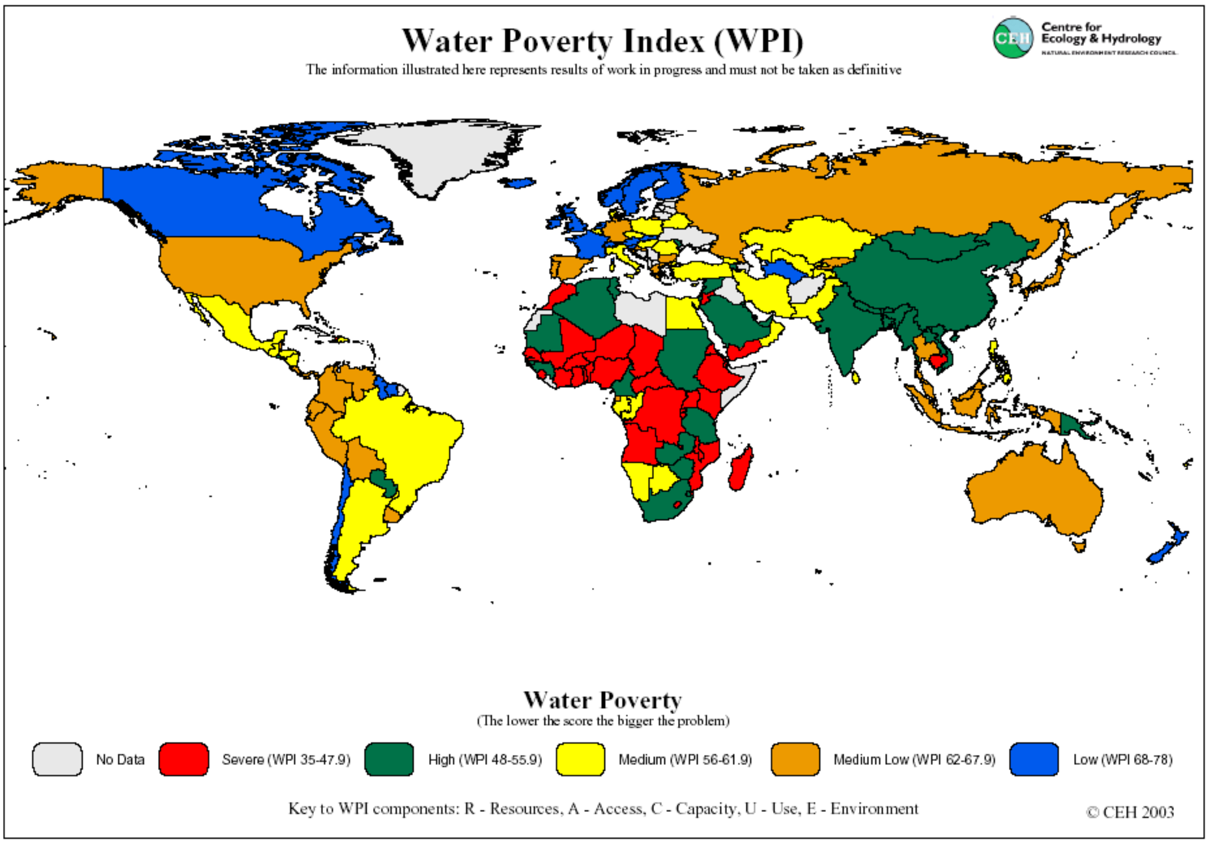

Figure 2.2: Water Poverty in the World (Source: Wallingford website, 2003)

2.3 Possible methods to address water poverty in rural areas

As described before, fresh water deficits will occur in many countries in the future. Especially during dry years, shortage will arise. But also intensification of human activities and population growth will contribute to the problem.

To abate water poverty in poor countries it is important that low priced and sustainable solutions are found. Only this way, water deficiency can be addressed in developing countries.

There are a number of promising interventions for improving water availability either for crop production or other uses in the dry parts of Sub-Saharan Africa. A few techniques have been proven successful but the majority remains unproven. One promising technology for rural semi-arid regions of Sub-Saharan Africa is rainwater harvesting. Rainwater can be harvested and stored in rock and roof catchments and in tanks. Other possibilities are groundwater storage in subsurface dams. These methods provide fairly cheap solutions for water of considerably high quality. Storage systems for the harvested rainwater offer the land user a tool for water stress control and dry spell mitigation. This could be a solution for the problems related to food security and recurrent famine. It is evident that the introduction of new technologies without the land user's participation, how novel they may be, is not successful. Although the potential for water harvesting has not been fully assessed, this potential is probably quite large in the Greater Horn of Africa where food security is a major concern (Ngigi, 2002).

2.4 Small groundwater retaining structures

For thousands of years, people have survived through dry seasons by scooping waterholes in sandy riverbeds in ecological zones ranging from semi-arid to desert. Even today many rural people use water-holes in sandy riverbeds as their only water source for domestic use, watering livestock and small-scale irrigation. Coarse sand and gravel in sand-rivers can trap and store water in 50 per cent of their volume. Up to 35 per cent of this water can be extracted. In other words, 350 litres of water can be extracted per cubic metre of sand (Nissen-Petersen, 1997). When the depth of the water in the sand deposits gets deeper as the dry season continues, the villagers find it often impossible to dig any further and travel long distances to fetch water. Damming the water during the rainy season and using it in the dry period is an obvious solution. Technically two ways of dam construction are possible, the conventional surface water dam and the groundwater-retaining dam. Though the water holding capacity of surface dams is high, its construction costs are high, water easily evaporates and the damage in case of failure is enormous (Shenkut, 2001).

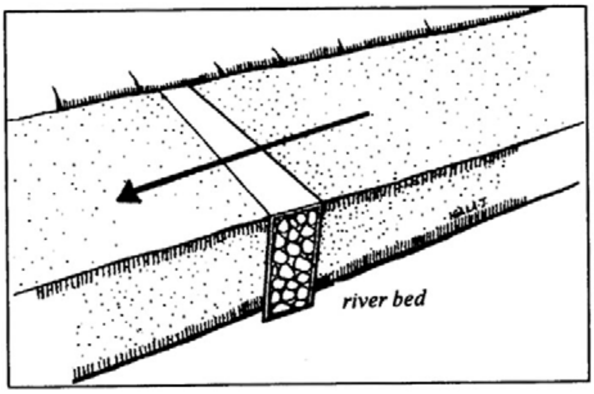

Figure 2.3: Sub-surface dam (Source: SASOL, Maji Na Ufansi, 1999)

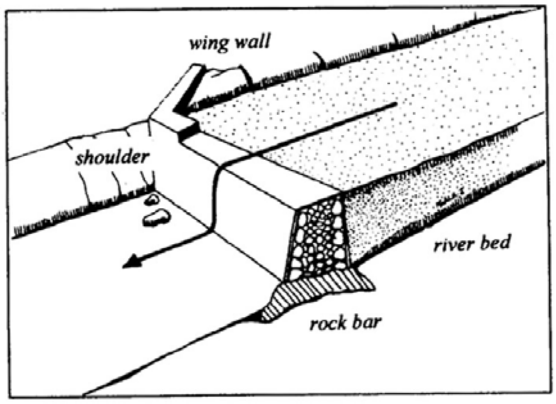

Figure 2.4: Sand-storage dam (Source: SASOL, Maji Na Ufansi, 1999)

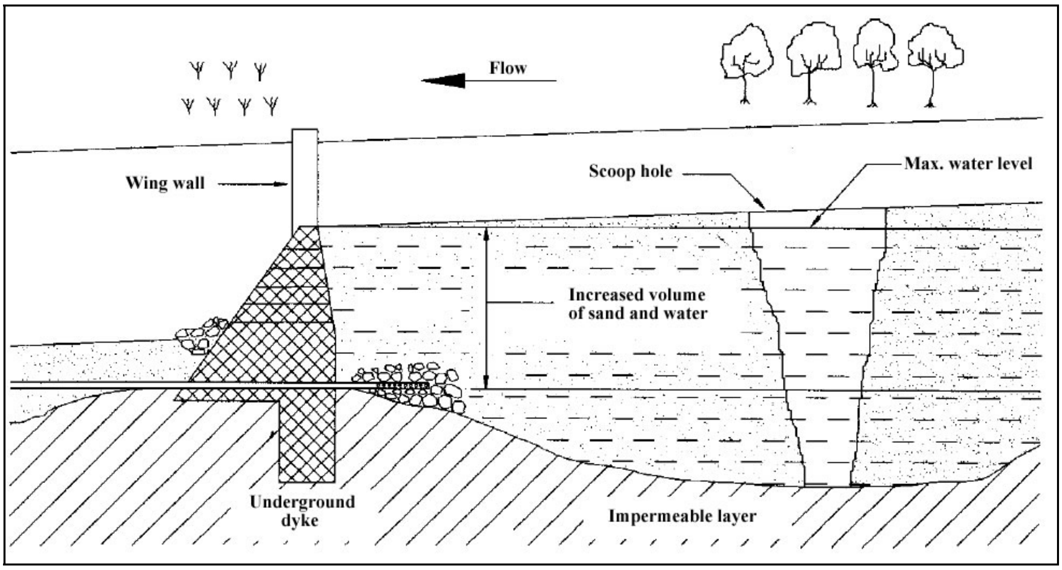

Figure 2.5: Cross-section of a sand-storage dam (Source: Nissen-Petersen, 1997)

In general there are two kinds of small groundwater retaining structures, sub-surface dams and sand-storage dams.

Sub-surface dams (Figure 2.3) are the cheapest and the easiest to construct. These dams can be a clay or masonry barrier installed below the surface of a river, and rests on a non-porous or solid bedrock across the riverbed. Sub-surface dams are built in wide seasonal rivers with a gentle slope, where the river has enough volume to store water (Nissen-Petersen, 1982). The term can also refer to an impervious underground barrier in a low-lying area that prevents the lateral flow of groundwater and maintains or raises the water table (SASOL and Maji Na Ufansi, 1999). In contrast with a subsurface dam, *a sand-storage dam* (Figure 2.4, Figure 2.5) is made as a concrete or masonry barrier, constructed above the ground level of an ephemeral river (SASOL and Maji Na Ufansi, 1999). The sand-storage dams are built upon an impermeable rock layer to avoid seepage. The upstream reservoir of a mature sand-storage dam is silted up with coarse sand, resulting in an artificial aquifer, which is replenished each year by the runoff in the valley (Shenkut, 2001). Sand-storage dams are appropriate for steeper, narrow rivers.

These dam types are easy to design and construct because surplus runoff just passes over the top of the dam without damaging it. As part of the dam structure the reservoir is silted up by coarse sand. Thus silting with coarse sand is not a problem but a gain. Water is stored between the coarse sand, so evaporation is eliminated to a minimum. Another advantage is that mosquitoes and bilharzia parasites cannot breed in a subsurface reservoir. Therefore there will be no increase in malaria and bilharzia. Because people, livestock and wild animals cannot see the water it is also easier to prevent pollution. By drawing water from the subsurface reservoir through a shallow well it is not difficult to maintain a clean and reliable water source (Nissen-Petersen, 1982). If the construction of the dams is not connected with the construction of shallow wells, the communities will keep on digging scoop holes, this implies a higher risk for pollution.

The construction of small water retaining structures in rivers has a major impact on the communities, on agriculture and on the environment. The impact on health and pollution prevention is already mentioned above. Construction of sand-storage dams impedes downstream flow and is believed to recharge the riverbanks, from which water returns as the dry season proceeds. This has the effect of maintaining a steady water level for a longer period. As a consequence of the higher infiltration rate scoop holes do not have to be so profound and because water is available for a longer period women and children do not have to spend so much time searching for water (SASOL, 2000). Because there is more water and time available, people can start growing irrigated cash crops in plots close to the river, which can provide an extra income and which can lead to improvements in nutrition. Raising the bed level of the river by installing dams reduces the erosion of the riverbanks and of the watercourses leading into the river (SASOL and Maji Na Ufansi, 1999). Also, raising the water table stimulates vegetation growth along the riverbanks and improves the stability of the banks (SASOL, 2000).

The dams are mostly constructed in groups of 3 or 4 dams. Experience from the Utooni project at Kola in Machakos district, Kenya, indicates that sand dams do not reduce the

flow of water downstream. It is believed that there is even more water available downstream than in the past as the overall flow is slowed. Where there is general rainfall, the dams should be recharged by runoff from adjacent areas as well as by water coming down the river over upstream dams (SASOL and Maji Na Ufansi, 1999).
Sand-storage dams can be classified as runoff based storage constructions for rainwater harvesting. These differ from in situ rainwater harvesting technologies as contouring and other cultural practices. The main difference is that the storage techniques can provide water in dry spells while in situ techniques give the farmers no control over timing as runoff can only be harvested when it rains (Ngigi, 2002). A mixture of all appropriate techniques should be implemented in the battle for water and dry spell mitigation. Storage of water is a solution. Nevertheless in situ water harvesting should be promoted as well.

2.5 Background of the study

2.5.1 REAL-Project

The study is embedded in the REAL-project (Rehydrating the Earth in Arid Lands). The REAL-project is sponsored by the European Commission in the fifth framework program, International Cooperation with Developing Countries (INCO-DEV). Participants of the project are the Delft University of Technology, the Netherlands; the International Water and Sanitation Centre (IRC), the Netherlands; Katholieke Universiteit Leuven, Belgium; SASOL, Kenya; University of Nairobi, Kenya; University of Dar Es Salaam, Tanzania; Westerfeld Conservation Trust, Kenya/the Netherlands and Protos, Belgium.
The REAL-project focuses on the semi-arid and arid areas (ASALs) in Kenya and Tanzania. The setting of demanding natural circumstances, growing pressure on natural resources and difficult economic conditions, including rural-urban migration, requires improving the rural and semi-urban local conditions. In Eastern Kenya, in the Kitui and Tsavo regions, several successful groundwater structures were built over the last 6 years. The project investigates the different parameters for success of the Kenyan systems with respect to technological possibilities sustained by social, economic, organisational and managerial factors of the local communities and the government. The goal of this project is the production of a manual for design, operation and maintenance of small water retaining

structures, with focus on local management and community participation (European Commission, 2003).

The general objective of the research project is to clarify the relations between local practices and theoretical approaches, by focusing on the design, management and performance of small groundwater retaining structures on a communal level linking both the individual and the community as theory and practice, resulting in guidelines for participatory design of small water retaining structures in semi-arid regions world wide (INCO-DEV REAL, 2001).

Part of the research of the third work package of the REAL-project is performed by the Katholieke Universiteit Leuven (K.U.Leuven). The research integrates land evaluation aspects into a design approach and a manual. Definition and implementation of a land evaluation survey for designing water-harvesting systems, including land use, soil, topography and hydrological issues in the areas is a second goal. The existing approach is tested and improved by extending the activities to other parts of the Kitui District, with different soils and topography and in different social structures. The K.U.Leuven has divided the project into two main parts, which afterwards will be merged into a final deliverable. One part makes an assessment of the sustainability of small scale irrigation activities, supplied by small groundwater retaining structures, the other focuses on the water harvest capacities of those structures as determined by the regional water balance.

2.5.2 The SASOL foundation

The local partner in the REAL-project is the non-governmental organisation (NGO) SASOL (Sahelian Solutions). The organisation was founded in 1990 and started its operations in the Kitui District in 1995.

When founded, SASOL’s main goal was to improve water supplies for schools through shallow wells and rainwater storage tanks. Nowadays the main activities of SASOL are building sand-storage dams and shallow wells. SASOL’s objective is to build sand-storage dams in all rivers in the central division of Kitui District, covering an area of approximately 200 km². Recently projects in the south of the Kitui district were started.

The community is the starting point of every project. SASOL’s goal is to create a network of water points using shallow wells and sand-storage dams supplemented by roof catchment tanks, rock catchments and other sources, so that no family has to walk more than 2 km to reach a secured supply. SASOL's bottom-up development is preferred due to the failure of the conventional top-down approach in which outsiders (NGO, local, national or international governments) make decisions about how and what should be done, with little consultation of the local people affected. Materials purchased are delivered directly to the community and the masons that SASOL employs are housed by the communities. Maximum use is made of local resources. Stones, sand, ballast, water for mixing concrete and labour are all provided by the community. SASOL's task is to provide technical assistance in the form of trained masons and to seek financial help for cement and reinforcement (SASOL and Maji Na Ufansi, 1999).

Sand-storage dams are not new to Kenya, but few had been installed in the Kitui District before the SASOL project. The earliest were constructed during the colonial period, and most of these are still in existence. An example is the dam at Mukongwe on the Muewe River, which was constructed in 1958. A lot of sand-storage dams were also constructed in the Machakos District. Since SASOL started operating in the Kitui District in 1995, over 320 new sand-storage dams were constructed in the central division. Globally this is the highest concentration of sand dams constructed (SASOL and Maji Na Ufansi, 1999).

3 Problem statement and Objectives

3.1 General problem statement

Sand-storage dams work through obstruction of the natural ground water flow and thus they detain water below the ground surface. The capacity and performance of the dams is dependant on several parameters. These parameters are the location of the dam (narrow steep river, wide river, different types of land use and soil parameters of the contributing area,..), the construction parameters of the dam (height of the spillway, materials,..), the existence of other dams in the ephemeral river, the porosity of the sand in the reservoir and the available budget of the community.

3.2 Objectives

The water balance of the Ngunga-catchment will be simulated with the AVSWAT-model. To examine the effect of land use on water availability, different scenarios will be set up and their output will be compared. The main hydrological processes of the semi-arid watershed will be examined.

Also a local water balance for the sandy reservoir behind the sand-storage dam will be set up to make an estimation of the quantity of the retained water by the dam and to obtain information on the dynamics of the water storage.

3.3 Hypothesis

The software model AVSWAT is a suitable hydrological model to simulate the water balance of watersheds in arid and semi-arid regions (Conan et al., 2003). Limited data inputs will not compromise the potential of AVSWAT.

3.4 Field work

Data collection in the field is not obvious because of the extent of the area and the difficult transportation in this region. The area is rural and almost no research has been performed in the area. Because of the shortage of experimental data, a quantitative calibration cannot be performed. The research will therefore be methodological and qualitative.

4 Materials and methods

4.1 Study area

(authors: Dirk Neesen and Sam Puttemans)

The study was performed in Kisayani, a village in the south of the Kitui district, Kenya.

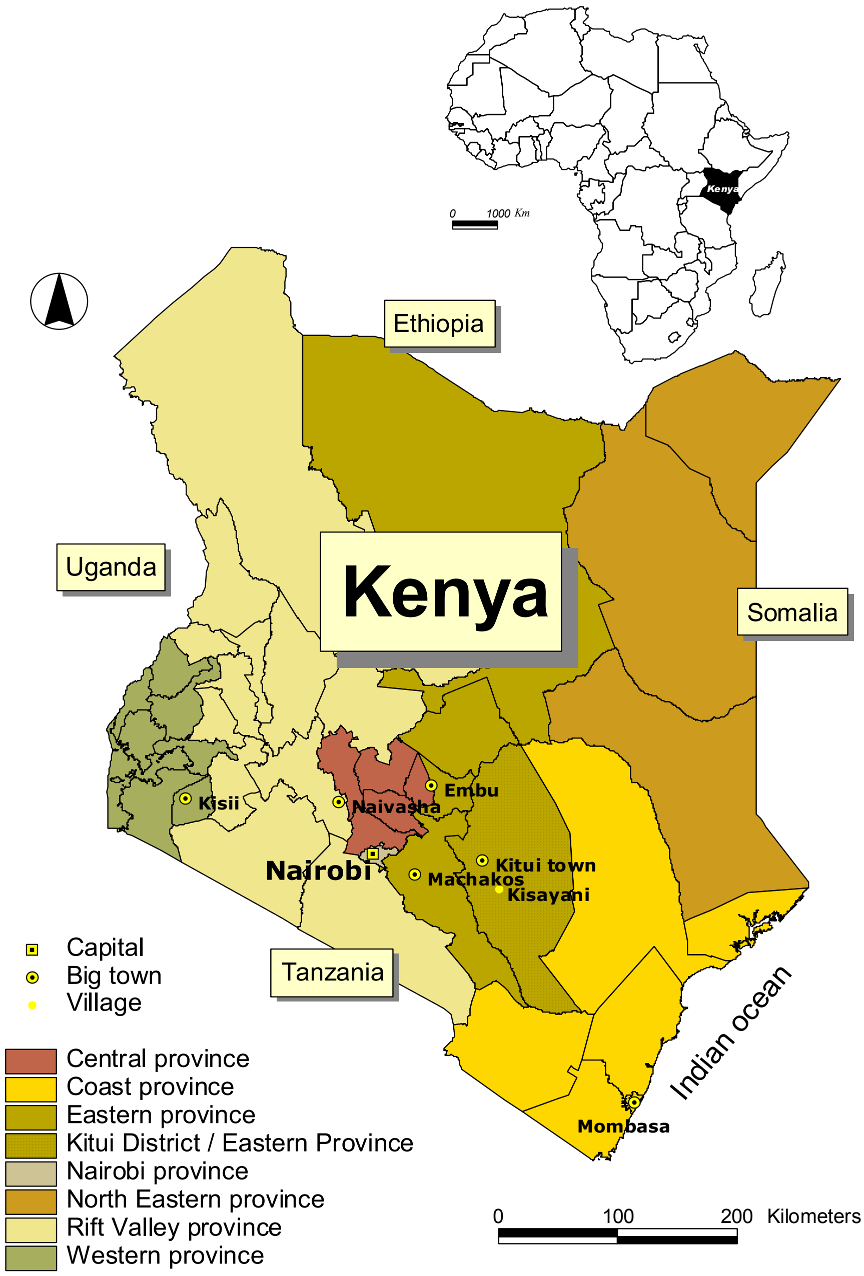

Figure 4.1: Administrative boundaries of Kenya (Source: FAO-Africover, 2003; Maidment D.R. and Reed S. M., 1996)

4.1.1 Kenya

Kenya, an East-African country, is located between Latitudes 4°21'N and 4°28'S and between Longitudes 33°50' and 41°45'E and has a surface area of approximately 582000 km². The total population in 2002 was 31.3 million with an annual population growth of 1.8% (The World Bank, 2002).
The dominant characteristic of rainfall in East-Africa is its seasonality. This is a result of the north-south movement of the inter-tropical convergence zone (ITCZ) and its associated rains. The large inter-annual variation in the rains is caused by large-scale phenomena related to the El Niño Southern Oscillation (ENSO) (McWilliam and Packer, 1999).
The typical rainfall anomaly associated with ENSO is a dipole rainfall pattern with eastern Africa being in phase with the warm ENSO episodes (McCarthy *et al.*, 2001).
Kenya is divided into 7 agro-climatic zones based on a moisture index derived from annual rainfall expressed as a percentage of potential evapotranspiration (Table 4.1). Areas with an index greater than 50% have high potential for cropping, and are designated zones I, II, and III. These zones account for 12% of Kenya's land area. The semi-humid to arid regions (zones IV,V,VI, and VII) have indexes of less than 50% and a mean annual rainfall of less than 1100 mm. Semi-arid to very arid zones are generally referred to as the Kenyan rangelands and account for 88% of the land area.

Agro-Climatic zone	Classification	Moisture index (%)	Annual Rainfall (mm)	Fraction of land area (%)
I	Humid	>80	1100-2700	
II	Sub-humid	65-80	1000-1600	12
III	Semi-humid	50-65	800-1400	
IV	Semi-humid to Semi-arid	40-50	600-1100	5
V	Semi-arid	25-40	450-900	15
VI	Arid	15-25	300-550	22
VII	Very arid	<15	15-350	46

Table 4.1: Agro climatic zones in Kenya with rainfall and fraction of land (Source: Orodho, 2003)

The seven agro-climatic zones are each sub-divided according to mean annual temperature to identify areas suitable for growing each of Kenya`s major food and cash crops. Most of the high potential land areas are located above 1200 m altitude and have mean annual

temperatures below 18° C, while 90% of the semi-arid and arid zones (ASAL's) is below 1200 m and has mean annual temperatures ranging from 22° C to 40° C (Orodho, 2003).
The most unstable rainfall occurs in the semi-arid and arid zones of the lowlands (Nissen-Petersen, 1982). Rainfall is highly erratic and generally comes with intensive storms, with high intensity and spatial and temporal variability. The result is a high risk for annual droughts and intra seasonal dry spells. The potential evapotranspiration is high. Cumulative evapotranspiration reaches 600-900 mm over the growing period. Erratic rainfall and high evapotranspiration explains the persistence of water scarcity coupled with low crop yields. Water scarcity could also be attributed to poor rainfall partitioning leading to large proportions of non-productive water flows, not available for crop production. This results in severe crop yield reductions caused by dry spells occurring 1 to 2 years out of 5, while total crop failure caused by annual droughts occurs once in every 10 years. This means that poor distribution of rainfall leads to crop failure instead of absolute water scarcity due to low cumulative annual rainfall. Most dry spells occur during critical crop growth stages, which explains the frequent crop failure and low yields. Approximately 85% of the Kenya people is making their living from rain fed agriculture and depend to a large extent on smallholder, subsistence agriculture. Hence, the need for dry spell mitigation by improving water productivity in Sub-Saharan Africa is high (Ngigi, 2002).
Other characteristics of these areas includes soils that are fragile and prone to dramatic decline in productivity, erosion hazard due to poor natural and human-modified vegetation cover, and very low land value with low production per unit area (Hatibu *et al*., 2002).
Kenya, as an African country with 88% of its land being arid and semi-arid (see previously in this paragraph), deals with severe water poverty. The annual per capita renewable water resources of Kenya are 672 m³. Belgium has annual per capita renewable water recourses of 1181 m³ (WRI, 1998). The main difference is that Kenya has a low gross national product and limited financial borrowing capacities. The ability to pay for water resources development is low. The rainfall is also very unevenly distributed over the country. Water availability thus varies strongly within the country. It has to be remarked that the annual per capita internal water resources within each country gives a very crude indication of the challenge faced by the different countries. However, it does not give any indication of water quality problems. Keeping in mind the relatively high population growth and the increasing pollution, the long-term cost per capita will only increase (Feitelson and

Chenoweth, 2002). Kenya has made significant progress in its water development over past few years but sustainable solutions have to be maintained and extended.

4.1.2 Kitui

Kenya is divided into eight provinces and each province is divided in districts. The Kitui district is situated in the Eastern province (Figure 4.1). The district extends for roughly 200 km from north to south and 120 km from east to west. It covers an area of approximately 20.000 km² including more or less 6.400 km² occupied by the uninhabited Tsavo National Park.

The Kitui district is populated by the agro-pastoral Akamba tribe. The district has a population of approximately 515.000 people (1999). The total annual population growth is 3.8% (1989) (Muticon).

Water remains the most essential development commodity in the Kitui District. The major sources of water in the District are ephemeral rivers. The Athi river, the southwestern boundary between Kitui and Machakos, is the only perennial river (Muticon).

The district is classified as one of the arid and semi-arid lands of Kenya. Lack of water is a perennial story in most parts of the district.

The low productive agriculture requires seasonal relief food from donor agencies. To avail food to the majority of the population, there is need to improve water supply in the district so that production can be increased (Muticon).

4.1.3 Kisayani

Each district of Kenya is divided into divisions, which are subdivided in locations. Kisayani is a village in the Kebwea location of the Mutomo Division in the south of the District. The village is situated in the catchment area of the Ngunga river. Kisayani is located in a rural area and is quite isolated. Because of the extent of the area and the difficult transportation in this region, collection of data was difficult and time consuming.

Extending its activities to the southern part of the District, the NGO (non governmental organisation) SASOL (Sahelian Solutions) has started a research project in the Kebwea location.

At the time of our field campaign the construction of two sand-storage dams was already finished. The Kamunyuni Dam, situated most upstream of the Ngunga river, was finished

in April 2003. The other dam is the Ngunga Kwoko and is situated 6 km downstream of the first one. In between the two already mentioned dams and approximately 1 km downstream from the Kamunyuni dam, SASOL is planning to build a third dam. This dam will be called "the proposed dam" in this thesis document.
A lot of natural barriers are present in the riverbed upstream from the Kamunyuni dam. According to the farmers these barriers can keep up enough water to irrigate the whole year through.

4.2 Software AVSWAT and MIKE BASIN

In this paragraph the model 'Soil and Water Assessment Tool' (SWAT), used in this thesis will be introduced and compared with the MIKE BASIN software, an alternative river basin modelling tool. The advantages, disadvantages and possibilities of both models will be considered.

4.2.1 SWAT

SWAT is a river basin or watershed scale model, developed by Dr. Jeff Arnold of the USDA Agricultural Research Service (ARS) (Neitsch *et al.*, 2001 a).
SWAT was developed to predict the impact of land management practices on water quantity and quality and on the transport of sediment and agricultural chemicals. The model is created to simulate large complex watersheds with varying soils, land use and management conditions over long periods of time.

4.2.1.1 Software

The SWAT software can be downloaded as freeware. Since SWAT was developed in the early 90s, it has undergone continuous reviews and expansion of capabilities. In this study, the latest version, SWAT2000 is used. This program uses a 'geo-graphical' user interface, which is a pre-processor of spatial input data for the model SWAT. The ArcView SWAT2000 (AVSWAT2000) extension evolved from AVSWAT, an ArcView extension developed for an earlier version of SWAT (Di Luzio *et al.*, 2001). The graphical user interface allows the user to calculate some input parameters and to create and visualise input files for the model based on topographic, soil and land use maps of the catchment.

In AVSWAT2000, the creation of input data (pre-processing) and the analysis of output data (post-processing) are done in the ArcView GIS 3.2a (Geographical Information System) environment. Processing is done by SWAT2000, a DOS program. The advantage of AVSWAT2000 over SWAT2000 is that it is more user friendly and allows the user to visualise geographic input and output files.

The SWAT/ArcView interface requires ArcView 3.1 of 3.2 and Spatial Analyst 1.1 or higher. These software packages are developed by ESRI and are no freeware. As a guideline, ArcView GIS 3.3 costs €1000 ($1195) and Spatial Analyst 2 costs €1850 ($2495) (DHI, 2003 b; ESRI website, 2004).

4.2.1.2 General model description of SWAT

4.2.1.2.1 Concept

The SWAT-model is physically based. In stead of incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information of weather, soil properties, land use, topography, vegetation and land management practices as input. More in detail, this model requires two types of information: ArcView map themes (Digital Elevation Model, Land Cover/Land Use and Soil) and information in the form of tables (dBase) or text files. These files contain information on weather characteristics, soil properties, land use properties and locations of weather stations. The physically based processes associated with water movement, sediment movement, crop growth and nutrient cycling are directly modelled by SWAT using the input data. The benefits of this approach are that watersheds with no monitoring data can be modelled. This means that no time series of the period of simulation are required. SWAT can also quantify the relative impact of alternative input data (land management, climate, vegetation,…). The model can be used to study specialized processes such as bacteria transport, but to run the program, minimum data available are sufficient. These data like precipitation, minimum-maximum temperature, humidity, wind speed, solar radiation, relative humidity, land cover and soil maps are (in most cases) available from government agencies.

SWAT allows the user to study long-term impacts. A disadvantage of SWAT is that it cannot simulate single events in time because it is a continuous model. So no “snap shots” in time can be produced (Neitsch *et al.*, 2001 a).

4.2.1.2.2 Watershed configuration

The first step in setting up a watershed simulation is to split the watershed into different subunits. The first level of subdivision is the sub-basin. Sub-basins possess a geographic position in the watershed and are spatially related to one another. Input information for each sub-basin is grouped or organised into the different categories, namely: weather or climate, hydrological response units (HRUs), ponds/reservoirs, groundwater and the reach or main channel draining the sub-basin. An HRU is a collection of grid cells of a sub-basin, possessing a unique combination of land use/management/soil attributes. The inclusion of HRUs allows SWAT to account for the diversity of land use and soils within the boundaries of the sub-basins. HRUs also allow the user to find an equilibrium between the quality of the simulation and the time efficiency. This can be done by taking only the dominant HRUs into consideration, or by using a high threshold level for the HRU.

In contrary with sub-basins, who are spatially related to each other, there is no interaction between HRUs in one sub-basin. The loadings (runoff with sediment, nutrients, chemicals, etc. transported by the runoff) of each HRU in the sub-basin are calculated separately and summed together to determine total loadings from the sub-basin. If interaction between land use areas is important, they should be defined as sub-basins (Neitsch *et al.*, 2001 b).

To simulate hydrological processes, SWAT is using the water balance. The simulation of the water balance can be separated into two major items. The first item is the land phase of the hydrological cycle. The land phase controls the amounts of water, sediment, nutrient and pesticide loading to the main channel of each sub-basin. The second item is the water or routing phase of the hydrological cycle. This phase can be defined as the movement of water, sediment etc. through the channel network of the watershed to the outlet of the watershed. (Neitsch *et al.*, 2001 a).

4.2.1.2.3 Land phase of the hydrological cycle

The hydrological cycle is based upon the water balance equation:

$$SW_t = SW_0 + \sum_{i}^{t} (R_i - Q_{surf,i} - E_{a,i} - w_{seep,i} - Q_{gw,i}) \quad \textbf{(4.1)}$$

With: SW_t: the final soil water content (mm H_2O)

SW_0: the initial water content on day i (mm H2O)

T: the time (days)

R_i: the amount of precipitation on day i (mm)

$Q_{surf,i}$: the amount of surface runoff on day i (mm)

$E_{a,i}$: the amount of evapotranspiration on day i (mm)

$W_{seep,i}$: the amount of percolation on day i (mm)

$Q_{gw,i}$: the amount of base flow on day i (mm)

The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. As noted before, runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance.

Different inputs and processes are required to model the land phase of the hydrological cycle. To calculate the surface runoff Q_{surf}, SWAT offers two possibilities: the SCS curve number method and the Green and Ampt infiltration method. To calculate the actual evaporation the potential evapotranspiration is first calculated. The SWAT-model offers three options for estimating potential evapotranspiration: the Penman-Monteith method, the Priestley-Taylor method and the Hargreaves method. These three models require different input. Based on the potential evapotranspiration, the actual evapotranspiration is calculated. SWAT first evaporates any rainfall intercepted by the plant canopy. Next, SWAT calculates the maximum amount of transpiration and the maximum amount of soil evaporation. The maximum amount of soil evaporation is reduced during periods of high plant water use. This reduced soil evaporation is called the maximum soil evaporation adjusted for plant water use on a given day. The actual amount of evaporation from the soil is then calculated. When an evaporation demand for soil water exists, SWAT must first partition the evaporative demand between the different layers. To do this, the depth distribution is calculated to determine the maximum amount of water allowed to be evaporated at a certain depth. The coefficients of the used equation were selected so that

50% of the evaporative demand is extracted from the top 10 mm of soil and 95% of the evaporative demand is extracted from the top 100 mm of soil (Neitsch *et al.*, 2001 a).

Other simulated processes in the land phase are climate processes, infiltration, redistribution, erosion (sediments), nutrient and pesticide transport and transformation, plant growth and land cover, management practices etc. (Neitsch *et al.*, 2001 a).

4.2.1.2.4 Routing phase in the hydrologic cycle

Once SWAT determines the loadings of water, sediments, nutrients and pesticides to the main channel, the loadings are routed through the stream network and reservoirs of the watershed.

Routing in the main channel can be divided into 4 components: water, sediment, nutrients and chemicals. Because this study focuses on water quantity, only the water component will be discussed here. As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss of water is through utilization for agricultural or human purposes. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Flow is routed through the channel using the *variable storage routing method* or the *Muskingum river routing system*.

Routing through the reservoirs of the watershed is determined by calculating the water balance for the defined time steps for the reservoirs.

In the *variable storage routing method*, storage routing is based on the continuity equation for a given reach segment:

$$V_{in} - V_{out} = \Delta V_{stored} \quad \textbf{(4.2)}$$

Where V_{in} is the volume of inflow during the time step (m^3 H_2O), V_{out} is the volume of outflow during the time step (m^3 H_2O), and V_{stored} is the change in volume of storage during the time step (m^3 H_2O).

With a storage coefficient, dependent on the length of the time step and the travel time, the outgoing volume at the end of the time step can be calculated with the average incoming volume during the time step and the storage volume at the beginning of the time step.

The *Muskingum method* is a hydrologic routing method that is based upon a variable discharge-storage relationship. This method models the storage volume of flooding in a river channel by a combination of wedge and prism storage (see Figure 4.2). When a flood wave advances into a reach segment, inflow exceeds outflow, producing a wedge of storage. During the recession, outflow exceeds inflow in the reach segment, resulting in a negative wedge. In addition to wedge storage, there is a prism of storage that is formed by a volume of constant cross-section along the length of the prismatic channel. The volume of the prism storage can be expressed as K.Q. Where K is the ratio of storage to discharge and has the dimension of time and Q is the discharge. In a similar manner, the volume of wedge storage can be expressed as K.X. (I-Q), where X is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach; Q is the discharge rate and I the inflow rate. (Neitsch *et al*, 2001 a; Mays, 2001).

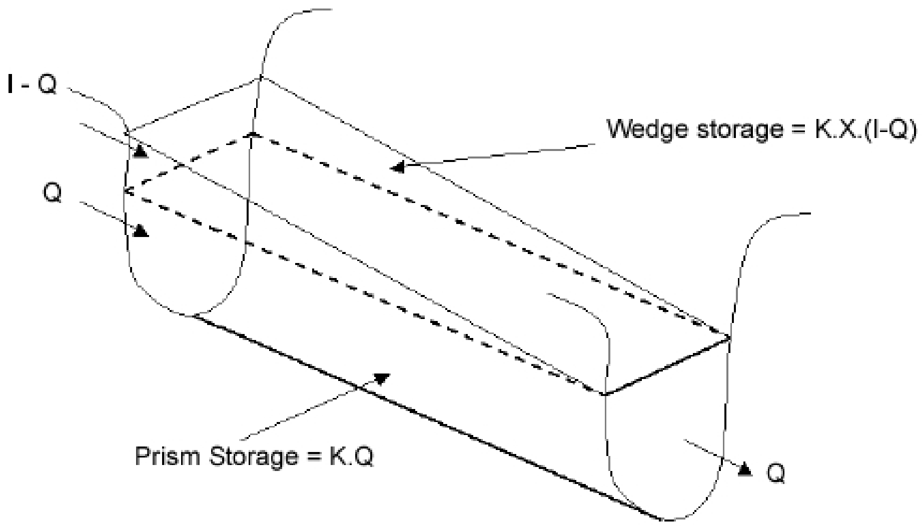

Figure 4.2: Prism and wedge storages in a channel reach

4.2.2 MIKE BASIN

MIKE BASIN is a modelling tool for river basin planning and management developed by the Danish Hydraulic Institute (DHI). It was developed to make an attempt to identify the best possible utilization of the available water resources given certain soil, land, agricultural engineering and social constraints. The planning for future water developments within a basin requires that conclusions originating from the study of particular aspects are gathered and brought together in a framework capable of undertaking an integrated analysis.

The model description is based on literature, not on experience. Therefore it has to be noticed that the comparison between AVSWAT and MIKE BASIN may be incomplete.

For instance, to compare the computational speed of both programs in an adequate way, simulations with comparable datasets have to be evaluated.
For a more detailed description is referred to MIKE BASIN 2003 Manual (DHI, 2003 a), the DHI website (DHI, 2004) and Vanham (2003).

4.2.2.1 Software

MIKE BASIN consists of four modules: a water quantity module, a groundwater module, a water quality module and a rainfall-runoff module. The water quantity module and the groundwater module are included in the basic MIKE BASIN version, the quality and rainfall-runoff modules have to be purchased separately. As a guideline, the actual price of the basic MIKE BASIN module is 4000 € and the additional water quality and rainfall-runoff module are respectively 3000 and 2000 €. A university licence for which the use is strictly limited to educational and research proposes, is 50% of the actual price (DHI, 2003 b).
MIKE BASIN uses a graphical user's interface, which links the MIKE BASIN computational engine with ArcView GIS. ArcView 3.2a or 3.3 is required. Spatial Analyst is not necessary to run the program. However, if grid files are uses as for the creation of the river network, Spatial Analyst is required as a raster processor. Spatial analyst is also required for using the catchment delineation functionality.

4.2.2.2 Model description

4.2.2.2.1 Concept

In general terms, MIKE BASIN is a mathematical representation of the river basin, encompassing the configuration of the main rivers and their side streams. The mathematical concept of MIKE BASIN is to find stationary solutions for each time step. MIKE BASIN can be used to find typical "values" for water quantity and quality in a slowly changing system. MIKE BASIN's advantages are its moderate data requirement and the computational speed, allowing extensive explorations of many scenarios. However these approximations are stationary, for dynamic problems other software should be used.
MIKE BASIN is very flexible in that it can use time series data with any time interval, or even with changing intervals. MIKE BASIN has also a very useful feature called "data-

cycling”. With this feature it is possible to run MIKE BASIN for simulation periods for which some data are lacking, just as long as equivalent data are available for earlier or later periods. In these situations, data-cycling will find the closest possible equivalent time period in the data and use that period instead (DHI, 2003 a). Although data-cycling is very useful, it is still limited because equivalent data must be available. By comparison, lacking data in SWAT will be generated by means of the weather parameters in the weather generation file.

4.2.2.2.2 Model schematisation

Before starting the model development it is recommended to define the appropriate schematisation of the river basin and the characteristics to be included. The evaluation of water resources in large river basins requires the incorporation of numerous individual demands and features. For example, a large number of small irrigation users are typically scattered in an area. To incorporate all these entities as individual schemes would in most cases require enormous effort. It is therefore important in the model development to define a flexible schematisation reflecting the overall natural conditions and based on the objectives of the modelling, the availability of information and the spatial resolution of output data required. The schematisations should represent the activities at the level of detail that is desired (Vanham, 2003).

Different types of spatial schematisation may be introduced:

- Lumping of smaller rivers into a single branch upstream of an intake point;
- Lumping of small irrigation areas into a single scheme with one intake point;
- Lumping town supply and industrial water supply into one entity.

4.2.2.2.3 Components of the model

Following themes can be inserted in the model:

- Network
- Nodes
- Branches
- Runoff
- Reservoir
- Water supply

- Irrigation
- Hydropower

4.2.2.2.4 Network, nodes and branches

The rivers and their main tributaries of the river basin are represented by a network consisting of branches and nodes. The branches represent individual stream sections while the nodes represent confluences, diversion, locations where certain water activities (reservoir, river diversion, intake/outlet for different water users as irrigations schemes, etc.) take place or important locations where model results are required.

The river network for a MIKE BASIN model can be generated from catchment delineation (another MIKE INFO tool), using a Digital Elevation Model (DEM). To perform this delineation, ArcView Spatial Analyst is required. The river can also be manually digitized in the ArcView environment. Information of the river basin (such as shape files, grids or tiffs) can be loaded in the model as a basis for the creation of the river network. The river network is always digitized in downstream direction. When this is done the different nodes are digitized after which automatically links (branches) are established between the individual nodes along the river. River flow is computed at each node.

The flow in a node at the downstream end of a particular branch will be a function of:

- The flow from the nearest upstream node;
- The estimated inflow from a sub-catchment belonging to the upstream branch;
- The return flow and /or extraction of water tanking place at the river node.

On the river network, two basic types of nodes are available, so-called catchment nodes and simple nodes. *Catchment nodes* have an upstream sub-catchment area attached (representing the outlet of a sub-catchment) for which runoff characteristics have to be specified. *Simple nodes* are not attached to a sub-catchment. Within these two node types, there is a subdivision in three different forms: the normal form, the diversion node form (a river branch entering the node is split into two branches) and the off take node (for water supplies, irrigation or hydropower). A simple node can be of the three forms, while a catchment node cannot have the diversion node form (Vanham, 2003; DHI, 2003 a). The different types of nodes are represented in Figure 4.3:.

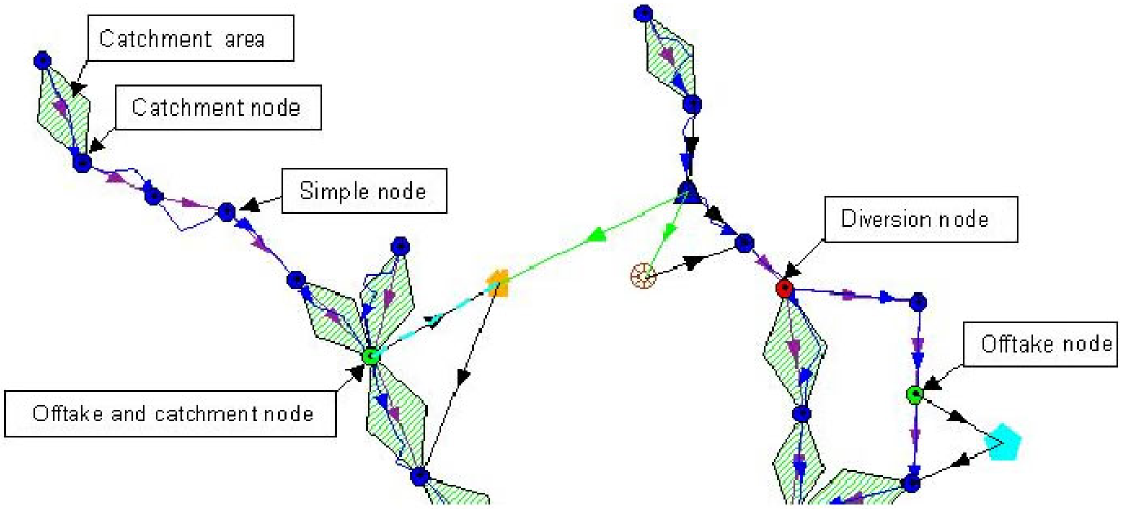

Figure 4.3: The different types of nodes (DHI, 2003 a)

4.2.2.2.5 Runoff, reservoirs, water supply, irrigation and hydropower

All the information regarding the location of water users, reservoirs and intakes and outlets of return flow are defined manually by screen editing based upon loaded GIS information.

For each sub-catchment the runoff characteristics have to be specified. These are the catchment area and the runoff time series. The time series can be calculated with the extra rainfall-runoff module in MIKE BASIN or with other software. In comparison the calculation procedure of the runoff time series is incorporated in AVSWAT. AVSWAT provides two methods for estimating surface runoff: the SCS curve number procedure and the Green & Ampt infiltration method.

Also multi-purpose multiple reservoir systems can be accommodated in the MIKE BASIN model. The different input data to be introduced in the model for a reservoir are: initial water level, operational rule curves, stage-area-volume curve, time series of rainfall in the reservoir, and time series of evaporation from the reservoir.

The activity 'water supply' means that there is a simple relationship between the variation in water extraction (from the river and ground water) and return discharge. The same definition stands for the activity defined as irrigation. Water supply and irrigation have to be assigned to the river nodes as time series. These time series cannot be calculated within MIKE BASIN.

Hydropower generation in relation to reservoir operation can be simulated in MIKE BASIN. In this way, the influence of water utilization upstream of a power plant can be estimated on the power generation (Vanham, 2003).

4.2.3 General comparison between AVSWAT and MIKE BASIN

Although both described modelling tools use a graphical user interface which links the tools with ArcView GIS, there are some basic differences.

First there is a difference in availability of the two models. AVSWAT is freeware and can be downloaded as an integrated package which includes all offered features. In contrast, MIKE BASIN is commercial software and consists out of 4 modules: the water quantity, water quality, groundwater and rainfall-runoff module. The basic MIKE BASIN version includes only the water quantity and the groundwater module. This implies for instance, that when working with the basic MIKE BASIN version, runoff time-series have to be calculated with another programme or that the extra rainfall-runoff module has to be purchased. In comparison, the AVSWAT software includes runoff calculations and works with the SCS Curve Number procedure or the Green and Ampt infiltration procedure. Also the water quality module is not included in the basic MIKE BASIN version. Moreover the water quality simulation in AVSWAT is more extended than in MIKE BASIN. While the latter can simulate ammonia, nitrate, dissolved oxygen, total phosphorus, total nitrogen and biological and chemical oxygen demand, AVSWAT can also simulate sediment and pesticide transport and transformation. MIKE BASIN does have the extra feature that it can simulate hydropower generation. This can be important to assess the economical consequences of water use.

When analysing the purchasing costs, also the required GIS software must be accounted for. Both programs require ArcView, AVSWAT also requires Spatial Analyst. Spatial Analyst is not essential for MIKE BASIN, however if grid files (for instance a Digital Elevation Model) are loaded for the creation of the river network, Spatial Analyst is required as a raster processor. Spatial analyst is also required for using the catchment delineation functionality of MIKE BASIN.

If all is taken into account, AVSWAT is less expensive than MIKE BASIN. In comparison, the AVSWAT software with Spatial Analyst 2 and ArcView 3.3, costs €2800. To run MIKE BASIN fully for this study, ArcView and the additional MIKE BASIN rainfall-runoff module are required. The university license for this package would be €4000. Not only is the AVSWAT-software less expensive, it also offers more possibilities.

Another important difference between the two models is that AVSWAT does not require time-series of climate and runoff during the period of simulation. Once the weather generation file is produced, AVSWAT can generate time series of the climate. Runoff series are generated with the SCS Curve Number method. In contrast, MIKE BASIN does need time-series to run the program. There is however the advantage that time-series of any interval and even changing intervals can be used. MIKE BASIN also has the advantage that data-cycling can be applied. The consequence of these two different approaches is that AVWAT does not need as much input data as MIKE BASIN to run a simulation.

AVSWAT is a continuous time model (a long-term yield model), and thus cannot simulate single events in time (for example single-event flood routing), in comparison; MIKE BASIN can find stationary solutions for each time step's boundary conditions. MIKE basin can simulate single events in time such as flood routing.

In both AVSWAT and MIKE BASIN the stream network can digitized automatically using a digital elevation model. In AVSWAT the digitized network can be adjusted by changing the dimensions of the sub-basins. In MIKE BASIN the digitized network can also be added manually (see under § 4.2.2.2.4).

In AVSWAT, flow is routed through channels using the variable storage routing method or the Muskingum river routing system. In MIKE BASIN the Muskingum river routing system can also be used. By default however, no routing system is used. It will be then assumed that transport of water to the outlet only occurs through surface flow, not trough channel flow. This will affect the discharge output of the model. The discharge differences will be determined by the differences between the evaporation and seepage of the routing phase and the evapotranspiration of the land phase.

An important difference between AVSWAT and MIKE BASIN is the way runoff calculations are allocated. In AVSWAT loadings from each HRU are calculated separately and summed together to determine to total loading of the sub-basin. In MIKE BASIN however, the runoff is calculated for every sub-catchment. These sub-catchments are defined by the user as well as there surface area and runoff time-series. This method implicates that for not all areas in the basin, runoff is calculated. In AVSWAT though the whole basin is subdivided in HRUs for which runoff is calculated. It is not possible to make an evaluation on the differences in results of these diverse approaches. However, because the size and allocation of sub-catchments are user defined it can be expected that the MIKE BASIN model is more dependent on the decisions and interpretation of the user.

	AVSWAT	MIKE BASIN
Similarities	▪ ArcView user interface (Spatial Analyst required) ▪ Physically based	▪ ArcView user interface (Spatial Analyst optional) ▪ Physically based
Differences	▪ Freeware ▪ Integrated software package ▪ Price of a work package (ArcView, Spatial Analyst, AVSWAT): €2800 ▪ Extended water quality simulation ▪ No hydropower simulation possible ▪ Runoff calculated in HRUs, the whole basin is accounted for ▪ Routing by variable storage routing system or Muskingum	▪ Commercial software ▪ Software consists of 4 modules (2 modules in the basic package) ▪ Price of a work package (ArcView, MIKE BASIN basic module): €4000 ▪ Limited water quality simulation ▪ Hydropower simulation possible ▪ User defined runoff sub-catchments (lumped together) runoff not calculated for the whole basin ▪ By default no routing is used (Muskingum can be used)

Table 4.2: General comparison between AVSWAT and MIKE BASIN: overview

4.3 Input data for the pre-processing faze of AVSWAT

In the pre-processing faze, the creation of input data is done in the ArcView GIS 3.2a environment. Before the data can be imported in the program, they have to be delivered in the appropriate form. These are ArcView maps (digital terrain model, land use and soil) and database files. These files provide specific information about climate, daily precipitation soil parameters. During this pre-processing faze, AVSWAT does calculations with the input data (delineation of the watershed, overlays of land use and soil,…)

4.3.1 Digitized maps

A topographic map (Transverse Mercator projection, Meridian of Origin 39°00’ East of Greenwich, Clarke 1880 (Modified) Speroïd. 1:50000) was digitized to obtain the elevation contours, the rivers and the roads of the area.

4.3.2 Digital Elevation Model (DEM)

From the digitized contour map, a digital elevation model was interpolated. This interpolation has been performed with an ArcView extension that uses a linear interpolation between any 2 neighbouring contour lines (Stuckens, 2004). The interpolated grid has a resolution of 2*2 metres. Altitudes in the area range from 680 metres to 1000 metres above sea level.

4.3.3 Delineation of the watershed

The watershed has been determined by means of the digitized elevation model. However, this delineation gives strange results. The sub-basins in the north of the catchment are very irregular. Because at the site, a plane was observed and not a slope as the contour lines indicate, the river map is assumed correct. The failure in the delineation can therefore be attributed to a mistake in the digital elevation model (Figure 4.4).

To solve this problem, a mask has been added so that the two adjacent watersheds are separated. The result of this new delineation can be seen in Figure 4.5.

The watershed is 66, 8 km² big and is divided into 147 sub-basins.

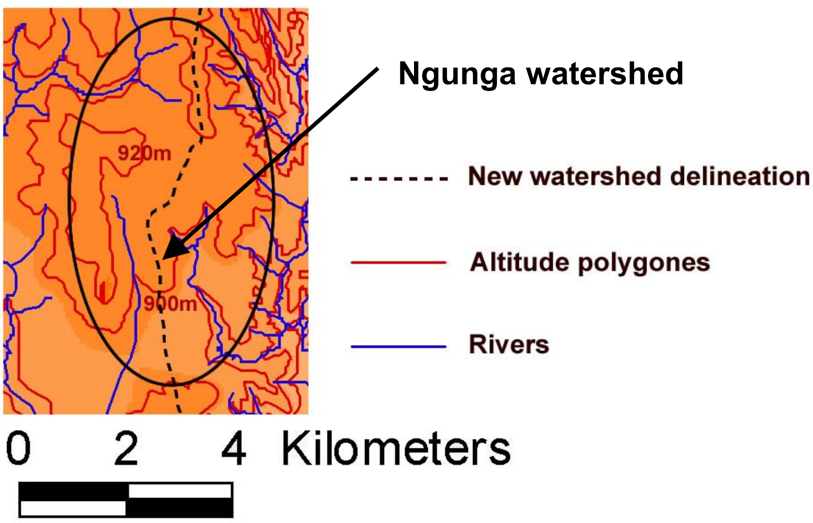

Figure 4.4: Failure in the watershed due to a DEM error

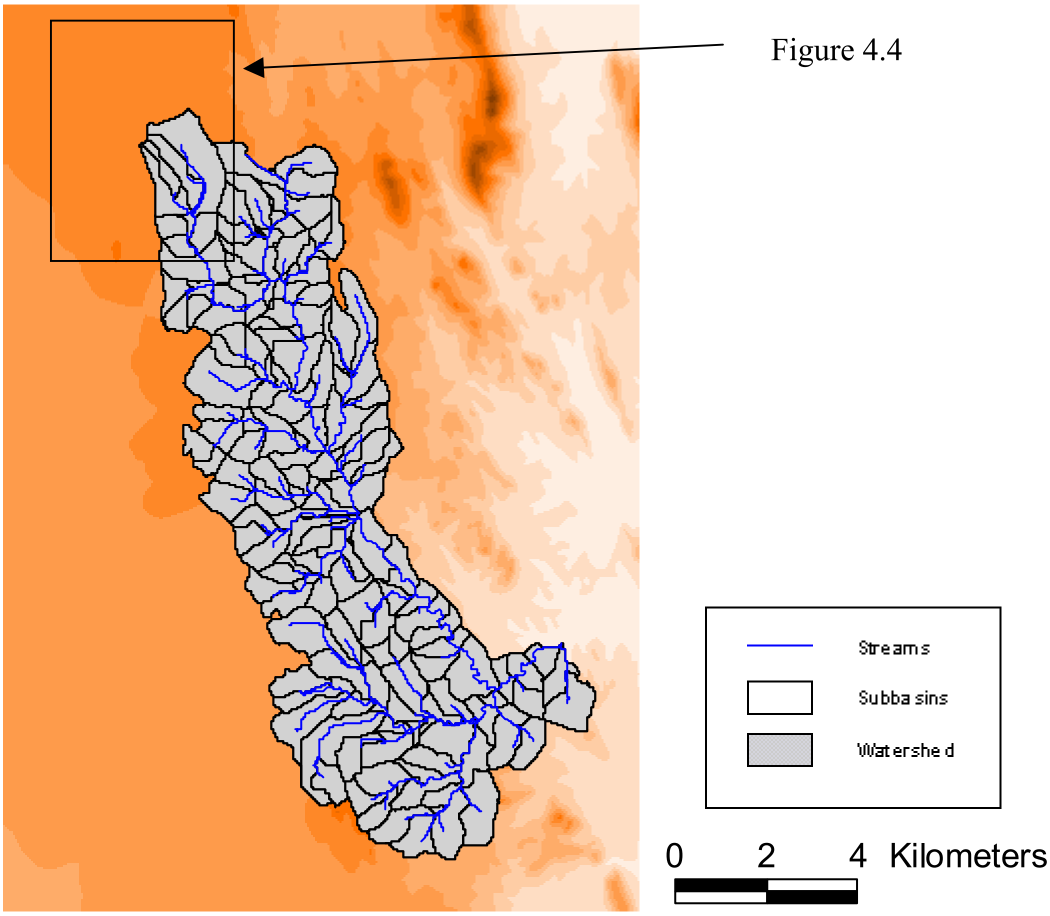

Figure 4.5: Ngunga watershed

4.3.4 Land use

4.3.4.1 Field work

Land use of the catchment had to be obtained in situ because the spatial resolution of the available LANDSAT images of the area was too low (30*30 meters).

In Kenya there was no GPS (Global Positioning System) available to determine the correct geographical coordinates of the field boundaries. Another strategy had to be chosen. A map of the land use, seen from rocks and hills surrounding the catchments was drawn on the base map (Transverse Mercator projection, Meridian of Origin 39°00' East of Greenwich, Clarke 1880 (Modified) Speroïd. 1:50000). A compass was used to orientate the map as good as possible to minimize the errors. The local knowledge of farmers was useful to correct the map and to fill in gaps.

Afterwards the identified land use was verified by walking or cycling transects and by validating the recognized area from another viewing angle. Although this strategy is time consuming, it does give a good idea of the field/bush ratio in the area.

The identified land use classes were: bush, low bushes, mixed maize and cowpeas fields, low-density residential area and rock outcrops. It has to be mentioned that the land use classification took place in the dry season and that fields are often hard to distinguish from bush.

Kisayani is a village in expansion so a lot of new fields were prepared for cultivation at the end of the dry season. This means the land use in the area is a very dynamic variable. The land use can quickly change, because of the expansion of the village.

4.3.4.2 Digitizing the map

The manually drawn map has been scanned and georeferenced through map-to-map matching with the digitalised roads map. Then, polygons have been drawn over the different land use types to obtain the digital land use map. The different land units that have been distinguished are bush (mainly Acacia type), grass with scattered trees, villages (low density), rock and maize and cowpeas fields.

The five observed land use types have been assigned to the land use classes that can be founded in the AVSWAT land use file. Not all the land use classes could be recognized so the best available types have been chosen. Bush has been assigned to range brush (RNGB), grass with scattered trees to range grass (RNGE), villages (low density) to residential-low density (URLD), rock to residential high density (URHD) and maize and cowpeas fields to corn (CORN). Because no rock was present in the database, residential high-density land use was chosen, because of the similar runoff. The percentage of rock however is very small in the catchment so that it will be excluded by defining the HRU threshold values.

The result is displayed in Figure 4.6.

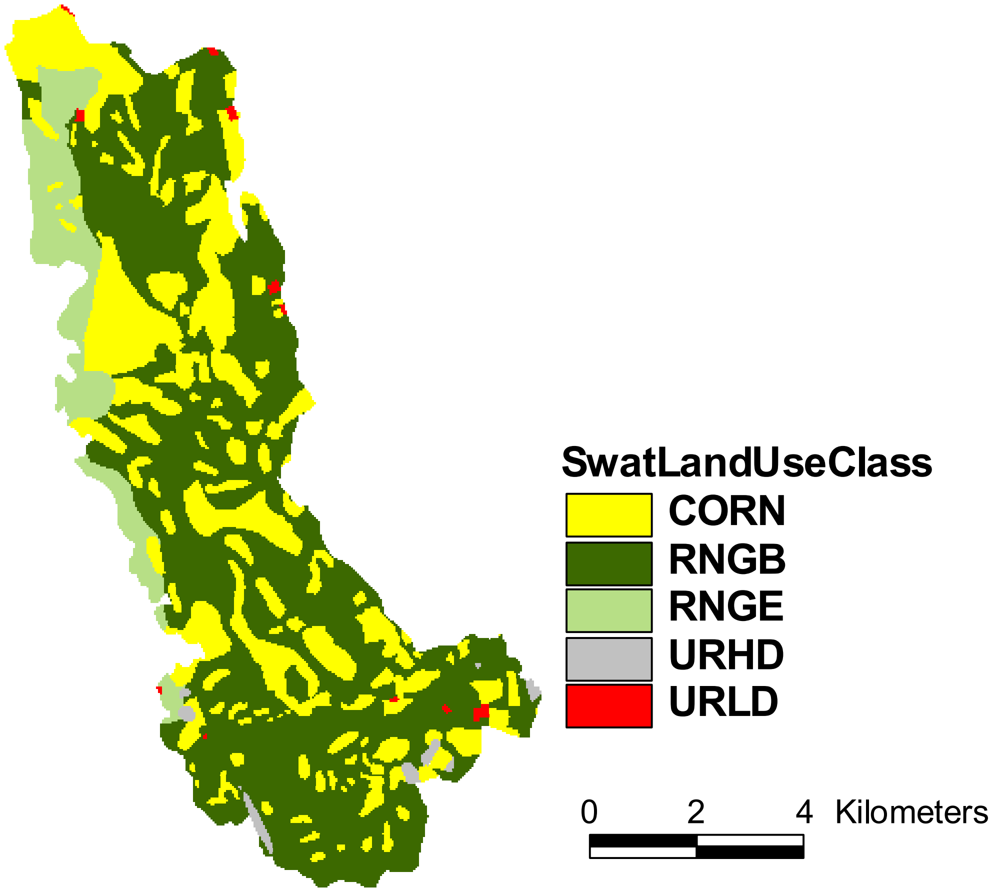

Figure 4.6: Land use of the Ngunga watershed

4.3.5 Soil

4.3.5.1 Field work

To determine the soil types with their corresponding physical soil characteristics of the studied area, a rough soil investigation was preformed. Six profile pits were dug in the catchment. Because transportation throughout the region is difficult the choice of the location of the pits was pragmatic. That is why the surroundings of the dam was examined most intensive. Local knowledge was used to determine and locate different soil types.
From the profile pits undisturbed samples were taken in the form of kopecki-rings. From each layer, 3 samples were taken. Disturbed samples were taken for texture analysis.
Additional to the pits 20 drillings were carried out from which disturbed samples were taken. These drillings have been done in the whole catchment although, again for the same reasons, the south of the area was sampled more extensively.

4.3.5.2 Soil analysis

From the different layers of the sampled soils the undisturbed samples were used to determine following parameters: saturated hydraulic conductivity (K_{sat}), bulk density, water content at field capacity (FC) and water content at wilting point (WP).

The *saturated hydraulic conductivity* is measured by means of the constant head method. A constant height of water is maintained over the upper end of the soil sample by an external manometer, and the bottom end is open to the atmosphere. The water volume flow is collected at the bottom and is used to calculate the water flux.

The *bulk density* is determined by drying the soil samples for 24 hours in an oven of 105°C. The dry weight can then be determined and divided by the volume of the sample in the kopecki-ring (100 cm^3) to obtain the bulk density.

The *water content at field capacity* is obtained by bringing the soil samples to a steady state condition in a low pressure press at a pressure corresponding with pF = 2.3 (negative pressure of 20 kPa). The sample can then be weighed and the water content can be determined through the known the dry weight of the sample.

The procedure for the moisture content at wilting point is similar. The procedure takes place with smaller samples in a high-pressure press at a negative pressure of 1550 kPa (pF = 4.2).

The obtained gravimetric water content can be recalculated to the volumetric volume content by means of the bulk density (Jury *et al.*, 1991).

The available water content (AWC) is calculated through following formula:

$$AWC=WP\text{-}FC \quad \textbf{(4.3)}$$

Soil texture is determined of the disturbed samples, although at first the soil texture of the undisturbed samples would be measured. However due to a misunderstanding this was not possible anymore. The analysed disturbed samples were chosen to be representative to the analysed undisturbed samples. This way, a file with all necessary soil characteristics of the specific soils can be produced.

Soil texture is determined according to the ISO 11277: 1998(E) guidelines. The procedure consists of the determination of particle size distribution through sieving and sedimentation. First the particles larger then 2 mm (small pebbles) are removed by dry sieving. Organic matter is then destroyed by H_2O_2 . Soluble salts and gypsum are removed through dilution. If necessary, iron oxides and carbonates are removed as well (with sodium dithionite and HCl). The sand fraction is separated through wet sieving (> 53 μm). The clay and silt fractions are determined by Stokes' Law through sedimentation (International Standard, 1998).

4.3.5.3 Digitizing the map

A digital soil map was produced with the different soil types of the area. The classification and delineation of the different soils is based on the experimental field and laboratory work. Delineation of the soils has been performed through interpolation of the analysed soils according to the contour lines. The soil map has been verified with existing soil reports of surrounding area's (Gachene, C.K.K. *et al.*, 1986; Mugai, E.N.K., 1978) and a soil map (scale 1: 250000; United States Department of Agriculture Soil Conservation Service, *et al.*, 1978). For more information on the major soil types of the Ngunga-catchment see Annex III. The produced soil map is displayed in Figure 4.7.

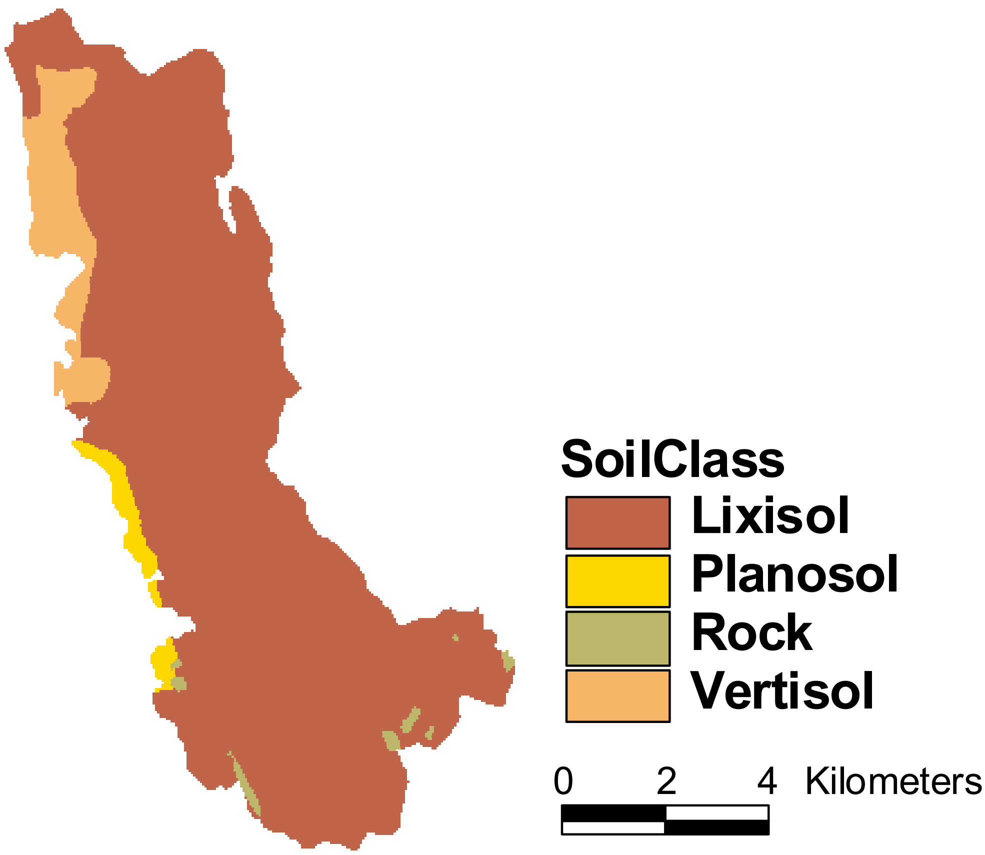

Figure 4.7: Soils of the Ngunga watershed

4.3.5.4 Soil database file

A file with following soil information is created:

- Soil hydrologic group
- Maximum rooting depth of soil profile
- Fraction of porosity (void space) from which anions are excluded
- Potential or maximum crack volume of the soil profile
- Depth from the soil surface to the bottom of the layer
- Moist bulk density per layer
- Available water capacity of the soil layer
- Saturated hydraulic conductivity per layer
- Organic carbon content per layer
- Clay content per layer
- Silt content per layer
- Sand content per layer
- Rock fragment content per layer
- Moist soil albedo
- USLE equation soil erodibility per layer

The values were partly obtained from the experimental analysis. However because not all parameters could be measured, values of soil reports of surrounding area's were used (Gachene, C.K.K. *et al.*, 1986; Mugai, , E.N.K., 1978). For more information of calculation and used values see Annex II.

4.3.6 HRUs

For the HRU distribution in the sub-basin, the decision was made to use the 'Dominant Land Use and Soil"option. With this option, the dominant land use and soil class in the sub-basin are simulated in the HRU. This way, only one HRU will be created for each sub-basin. This decision was made because the watershed already consists of 147 sub-basins, if several HRUs would be created, the model would be too complex and simulation time would take too long.

4.3.7 Climate

4.3.7.1 Field work

Because no weather stations are present in the studied catchment, two measurement stations were set up. One station is located in the Mbitini secondary school, in the north of the catchment and another station was set up in the Kisayani primary school at the southern border of the Ngunga-catchment. The measured data are daily minimum and maximum temperature and daily precipitation. In the weather station in Kisayani primary school also an evaporation pan and a humidity meter was installed. To guaranty the correct use of the instruments by the local people a manual was created (see Bossenbroek & Timmermans, 2003) in cooperation with the Dutch colleagues of the DUT.

However the collection of the data is still in a preliminary stadium and the collected data are too few to be used as input for the AVSWAT-model. This is why other data of further located weather stations are used.

4.3.7.2 Precipitation data

The weather data were partly purchased from the Institute for Meteorological Training & Research (IMTR) in Nairobi and partly obtained from the Food and Agriculture Organization of the United Nations (FAO). Although several meteorological stations can be found in a range of 50 kilometres around Kisayani, the weather data of the stations are often irregular or imprecisely measured (missing precipitation data range from 12 % to 69 %). For the simulations, the “Mutomo agricultural station”, that has the most complete dataset and is located the closest to the study area, is chosen. In this area with erratic rainfall it is the most relevant to take the data of the weather station that is located the closest to the survey area.

4.3.7.3 Other meteorological inputs

For good modelling, the AVSWAT computer program requires several meteorological input data. These data are daily precipitation, daily minimum and maximum temperatures, average daily wind speed per month, average daily dew point temperature per month (estimated from relative humidity), average daily solar radiation per month.

4.3.7.4 Creation of a hybrid meteorological station

Not all data was available for each weather station. This means that a hybrid meteorological weather station for AVSWAT had to be created. The hybrid station is a collection of data from two stations: "Kitui agricultural office" and "Mutomo agricultural station".

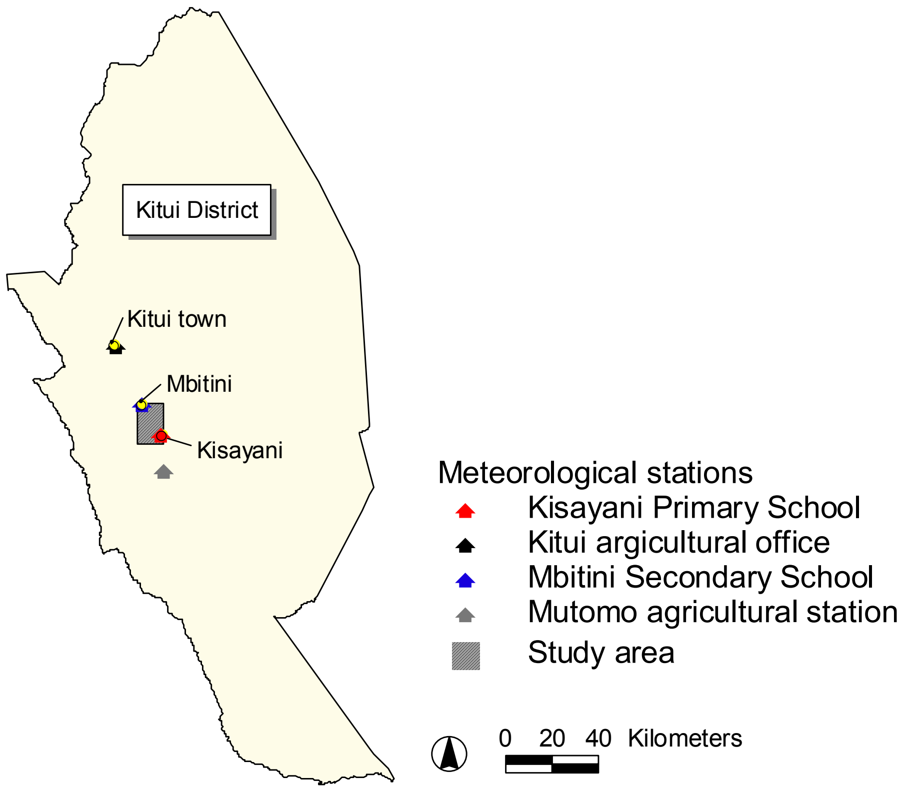

Figure 4.8: Used meteorological stations

The hybrid weather station is placed in Mutomo because this is where the precipitation data were purchased. Precipitation is considered as the most spatially variable of all weather data.

Daily precipitation records of 21 years (1979-1999) were used. It must be noticed that 16,7% of the data was missing.

Average daily solar radiation per month, average daily dew point temperature per month, average daily wind speed per month and average minimum and maximum temperatures per month were acquired from the "Kitui agricultural office" weather station. These data are obtained from the FAO (FAO, 2000). For more information, see Annex I.

4.3.7.5 Creation of 6 fictive rain gauges

Because the results of the output of the simulation with one rain gauge were not satisfactory (see § 5.1.1) it was decided to create 6 fictive rain gauges. The "Mutomo agricultural station" is kept as weather station with other meteorological inputs as done in the former simulation. The rain gauges have been created because it is generally accepted that rainfall in semi-arid areas is highly erratic and normally falls as intensive storms, with high intensity and spatial and temporal variability (Rockström, 2000). It would be therefore unreasonable to assume that the rainfall will be uniform over an area of 66 km^2.

Because no precipitation data of weather stations within the catchment were available, the precipitation data of "Mutomo agricultural station" were used. For the simulation, the precipitation data were scrambled over the 6 years of the simulation period. The general idea behind this approach is that precipitation that falls in particular weather station in one year can fall in another place within the catchment in another year. The precipitation is distributed over the catchment by Thiessen polygons. Although this approach uses a few presumptions, it can provide an insight in the hydrology of a semi-arid catchment.

In Figure 5.5 the precipitation distribution is displayed of 12 December 1981 of the two simulation methods.

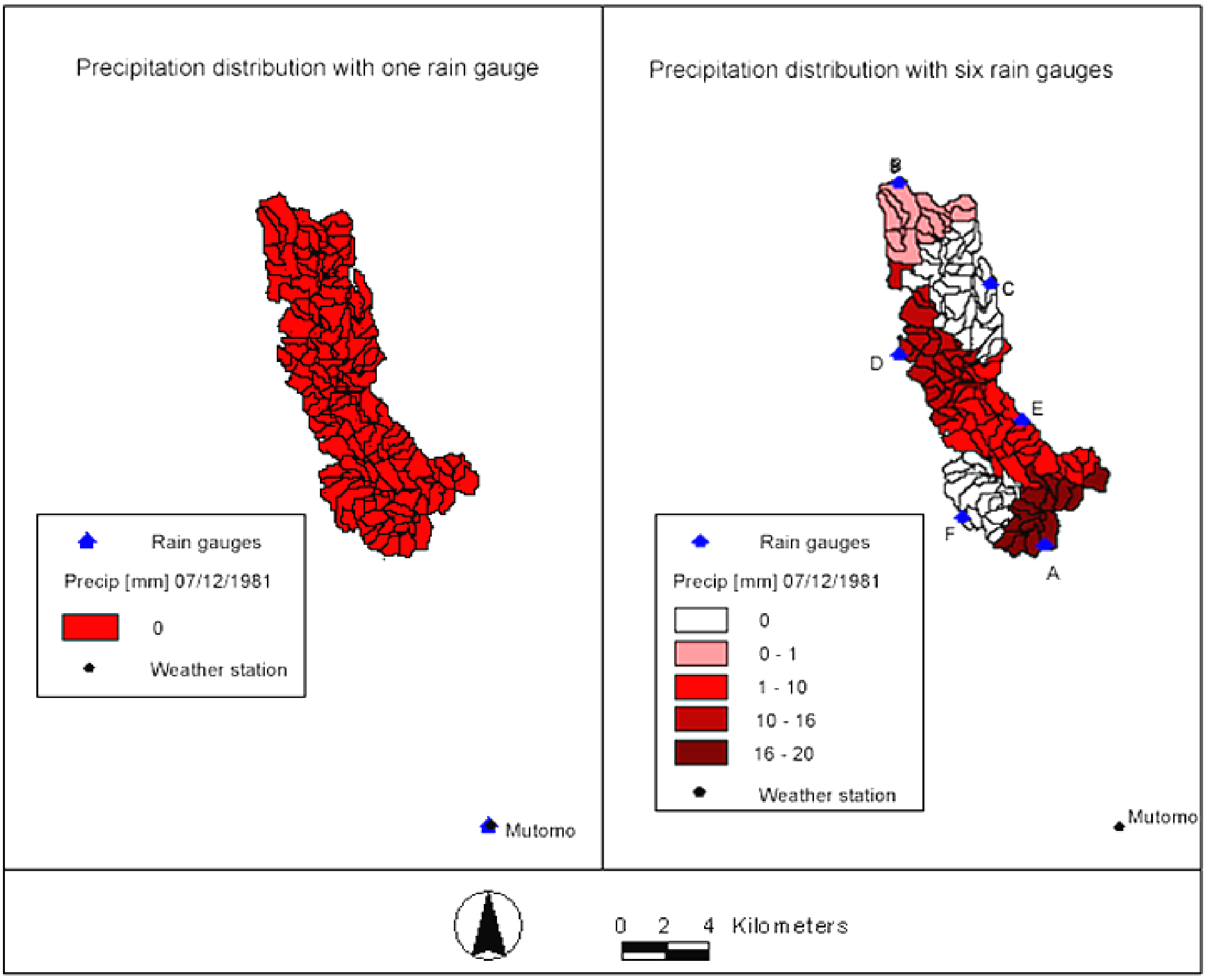

Figure 4.9: Precipitation distribution

4.3.7.6 Weather generation database file

A file with following information has been created:

- The number of years of maximum monthly 0.5 h rainfall data
- Average or mean daily maximum air temperature per month
- Average or mean daily minimum air temperature per month
- Standard deviation for daily maximum air temperature per month
- Standard deviation for daily minimum air temperature per month
- Average or mean total monthly precipitation
- Standard deviation for daily precipitation per month
- Skew coefficient for daily precipitation per month
- Probability of a wet day following a dry day per month
- Probability of a wet day following a wet day per month

- Average number of days of precipitation per month
- Average daily solar radiation per month
- Average daily dew point temperature per month
- Average daily wind speed per month

For the calculation method and the used climate data see Annex I.

4.3.7.7 Precipitation database files

Files with daily precipitation data (from June 1980 to May 1986) have been created. These values have been measured in the “Mutomo agricultural station” and scrambled for the six fictive rain gauges.

4.3.8 Run SWAT

The period of simulation is June 1980 to May 1986. For the simulation, the calculation of runoff is based on the SCS CN-method, potential evapotranspiration is calculated through the Penman-Monteith method. The precipitation distribution is set on skewed normal. Because of the existence of Vertisols in the watershed, crack flow has been activated. For the routing method, the Muskingum method was chosen.

4.4 Data for calibration of the AVSWAT-model

4.4.1 Discharge measurements

Discharge measurements of the river are needed for calibration and validation of the hydrological AVSWAT-model. However, the field study was performed in the dry season, so the Ngunga, an ephemeral river, did not flow. Therefore discharge measurements were impossible to perform.

4.4.2 Measurement of the groundwater table

4.4.2.1 Placing piezometers

Measurements of the groundwater table are necessary to calibrate and validate the water balance of the reservoir model. This part of the study was carried out by students of the

DUT. They have set up a groundwater measuring system by means of piezometers in and around the riverbed. The piezometer tubes are perforated PVC tubes placed inside a manually drilled hole. In some cases drilling was difficult due to the stone content of the soil. For more information about the technical approach see Bossenbroek & Timmermans, 2003.

In addition to this measuring system four extra piezometers were placed. Two piezometers were placed upstream of the existing Kamunyuni dam and two were placed downstream of the Kamunyuni dam. This was done to investigate the rise of the groundwater level caused by the dam.

4.4.2.2 Measuring the riverbed and piezometer locations

The location of the piezometer tubes, the height of the riverbed and the dept of the tubes, were measured with a theodolite. Also the river boundaries and the higher banks along the river were measured. Based on the measurements a map is produced in AUTOCAD through entering the points as polar coordinates (Coppin, 2002). The AUTOCAD map is then exported to ArcView to produce a general overview of the riverbed and river valley with all the tubes.

4.4.2.3 Measuring the piezometers

The water level inside the piezometers was measured with a float, attached to a rope. The float was constructed of an empty bottle that was made heavier with a pebble. When the float hits the water, a sound is produced. Then the length of the rope was measured. The depths of the water levels are recalculated with the height of the piezometers as recorded with the theodolite. This way comparison between water levels could be made. It has to be noted that effective measurements of the piezometers were few, because the tubes were placed in the dry season. They were drilled until the rock layer was reached. Because of the extremely dry period, almost all of the piezometers were found dry. However, most of the tubes have not survived the beginning of the wet season for effective measurements. This is mainly due to collapsing of the tubes with dry sand after damage of the lit by cattle or curious people. To measure the groundwater level effectively in the future, a more sustainable solution must be found. The piezometers can be made of a stronger material, the lids should be more solid and should be able to be locked so that curious passengers cannot damage them. The extra costs of these adjustments will have to be considered. The auguring cannot be done in the dry season, however if is an idea is to be obtained of the groundwater level in the sand bed of the river, piezometers will have to be installed in the riverbed. This will be impossible during the rainy season if the river is flooding. If the sand is saturated with water it will even be difficult to auger because auger holes in saturated sand are likely to collapse. Therefore it can be considered to install piezometers on the sides of the riverbed, were the texture of the soils is somewhat courser but where still an idea of the ground water level in the riverbed can be obtained.

4.5 Water balance for a sandy reservoir

To estimate the water supply of a sand-storage dam, a local water balance of the sandy reservoir will be set up. Although several parameters of this balance are uncertain, the water balance can gain an insight in the dynamics of the reservoir. The balance will be dynamic so that in a later stadium it can be easily adjusted when more detailed data are available.

4.5.1 Water balance

Theoretically, a water balance for the sandy reservoir of the sand-storage dam can be calculated by following formula:

$$\frac{dV}{dt} = Q + PA_r - EA_r - S - I \qquad \textbf{(4.4)}$$

With: V: the water volume in the sand reservoir (m^3)

t: time (d)

Q: discharge (AVSWAT output) (m^3d^{-1})

P: precipitation ($m\ d^{-1}$)

A_S: sand-storage surface (m^2)

E: evaporation (md^{-1})

S: seepage (m^3d^{-1})

I: irrigation and domestic withdrawal (m^3d^{-1})

4.5.2 Estimation of the subsurface dam volume

The volume and water holding capacity of the reservoir is required to estimate the depth of the water table on every time step of the water balance. The depth of the water table is required to make an estimation of the actual evaporation.

An estimation of a subsurface reservoir is a difficult operation to perform. The underlying rock layer limits the subsurface sand reservoir. However, geological deposits are very irregular. To obtain the real reservoir volume, numerous measurements of the depth of the underlying rock have to be done. These measurements are not available. In the dry season it is very difficult to drill in the dry sandy river sediment. Auger holes are very likely to collapse so drilling until the rock layer is in most cases virtually impossible. From 10 points in the river, the depth of the underlying rock layer is known. If the depth of the underlying rock layer would be interpolated for the whole region just based on these 10 points, strange results are obtained.

An overview of the situation is given in Figure 4.10.

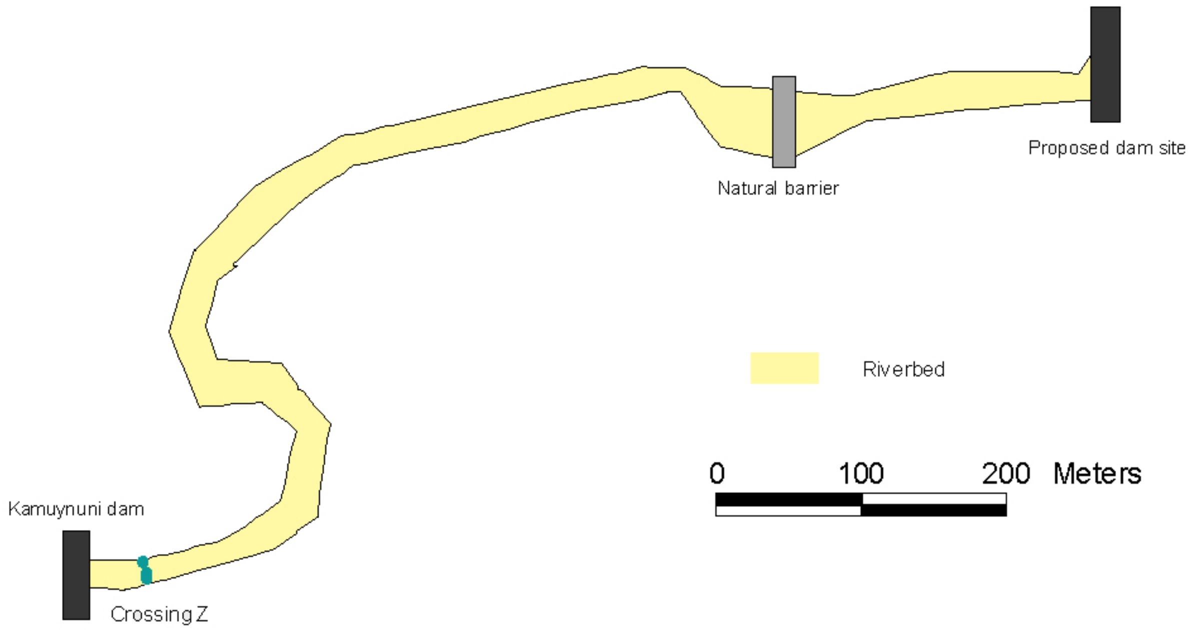

Figure 4.10: Riverbed between Kamunyuni dam and "Proposed dam site"

To perform an estimation of the subsurface volume of the sand reservoir, a few assumptions have to be made.

First it is assumed that the sand reservoir of the "proposed dam" will be located between the "proposed dam site" and the natural barrier. This natural barrier is a natural rock outcrop in the river that stops the water (Figure 4.10).

From one cross-section, the depth of the impervious rock is known at three points in the river. To estimate the average depth (D) of the sand bed in the river, the deepest point will be taken. Although from local knowledge, it is known that these auger holes are not the deepest in the riverbed, this point will be taken as an average. This is because, in some points, the rock layer comes to the surface, but on other points the rock layer is deeper than this depth.

To estimate the shape of the sandy reservoir, it is assumed that the river has eroded the geological underground in a same way as the surrounding valley (Figure 4.11); this is a trapezoidal form. The surface of the river is measured with the theodolite. To obtain the length of the river, the following formula is used:

$$L = \frac{P - W_{nat.barrier} - W_{prop.dam}}{2} \tag{4.5}$$

with L: length of the river

P: perimeter (calculated in ArcView)

$W_{nat.barrier}$: width of the river at the natural barrier

$W_{prop.dam}$: width of the river at the "proposed dam site"

The surface of the river is simplified to a rectangle, so the average width can be calculated through following formula:

$$W_{riv} = \frac{A}{L} \tag{4.6}$$

with L: length of the river

A: surface area of the river (calculated in ArcView)

W_{riv}: average width of the river

D: maximum depth of the sand reservoir

The angel γ is estimated according to the surrounding riverbanks.

Following values have been calculated:

L	209 m
W_{riv}	24,8 m
D	2 m 78
γ	60°

Table 4.3: Reservoir parameters

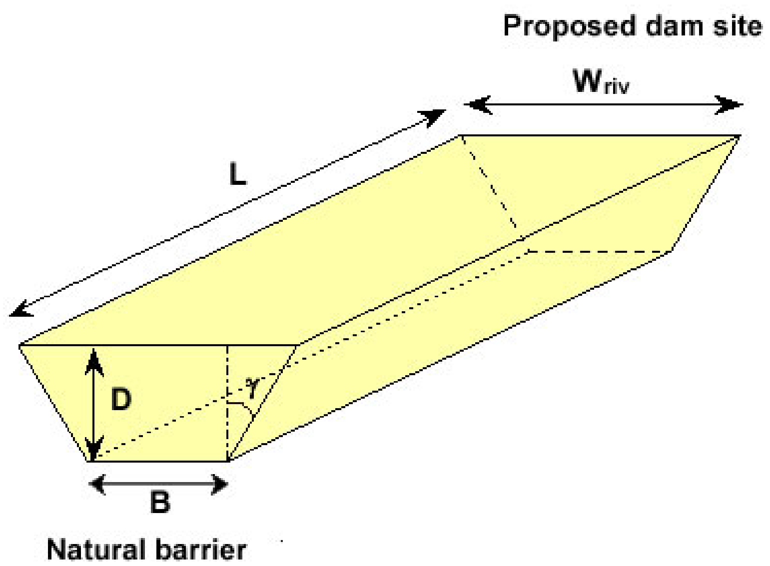

Figure 4.11: Reservoir dimensions

Through following formula the maximum volume of the sand reservoir is calculated:

$$V = L * \left[(B * D) + D^2 * Tan(\gamma) \right] \qquad \textbf{(4.7)}$$

This way, a volume of 11611,63 m³ was obtained. This is however the volume of a reservoir filled with sand. To calculate the maximum volume of water this reservoir can contain, the porosity of the sand must be calculated with following formula:

$$n = 1 - \frac{\rho_b}{\rho_{part}} \qquad \textbf{(4.8)}$$

With n: porosity

ρ_b: bulk density (bulk density of the river sand is 1,65 g/cm³)

ρ_{part}: particle density (particle density of sand is 2,65 g/cm³)

With this calculation, the water volume that can be contained by the sand reservoir is estimated at 4381,75 m³.

4.5.3 Irrigation and domestic water withdrawal

Irrigation will be ignored because the sand-storage dam has not yet been built. It is therefore difficult to estimate these requirements. In a later stadium however this parameter will have to be accounted for, as the dam will supply water for cattle, households and irrigation and withdrawals will be significant. For potential for small scale irrigation see Puttemans (2004).

4.5.4 Precipitation

Cumulative precipitation is a direct input in the reservoir. Absolute quantities have been obtained through multiplying the precipitation with the surface area of the sand reservoir.

4.5.5 Actual evaporation

The actual evaporation of the sandy surface was calculated as a function of the depth of the water table. To estimate the actual evaporation, the model HYDRUS-1D was used (Simunek *et al.*, 1998 a). HYDRUS-1D is a Microsoft Windows-based modelling environment for the analysis of water flow and solute transport in variably saturated porous media.

To estimate the actual evaporation, the water flux through a uniform sand profile was calculated for several water table depths.

The physical parameters of this sandy profile (texture, bulk density, water content at field capacity and wilting point) have been measured previously (see § 4.3.5.2). With these physical parameters the necessary Genuchten water retention parameters (residual soil water content, saturated soil water content, α: a parameter in the van Genuchten soil water retention curve, pore-size distribution) and the saturated hydraulic conductivity are calculated with the incorporated Rosetta DLL (Dynamically Linked Library) program. This way the water retention curve can be reconstructed with the van Genuchten model (Simunek *et al.*, 1998 b).

A constant potential evapotranspiration was maintained above the profile and the necessary boundary conditions were specified (pressure head of zero at the water table and wilting point is assumed at the top of the profile). Through iteration HYDRYS-1D finds the water flux at steady state through the profile.

The iteration was performed for 27 different water depths. As can be seen from Figure 4.12 the evaporation stays constant until a depth of 50 centimetres, and then the evaporation decreases exponentially. With the water table at a depth of 190 cm the evaporation is assumed to be zero.

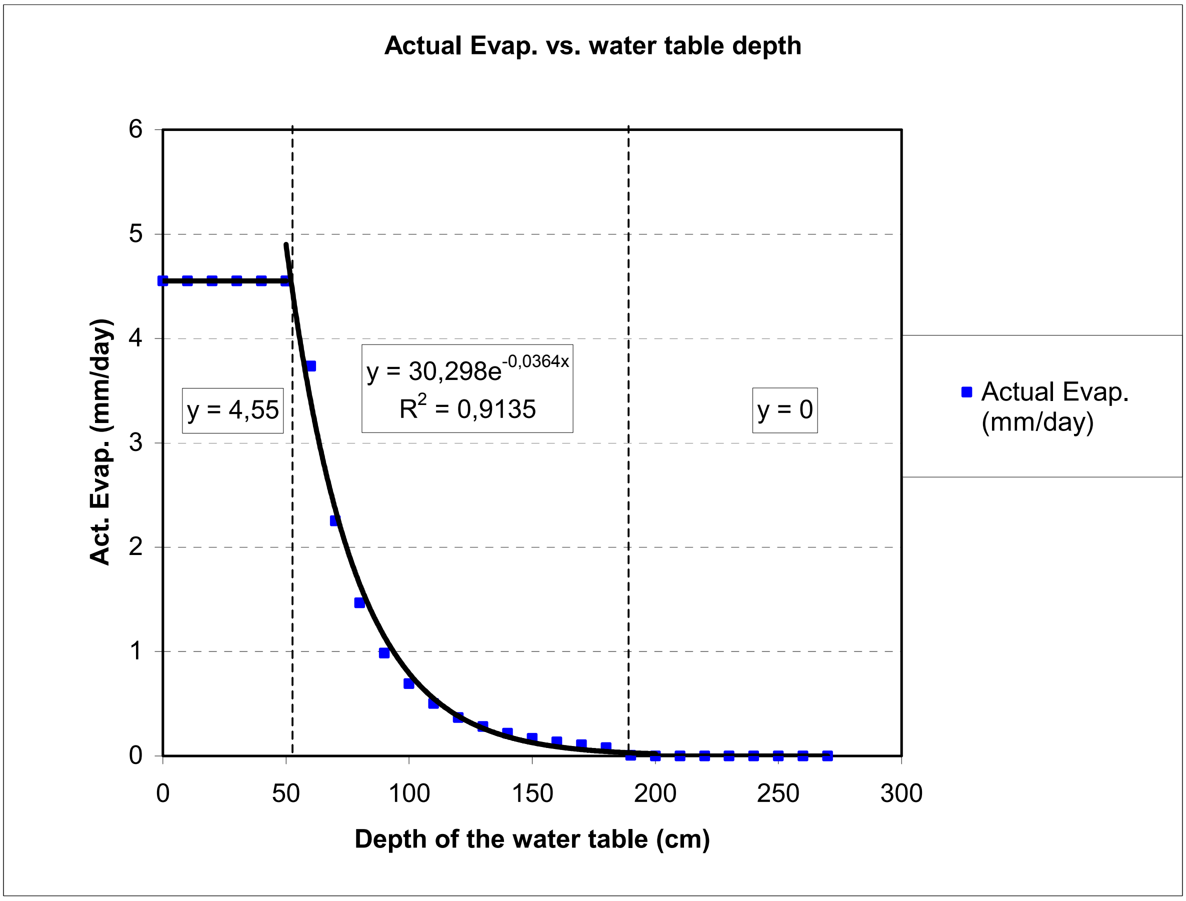

Figure 4.12: Actual evaporation vs. water table depth

Actual quantities of evaporation have been obtained through multiplication with the surface area.

4.5.6 Discharge

The values of discharge have been obtained from the output of AVSWAT.

4.5.7 Seepage

It is impossible to estimate the seepage of a sand-storage dam as this is dependent on the local conditions of the dam. Seepage is possible through the concrete dam, through the underlying rock layer and through the riverbanks. Although local knowledge states that seepage through the dam and through the "impervious" rock layer causes a raise of the water table downstream of the dam, no experimental research has been performed on this topic. For this research, it will be assumed that the sand-storage dams obstruct the water completely and do not have any seepage. If later research can provide a seepage coefficient, this can easily be integrated in the existing water balance.

4.5.8 Calculation procedure

The water balance of the reservoir is calculated at every daily time-step. The water volume is calculated as follows:

$$V_{t+1} = V_t + (P_{t+1} - E_{t+1})A_s - S_{t+1} + Q_{t+1} \quad \textbf{(4.9)}$$

The water volume is recalculated to the volume this water takes in the reservoir (dependent on the porosity of the sand). With the volume of the previous day, the depth of the water table can be calculated and the evaporation will be estimated according to Figure 4.12

5 Results and discussion

5.1 The AVSWAT-model

5.1.1 Simulation with one rain gauge

First, a simulation over six years (June 1980-May 1986) of the discharge is performed based on the precipitation data of one weather station and one rain gauge, both placed in the "Mutomo agricultural station". The discharge versus time graph is displayed in Figure 5.1.

As can be seen from the graph, an extremely high discharge (5620320 m³/day) is reached on November 12th, 1984. This amount of water would put 8 centimetres of water on the whole catchment (of 66 km²) if this would be flat. A discharge of this extent in a semi-arid watershed is impossible. The large discharge follows on a day with 200 mm of precipitation. Because the model is set up with only one rain gauge, this amount of precipitation is assumed to be evenly distributed over the whole catchment. In a semi-arid region with known spatial variability of rainfall, this is however unlikely, especially for an intensive storm of 200 mm.

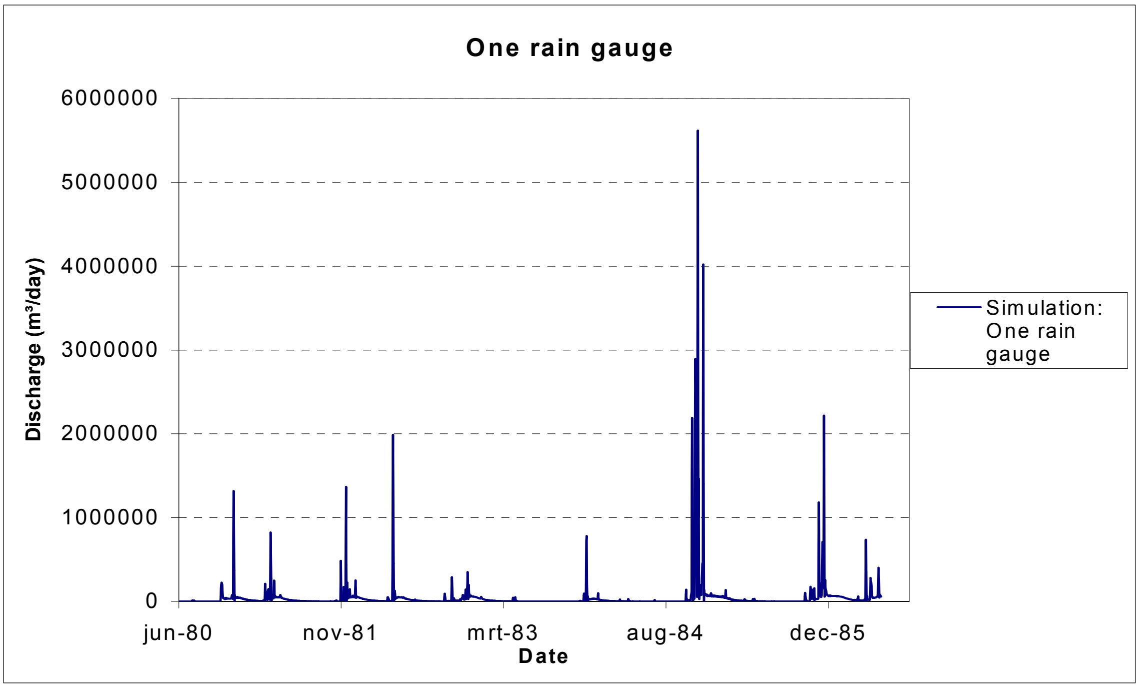

Figure 5.1: Discharge versus time: Simulation with one rain gauge (calibrated)

5.1.2 Simulation with six rain gauges

Because a simulation with one weather station and one rain gauge results in high, unrealistic peaks, a simulation with 6 rain gauges has been set up as been described in § 4.3.7.5. If the 6 years of precipitation are scrambled as described in § 4.3.7.5, the high rainfall intensity (for instance the 200 mm) will not occur at the same time in all the weather stations. The high amount of rainfall will therefore not fall over a large area (see Figure 4.9), but will be spatially spread over the catchment. This scenario is more realistic because it represents the fact that rainfall in semi-arid regions has got a strong local nature. The scenario results in lower discharge peaks in comparison with the first simulation (Figure 5.2). The maximum discharge is 1322784 m³/day.

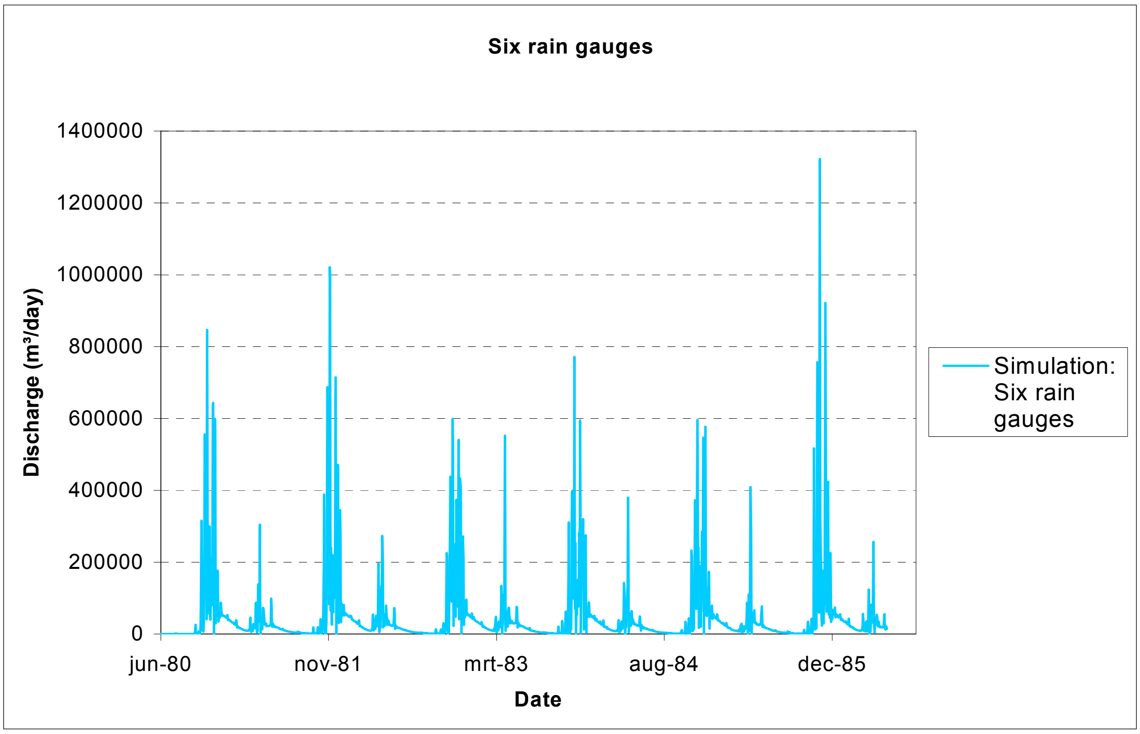

Figure 5.2 Discharge versus time: Simulation with six rain gauges (calibrated)

5.1.2.1 Qualitative calibration

Because no observed discharge data are available, a quantitative calibration cannot be performed. To conclude whether the model is realistic, a few parameters can be examined and compared with other case studies and measured records. Although this procedure does not provide more quantitative information, it does gain an insight into the main hydrological processes of the catchment.

5.1.2.1.1 *Visual calibration of the discharge output*

The visual calibration was performed because the discharge graph did not represent a normal display. Normally the discharge curve has an exponential slope because infiltration decreases exponentially with time. In the uncalibrated output this was however not the case. The model was calibrated on processes of channel routing, deep percolation and the effective hydraulic conductivity of the channel to obtain an exponential slope. Figure 5.3 represents the logarithm of the discharge, as function of the time; in this graph the slope should be linear. The calibrated output has got more or less a linear slope in the logarithmic discharge graph. However because no observed discharge data are available, the calibration will be done visually, based on the hydrograph.

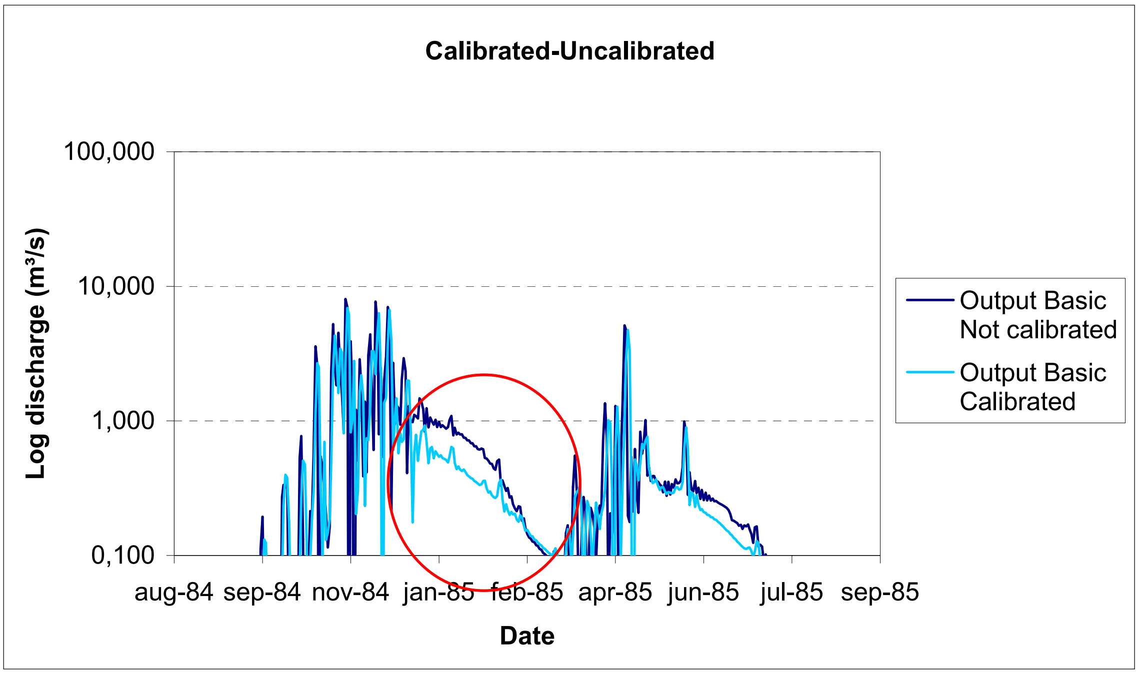

Figure 5.3: Date vs. log discharge of the calibrated and uncalibrated output

When the discharge as a function of time is compared with similar case-studies (Andersen *et al.,* 2001; Conan *et al*., 2003; Ye *et al*., 1998) in semi-arid watersheds it can be concluded that the discharge curve is similar. High discharge peaks in times of precipitation are alternated with periods of no or almost no discharge in the dry season (Figure 5.2). This demonstrates the strong dependency of the discharge at the outlet of the catchment on the rainfall in the catchment.

5.1.2.1.2 Discharge response and actual evapotranspiration

Discharge response

Figure 5.2 shows that high discharge peaks occur. Periods of high discharge follow immediately days with high rainfall. This indicates the distinct rainfall-runoff response in the Ngunga-catchment. More rainfall results immediately in a higher discharge at the outlet of the basin. This clear response indicates the importance of the runoff to the discharge. In semi-arid areas, the contribution of base flow to the discharge is minor because the perennial rivers are located above the water table, which is usually located at a profound depth. Flow in the saturated zone therefore does not contribute to the discharge of the river.

Evapotranspiration

The actual evapotranspiration, generated by AVSWAT, per day is never higher then the generated daily potential evaporation. When the total actual evapotranspiration per month generated by AVSWAT is compared with the measured total potential evapotranspiration (PET) per month of the "Kitui agricultural office", the actual evapotranspiration is on an average yearly basis 84% lower than the potential evapotranspiration. The average monthly actual and potential evapotranspiration as generated by AVSWAT is displayed in Figure 5.4.

Potential evapotranspiration is the amount of water transpired by a short green crop, completely shading the ground, of uniform height and never short of water. (Neitsch, *et al.,* 2001). In semi-arid areas however, vegetation will almost never be fully supplied by water. Plants will therefore have a limited transpiration and the soil evaporation will be drastically restricted.

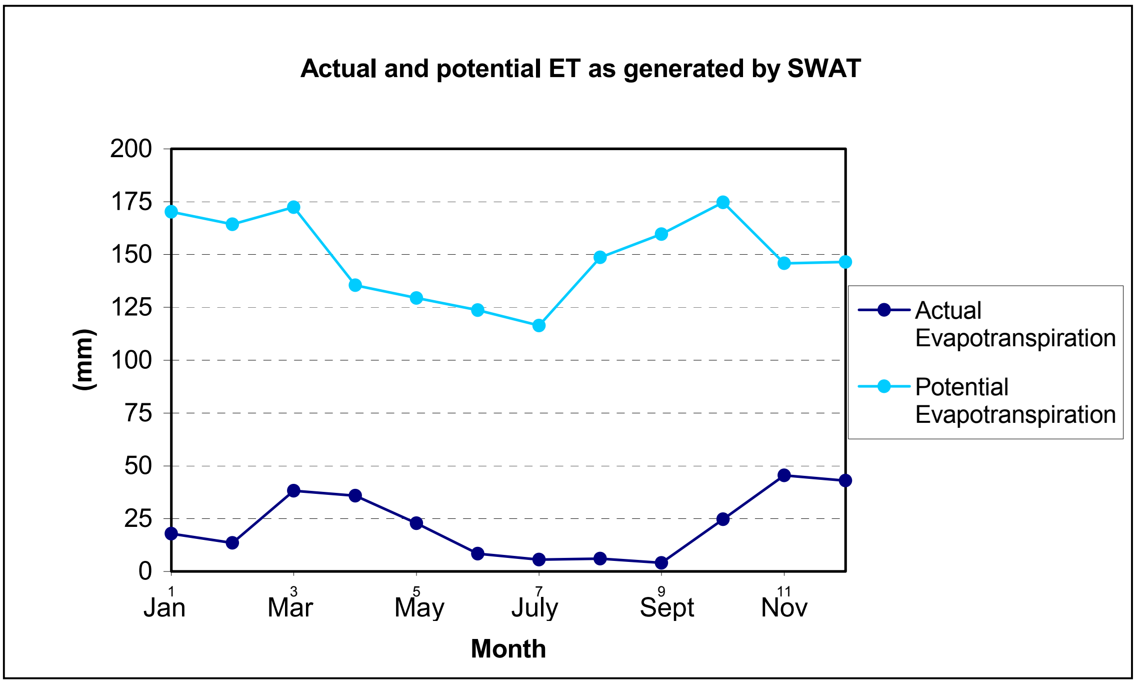

Figure 5.4: Actual and potential ET as generated by AVSWAT

5.1.2.2 Land use scenario analysis

To understand the importance of changing land use on the water balance of a watershed, different input scenarios will be provided and the output results will be examined.

The basic scenario will be with the experimentally determined soil classes, land use and climate parameters as described above.

For scenario 1, the output will be examined when the whole catchment will be cultivated with maize and cowpeas.

For scenario 2, influence on the output will be examined when the whole catchment will be under a sparse grass vegetation (range grass), as a result of the degraded soil.

The two scenarios are compared with the basic scenario; the result is displayed in Figure 5.5.

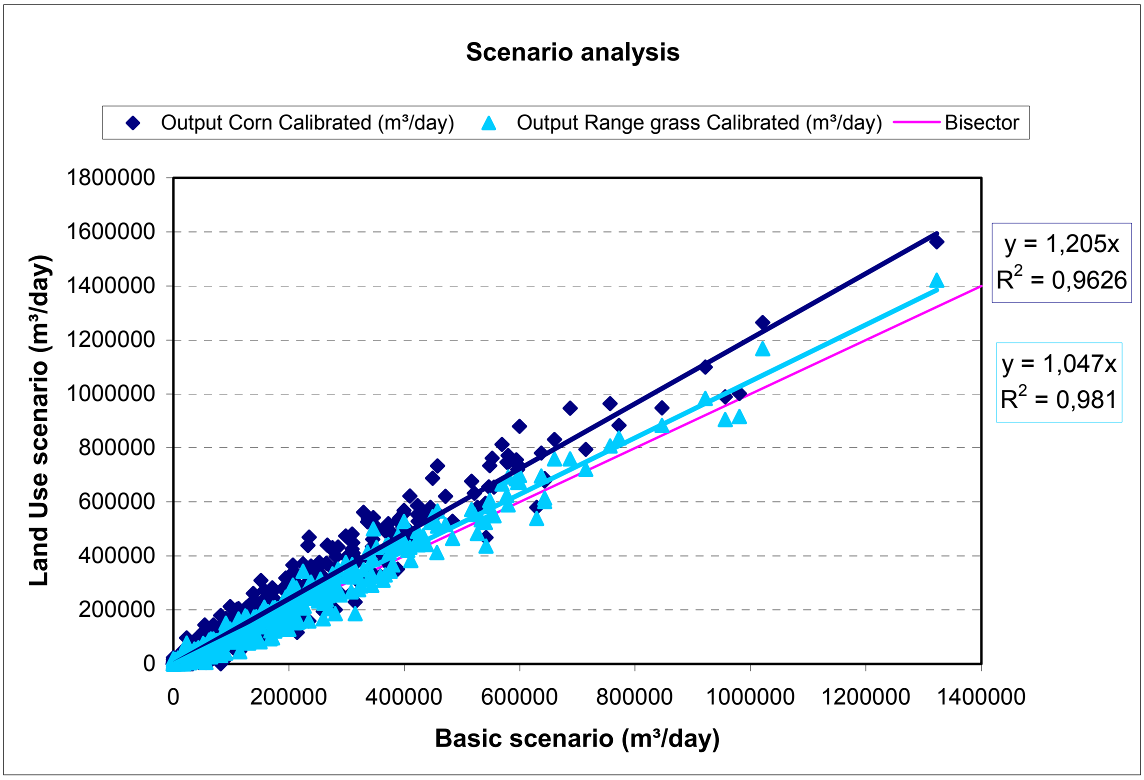

Figure 5.5: Scenario analysis

5.1.2.2.1 Discussion

As can be seen in the previous paragraph, land use has only a minor response on the runoff characteristics of the catchment. Changes in land use have an influence on the surface runoff, infiltration and the actual evapotranspiration.

Soil Conservation Service (SCS) Curve Number (CN) procedure

The SCS curve number equation is used to calculate the runoff:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad \textbf{(5.1)}$$

with: Q_{surf}: the accumulated runoff or rainfall excess (mm H_2O)

R_{day}: the rainfall depth for the day (mm H_2O)

I_a: the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), commonly approximated as 0.2S

S: the retention parameter (mm H_2O)

This equation is influenced by land use on the interception and infiltration of water in the soil. With different vegetation, these parameters will change.

The retention parameter S is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{5.2}$$

with: CN the curve number for the day

The curve number is a function of the soil's permeability, land use and antecedent soil water conditions (Neitsch *et al.* 2001 a). Different kind of land use will therefore have a different curve number and thus different runoff.

Actual evapotranspiration

AVSWAT first evaporates any free water intercepted by the plant canopy. The amount of free water that can be held in the canopy varies as a function of the leaf area index.

Next the transpiration is calculated. Because the Penman-Monteith equation is selected as the potential evaptranspiration method, transpiration is also calculated with this equation. The evaporation from the soil will then be calculated; this is dependent on the soil cover index (function of the aboveground biomass and residue) and the potential evapotranspiration.

As can be seen from Figure 5.5, both scenarios result in a slightly higher discharge. The runoff surplus can be explained through a higher curve number in the two scenarios. Corn and range grass can retain less water than bush, by consequence the infiltration will decrease.

5.2 Water balance for a sandy reservoir

5.2.1 Results

The output of AVSWAT and of the evaporation calculation is imported into the water balance model. The result is displayed in Figure 5.6.

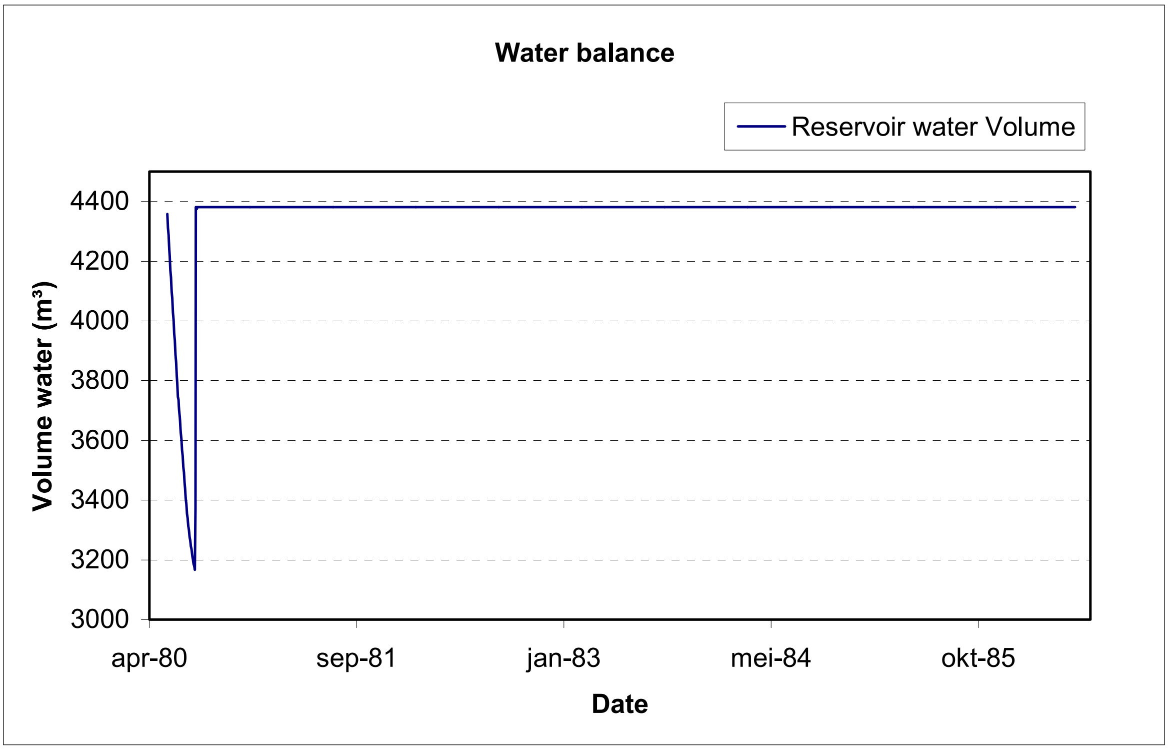

Figure 5.6: Volume water in the sandy reservoir versus time

5.2.2 Discussion

From Figure 5.6 can be seen that the sandy reservoir is almost always filled with water until the top. However, this is not what is observed in the field and is known from other sand-storage dams. It is therefore reasonable to assume that the water balance gives an overestimation of the retained water in reality. There are several reasons for this overestimation. First, this water balance model is very dependent on the output generated by AVSWAT. This is because the sandy reservoir is provided by a very large runoff area. The output of AVSWAT will therefore be the most important contributor of the water balance model. Direct rainfall and evaporation occur over the relatively small surface of the sandy reservoir and will therefore have only a negligible contribution to the water balance.

However, the output of AVSWAT is uncertain because the model remains uncalibrated. Furthermore, because of the scrambling of the precipitation data, there are fewer days without precipitation anywhere in the catchment. In reality however, it regularly happens that a rainy season is delayed or that the rains stay away and a long dry period occur. By scrambling the rainfall data of one dataset, the locality of the rainfall can be modelled, but also a more regular course of the rainfall over the whole catchment will be shown. In reality, however, rainfall shows a highly erratic course. This means that the discharge modelled with the AVSWAT-model with six rain gauges will be less erratic and has got a more regular display (compare Figure 5.1 and Figure 5.2). Because of this feature, the sand-storage dam will be supplied with water on a more continuous way. Sand-storage dams will fill up almost immediately when a high rainfall occurs (Ertsen and Biesbrouck, in press). The final result will be that with output of the AVSWAT-model with six rain gauges, the sand-storage dam will be filled completely with water for a longer time, but that the extreme peaks in the discharge of the river will be lower.

Other uncertainties are the estimation of the sub-surface reservoir of the sand-storage dam. Because of the irregularities in the depth of the underlying rock, it is difficult to estimate the volume of the sub-surface reservoir. The irrigation and domestic requirements could not be included in the water balance because the dam is not yet built. Once the dam is built, also these parameters can be taken into account.

Seepage is another unknown parameter of the balance. Through measurements of the water levels before and behind the dam, an estimation of the loss of the water through seepage can be obtained. This parameter is also strongly dependent on the specific dam location and construction parameters.

An estimation of the emptying of the sand-storage dam is made. Hereby, it is assumed that there is no rainfall and the only source of water loss is through evaporation (no seepage). From this simulation it can be seen that the initially filled sand-storage dam will still be filled for 39% after two years. This simulation indicates that the water stored by sand-storage dams built with expertise is available for a long period and that a sand-storage dam can overcome the temporal shortage of water.

6 Conclusions

6.1 The AVSWAT software

AVSWAT is a budget friendly program with extended possibilities. In comparison with MIKE BASIN, less data are necessary to run the program. Especially the fact that AVSWAT does not need full time series to perform a simulation is a considerable advantage for simulating catchments of developing countries where the needed input data are often incomplete or unavailable and budgets are restricted. Input data in AVSWAT are not lumped together as in MIKE BASIN (in the runoff sub-catchments), this has the advantage that the catchment area can be surveyed in a less intensive way and that decision-making is less subjective. In developing countries it is important that economical and sustainable solutions are found. Therefore the purchase price of the modelling software is also important. Based on the former mentioned features (see § 4.2.3) AVSWAT is preferred over MIKE BASIN to model the studied river basin.

Although the AVSWAT software can provide a good simulation with limited data, it does have some limitations and practical difficulties.
First, it is very time consuming to start a simulation from scratch. A lot of time is spent in creating the input of the model. A lot of errors can be made in creating this input. The fields of the required dbf-files all need a specific format (string, integer, character,..). These input files can therefore not be quickly adjusted with Excel. When input errors occur, the simulation cannot proceed. Often it is difficult to track the cause of these errors. A lot of time is therefore spent in tracking and correcting input errors.
Another disadvantage AVSWAT is the amount of hard disk-space a project needs (up to 3 gigabytes in this specific case). This makes it very difficult to backup and to work on several projects without having a lack of hard disk-space. Some calculations in the pre-processing faze of AVSWAT take a long time (up to 6 hours for some calculations). Even with an up-to-date computer (Pentium IV processor: 2,26 GHz; 512 Mb RAM memory) AVSWAT will still regularly crash. It is therefore very important that an up-to-date computer with enough hard disk space is available to simulate a complex watershed with

AVSWAT. This makes it difficult to introduce AVSWAT as a sustainable and economical modelling tool in developing countries.

Also the ArcView interface of AVSWAT contributes to the practical inconveniences. It is not possible to simply copy the AVSWAT-project to another directory or another computer. The project needs to be opened from the same directory as were it has been created. If not, the file paths have to be redefined. However an AVSWAT-project can contain more than 3000 separate files for all of which the paths have to be redefined. This makes it very difficult to pass on projects from one user to another.

Once the input of a project is finished, the simulation is performed relatively fast (± 1 hour to run SWAT and view the output). Mainly the calculations in the previous pre-processing steps are the most time consuming.

The previously mentioned features make the AVSWAT-model a complex model to use with quite a lot of practical inconveniences. These practical inconveniences and the need of expensive, up-to-date computers can complicate or even prevent the introduction of AVSWAT in developing countries. Even if a solution for the expensive hardware is found, these practical inconveniences can cause that AVSWAT will not be used although modelling results are satisfying. The model can be introduced but close monitoring has to be performed and education must be given to make sure that the introduction is sustainable.

6.2 The AVSWAT-model

Although the model is not quantitatively calibrated, a few conclusions can be made.

As can be seen from Figure 5.2, the hydrograph has high discharge peaks and distinct periods of no or negligible discharge. This points out that the discharge is mainly caused by surface runoff and that there is a limited contrition of base flow to the discharge. The surface runoff has a rapid response on rainfall anywhere in the catchment.

If an accurate model from a semi-arid watershed is to be made, sufficient rainfall data should be collected within the catchment. Especially in a catchment of this size several rain gauges should be set up to analyse the temporal and spatial distribution of the rainfall. Collection of rainfall data for model studies is even more important in semi-arid climates than in temperate climates because of the erratic rainfall.

Modelling in semi-arid climates is especially difficult because the dry periods cause changes in the density of the vegetation and in the structure of the soils (influences infiltration and runoff).
As can be seen from the scenario analysis, there is a limited influence of land use changes on the discharge of the catchment. The two investigated scenarios are extreme situations. If land use changes (taking barren land into cultivation or degradation of vegetation), there will be no or a negligible effects on the water supply at the outlet of the catchment. Although local effects such as erosion and mudflows can occur.

6.3 Water balance

The water balance is highly dependent of the AVSWAT results. The main reason of the overestimation of the water volume in the dam reservoir will be that the simulated discharge that is too regular. Because seepage and water use for irrigation and domestic purposes are not taken into account, the volume of water stored in the dam reservoir will be overestimated.

6.4 General conclusions and recommendations

AVSWAT is a hydrological tool that can be used for modelling in semi-arid watersheds. However, the introduction in developing countries has to be considered carefully because of the expensive computers necessary and the practical inconveniences of the software.
The Ngunga watershed has a distinct rainfall-runoff response resulting in high discharge peaks in periods of high rainfall and no or negligible discharge during the dry season. To perform a valid simulation several rain gauges are required in the studied area. It is therefore essential that the weather stations that have been set up in the area are maintained and if possible a few rain gauges can be set up in the centre of the Ngunga-catchment. The local character of rainfall can be simulated through scrambling of the rainfall data, however this results in a rainfall pattern that is too regular because of the return of the same rainstorms every year. This simulation was however the best possible method to follow with the limited data available. Conclusions about the quantity of the retained water cannot be made because the model remains uncalibrated.

Land use changes have a limited contribution to discharge changes at the outlet. It is therefore more important to spend the available budget on the collection of rainfall data, instead of monitoring the land use changes in the area.

To calibrate the model, discharge measurements and groundwater level measurements are indispensable. As been indicated before, installing piezometers is not straightforward in the area. Piezometers can be placed on the sides of the riverbed, where the texture of the soils is somewhat courser but where still an idea of the ground water level in the riverbed can be obtained. The piezometers can be made of a stronger material and the lids should be made more solid. They should also be able to be locked so that curious passengers cannot damage them. If more shallow wells are constructed in the region, these can also be used to measure the groundwater level.

In future research, more information should be obtained about seepage of sand-storage dams. Also monitoring of the use of water for irrigation and domestic purposes should be performed. The depth of the underlying rock can be estimated by using a terrameter. This way, more transects of the river can be investigated so a more reliable interpolation of the rock surface can be performed. An estimation of the volume of the sandy reservoir can be performed more in detail this way.

7 References

Andersen J., Refsgaard J.C., Jensen K.H. (2001). Distributed hydrological modelling of the Senegal River Basin – Model construction and validation. *Journal of Hydrology 247.* p. 200-214. . [17.02.2004, science direct: http://www.sciencedirect.com].

Biesbrouck B., Wyseure G., Van Orshoven J. and Feyen J. (2002). AVSWAT 2000 [26.02.2003, http://www.agr.kuleuven.ac.be/vakken/avswat/files/manual/own/avswat2000.pdf].

Bossenbroek J.-K. & Timmermans T., (2003). Research at sand-storage dams: Setting up a measuring program at Kisayani, Kenya; Traineeship report: p. 71-89.

Centre for Ecology and Hydrology, Wallingford, United Kingdom [17.12.2003, http://www.nerc-wallingford.ac.uk/research/WPI/images/WPIworldmap.pdf].

Conan, C., de Marsily, G., Bouraoui, F., Bidoglio, G., (2003). A long-term hydrological modelling of the Upper Guadiana river basin (Spain). *Physics and Chemistry of the Earth 28*, p. 193–200. [17.02.2004, science direct: http://www.sciencedirect.com].

DHI (2003 a). MIKE BASIN 2003. A Versatile Decision Support Tool for Integrated Water Resources Management Planning. Guide to get started and Tutorial. DHI (Danish Hydraulic Institute) Water and Environment.

DHI (2003 b). WATER RESCOURCES SOFTWARE. Price List 2003.

DHI (2004) http://www.dhisoftware.com/mikebasin [01/07/2004].

Di Luzio M., Srinivasan, R., Arnold J.G. (2001). ArcView Interface For SWAT2000, User's Guide. Blackland Research Center. USDA-ARS, Texas Agr. Experiment Station, Texas. 342p.

Ertsen M. and Biesbrouck B. (in press). Different scales in groundwater management in Kenya: from individual structures to climate impacts.

ESRI website (2004). www.esri.com [01/15/2004].

European Commission. (2003). *Water for life, EU water initiative, International cooperation–from knowledge to action, Annex project summary information*. Luxembourg: Office for official publications of the European Communities. [19.12.2003, The European Union Online: http://europa.eu.int/comm/research/water-initiative/pdf/water-for-life-annexes_en.pdf].

FAO (2000). Faoclim 2: A CD-ROM with World-Wide Agroclimatic Data; Version 2.01.

FAO (2001). Lecture notes on the major soils of the world.

FAO-Africover. (2003). [29.10.2003, MADE Multipurpose Africover Databases on Environmental Resources: http://www.africover.org].

Feitelson, E., Chenoweth, J. (2002). Water poverty: towards a meaningful indicator. *Water policy, volume 4 (issue 3).* p.263-281 [16.12.2003, science direct: http://www.sciencedirect.com].

Hatibu, N., G.P. Msumali,& Rao K.P.C. (2002). *Proceedings of the Strategic Planning Workshop held in Arusha, June 2001. SwMNet Discussion paper No. 1* (*chapter 3.4*) [16.12.2003, Asareca Association for strengthening agricultural research in Eastern and Central Africa: http://www.asareca.org/swmnet/dpaper/kenya_d1.pdf].

INCO-DEV-REAL International Cooperation with Developing Countries. (2001). Rehydrating the earth in arid lands: Systems research on small groundwater retaining structures under local management in arid and semi-arid areas of east Africa, Part B: Description of the research work.

IWMI (The International Water Management Institute) (2000). *World Water Supply and Demand: 1995-2025.* Chapter 1&2.

Jury, W.A., Gardner W.R., Gardner W.H. (1991). *Soil physics (5th ed.).* Chapter 3: p. 80.

Maidment D.R. and Reed S. M. (1996). FAO/UNESCO Water Balance of Africa, Center for Research in Water Resources University of Texas, Austin: [10.02.2004, http://www.ce.utexas.edu/prof/maidment/gishydro/africa/ex3af/ex3af.htm].

Mays, L.W. (2001). *Water Resources Engineering*. Chapter 9: p. 288-292.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (2001). Climate change 2001: Impact, adaptation and vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, United Kingdom: Cambridge University press. [16.12.2003, http://www.grida.no/climate/ipcc_tar/wg2/index.htm].

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. (2001 a). Soil and Water Assessment Tool, Theoretical Documentation, Version 2000. Blackland Research Center. USDA-ARS, Texas Agr. Experiment Station, Texas. 506p.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. (2001 b). Soil and Water Assessment Tool, User Manual, Version 2000. Blackland Research Center. USDA-ARS, Texas Agr. Experiment Station, Texas. 448p.

Nissen-Petersen, E. (1982). *Rain catchments and water supply in rural Africa: a manual*. United Kingdom: Hodder and Stoughton.

Nissen-Petersen, E. (1997). Water from sand-rivers. Water and Sanitation for All: Proceedings of the 23rd WEDC Conference, Session J: Water Resources. p.394-396 [23.12.2003, Water, Engineering and Development Centre (WEDC) at Loughborough University: http://wedc.lboro.ac.uk/publications/details.php?book=0%20906055%2054%207 #SESSION%20J].

Puttemans, S. (2004). *Mogelijkheden voor kleinschalige irrigatie vanuit grondwaterdammen, gelegen in Zuid Kitui, Kenia. [Master thesis]*. Leuven, Belgium: Katholieke Universiteit, Faculty of agricultural and applied biological science, Departement land management, Spatial application division Leuven (SADL). 110p.

Odido, M. (1996). Marine science country profile for Kenya: A report prepared for IOC/UNESCO and WIOMSA [16.12.2003, http://www.wiomsa.org/download/Kenya.pdf].

Orodho, A. B. (2003). *Country pasture/ fourage resource profiles, Kenya.* Kakamega. [09.02.2004, FAO grassland and pasture crops: http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGP/AGPC/doc/Counprof/Kenya.htm#1].

Rockström J. (2000). Water resources management in smallholder farms in eastern and southern Africa: an overview. *Phys. Chem. Earth (B)* 25 3 (2000), p. 275–283.

SASOL (Sahelian Solutions) and Maji Na Ufansi (Water and Development), Thomas, Donald B. (1999). Where there is no water, a story of community water development and sand dams in Kitui district, Kenya. Nairobi: Majestic Printing Works Limited.

Shenkut, M. (2001). Rainwater Harvesting with Subsurface and Sand Dams.10th International Rainwater Catchment Systems Conference (IRSCA): Rainwater International 2001, Topic 2: Rainwater Catchment in Humid and Arid Regions, Mannheim, Germany. [23.12.03, IRSCA: http://www.eng.warwick.ac.uk/ircsa].

Shiklomanov, I. A. (2000). Appraisal and Assessment of World Water Resources. From International Water Resources Association, *Water International, Volume 25.* p. 11-32.

Simunek, J., Huang, K., Sejna, M., and Van Genuchten, M.Th. (1998 a). HYDRUS-1D: Version 2.02. Riverside, California, USA: U.S. Salinity Laboratory, USDA/ARS.

Simunek, J., Huang, K., Sejna, M., and Van Genuchten, M.Th. (1998 b). HYDRUS-1D: Version 2.02, *Help-files*. Riverside, California, USA: U.S. Salinity Laboratory, USDA/ARS.

Stuckens, J. (2004). Contour Gridder [5/07/2003, http://users.skynet.be/contourgridder/]

Taylor S.A. and Ashcroft. G.L. (1972). *Physical edaphology: the physics of irrigated and non-irrigated soils*, W.H. Freeman and Company, San Francisco, CA.

The World Bank. (2003). Kenya data profile. [16.12.2003, World development indicator database: http://devdata.worldbank.org].

Van Rompaey, A. (2001). *Geomorphic and land use change modelling at regional scale. PhD-dissertation.* Faculty of Sciences, K.U.Leuven, Belgium.

Vanham, D., (2003). *Water balance of the Cutuchi river basin (Ecuador), for two scenarios of land development. Master dissertation in partial fulfilment of the requirements for the Degree of Master of Science in Water Resources Engineering.* Vrije Universiteit Brussel-Katholieke Universiteit Leuven. 93 p.

WRI World Resources Institute. (2001). Freshwater resource withdrawals. [22.12.03, world resources 2000-2001: http://www.wri.org].

Ye, W., Jakeman, A.J., Young P.C., (1998). Identification of improved rainfall-runoff models for an ephemeral low-yielding Australian catchment. *Environmental Modelling & Software 13*, p. 59-74. [12/03/2004, science direct: http://www.sciencedirect.com].

I Annex: Weather generation

- **RAIN_YRS**

The number of years of maximum monthly 0.5 h rainfall data used to define values for the extreme half-hour rainfall for month *mon* (RAIN_HHMX (mon)).
If no value is input for RAIN_YRS, SWAT will set RAIN_YRS = 10.

- **TMPMX(mon)**

Average or mean daily maximum air temperature for month *mon* (ºC). This value is calculated by summing the maximum air temperature for every day in the month for all years of record and dividing by the number of days summed:

$$\mu mx_{mon} = \frac{\sum_{d=1}^{N} T_{mx,mon}}{N}$$

where μmx_{mon} is the mean daily maximum temperature for the month (°C), $T_{mx,mon}$ is the daily maximum temperature on record d in month *mon* (°C), and *N* is the total number of daily maximum temperature records for month *mon*.

- **TMPMN(mon)**

Average or mean daily minimum air temperature for month *mon* (ºC). This value is calculated by summing the minimum air temperature for every day in the month for all years of record and dividing by the number of days summed:

$$\mu mx_{mon} = \frac{\sum_{d=1}^{N} T_{mn,mon}}{N}$$

where μmn_{mon} is the mean daily minimum temperature for the month (°C), $T_{mn,mon}$ is the daily minimum temperature on record *d* in month *mon* (°C), and *N* is the total number of daily minimum temperature records for month *mon*.

- **TMPSTDMX(mon)**

Standard deviation for daily maximum air temperature in month *mon* (ºC). This parameter quantifies the variability in maximum temperature for each month. The standard deviation is calculated:

$$\sigma mx_{mon} = \sqrt{\left(\frac{\sum_{d=1}^{N} (T_{mx,mon} - \mu mx_{mon})^2}{N - 1} \right)}$$

where σmx_{mon} is the standard deviation for daily maximum temperature in month *mon* (ºC), $T_{mx,mon}$ is the daily maximum temperature on record *d* in month *mon* (°C), $\mu_{mx,mon}$ is the average daily maximum temperature for the month (°C), and *N* is the total number of daily maximum temperature records for month *mon*.

- **TMPSTDMN(mon)**

Standard deviation for daily minimum air temperature in month *mon* (ºC). This parameter quantifies the variability in minimum temperature for each month. The standard deviation is calculated:

$$\sigma mn_{mon} = \sqrt{\left(\frac{\sum_{d=1}^{N} (T_{mn,mon} - \mu mn_{mon})^2}{N - 1} \right)}$$

where σmn_{mon} is the standard deviation for daily minimum temperature in month *mon* (ºC), $T_{mn,mon}$ is the daily minimum temperature on record *d* in month *mon* (°C), $T_{mn,mon}$ is the average daily minimum temperature for the month (°C), and *N* is the total number of daily minimum temperature records for month *mon*.

- **PCPMM(mon)**

Average or mean total monthly precipitation (mm H_2O).

$$\overline{R}_{mon} = \frac{\sum_{d=1}^{N} R_{day,mon}}{yrs}$$

where $\overline{R}_{mon}$ is the mean monthly precipitation (mm H_2O), $R_{day,mon}$ is the daily precipiation for record *d* in month *mon* (mm H_2O), *N* is the total number of records in month *mon* used to calculate the average, and *yrs* is the number of years of daily precipitation records used in calculation.

- **PCPSTD(mon)**

Standard deviation for daily precipitation in month *mon* (mm H_2O/day). This parameter quantifies the variability in precipitation for each month. The standard deviation is calculated:

$$\sigma_{mon} = \sqrt{\left(\frac{\sum_{d=1}^{N} (R_{day,mon} - \bar{R}_{mon})^2}{N - 1} \right)}$$

where σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H_2O), $R_{day,mon}$ is the amount of precipitation for record *d* in month *mon* (mm H_2O), $\bar{R}_{mon}$ is the average precipitation for the month (mm H_2O), and *N* is the total number of daily precipitation records for month *mon*. (Note: daily precipitation values of 0 mm are included in the standard deviation calculation)

- **PCPSKW(mon)**

Skew coefficient for daily precipitation in month *mon*. This parameter quantifies the symmetry of the precipitation distribution about the monthly mean. The coefficient of skewness is calculated:

$$g_{mon} = \frac{N \cdot \sum_{d=1}^{N} (R_{day,mon} - \bar{R}_{mon})^3}{(N - 1) \cdot (N - 2) \cdot (\sigma_{mon})^3}$$

where g_{mon} is the skew coefficient for precipitation in the month, *N* is the total number of daily precipitation records for month *mon*, $R_{day,mon}$ is the amount of precipitation for record *d* in month *mon* (mm H2O), $\bar{R}_{mon}$ is the average precipitation for the month (mm H_2O), and σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H_2O). (Note: daily precipitation values of 0 mm are included in the skew coefficient calculation)

- **PR_W(1,mon)**

Probability of a wet day following a dry day in month *i*. This probability is calculated:

$$P_i(W/D) = \frac{days_{W/D,i}}{days_{dry,i}}$$

where *Pi(W/D)* is the probability of a wet day following a dry day in month *i*, $days_{W/D,i}$ is the number of times a wet day followed a dry day in month *i* for the entire period of record, and $days_{dry,i}$ is the number of dry days in month *i* during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation.

- **PR_W(2,mon)**

Probability of a wet day following a wet day in the month *i*. This probability is calculated:

$$P_i(W/W) = \frac{days_{W/W,i}}{days_{wet,i}}$$

where *Pi(W/W)* is the probability of a wet day following a wet day in month *i*, $days_{W/W,i}$ is the number of times a wet day followed a wet day in month *i* for the entire period of record, and $days_{wet,i}$ is the number of wet days in month *i* during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation.

- **PCPD(mon)**

Average number of days of precipitation in month *i*. This parameter is calculated:

$$\bar{d}_{wet,i} = \frac{days_{wet,i}}{yrs}$$

where $\bar{d}_{wet,i}$, is the average number of days of precipitation in month *i*, $days_{wet,i}$ is the number of wet days in month *i* during the entire period of record, and *yrs* is the number of years of record.

- **SOLARAV(mon)**

Average daily solar radiation for month *mon* (MJ/m^2/day). This value is calculated by summing the total solar radiation for every day in the month for all years of record and dividing by the number of days summed:

$$\mu rad_{mon} = \frac{\sum_{d=1}^{N} H_{day,mon}}{N}$$

where μrad_{mon} is the mean daily solar radiation for the month (MJ/m^2/day), $H_{day,mon}$ is the total solar radiation reaching the earth's surface for day *d* in month *mon* (MJ/m^2/day), and *N* is the total number of daily solar radiation records for month *mon*.

- **DEWPT(mon)**

Average daily dew point temperature in month *mon* (ºC). The dew point temperature is the temperature at which the actual vapour pressure present in the atmosphere is equal to the saturation vapour pressure. This value is calculated by summing the dew point temperature for every day in the month for all years of record and dividing by the number of days summed:

$$\mu dew_{mon} = \frac{\sum_{d=1}^{N} T_{dew,mon}}{N}$$

where μdew_{mon} is the mean daily dew point temperature for the month (ºC), $T_{dew,mon}$ is the dew point temperature for day *d* in month *mon* (ºC), and *N* is the total number of daily dew point records for month *mon*.

- **WNDAV(mon)**

Average daily wind speed in month *mon* (m/s). This value is calculated by summing the average or mean wind speed values for every day in the month for all years of record and dividing by the number of days summed:

$$\mu wnd_{mon} = \frac{\sum_{d=1}^{N} \mu_{wind,mon}}{N}$$

where μwnd_{mon} is the mean daily wind speed for the month (m/s), $\mu_{wnd,mon}$ is the average wind speed for day *d* in month *mon* (m/s), and *N* is the total number of daily wind speed records for month *mon*.

(Neitsch *et al.*, 2001 b).

	Jan	Feb	Mrt	Apr	Mei	Jun	Jul	Aug	Sep	Okt	Nov	Dec
Complete Years (of 21)	19	18	20	18	18	17	14	14	17	17	19	19
PCPMM	82,04	17,09	74,43	141,66	29,16	3,39	2,89	8,36	17,79	48,33	294,62	160,85
PCPSTD (mon)	11,20	5,22	10,19	14,50	4,04	1,24	0,85	2,60	3,80	8,08	22,15	16,03
PCPSKW (mon)	6,32	11,22	5,89	4,64	6,35	13,78	10,81	15,95	7,62	8,59	3,51	2,93
PR_W(1,mon)	0,07	0,02	0,09	0,17	0,05	0,02	0,02	0,02	0,03	0,07	0,23	0,16
PR_W(2,mon)	0,50	0,18	0,30	0,39	0,45	0,11	0,11	0,17	0,36	0,32	0,58	0,51
PCPD(mon)	3,58	0,61	3,50	6,50	2,72	0,53	0,64	0,86	1,29	2,88	10,63	7,47
TMPMX (mon)	27,70	29,30	30,00	27,70	26,60	26,00	25,00	25,50	27,10	28,20	26,60	26,00
TMPMN (mon)	16,00	16,60	17,10	17,10	16,60	14,30	13,80	13,80	13,80	15,50	16,60	16,60
TMPSTDMX (mon)	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51
TMPSTDMN (mon)	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35	1,35
WNDAV (mon)	2,30	2,50	2,50	2,20	2,60	2,60	2,80	3,10	2,80	3,20	2,60	2,80
DEWPT (mon)	16,80	17,20	17,80	18,30	17,10	15,20	14,00	13,60	13,70	14,60	17,10	17,40
SOLARAV (mon)	24,37	25,62	23,40	20,72	19,76	18,46	15,66	19,05	21,44	22,40	21,14	21,86
RAINYRS	10											

Table I.1 Weather generation

	Source	Years
Daily precipitation	Mutomo (IMTR)	21 (not all complete)
TMPMX (mon)	Kitui Argic (FAO)	7
TMPMN (mon)	Kitui Argic (FAO)	7
WNDAV (mon)	Kitui Argic (FAO)	7
DEWPT (mon)	Kitui Argic (FAO)	8
SOLARAV (mon)	Kitui Argic (FAO)	?

Table I.2 Source and years for calculation of weather generation

II Annex: Soil input data

- **HYDGRP**

Soil hydrologic group (A, B, C, or D). The definitions for the different classes are represented in Table II.1.

A	Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of sands or gravel that are deep and well to excessively drained. These soils have a high rate of water transmission (low runoff potential).
B	Soils having moderate infiltration rates when thoroughly wetted, chiefly moderately deep to deep, moderately well to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C	Soils having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water or of moderately fine to fine texture and a slow infiltration rate. These soils have a slow rate of water transmission (high runoff potential).
D	Soils having very slow infiltration rates when thoroughly wetted, chiefly clay soils with a high swelling potential; soils with a high permanent water table; soils with a clay pan or clay layer at or near the surface; and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission.

Table II.1: Soil hydrologic group

- **SOL_ZMX**

Maximum rooting depth of soil profile (mm)

If no depth is specified, the model assumes the roots can develop throughout the entire depth of the soil profile.

- **ANION_EXCL**

Fraction of porosity (void space) from which anions are excluded.

If no value for ANION_EXCL is entered, the model will set ANION_EXCL = 0.50.

Because no values were found, this parameter was given the value 0.01. (Biesbrouck B. *et al.,* 2002).

- **SOL_CRK**

Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume. To accurately predict surface runoff and infiltration in areas dominated by Vertisols, the temporal change in soil volume must be quantified. (Optional)

- **SOL_Z(layer #)**

Depth from soil surface to bottom of layer (mm).

- **SOL_BD(layer #)**

Moist bulk density (Mg/m^3 or g/cm^3).

The soil bulk density expresses the ratio of the mass of solid particles to the total volume of the soil, $\rho_b = M_S / V_T$. In moist bulk density determinations, the mass of the soil is the oven dry weight and the total volume of the soil is determined when the soil is at or near field capacity. Bulk density values should fall between 1.1 and 1.9 Mg/m^3.

- **SOL_AWC(layer #)**

Available water capacity of the soil layer (mm H_2O/mm soil).

The plant available water, also referred to as the available water capacity, is calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity: WP – FC = AWC

where *AWC* is the plant available water content, *FC* is the water content at field capacity, and *WP* is the water content at permanent wilting point.

- **SOL_K(layer #)**

Saturated hydraulic conductivity (mm/hr).

The saturated hydraulic conductivity, K_{sat}, relates soil water flow rate (flux density) to the hydraulic gradient and is a measure of the ease of water movement through the soil. K_{sat} is the reciprocal of the resistance of the soil matrix to water flow.

- **SOL_CBN(layer #)**

Organic carbon content (% soil weight). When defining by soil weight, the soil is the portion of the sample that passes through a 2 mm sieve. The organic carbon content is based on a soil report close to the catchement area (Biesbrouck B. et al., 2002).

- **CLAY(layer #)**

Clay content (% soil weight).
The percent of soil particles which are < 0.002 mm in equivalent diameter.

- **SILT(layer #)**

Silt content (% soil weight).
The percentage of soil particles which have an equivalent diameter between 0.05 and 0.002 mm.

- **SAND(layer #)**

Sand content (% soil weight).
The percentage of soil particles which have a diameter between 2.0 and 0.05 mm.

- **ROCK(layer #)**

Rock fragment content (% total weight).
The percent of the sample which has a particle diameter > 2 mm, i.e. the percent of the sample which does not pass through a 2 mm sieve.

- **SOL_ALB(layer #)**

Moist soil albedo.
The ratio of the amount of solar radiation reflected by a body to the amount incident upon it, expressed as a fraction. The value for albedo should be reported when the soil is at or near field capacity. Only the moist albedo for the first layer has been specified because it is assumed that the soil layers will not move. The used values (see Table II.2) are based on Taylor and Ashcroft (1972).

Dry sand	0.35-0.45
Wet sand	0.20-0.30
Dark soil	0.05-0.15
Wet gray soil	0.10-0.20
Dry light clay soil	0.20-0.35
Dry light sand soil	0.25-0.45

Table II.2: Moist soil albedo

- **USLE_K(layer #)**

USLE equation soil erodibility (K) factor (units: 0.013 (metric ton m^2 hr)/ (m^3-metric ton cm)). These values are based on Van Rompaey (2001) (see Table II.3). The right textural class can be found with the textural diagram.

Textural class	USLE_K
A	0.041
L	0.037
P	0.026
S	0.019
Z	0.012
E	0.029
U	0.028

Table II.3: Soil erodibility factor

(Neitsch *et al.*, 2001 b).

Lixisol														
HYDGRP	B	**Layer**	**SOL_Z**	**SOL_BD**	**SOL_AWC**	**SOL_K**	**SOL_CBN**	**CLAY**	**SILT**	**SAND**	**ROCK**	**SOL_ALB**	**USLE_K**
SOL_ZMX	1000	1	200	1,36	0,0993	273,39	0,7	12,26	13,37	74,36	0	0,25	0,019
ANION_EXCL	0,01	2	500	1,33	0,0598	270,39	0,5	22,67	1,45	66,90	0	0	0,029
SOL_CRK	0	3	700	1,39	0,0864	29,81	0,2	22,51	12,74	64,75	0	0	0,029

Table II.4: Soil characteristics of Lixisol

Planosol													
HYDGRP	D	**Layer**	**SOL_Z**	**SOL_BD**	**SOL_AWC**	**SOL_K**	**SOL_CBN**	**CLAY**	**SILT**	**SAND**	**ROCK**	**SOL_ALB**	**USLE_K**
SOL_ZMX	800	1	40	1,40	0,0840	60,12	1,0	10,12	9,84	80,04	0	0,25	0,019
ANION_EXCL	0,01	2	1000	1,42	0,0810	40,00	0,5	20,14	7,65	72,21	0	0	0,029
SOL_CRK	0												

Table II.5: Soil characteristics of Planosol

Vertisol													
HYDGRP	D	**Layer**	**SOL_Z**	**SOL_BD**	**SOL_AWC**	**SOL_K**	**SOL_CBN**	**CLAY**	**SILT**	**SAND**	**ROCK**	**SOL_ALB**	**USLE_K**
SOL_ZMX	400	1	550	1,49	0,1538	5,693	1,0	28,05	19,24	52,71	0	0,1	0,029
ANION_EXCL	0,01	2	850	1,44	0,1281	0,6693	0,5	31,20	19,47	49,33	0	0	0,029
SOL_CRK	0,15	3	1000	1,27	0,1670	2,8771	0,5	35,80	18,20	45,99	0	0	0,028

Table II.6: Soil characteristics of Vertisol

III Annex: Major soil units in the Ngunga-catchment

Lixisols

The dominant soils in the Ngunga-catchment are the strongly weathered Lixisols. In these soils the clay has been washed out of an eluvial horizon down to an argic subsurface horizon that has low activity clays and a moderate to high base saturation level. The argic horizon can be overlain by loamy sand or coarser textures.

Lixisols are typically found in regions with a tropical, subtropical or warm temperate climate with a pronounced dry season. Many Lixisols are assumed to be polygenetic soils with characteristics formed under a more humid climate in the past. Proofs of this more humid climate are the inclusions of fossil plintite found round eroded roads and hills in the catchment. Lixisols in the upper regions are associated with rock outcrops.

Most ‘unreclaimed’ Lixisols in the Ngunga-catchment are under bush or open woodland vegetation and are used for low volume grazing. The main crops on Lixisols in the area are maize and cowpeas. The fields are cleared by slash and burn. Soil labour is done by native hoes. Slash and burned releases necessary nutrients to the soils, which are by native poorly supplied with nutrients. However, to have an acceptable yield, these soils require recurrent inputs of fertilizers and/ or lime.

In the sloping study-area, the unstable surface soil structure makes Lixisols very prone to slaking and erosion through the direct impact of raindrops. It is therefore important to introduce conservation techniques to preserve the surface soils with its important organic matter. Tillage and erosion control measures such as terracing, contour ploughing, mulching and the use of cover crops help to conserve the soil (FAO, 2001). A Lixisol sample profile of the region is described in Figure III.1.

Horizon	Depth	Description
Ap	0-20 cm	Dark brown, loamy sand; many roots; gradual smooth boundary.
AB	20-50 cm	Reddish brown, clay, slightly hard, sticky many roots, many fine and few coarse pores, few calcareous concretions; smooth boundary.
B_t	50-100 cm	Light reddish brown, clay, sticky, plastic; roots until 100 cm; moderate medium subangular blocky; few calcareous concretions.

Figure III.1: Sample profile: Lixisol

Vertisols

In the East part of the Ngunga-catchment, a small area of Vertisol occurs. This area forms a part of a large, relatively flat Vertisol plain that reaches until the Semea River near Ikanga in the East.

Vertisols are heavy clays with a high proportion (>30%) of 2:1 lattice clays. These clays swell during the rainy season and shrink during the dry season with deep wide cracks from the surface downward as a consequence (see Figure III.2). Vertisols are soils with good water holding properties. However, a large proportion of all water in Vertisols, and notably the water held between the basic crystal units, is not available to plants.

Though these soils form a considerable agricultural potential, the major part of the Vertisols in the study-area are still unused. To cultivate Vertisols, appropriate management has to be applied. Although Vertisols have a high chemical fertility they are very difficult to cultivate because of the stickiness and plasticity in moist conditions and the hardness when dry. The susceptibility of Vertisols to water logging is an important factor that reduces the actual growing period. Surface drainage is therefore indispensable.

Natural vegetation on Vertisols consists of grass and scattered trees. Tree growth on Vertisols is limited because the roots have difficulties to establish themselves into the hard subsoil and because they are damaged as the soil shrinks and swells (FAO, 2001).

A Vertisol sample profile of the region is described in Figure III.3.

Figure III.2: Top view of the cracks in a Vertisol

Horizon	Depth	Description
Ap	0-10 cm	Black sandy clay, subangular blocky structure; surface cracks; sticky when wet; very plastic; smooth boundary.
AC1	10-55 cm	Black clay; few fine and medium whitish lime concretions; very hard; sticky when wet: very plastic; strong coarse prismatic structures; roots until 40 cm; smooth clear boundary.
AC2	55-85 cm	Black-dark grey clay; common whitish lime concretions; hard; sticky when wet; very plastic; slight coarse prismatic structures; gradual boundary.
C	85-100 cm	Grey clay with much lime concretions; very hard; sticky when wet; very plastic.

Figure III.3: Sample profile: Vertisol

Planosols

Associated with the Vertisols in the East, quite a large flat area of Planosols is found. Only a small part of this area is part of the Ngunga-catchment. The Planosols can be seen as the degraded form of Vertisols. Planosols are strongly degraded soils with bleached, greyish eluvial surface horizon with a sandy or loamy texture and a weak structure of low stability. The most prominent feature of Planosols is the marked increase in clay content on passing from the degraded eluvial horizon to the deeper soil. The latter may be a slowly permeable argic illuviation horizon, mottled and with coarse angular blocky or prismatic structural elements. Planosols show periodic water stagnation that is the result of the heavy texture in the subsurface.

The sandy surface material becomes hard when dry but not cemented. Especially on roads the top soil can become loose and single-grained and can cause clouds of dust.

In general, the poor Planosols are mostly left uncultivated. This is also the case in the study-area. The natural Planosol areas are covered with sparse grass vegetation with scattered shrubs and trees, similarly with the Vertisol vegetation. The trees have extensive, shallow root systems that are capable of withstanding both severe drought and seasonal or occasional water logging (FAO, 2001).

A Planosol sample profile of the region is described in Figure III.4.

Horizon	Depth	Description
A_h	0-20 cm	Grey coarse sand; hard but loose and dusty on the top; many pores; no cracks; diffuse boundary.
E	20-40 cm	Yellowish grey sand; hard; many pores; clear smooth boundary.
B_t	40-100 cm	Yellowish brown clay; hard; many pores; roots until 80 cm; moderate medium subangular blocky;

Figure III.4: Sample profile: Planosol