Katholieke Universiteit Leuven

Faculteit Landbouwkundige en
Toegepaste Biologische Wetenschappen

Mogelijkheden voor kleinschalige irrigatie vanuit grondwaterdammen, gelegen in Zuid Kitui, Kenia.

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Potential for small scale irrigation from groundwater dams in South Kitui, Kenya

Promotoren:

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Departement Landbeheer
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Prof. Dr. Ir. D. Raes
Departement Landbeheer
Laboratorium voor Bodem- en Waterbeheer

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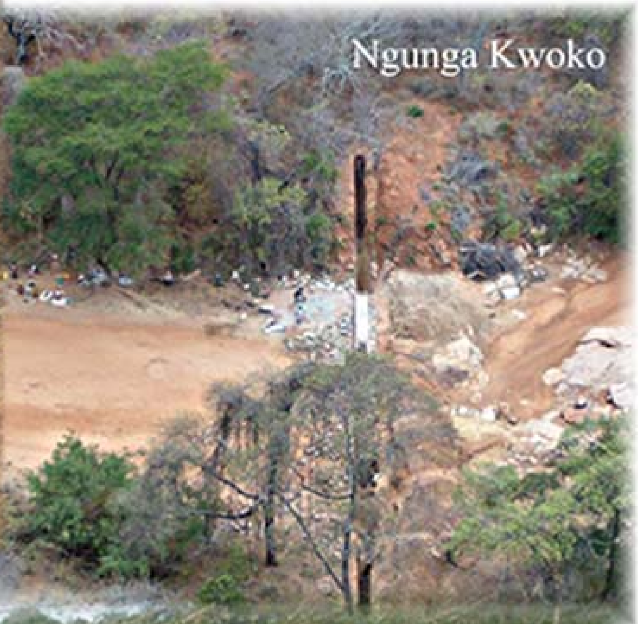
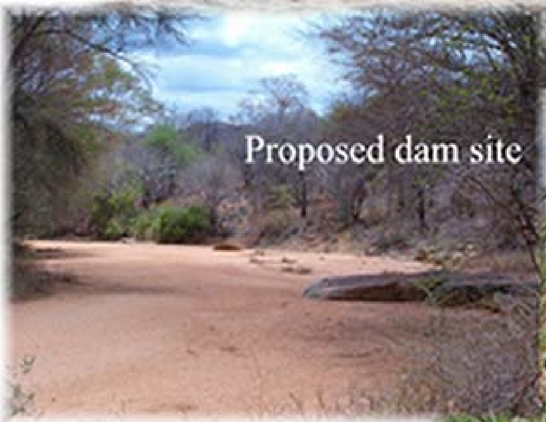
Ngunga Kwoko


Ngunga Kwoko


Mature dam
Kitui, Central Division


Proposed dam site


Field interviews

Malovoto maingi nimo maseuvasya ukanga (Kikamba).

A lot of drops make an ocean.

The picture in the SASOL field office.

DANKWOORD

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SUMMARY IN DUTCH

Hoofdstuk 1: Introductie tot en achtergrond van de studie

In de toekomst zal Kenia geconfronteerd worden met economische waterschaarste. In het land zijn er tot op heden genoeg watervoorraden maar naar de toekomst toe is er een noodzaak om deze te verhogen door een betere regelgeving en het realiseren van betere systemen voor de verdeling. Tezelfdertijd lijdt het land aan waterarmoede, wat wil zeggen dat het niet ten alle tijden de kosten kan dragen om op een duurzame manier proper water te voorzien aan al haar burgers. Een intensifiëring van de menselijke activiteiten en een sterke populatiegroei zullen deze problemen alleen maar doen toenemen. De delen van Kenia die het hardste getroffen worden door waterarmoede en economische waterschaarste zijn de arme, rurale, aride en semi-aride gebieden. Een van die gebieden is het Kitui district. Om de waterproblemen in deze gebieden te bestrijden, is het belangrijk dat er duurzame en tegelijkertijd goedkope oplossingen gevonden worden. Een veelbelovende technologie voor de semi-aride gebieden in Sub-Sahara Afrika is “rainwater harvesting”.

Een voorbeeld van deze technologie zijn de “sand-storage” dammen die in the Kitui district gebouwd worden op lokaal initiatief. Dit zijn ondergrondse dammen voor opslag van regenwater, gebouwd in de bedding van de efemere rivieren. De dammen zorgen ervoor dat er lokaal meer water voor een langere tijd aanwezig is. Ze dragen dus bij tot het verlagen van de kans waterschaarste. De kleinschalige dammen hebben een groot effect op de gemeenschappen die er gebruik van maken, op landbouw en op de omgeving. Doordat er meer water voor een langere tijd beschikbaar is, kan er gestart worden met geïrrigeerde landbouw. De opbrengsten hiervan worden verkocht op lokale markten. Deze geïrrigeerde landbouw gebeurt op kleine schaal op de rivieroevers en kan eigenlijk meer als tuinbouw geklasseerd worden.

Hoofdstuk 2: Objectieven en chronologie van de studie

Objectieven van de studie

Het hoofdobjectief van deze studie is bepalen of de traditionele irrigatiekalenders, gebruikt om gewassen te irrigeren met water van de “sand-storage” dammen, kunnen geoptimaliseerd worden op vlak van waterefficiëntie. Indien dit het geval is kunnen richtlijnen gegeven worden voor efficiëntere irrigatiekalenders. Dit gebeurt door eerst irrigatieschema’s te ontwikkelen voor de gewassen die nu verbouwd worden en deze daarna te vergelijken met de huidige irrigatiekalenders.

De waterbehoeften van de gewassen worden bepaald door gebruik te maken van het bodem-water balans model BUDGET (Raes, 2004). Deze balans is afhankelijk van binnenkomende en uitgaande waterfluxen en van de hoeveelheid water dat kan opgeslagen worden in het bodemprofiel. Binnenkomende fluxen zijn neerslag en capillaire opstijging van een ondiepe watertafel. Uitgaande fluxen zijn diepe drainage uit de wortelzone en evapotranspiratie naar de atmosfeer. Opslag wordt bepaald door de bodemkarakteristieken van de wortelzone. Om de waterbalans op te lossen heeft het BUDGET model input gegevens nodig. Deze werden verzameld en worden in deze studie geanalyseerd. De capillaire opstijging wordt gesimuleerd met het UPFLOW model (Raes, 2001).

Deze studie heeft eveneens het objectief om te bepalen welk volume water de “sand-storage” dam, die zal gebouwd worden in het studiegebied, kan leveren om aan geïrrigeerde landbouw te doen. Hierbij mag de watervoorziening van de mensen en het vee niet in gevaar komen. Als de hoeveelheid water die beschikbaar is voor irrigatie bekend is, kan een optimale oppervlakte voor irrigatie bepaald worden door gebruikt te maken van de opgestelde irrigatierichtlijnen.

Chronologie van de studie

Het veldonderzoek van deze studie vond plaats van juli tot oktober 2003 in Kisayani en rond Kitui stad, beiden gelegen in het Kitui district van Kenia. Dit onderzoek ter plaatse werd georganiseerd om gegevens te verzamelen die later als input voor het BUDGET model gebruikt konden worden. De data verzameling bestond uit het nemen van bodemstalen, verzamelen van meteorologische gegevens en interviewen van de lokale landbouwers om een beter zicht te krijgen op de verbouwde gewassen, gewaskalenders, irrigatiekalenders en gewasopbrengsten.

De gegevensverwerking en analyse van de bodemstalen vond plaats te Leuven, België, van oktober tot mei 2003.

Hoofdstuk 3: Materiaal en methoden

De onbetrouwbare neerslag in the semi-aride gebieden en het ontbreken van richtlijnen voor irrigatie op een voldoende kleine tijdstap bemoeilijken het nemen van beslissingen gedurende het groeiseizoen. Voor de kleine landbouwer zijn zelden irrigatierichtlijnen beschikbaar of vergen ze dure apparatuur voor opmeting en dataverwerking. Dit heeft als gevolg dat deze kleine landbouwers meestal een strikt interval behouden in hun irrigatiekalenders met of zonder empirische aanpassingen aan de weersituatie. De toedieningen worden dan ook meestal gekarakteriseerd door opeenvolgende periodes van over- en onderirrigatie.

Bodem-water balans modellen en gewasgroei modellen

In rurale gebieden zijn zelden resultaten van veldexperimenten aanwezig. Het opzetten van uitgebreid veldwerk is meestal financieel niet mogelijk zodat de risico's verbonden aan gewasproductie niet kunnen ingeschat worden door gebrek aan historische data. Een goedkoper alternatief is het bestuderen van de risico's door simulatiemodellen. Voordeel is het minimale en goedkoper veldwerk.

In de studie wordt gebruik gemaakt van het functionele, dynamische en deterministische BUDGET model (Raes, 2002) omdat dit een goed compromis is tussen een exacte moddelering aan de ene en beperkte gegevensbeschikbaarheid en financiële middelen aan de andere kant. Het is een alternatief voor het gebruik van mechanistisch modellen, zoals WAVE (Vanclooster *et al.*, 1994). Deze laatste modellen hebben een input dataset nodig die meestal niet aanwezig is buiten de onderzoekscentra.

Klimatologische data

De regenvalgegevens van 14 meteorologische stations in het Kitui district werd verzameld, deze stations zijn weergegeven in Appendix 1. Van deze datasets worden vier stations met dagelijkse neerslaggegevens, gelegen in de nabijheid van het studiegebied, verder gebruikt in deze studie. De dataset van het landbouwkundig station van Mutomo met 21 jaar aan dagelijkse observaties worden als basis gebruik. Via een analyse op de ontbrekende observaties en het aantal observaties zonder neerslag wordt getracht deze basisdataset aan te vullen met observaties van de andere drie datasets. Als een homogene dataset bekomen is, worden de dagelijkse gegevens omgevormd tot decade gegevens. Op deze 21 jaar lange dataset wordt een homogeniteitsanalyse en frequentie analyse gedaan gebruik makend van de RAINBOW software (Raes, 200b). De te verwachten neerslag die men voor een bepaalde decade in 20%, 50% en 80% van de jaren kan verwachten wordt hieruit bekomen.

Gemiddelde maandelijkse waarden voor temperatuur (gemiddeld, minimum en maximum), windsnelheid, fractie aan relatieve zonneschijn en globale radiatie van het landbouwkundig station in Kitui worden gebruikt voor de schatting van de evapotranspiratie. Omdat de dataset enkel gemiddelde maandelijkse gegevens bevat worden deze met de formule van Gommes (1983) omgezet naar decade gegevens. De gegevens worden ingegeven in de ET0 software (Raes, 2000a) waarmee de evapotranspiratie geschat wordt, gebruik makend van de Penmann-Montheit vergelijking.

De lengte van de groeiperiode van regengevoede gewassen kan bepaald worden volgens de methode van De Pauw (1989). Het is een continue periode waarin de neerslag groter is dan de helft van evapotranspiratie plus de tijd nodig om 100 mm extra water, opgeslagen in de bodem, te evapotranspireren. Voor elk regenseizoen van de 21 jaar lange dataset wordt op decadeniveau de lengte, het begin en het einde van de groeiperiode bepaald. Op deze data wordt een frequentieanalyse uitgevoerd met de RAINBOW software (Raes, 2000b).

Gewasgegevens en landbouwsystemen

De landbouwsystemen in het Kitui district kunnen geklasseerd worden als “permanent upland cultivation”, een systeem met een lage productie, een hoog risico op droogte en erosie en een hoge uitputtingsgraad van de bodem. De geïrrigeerde landbouw op kleine schaal kan echter een aanwijzing zijn dat het systeem aan het evolueren is naar een hoofdzakelijk op irrigatie gebaseerde landbouw. Deze evolutie naar grotere geïrrigeerde oppervlakten is onder meer afhankelijk van de hoeveelheid water die beschikbaar is. “Sand-storage” dammen zouden als een katalysator kunnen functionere in deze evolutie.

Het verzamelen van gewasgegevens gebeurde op twee manieren, eerst en vooral door interviews met de lokale boeren, waar vooral informatie over gekweekte gewassen, gewaskalenders, irrigatiekalenders en opbrengsten werden verzameld. Ten tweede worden er literatuurdata gebruikt voor de gegevens die meer plantspecifiek zijn als de gewascoëfficiënten (K_C), de opbrengst respons factoren (K_Y), de worteldiepte en parameters die met slecht management en water stress te maken hebben (p en K_S). *Allen et al.* (1998) bieden via een wegingsformule de mogelijkheid om de gewascoëfficiënten voor geïntercropte velden te berekenen. Aannames moeten wel gemaakt worden over de p fractie (bodem-water fracties waarbij er geen stress is) en de worteldiepte van de gewassen die samen gekweekt worden.

Bodemgegevens

Bodem gegevens worden verzameld door het nemen van ongestoorde en gestoorde stalen en door het uitvoeren van veldexperimenten. De ongestoorde stalen worden geanalyseerd op hun bodem-water karakteristieken zoals verzadigde hydraulische conductiviteit en watergehalte op verzadiging, veldcapaciteit en verwelkingspunt. De gestoorde stalen worden gebruikt om de textuur van de bodems te bepalen. De veldexperimenten waren de bepaling van de verzadigde hydraulische conductiviteit via de methode van de dubbele ring infiltrometer en de methode van Porchet.

Naast het effectief meten van de bodem-water karakteristieken bestaat er een goedkopere manier om deze te schatten, namelijk door het gebruik van textuur gegevens in combinatie met pedotransfer functies. In de studie worden twee van die functies gebruikt. Saxton *et al.* (1986) ontwikkelde een set van pedotransfer functies die enkel op basis van textuurgegevens de bodem-water karakteristieken te schatten. De gebruikte SPAW-hydrology software zorgt voor een vereenvoudiging van de berekeningen. Een tweede set van functies werd ontwikkeld door “Van Genuchten” (1980). Dit model laat de invoer toe van de gemeten bodem-water karakteristieken om zo een betere schatting te kunnen maken van de parameters die de bodem-water retentie curve (pF curve) beschrijven. Het ROSETTA model (Schaap et al., 2001) zorgt hier voor de vereenvoudiging van de berekeningen. Door het doorvoeren van de gemeten en de geschatte bodem-water karakteristieken in het BUDGET en het UPFLUW model en het vergelijken van de output, kan bepaald worden of het nuttig is voor later studies om minder dure technieken te gebruiken bij het schatten van deze parameters.

Uit de verzamelde gegevens worden vier bodems geselecteerd, die representatief zijn voor het studiegebied en waarmee verder in deze studie zal gewerkt worden.

Capillaire opstijging

Om de “steady state” capillaire opstijging vanuit een ondiepe watertafel the simuleren wordt gebruik gemaakt van de UPFLOW software (Raes, 2001). De grenscondities die ingevoerd moeten worden in het model zijn de gemiddelde gewasevapotranspiratie gedurende de simulatieperiode, het gemiddelde watergehalte van de toplaag van de bodem en de diepte van de watertafel onder die toplaag, het waterextractie patroon van het gewas, de dikte van de opeenvolgende bodemhorizonten. Eventueel kan ook het zoutgehalte van de waterlaag ingevoerd worden.

Om de resultaten niet aquifer-specifiek te maken zodat ze ook buiten het studiegebied kunnen dienen, worden er grafieken gemaakt waarmee aan de hand van de diepte van de watertafel (die in het veld kan bepaald worden) de capillaire opstijging voor een bodem kan bepaald worden. Hiervoor moeten er echter een paar abstracties gemaakt worden. De potentiële evapotranspiratie wordt verondersteld het hele jaar door de gemiddelde jaarlijkse waarde te zijn. Drie hypothetische gewassen worden gebruikt met verschillende worteldiepte en gewascoëfficiënten (K_C). Als bodem-water karakteristieken worden de parameters van het “Van Genuchten” model gebruikt samen met de gemeten verzadigde hydraulische konductiviteit. De geschatte verzadigde hydraulische konductiviteiten worden ook doorgevoerd in UPFLOW om het effect op de output te analyseren.

Richtlijnen voor irrigatie: het ontwikkelen van “irrigation charts”

In deze studie worden irrigatieschema’s ontwikkeld voor de traditionele irrigatie met emmers. Deze geven de landbouwers eenvoudige richtlijnen over hoe ze hun irrigatie kunnen aanpassen aan de actuele weersomstandigheden, aan de aanwezigheid van capillaire opstijging en aan watertekorten. De irrigatiekalenders worden ontwikkeld door gebruik te maken van een bodem-water balans techniek, gesimuleerd met het BUDGET model (Raes, 2004). De richtlijnen worden samengevat in “irrigation charts” die de situatie weergeven voor een bepaald gewas, een bepaalde bodem en een bepaalde irrigatietoediening. De ontwikkeling van “irrigation charts” vergt een goede kennis van de regionale klimatologie, bodem-water karakteristieken, de capillaire opstijging in functie van de watertafeldiepte, de gewaskarakteristieken en de traditionele irrigatiepraktijken. Hoe de intervallen, aangegeven in de “irrigation charts” worden bepaald en kunnen aangepast worden in functie van de klimatologische omstandigheden en de diepte van de watertafel wordt uitgelegd in paragraaf 3.6.1.2.

Irrigatierichtlijnen worden ontwikkeld voor de traditionele geïrrigeerde gewassen zoals tomaten, sukuma wiki (kool), uien en spinazie. Dit gebeurt voor de vier geselecteerde representatieve bodems, in het lange droge seizoen (mei-september) en met een netto applicatiediepte van 10 mm en 20 mm. Voor deze traditionele verbouwingspraktijken worden eveneens richtlijnen ontwikkeld die het effect van capillaire opstijging in rekening brengen. Ook nieuwe zaai- en plantdata worden onderzocht, echter alleen voor de oeverbodems. Richtlijnen worden ontwikkeld voor het verbouwen van de gewassen gedurende en tussen de korte regens (oktober-februari) en de lange regens (maart-april).

Voor de traditioneel regengevoede voedselgewassen en hun intercrops (maïs, maïs en bonen en maïs en cowpeas) worden richtlijnen voor supplementaire irrigatie aangeboden met een netto applicatiediepte van 20 mm en 40 mm.

Hoofdstuk 4: Resultaten en discussie

Klimatologische data

De neerslag dataset van het landbouwkundig station van Mutomo is deels aangevuld met observaties zonder neerslag van het landbouwkundig station van Ithookwe. Daardoor daalt het aantal ontbrekende observaties in de eerste dataset met 12%. De redenering achter deze bewerking is weergegeven en uitgewerkt in paragraaf 4.1.1.

De resultaten van de frequentie analyse op de neerslaggegevens en de schatting van de evapotranspiratie worden weergegeven in respectievelijk Appendix 2 en Appendix 3 en worden samengevat in Figure 4.3. Deze figuur toont de grote temporele variatie in neerslag. De ruimtelijke variatie tussen gegevens van nabijgelegen stations is ook significant.

De analyse van de lengte, het begin en het einde van het groeiseizoen toonde aan dat een verschil van een maand in het beginnen van het groeiseizoen evenals een verschil van 40 dagen in de lengte ervan niet uitzonderlijk zijn.

Gewasgegevens en landbouwsystemen

Relevante gewasparameters voor de simulatie van groei en opbrengst worden verzameld in gewasfiches in Appendix 5 voor enkele gewassen. De fiches voor de andere gewassen staan op de bijgevoegde CD-ROM. Deze fiches bestaan uit drie delen. Een eerste deel geeft de agronomische data weer zoals bijvoorbeeld de zaaidatum, de lengte van het groeiseizoen, de gewascoëfficiënten en de worteldiepte. Een tweede deel geeft de data weer in verband met het effect van water op de gewasopbrengsten. En een derde deel geeft opmerkingen in verband met irrigatie van het gewas.

Bodemgegevens

De bodem-water karakteristieken, gemeten in het veld en in het laboratorium en geschat met pedotransfer functies, worden weergegeven in Appendix 6. Figure 4.12 toont de ligging van de vier gekozen representatieve bodemprofielen in de topografie, samen met hun diepte.
De variabiliteit tussen de verschillende gemeten en geschatte bodem-water karakteristieken kan significant zijn op vlak van irrigatieplanning en zal dus in rekening moeten gebracht worden bij het simuleren met BUDGET en UPFLOW. De verzadigde hydraulische conductiviteit is de meest onzekere parameter.

Capillaire opstijging

De simulatieresultaten van de UPFLOW software worden grafisch weergegeven in Appendix 7. Per figuur wordt de capillaire opstijging in functie van de diepte van de watertafel voor de vier verschillen groeistadia die een plant doorloopt. Dit werd per geselecteerde bodem en per gewastype uitgevoerd. Deze grafieken zijn een gebruiksvriendelijke manier om de capillaire opstijging in het veld te bepalen als het gewastype, het groeistadium, het bodemtype en de diepte van de watertafel gekend zijn. Deze grafieken worden in de volgende paragraaf gebruikt om de bijdrage van capillaire opstijging aan de bodem-waterbalans te bepalen.
Het kweken van gewassen in de rivierbedding kan water-efficiënter zijn dan op de oevers omdat er water gebruikt wordt door planten dat anders enkel zou evaporeren van een onbegroeid rivieroppervlak. Het exces aan irrigatiewater dat draineert naar diepere lagen, zal de watervoorraden in het reservoir van de dam terug aanvullen. Het kweken van planten heeft wel als gevolg dat er een hogere evapotranspiratie is in vergelijking met wanneer het oppervlak ongbegroeid blijft.
Het effect van de verzadigde hydraulische conductiviteit op de UPFLOW output is het kleinst wanneer de verzadigde hydraulische conductiviteit geschat met het “Van Genuchten” model gebruikt wordt.

Richtlijnen voor irrigatie: het ontwikkelen van “irrigation charts”

Een paar van de “irrigation charts” die in het kader van deze studie ontwikkeld werden, zijn weergegeven in Appendix 8. Een lijst van alle ontwikkelde “irrigatie charts” kan eveneens gevonden worden in Appendix 8. Alle uitgewerkte “irrigation charts” zijn terug te vinden op de bijgevoedge CD-ROM. In Appendix 8 wordt ook een simpele formule gegeven die de landbouwers toelaat de netto applicatiediepte (in mm) weergegeven in de “irrigatie charts” om te rekenen naar het aantal emmers dat de landbouwers moeten toedienen per groeibed.

Uit analyses blijkt dat het gebruik van een kleinere netto applicatiediepte tot gevolg heeft dat er op seizoensbasis minder irrigatiewater gebruikt wordt. Het verschil in efficiëntie is te wijten aan de grotere verliezen aan diepe drainage bij grotere netto applicatiedieptes. Het gebruik van kleinere irrigatiedosissen heeft echter een hogere arbeidsinput als gevolg. Ook moet ervoor gezorgd worden dat de uniformiteit van de toediening niet in het gedrang komt.

Het gewas met de hoogste irrigatiebehoeften is ui. Dit komt door de combinatie van een lange groeicyclus en een klein irrigatie interval. Een oplossing voor de reductie van de kans op een oogstmislukking wordt gegeven door richtlijnen voor te stellen om uien tijdens en tussen de twee regenseizoenen te verbouwen (november-mei).
Tomaten en sukuma wiki hebben de kleinste waterbehoeften van de gecultiveerde gewassen, dit maakt ze meer geschikt voor cultivatie in het droge seizoen.

De bodems met een lichte tot medium-lichte textuur zoals de rivierbedding en de oevers hebben de hoogste irrigatiebenodigdheden en ook de hoogste drainageverliezen. Het verloren water komt echter terug terecht in het reservoir van de “sand-storage” dam. In de zwaardere kleibodems en de bodems hoger gelegen in de topografie zijn er minder waterverliezen door de slechtere drainagekarakteristieken.

Indien de waterbehoeften van maïs vergeleken wordt met zijn intercrops, is er geen significant verschil te zien op seizoensbasis. De reden voor het succes van de intercrops is waarschijnlijk het fertiliteitsaspect.

Wanneer de geschatte bodem-water parameters doorgerekend worden in het BUDGET model, wijken de resultaten (netto irrigatiebehoeften op seizoensbasis) maximaal 20 mm af.

Wanneer de capillaire opstijging in rekening wordt gebracht in de bodem-water balans, worden, zoals verwacht, de irrigatiebehoeften kleiner naarmate de capillaire opstijging stijgt. Als het verschil tussen het bodemoppervlak en de watertafel groter is dan 1 m, zal de capillaire opstijging minimaal zijn voor de gewassen met korte wortels (sukuma wiki, uien,

spinazie) die gekweekt worden op de bodems van de rivieroever. Voor gewassen met middellange wortels als tomaten zal het effect van capillaire opstijging voelbaar zijn tot een watertafel diepte van 1.6 m.
Gewassen die gekweekt worden in de rivierbedding, ondervinden een aanzienlijk effect van capillaire opstijging tot een watertafel diepte van 2.2m. Voor de zware kleibodems is de capillaire opstijgen nog aanzienlijk op een diepte van 1.7 m, de totale diepte van het profiel. In de hoger gelegen bodems zal de capillaire opstijging niet relevant zijn door het ontbreken van een watertafel.

Als laatste werden de gesimuleerde richtlijnen vergeleken met de irrigatiekalenders die werden geobserveerd tijdens het veldonderzoek. De gesimuleerde irrigatiebehoeften liggen een factor 2.5 tot 4 keer lager dan de huidige irrigatiekalenders, gebruikt door de geïnterviewde landbouwers in het Kitui district.

Hoofdstuk 5: Conclusies en aanbevelingen

Bij het opstellen van de irrigatierichtlijnen in deze studie werd de voorgeschreven methode strikt gevolgd, zonder vereenvoudigingen aan te brengen. Bij de implementatie van de “irrigation charts” kunnen eventuele vereenvoudigingen doorgevoerd worden. Hierbij moet opgepast worden dat er geen onderirrigatie, en bijgevolg ook geen waterstress, plaatsvindt. SASOL (Sahelian Solutions) kan een belangrijke rol spelen bij de implementatie van de irrigatierichtlijnen bij de lokale landbouwers.

Het water dat uit de “sand-storage” dammen onttrokken wordt voor irrigatie kan efficiënter gebruikt worden. Er kan een intensifiëring van de dammen doorgevoerd worden, zonder bijkomende investeringen en met een hogere opbrengst per eenheid water in de dammen als gevolg. De geïrrigeerde oppervlakte kan vergroot worden met een factor 2.5 tot 4 of het aantal oogsten per jaar kan vermeerderd worden. Bij deze laatste optie zouden de ontwikkelde “irrigation charts” voor het verbouwen van gewassen gedurende en tussen de regenseizoenen van pas komen. Een laatste mogelijk is het beginnen te irrigeren van de traditioneel regengevoede voedselgewassen.
De verliezen die gepaard gaan bij het gebruik van een 20 mm in plaats van 10 mm netto applicatiediepte, zijn dus te verwaarlozen in vergelijking met de verliezen die op dit moment plaatsvinden door het volgen de niet optimale irrigatiekalenders.

Indien er geen “sand-storage” dam aanwezig is, zal het effect van capillaire opstijging op de netto irrigatiebehoeften snel dalen naarmate het droge seizoen (en dus ook het groeiseizoen) vordert. Door het plaatsen van een “sand-storage” dam zal de bijdrage van de capillaire opstijging tot de waterbehoeften van de gewassen lokaal toenemen in vergelijking omdat de dammen de karakteristiek hebben om voor een langere tijd een hoge watertafel te behouden.

Ondanks het feit dat de geïrrigeerde gewassen genoeg water krijgen, werden er gedurende de interviews met de lokale boeren heel lage opbrengsten vastgesteld. De goede drainage eigenschappen van de bodems van de rivier en de oevers sluiten wateropstapeling in de wortelzone uit. Waarschijnlijk is het niet of onjuist gebruik van meststoffen en pesticiden de oorzaak van de lage opbrengsten. Wederom kan SASOL hier een belangrijke rol spelen in de informatieoverdracht naar de lokale boeren.

De lage opbrengsten van de traditioneel regengevoede voedselgewassen, zijn in de eerste plaats te wijten aan hun afhankelijkheid van de klimatologische condities. Richtlijnen werden ontwikkeld om supplementaire irrigatie te kunnen uitvoeren gedurende het regenseizoen om zo de kans op een oogstmislukking te verminderen. De hogere arbeidsinput of de hogere investeringen in nieuwe irrigatietechnieken zijn een paar argumenten die gepaard gaan met het irrigeren van grote oppervlakten en waarom een landbouwer niet zou overgaan tot het irrigeren van zijn voedselgewassen. Daarenboven kan een landbouwer meer financieel voordeel hebben om een extra oppervlakte aan groenten te irrigeren in plaats van dezelfde hoeveelheid water te gebruiken om voedselgewassen te irrigeren.

Het laatste objectief van deze studie, namelijk het inschatten van een optimale te irrigeren oppervlakte in functie van de hoeveelheid water die er in de dam aanwezig is, kon niet verwezenlijkt worden. De grote beperkingen hierin waren het gebrek aan data over het onttrekken van water voor huishoudelijk gebruik en voor het vee en het ontbreken van gegevens over runoff, gegenereerd stroomopwaarts van de plaats waar de nieuwe dam in Kisayani zal gebouwd worden. Een voorstel om dit in een toekomstige studie uit te werken wordt weergegeven in paragraaf 5.6, gebruik makend van een lokale waterbalans.

Ten slotte moet het benadrukt worden dat ondanks de poging om zo betrouwbaar mogelijke richtlijnen op te stellen, deze studie voornamelijk inleidend werk verricht. De studie heeft enkel tot doel de gewasopbrengsten te verhogen in functie van de watertoediening. De tijd die gereserveerd werd voor dataverzameling was te kort om voldoende grote datasets te ontwikkelen om de richtlijnen te valideren. Het is daarom aan te raden deze studie een paar jaar na het bouwen van de dam in Kisayani nog eens over te doen met een uitgebreidere dataset.

ABSTRACT

Kenya is faced with a problem of economic water scarcity and severe water poverty. Mainly poor, rural, arid and semi-arid regions like the Kitui district are struck by water poverty and water scarcity. A solution for the problems can be the construction of sand-storage dams for rainwater harvesting and storage, which are of great help in dry spell mitigation. Construction of the dams results in the start up of small-scale cultivation of irrigated cash crops. At this scale, farmers follow often a rather fixed irrigation calendar with or without some empirical adjustments to the actual weather conditions. The corresponding irrigation applications are mostly characterised by periods of over- and under-irrigation.

In this study, irrigation calendars, summarized in carts, were developed for the traditionally irrigated cash crops like tomato, sukuma wiki, cabbage, spinach and onions. This was done for the traditional sowing dates but also other dates are suggested to the farmers. Scenarios for irrigating the traditionally rainfed food crops like maize, beans, cowpeas and their intercrops were considered. The charts give farmers simple guidelines on how to adjust their irrigation intervals to the actual weather condition, to the presence of a shallow water table (capillary rise) and when shortage in the supply of irrigation water occurs. Crop water requirements were simulated by means of a soil water balance technique. The soil water balance was simulated with the BUDGET model (Raes, 2004). Capillary rise was simulated using the UPFLOW model (Raes, 2001).

The data used in this study were collected in the Kitui District during a field campaign of three months. Field observations, experiments and participatory rural appraisal interviews were carried out in order to collect the necessary input data for the models. The ET0 software (Raes, 2000a) was used to estimate the reference evapotranspiration using the Penmann-Montheit method. The RAINBOW software (Raes, 2000b) was used to make a frequency analysis of the historical rainfall. Soil water parameters were measured using samples and estimated using the SPAW software (Saxton, 2003) and the ROSETTA model (Schaap, 1999).

Finally, the simulated guidelines were compared with the irrigation calendars derived from the interviews with the local farmers in order to determine whether use of the sand-storage dams can be intensified without supplemental investments.

Keywords: sand-storage dam, BUDGET, UPFLOW, RAINBOW, ET0, SPAW, ROSETTA, irrigation charts, soil water balance, capillary rise, participatory rural appraisal

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LIST OF ABBREVIATIONS

ASALs	Semi-arid and arid areas
AVSWAT	ArcView 'Soil and Water Assessment Tool'
COFORD	International council for forest research and development
ENSO	El Niño Southern Oscillation
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
GNP	Gross National Product
IMTR	Institute for Meteorological Training & Research
INCO-DEV	International Cooperation with Developing Countries
IRC	International Water and Sanitation Centre
ITCZ	Inter-Tropical Convergence Zone
IWMI	International Water Management Institute
K.U.Leuven	Katholieke Universiteit Leuven
PODIUM	Policy Interactive Dialogue Model
PRA	Participatory Rural Appraisal
RAW	Readily available soil water
REAL	Rehydrating Arid Lands
SADL	Spatial applications division Leuven
SASOL	Sahelian Solutions
SAT	Saturation
SPAW	Soil-Plant-Atmosphere-Water Field & Pond Hydrology
TAW	Total available soil water
USDA-SCS	United States Department of Agriculture Soil Conservation Service
WP	Wilting Point
WRI	Water resources institute

LIST OF SYMBOLS

%C	Percent clay
%S	Percent sand
Δ	Slope vapour pressure curve [kPa °C^{-1}]
γ	Psychrometric constant [kPa °C^{-1}]
Ψ_e	Water potential at air entry
$(e_s - e_a)$	Saturation vapour pressure deficit [kPa]
A	Net application depth in millimetres as indicated in the irrigation charts that is being followed (e.g. 10 mm, 20 mm or 40 mm)
D	Deep percolation
D_1	10-day value for the first decade of the actual month
D_2	10-day value for the second decade of the actual month
D_3	10-day value for the third decade of the actual month
E	Actual evaporation
e_a	actual vapour pressure [kPa]
e_s	saturation vapour pressure [kPa]
ET_0	Reference evapotranspiration
ET_C	Crop evapotranspiration
F(x)	Cumulative probability distribution of the non-zero values of X [prob($X \leq x \mid X \neq 0$)]
G	Soil heat flux density [MJ m^{-2} day^{-1}]
G(x)	Cumulative probability distribution of all X [prob($X \leq x \mid X \geq 0$)]
h	Pressure head [cm]
I	Infiltration
Int	Crop interception
K_0	Hydraulic conductivity, fitted matching point at saturation
K_C	Crop coëfficiënt
$K_{C\ field}$	Crop coëfficiënt for an intercropped field
K_Y	Yield response factor
L	Length of the bed in metres as indicated in the figure
L_i	Length of the crop development stage
M_{act}	Mean monthly value of the actual month

M_{next}	Mean monthly value of the next month
M_{prev}	Mean monthly value of the previous month
N	number of buckets (20 Litres) that have to be applied uniformly over the plot
n/N	Relative sunshine fraction
p	Soil water depletion for no stress
P	Precipitation
p	Probability that X is zero
q	Constant upward flux
r	Radius
R	Water depth lost by runoff
R^2	Goodness of fit
R_n	Net radiation at the crop surface [MJ m^{-2} day^{-1}]
R_s	Global radiation
S_e	Effective saturation
S_k	Cumulative deviations from the mean
S_{max}	Maximum root water optake
T	Transpiration
T	Mean daily air temperature at 2 m height [°C]
T_{max}	Maximum temperature
T_{min}	Minimum temperature
U	Upward capillary flow
U_2	Wind speed at 2m height [m s^{-1}]
U_{mean}	Mean windspeed
W	Wide of the bed in metres as indicated in the figure
X_i	Records of the partial duration series (X_1,…X_n)
X_m	Mean of records of the partial duration series
Δt	Time step
Δz	Increment in depth
$\Delta\theta$	Change in water content
K_{SAT}	Saturated hydraulic conductivity
T_{mean}	Mean temperature
Ψ	Water potential
θ_{10}	water content at 10 kPa

θ_{FC}	Water content at field capacity
θ_r	Residual water content
θ_{SAT}	Water content at saturation point
θ_{WP}	Water content at wilting point
τ	Drainage characteristic [0-1]

CHAPTER 1: INTRODUCTION TO AND 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 worlds 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.

1.1. 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 effected. 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 1.1. According to the model's results Kenya will be suffering economic water scarcity in the future.

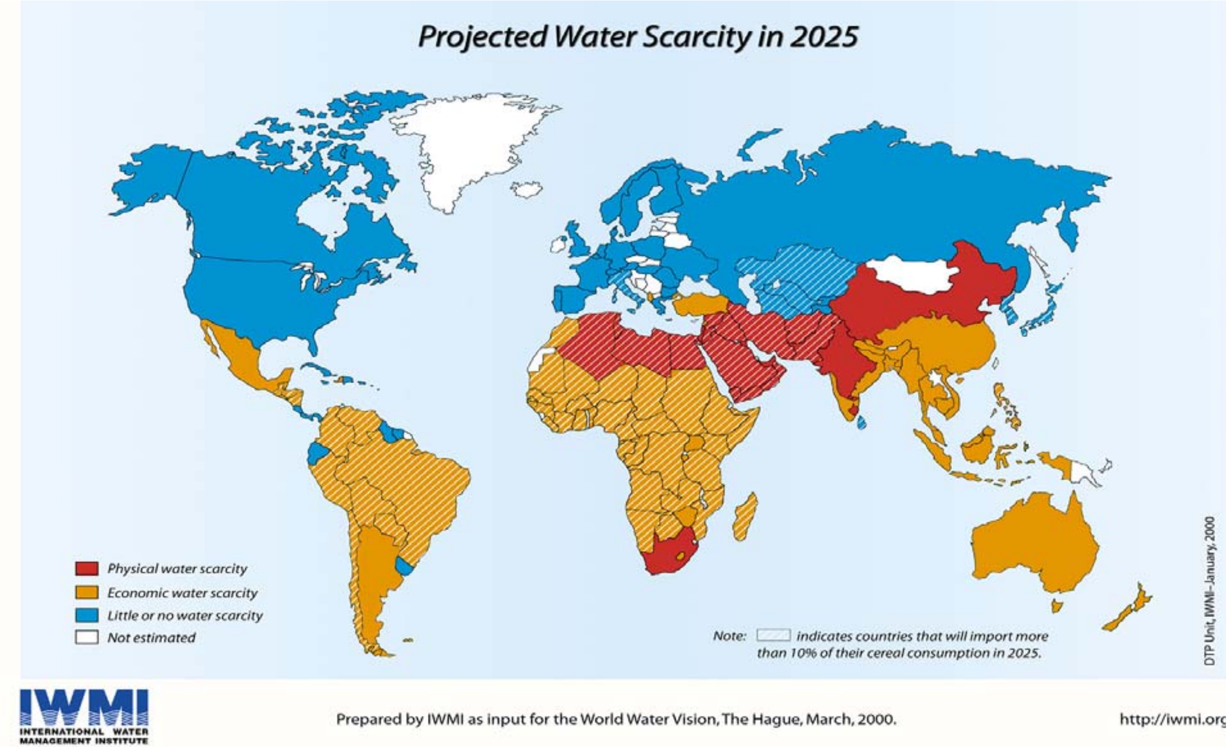

Figure 1.1: Projected Water Scarcity in 2025 (Source: IWMI, 2000).

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.

1.2. 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.

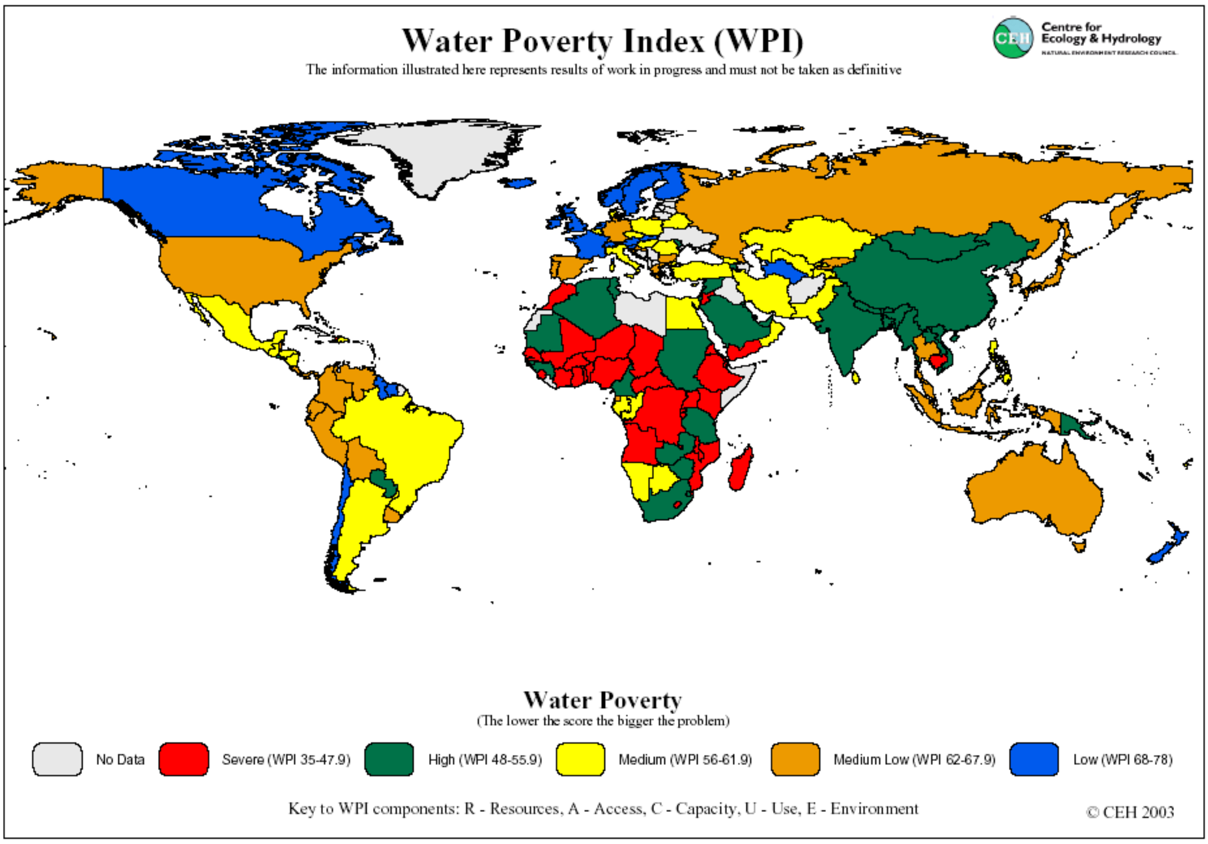

Figure 1.2: Water Poverty in the World (Source: Wallingford website, 2003).

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.

Countries struck the hardest by water poverty are the poor countries in arid and semi-arid regions in Africa as can be seen from Figure 1.2. These countries do not only have limited water supplies and a highly irregular precipitation, also their citizens can not support the costs of sustainable clean water. These countries have a limited ability to pay for water resources development (Feitelson and Chenoweth, 2002).

Kenya, as an African country with 88% of its land being arid and semi-arid (see paragraph 1.6.1), deals with severe water poverty. The annual per capita renewable water resources of Kenya are 672 m^3. Belgium has annual per capita renewable water recourses of 1181 m^3 (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 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.

1.3. 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 remain 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 land users 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).

1.4. 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 percent 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 damage in case of failure is enormous (Shenkut, 2001).

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

Sub-surface dams (Figure 1.3) 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 1.4, Figure 1.5) is made as a concrete or masonry barrier, constructed above the ground level of on 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.

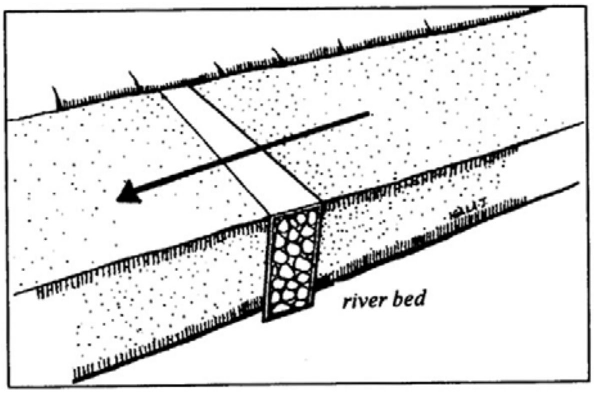

Figure 1.3: Sub-surface dam (Source: SASOL, Maji Na Ufansi, 1999).

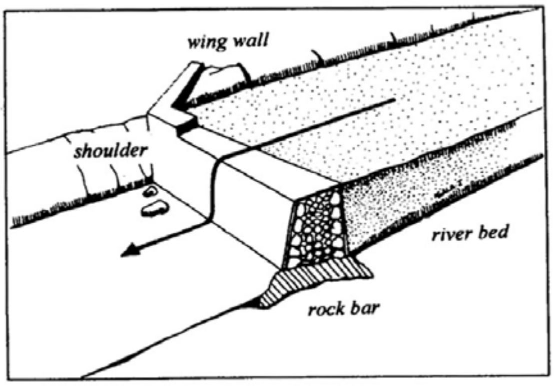

Figure 1.4: Sand-storage dam (Source: SASOL, Maji Na Ufansi, 1999).

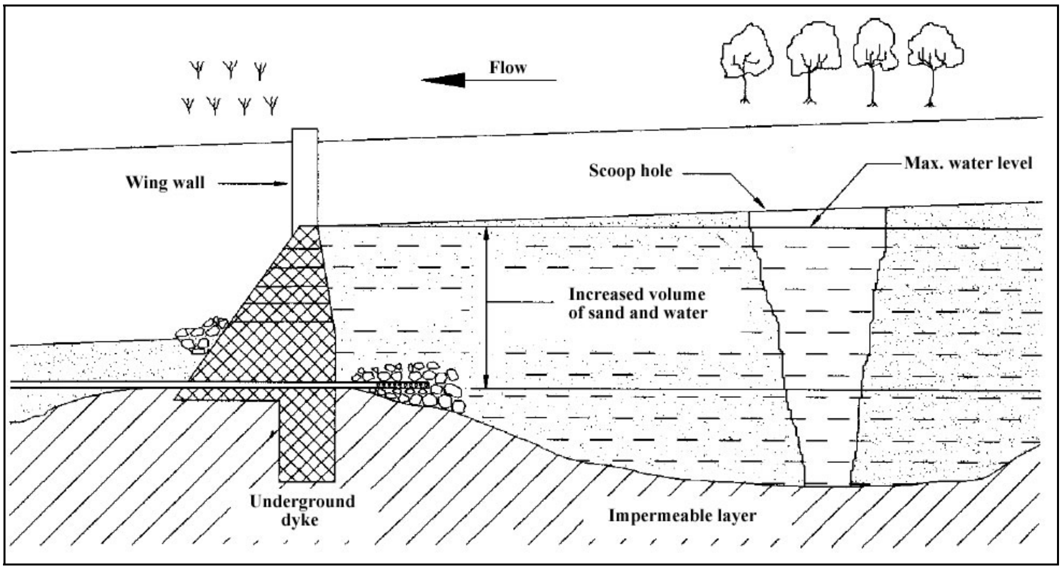

Figure 1.5: Cross-section of a sand-storage dam (Source: Nissen-Petersen, 1997).

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 that 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.

1.5. Framework of the study

1.5.1. 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.

1.5.2. 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 an 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).

1.6. Study area

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

1.6.1. 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 (Figure 1.6). 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 1.1).

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	12
II	Sub-humid	65-80	1000-1600	
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 1.1: Agro climatic zones in Kenya with rainfall and fraction of land (Source: Orodho, 2003).

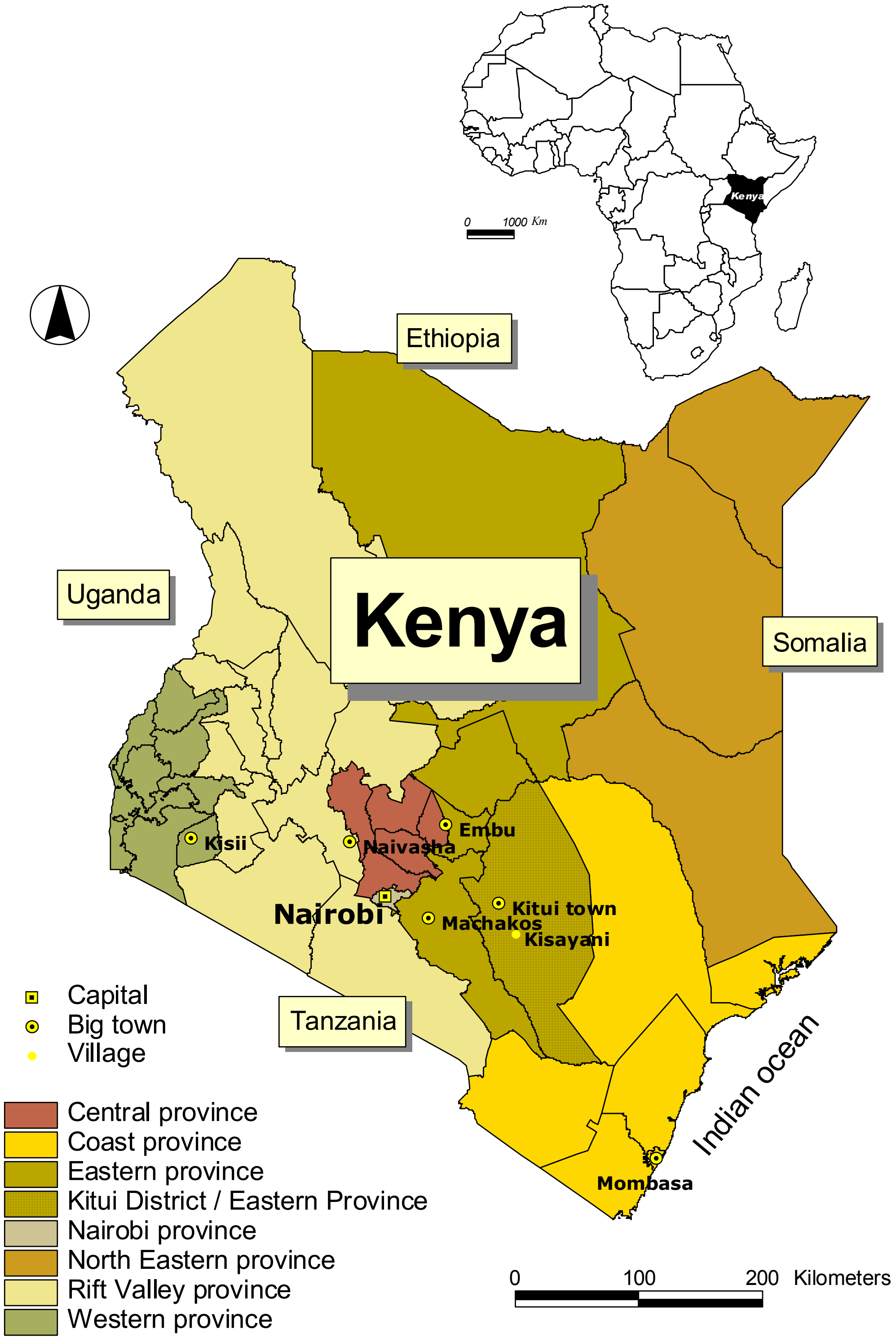

Figure 1.6: Administrative boundaries of Kenya (Source: FAO-Africover, 2003; Maidment D.R. and Reed S. M., 1996).

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 rainfed 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 semi-arid 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).

1.6.2. The Kitui district

Kenya is divided into eight provinces and each province is divided in districts. The Kitui district is situated in the Eastern province (Figure 1.6). 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).

1.6.3. Kisayani village

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. Compared to the Central Division where most of the NGO's activities are concentrated, rainfall is less and more erratic, topography is rougher and soils are different (see 3.4.2).

At the time of the 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.

The topography, soil and land use between the Kamunyuni dam and the proposed dam site are presented in Appendix 4. These maps were constructed during the field campaign. 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 for domestic use, cattle and irrigation the whole year through.

CHAPTER 2: OBJECTIVES AND APPROACH OF THE STUDY

2.1. Objectives of the study

The main objective of this study is to determine whether the use of the sand-storage dams to irrigate crops can be optimised and if so, to give guidelines for better irrigation practices. The collected data on the current irrigation practices, derived from field interviews with local farmers will be compared with the guidelines that are developed in this study in order to determine whether the dams are being used optimally.

Irrigation schedules for the crops currently cultivated -rainfed or irrigated- in the survey area will be developed. By means of the soil water balance model, BUDGET (Raes, 2004), the crop water requirements will be determined. The soil water balance depends on the incoming and outgoing water fluxes and on the amount of water that can be stored. Incoming fluxes are rainfall and capillary rise, while the outgoing fluxes are deep percolation and evapotranspiration. The soil water characteristics determine the storage capacity. These characteristics were measured in the field and analysed in the laboratory. Soil water characteristics will also be estimated making use of the Saxton and the Van Genuchten pedotransfer functions. The climatic data where collected from nearby meteorological stations. From the sunshine data, temperature data and wind speed data the reference evapotranspiration will be estimated using the Penman-Montheit equation. The variability of the rainfall will be integrated in the final guidelines for irrigation by making of a frequency analysis on the probability of rainfall exceedance. The capillary rise, simulated with the UPFLOW model (Raes, 2001) will also be integrated in the guidelines by taking into account different relevant depths of the shallow water table. Crop data for the BUDGET model (Raes, 2004) like sowing date, spacing, crop density and irrigation practices were collected in the field using participatory rural appraisal techniques. Other crop data like the crop coefficient, the response to water stress and rooting depth will be derived from literature data. The effect of the uncertainty of soil input parameters on the final output will be examined.

The final objective of this study is to assess the optimal area that can be irrigated as a function of the amount of water that is available for irrigation in the sand-storage dam, that is planned to be built in Kisayani. Care has to be taken not to endanger the water supply for domestic use and cattle. The area will depend on the water that is available in the sand-storage dam and subsequently also on the amount of rainfall. By using the different seasonal rainfall scenarios, farmers will be able to determine the optimal irrigation area.

2.2. Field survey approach

From July to October 2003 a field campaign was conducted in the Kitui district of Kenya. This campaign was organized to collect data on cultivated crops, cropping and irrigation calendars, harvest, meteorology and soil. Crop data were collected from interviews with the local farmers using participatory rural appraisal techniques. Soil samples were collected in the survey area. Local information centres and agricultural organisations were visited to collect information about soils and meteorology. In Nairobi contact was made with the Kenyan ministry of agriculture and the Kenyan Wildlife Service in order to derive historical daily meteorological data. It was only possible to get historical data on rainfall.

From October to May 2003 data processing was carried out at the K.U. Leuven, Belgium. Soil samples were analysed on their texture and soil water parameters in the laboratory of soil and water management of the K.U. Leuven.

CHAPTER 3: MATERIALS AND METHODS

The unreliability of rainfall, and the absence of guidelines at a short time-step often complicate decision making during the irrigation season. At small farmers' level, guidelines for scheduling are rarely available or require expensive monitoring equipment and data processing. As such small farmers follow often a rather fixed irrigation calendar with or without some empirical adjustments to the actual weather conditions. The corresponding irrigation applications are mostly characterised by periods of over- and under-irrigation. Excess water may cause water logging, excessive vegetative growth and loss of valuable nutrients out of the root zone. Withholding irrigation, especially during crop sensitive periods, will result in limited growth and reduction of crop yield.

In this study irrigation calendars are developed that give farmers simple guidelines on how to adjust their irrigation to the actual weather condition, to the presence of a shallow water table (capillary rise) and when shortage in the supply of irrigation water occurs. The developed irrigation guidelines will be presented in irrigation charts which incorporate guidelines for the traditional bucket irrigation of a specific crop, for a particular soil type in the survey area (Raes *et al.*, 2002d).

In rural, poor environments results of field research are hardly available. Setting up new extensive fieldwork is difficult due to limited resources. As such the consequences of the ever-present production risks are difficult to asses because historical data on the productivity of crops are not available. Instead of setting up extensive fieldwork one can also study the system by means of simulation models that only require limited and less costly fieldwork to collect the input parameters. The dynamic nature of the models makes them valuable instruments for exploring different soil and water management strategies. Furthermore, simulation models provide an easy, practical and economical way to investigate the different processes involved in crop growth and soil water movement to evaluate field experiments and to predict long a short-term impact of farming strategies. As such they can be used to develop specific measures to improve the farming management practices (Garcia Cardenas, 2003).

3.1. Soil water balance and crop growth models

3.1.1. Classification of the existing models

The yield of a crop is determined on the one hand by its genetic characteristics and on the other hand by the governing conditions in the growing environment, such as climate and weather conditions, soil fertility and salinity, pest and disease control, soil water stress and other factors affecting crop growth. The crop yield can vary widely in response to the governing equations.

Crop growth models normally have the ability to simulate crop growth in response to the environment and management variables. There are many examples of crop growth models such as CERES-Maize (Jones *et al*., 1986) and SUCROS (Spitters *et al*., 1988). Such types of models simulate not only yield but also crop development throughout the growing cycle (Raes et al., 2003). CROPWAT (Smith, 1990) and BUDGET (Raes, 2002b) are examples of models that use the soil water budget to determine the soil water content in the root zone for a specific period, the crop evapotranspiration and subsequently the effect of the water stress on crop yield (Garcia Cardenas, 2003).

Another distinction can be made between mechanistic and empirical models. Mechanistic models describe the system in terms of lower level attributes. They incorporate detailed mathematical descriptions of the lower level processes. These models have the ability to mimic relevant chemical, physical or biological processes and to describe how and why a particular response results (Cheeroo Nayamuth, 1999). Hence, these models have an explanatory character.

Empirical of functional models are direct descriptions of observed data and are generally expressed as regression equations. These models depend on simplified, empirical conceptualisations of water and chemical movement characterized by static capacity terms, such as field capacity, saturated water content and bulk density of the soil. Examples of such models include the response of crop yield on fertiliser and/or water application. This simplification of the model structure reduces input data and requirements computational time. These models do not, however allow one to learn much about system behaviour in terms of basic processes (Garcia Cardenas, 2003).

A static model is one that does not contain time as a variable even if the end products of cropping systems are accumulated over time. Dynamical models explicitly incorporate time as a variable and most dynamic models are first expressed as differential equations. A deterministic model is one that makes definite predictions for crop yield quantities without any associated probability distribution, variance or random element. When variation and uncertainty reaches a high level, it becomes advisable to develop a stochastic model that gives an expected mean value as well as the associated variance. However, these models tend to be technically difficult to handle and can quickly become complex (Cheeroo Nayamuth, 1999).

3.1.2. The BUDGET model

In the functional, deterministic and to a certain extend dynamic soil water balance model BUDGET (Raes, 2004), the change of water stored in the root zone is determined on a daily basis by keeping track of the incoming (rainfall, irrigation) and outgoing (evapotranspiration, deep percolation) water fluxes at its boundaries. The capillary rise is not incorporated in the model but can be, if known, taken into account by lowering the evapotranspiration. The soil water flow is only described in the vertical direction. Given simulated soil water content in the root zone, the crop water stress and the corresponding yield decline are subsequently estimated (Raes et al., 2003). By selecting appropriate time and depth criteria irrigation schedules can be generated.

BUDGET is composed of a set of validated subroutines describing the various processes involved in water extraction by plant roots and water movement in the soil profile. The described processes are infiltration of rain and/or irrigation water, surface runoff, internal drainage and deep percolation losses, evaporation and transpiration (Raes, 2002b).

The estimation of the amount of rainfall lost by surface runoff is based on the curve number method developed by the US soil conservation service (USDA, 1964; Rallison, 1980; Steenhuis *et al*., 1995). Since irrigation is assumed to be fully controlled, the runoff sub model is bypassed when irrigation water infiltrates into the soil. The maximum amount of water that can infiltrate into the soil is however limited by the maximum infiltration rate of the topsoil layer.

The infiltration and internal drainage are described by an exponential drainage function (Raes, 1982; Raes *et al*., 1988) that takes into account the initial wetness and the drainage characteristics of the various soil layers.

Irrigation schedules can be generated by time and depth criteria as described by Smith (1985) and used in the irrigation scheduling software packages IRSIS (Raes *et al*., 1988) and CROPWAT (Smith, 1990). The procedure for developing irrigation guidelines will be explained in paragraph 4.5.

With the help of the dual crop coefficient procedure (Allen *et al*., 1998) the soil evaporation rate and crop transpiration rate of a well-watered soil is calculated. The actual soil evaporation is derived from soil wetness and crop cover (Ritche, 1976; Belmans *et al*., 1983) that takes into account root distribution and soil water content in the soil profile. The actual water uptake by plant roots is described by means of a sink term (Feddes *et al*., 1978; Hoogland *et al*., 1981; Belmans *et al*., 1983) that takes into account root distribution and soil water content in the soil profile. The effects of water logging and water shortage on crop evapotranspiration are described by multiplying the crop coefficient by a water stress factor (K_S). Under optimal water conditions K_S is equal to one, but when the soil water content in the root zone is above anaerobiosis point or below a threshold value (the readily available soil water, RAW) the water uptake of crops will be affected and K_S is smaller than one (Raes *et al*., 2003). By integrating the sink terms over all compartments of the root zone, one obtains the actual transpiration rate that can never exceed the potential transpiration.

For a given water stress during a specific growth stage, the resulting yield depression is estimated by means of the yield response factor K_Y (Doorenbos *et al*., 1979). By using the procedure presented by Tsakiris (1982), the effect of water stress on relative yield during a short time period is derived from the relative crop evapotranspiration by means of a the empirical model of Jensen (1968).

When climatic data consist of 10-day or monthly values, the interpolation procedure presented by Gommes (1983) is used to estimate reference evapotranspiration and rainfall rates. Since it is highly unlikely that rainfall is homogenously distributed over all the days of the 10-day period or month, rainfall data is further processed by means of the USDA soil conservation service (1993) to determine the part of rainfall that is stored in the topsoil as effective rainfall. The salt module (Raes *et al.*, 2001) simulates the building up of salts in a cropped soil profile as a result of irrigation with low quality water. This module is not used because literature data of the study area doesn't mention a risk for building up of salts in a cropped soil profile.

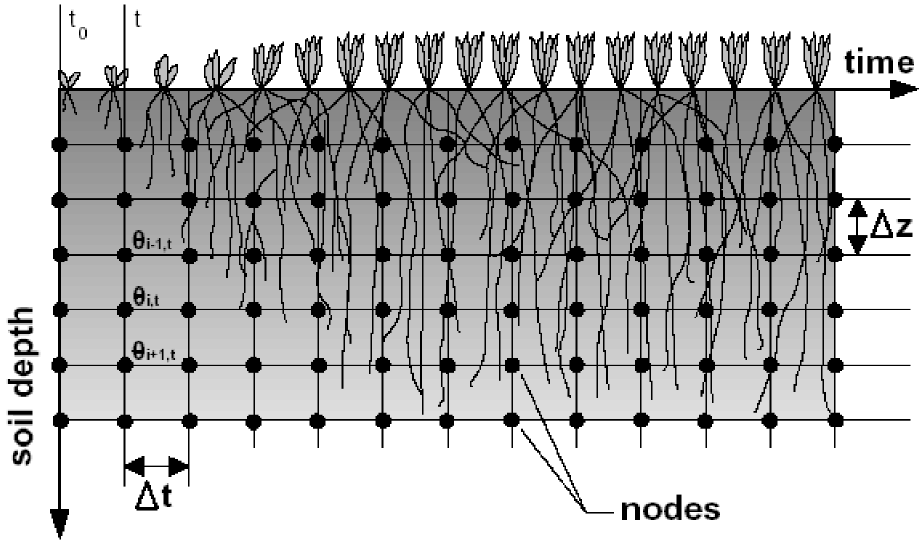

Figure 3.1: Time (t) –depth (z) grid for the solution of the soil water balance with the BUDGET model (Source: Raes, 2002b).

To describe accurately the retention, movement and uptake of water in the soil profile throughout the growing period, BUDGET divides both the soil profile and time into small fractions. As such the one-dimensional vertical water flow and root water uptake is solved by means of a finite difference technique. As shown in Figure 3.1 a mesh of grid lines with spacing Δz and Δt is established throughout the region of interest occupied by the independent variables, the soil depth and time. In BUDGET the depth increment is by default 0.10 m and the time increment is fixed at one day. The flow equation and water extraction by plant roots is solved for each node at different depths (z) and time levels (t) so that the dependable variable, the moisture content (θ_{ij}), is determined for each node of the solution mesh and for every time step. The differential flow equation is replaced by a set of finite difference equations (the subroutines), written in terms of the dependable variable θ. The simulation starts with the drainage of the soil profile. Subsequently water infiltrates into the soil profile (after the subtraction of the surface runoff), and finally the amount of water lost by evaporation and transpiration is calculated. In each of the described subroutines the soil water content is updated at the end of the time step (j) and at each grid point (i), according to the calculated water content variation ($\Delta\theta$). The calculation scheme of the model is shown in Figure 3.2

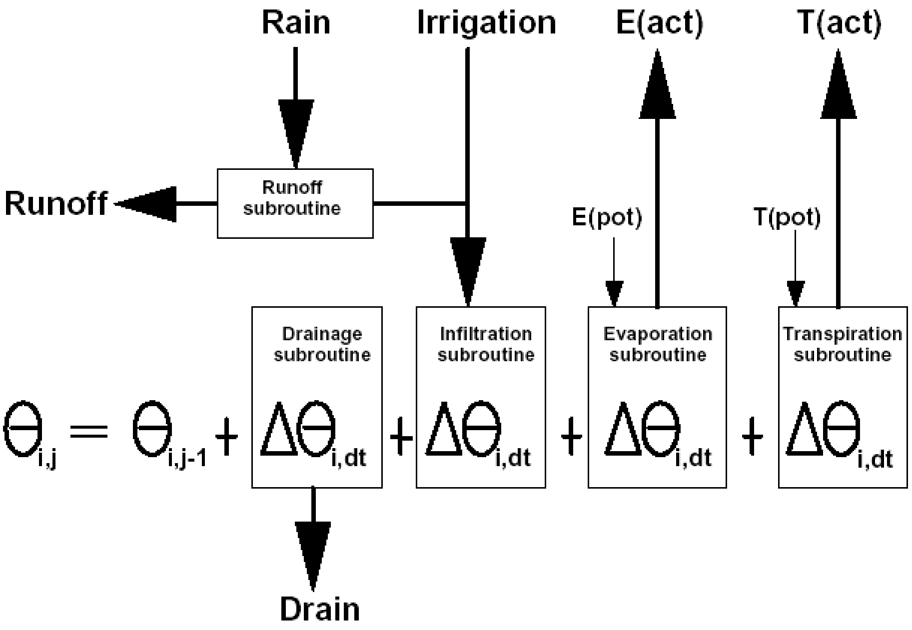

Figure 3.2: Calculation scheme of the BUDGET model (Source: Raes, 2002b).

The input data to run the BUDGET model can be divided in 4 categories, climatic input, crop data, soil input and initial conditions. The climatic input consists on daily, mean 10-day or mean monthly reference evapotranspiration and rainfall observations. Simulations can be run with data of a specific year, mean average data not linked to a specific year or with dependable rainfall and reference evapotranspiration. Important crop data are crop type, length of the growing period, crop coefficients during the mid season and late season stage, rooting depth, sensitivity to water stress and degree of ground cover at maximum crop canopy. Soil inputs should consist of type of soil surface, number of soil layers and their thickness and class type or most important hydraulic properties (θ_{SAT}, θ_{FC}, θ_{WP}, K_{SAT} and τ [0–1], the drainage characteristic as defined by Barrios Gonzales, 1999).

Relevant output files are the water content of each soil compartment and of each soil layer, the values of the different terms of the water balance, the fluxes between the compartments (0.10 m), the root zone depletion at the beginning and end of the day and the net irrigation requirements.

3.1.3. The WAVE model

The WAVE model (Vanclooster *et al.*, 1994) is a deterministic and mainly mechanistic model for the description of mass and energy fluxes in the soil-crop system. In the vertical direction, the model considers the heterogeneity of the soil profile as reflected by the presence of soil horizons. The soil horizons are subdivided in a range of numerical compartments. Halfway each soil compartment a node is identified, for which the state variable is calculated using finite difference techniques.

The WAVE-model uses a time step smaller than a day to calculate the different system state variables, for processes that are strongly dynamic (water transport, heat transport, solute transport; solute transformations). The time step is variable and is chosen as to limit mass balance errors induced by solving the water flow and solute transport equations. Less dynamic processes (crop growth) are only integrated at a fixed daily time step. The model input is specified on a daily basis. State variables are integrated after each day to yield daily output. The simulation period should not exceed one single year. Post processing modules however, allow the model easily to be used for longer time periods.

The model consists of a series of modules simulating the behaviour of water and solutes in the soil-plant continuum. The current modules available are shown in Figure 3.3. WAT is a module for calculating the water balance, SOL is for calculating the solute balance, TEMP is a module for calculating the heat balance, CROP simulates crop growth, NIT calculates the nitrogen balance and PEST the pesticide balance. The user is also free to add his own modules without the need to adapt the model structure or existing input files of the model.

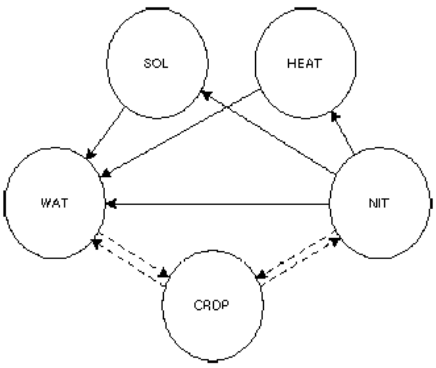

Figure 3.3: Schematic representation of the WAVE model (Source: Muñoz-Carpena *et al.*, 1998).

Within the water module (WAT), the soil water flow equation is numerically solved to quantify the unknown terms of the water balance,

$$\Delta\theta = (P + I + U) - (R + E + D + T + Int)$$

Where,

$\Delta\theta$: the change in water content [mm] in the soil volume
P: precipitation [mm]
I: the irrigation depth applied [mm]
U: the upward capillary flow into the soil profile [mm]
R: water depth lost by runoff [mm]
E: actual evaporation [mm]
D: percolation or drainage water depth (in the case of soil crop). [mm]
T : transpiration [mm]
Int: crop interception [mm]

Generally P and I are known system inputs, while U, R, T, E and D are unknown terms of the water balance and have to be calculated (Timmermans *et al.*, 2003).

The model describes one-dimensional water transport considering the soil as a homogeneous isotropic isothermal rigid porous media using Richards equation (Jury *et al.*,1991). The Richards equation, conceived for infinitesimal small soil element, is integrated in a numerical way in order to consider the variability of the soil physical properties and the boundary conditions in a consistent way. To handle more general flow situations, the capacity ($d\theta(h)/dh$, the slope of the water retention curve) of the soil water flow equation, applicable for both unsaturated and saturated flow conditions, is solved in the WAVE model. To solve the flow equation, the moisture retention curve, $\theta(h)$, and hydraulic conductivity curve, $K(h)$, need to be specified. Several parametric models are available to describe the shape of these curves allowing to handle flow as well in single as multi porous soil system. An example is the Van Genuchten-Mualem model that will be described in paragraph 3.4.3.2 and of which the parameters are used in the UPFLOW model (Raes, 2001) as explained in paragraph 3.5.3. Hysteresis of the soil moisture retention curve can also be considered.

When modelling the water balance of cropped soils crop transpiration and interception are part of the water balance. The interception capacity of water by the crop is not modelled in the WAVE-model, but specified as input. At a specified time step, the storage of water in the canopy is calculated as the minimum of the sum of the potential precipitation and irrigation during that day and the specified potential interception capacity reduced with that water that is still stored from the previous time step. In calculating the actual transpiration, the amount stored in the canopy is assumed to evaporate first. Hence, this amount is subtracted from the potential transpiration. The potential transpiration rate is calculated as a fraction of the maximum potential evapotranspiration. The latter is obtained by multiplying the potential evapotranspiration of the reference crop or surface, calculated using the Penman equation, with a crop specific coefficient which varies as a function of the crop development stage (Doorenbos and Pruitt, 1977; Raes et al., 1986; Feddes, 1987). The fraction of the potential evapotranspiration allocated to the evaporation is calculated according to the leaf area index (Belmans *et al.*, 1983). The sum of soil evaporation, evaporated interception water and transpiration can of course not exceed the ET_C. Finally, the potential transpiration and evaporation are reduced to an actual level, based on weather conditions, soil cover and moisture conditions in the root zone.

There are two possibilities to specify crop development in the WAVE-model: (i) the leaf area and root development are specified as model input or (ii) leaf area and root growth are calculated using a crop growth model. Taking the first approach, only the water uptake mechanism in the root zone is dynamically represented in the model. Other processes are not explicitly considered in the simulated system. Hence the leaf area and rooting depth are needed as input variables to the model. Water uptake by roots is the result of a complex process that is controlled by soil, plant and atmospheric conditions. To simplify the description of the root water uptake, Feddes et al. (1978) introduced the maximal root water uptake rate as a function of depth $S_{max}(z)$. In the WAVE-model the relation $S_{max}(z)$ with depth is input. Note that this relation summarizes the influence of both crop and soil on root water uptake. Water uptake is strongly reduced at high pressure head values, near saturation, due to anaerobiosis, and at low pressure heads, due to moisture stress. This phenomenon is described in the WAVE-model by specifying the dimensionless reduction function $\alpha(h)$, which reduces the maximum extraction rate. The $\alpha(h)$-factor that expresses the effect of pressure head on the root water uptake is insufficient to describe actual root water uptake. It is still necessary to specify at which depths water will be extracted. Several experiments have shown that water is preferentially extracted near the soil surface. Only when moisture stress occurs is water extracted at larger depths. In the root extraction model of Hoogland et al. (1980) a similar process is mimicked by integrating the root water uptake term from the soil surface to an increasing depth z less or equal to the rooting depth L_r, until the integral becomes equal to the potential transpiration rate. If the integration over the complete rooting depth is insufficient to explain the potential transpiration rate, water stress is considered to occur and the actual transpiration rate is set equal to the integral of the sink term over the rooting depth.

When also simulating the crop development and growth, the crop system and the soil water system are completely integrated, offering a framework with many more possibilities for including feed back mechanisms of soil moisture and nutrient availability on crop development (Vanclooster *et al*., 1994). A crop growth model enables the calculation of energy fluxes in the crop in terms of carbon assimilation, based on the photosynthetic process. A fraction of the assimilated energy is used to maintain the crop. The remaining part can be applied to build structural biomass. The growth rates for the structural biomass are next divided in growth rates of the different plant components. The crop specific distribution keys vary as a function of the plant development stage. The growth rate of the crop components is finally translated into leaf area, root length and root density extension rates. The crop growth model, included in WAVE, is a simple universal and comprehensive crop growth model with the acronym SUCROS (Spitters et al.,1988). It calculates the crop development rate, dry matter accumulation rate of the different plant organs and leaf area index (LAI) development rate, as functions of a set of climatic (radiation and temperature) and plant phenologic parameters. The model is extended to calculate daily root length and root density profiles. The potential crop growth is limited when water stress in the root zone of the plants occurs. Crop parameters for winter wheat (barley), spring wheat (barley), maize, potato and sugar beets, estimated from a set of field trials mainly under Dutch conditions, are available in the WAVE-version. So far, the model can only be used for these five crops, which represent a large part of the field cropping area in Western Europe.

The solute transport, nitrogen fate and pesticide fate modules will not be explained, since the effect of these governing conditions in the growing environment will not be considered in these thesis.

The input data set is large as can be expected in a mechanistic type of model. The WAVE manual gives literature values for some of the parameters. In the case of the soil hydraulic parameters, if no good measurements are available, these can be obtained from pedotransfer functions based on soil bulk density, carbon content, sand content and clay content. Tabulated crop growth parameters are handled internally for the five already mentioned crops. For other crops the user need to specify a minimal set of inputs. Each aspect of the model (water, solute, nitrogen specific addition to solute, plants and heat) is written to different files. The output files contain summaries of the main state variables in the programme. Summaries are produced at a fixed or variable time intervals defined by the user in the input. Summaries are produced for the complete soil profile or selected volumes depths within the soil profile.

3.1.4. Justification for the use of BUDGET model

The mechanistic models generally require a huge set of input data that is often not readily available outside research stations. Since they are often specific for a particular crop type and require site-specific calibration before they can be applied, crop growth models are not very useful for practical applications in irrigation management or regional yield estimates (Raes *et al.*, 2003).

For planning and evaluation purposes with limited data in a poor, rural environment a more general and simpler approach is required. That’s where BUDGET, with its user-friendly interface and limited data demand, is an alternative for more specialist models like WAVE. The use of the BUDGET model is a compromise between simulating as exact as possible and a limited availability of input data.

3.2. Climatic data

The determination of crop water requirements and the development of irrigation calendars require an extensive knowledge of the meteorology of the area of interest. Important climatic input parameters for the soil water balance are the rainfall and the evapotranspiration.

3.2.1. Data collection

Rainfall data were collected from fourteen different meteorological stations in the Kitui District. The completeness of the data is presented in Appendix 1, together with the coordinates and the sources of the data. Figure 3.4 shows the location of the relevant meteorological stations.

During the field campaign in Kenya, a meteorological station was started up by the thesis students in the Kisayani primary school. A “science club” was started where the teachers were trained to read the installed rain gauge and minimum-maximum thermometer. A manual was written and data sheets were developed to facilitate the daily measurements. Measurements started in august 2003. A similar project was started in Mbtini secondary school. Here, the Institute for Meteorological Training and Research of Kenya (IMTR) already installed a rain gauge in 2002. A minimum-maximum thermometer was added to the schools equipment.

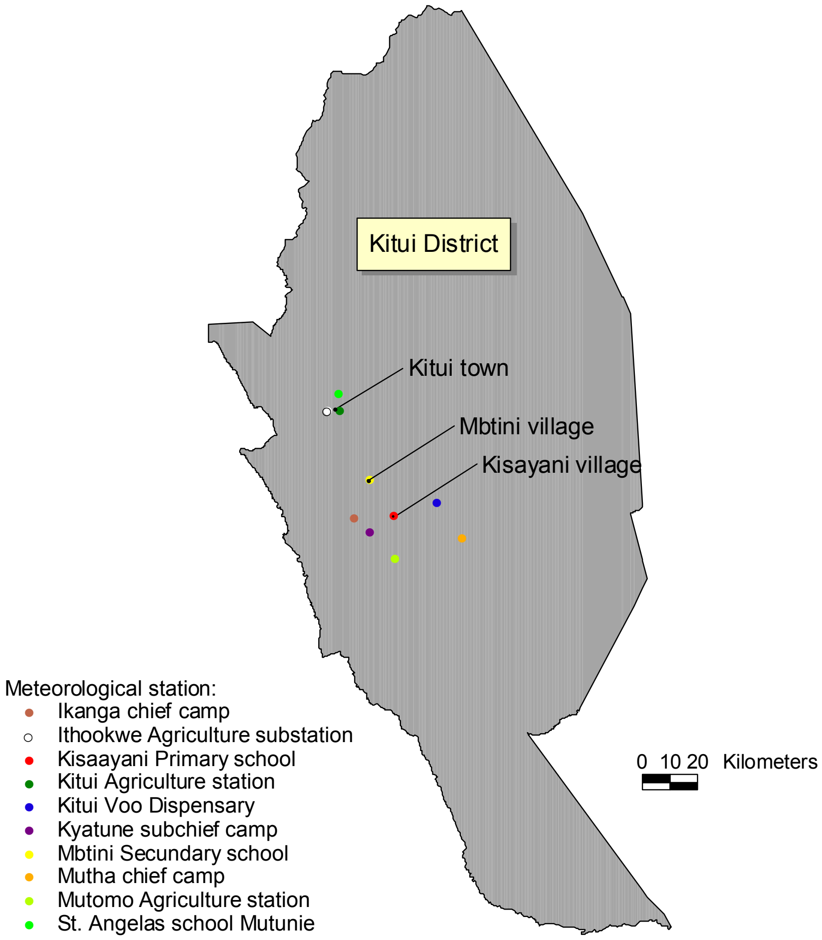

Figure 3.4: Location of the relevant meteorological station in the Kitui District (Source: FAO-Africover, 2003).

Mean monthly values for temperature (T mean), minimum and maximum temperatures (Tmin and Tmax), wind speed data (U mean), relative sunshine fraction (n/N with n the actual daily duration of sunshine and N the maximum possible duration of sunshine per day) and global radiation data (Rs) were derived from the Kitui Agriculture station and are shown in table 3.1 and Figure 3.5. FAOCLIM (2000) indicates that the mean values for temperature and wind speed were calculated from data of 7 years, beginning in 1948. Table 3.1 also shows the mean of all monthly values of one year and the standard deviation. There is little variation in temperature data. In semi-arid areas near the equator it can be assumed that the spatial variability of temperature is limited if there is not much variation in topography.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Mean*	*St. dev.*
T mean [°C]	21,8	23,0	23,5	22,5	21,6	20,1	19,3	19,6	20,5	21,8	21,6	21,3	21,4	1,31
T min [°C]	16,0	16,6	17,1	17,1	16,6	14,3	13,8	13,8	13,8	15,5	16,6	16,6	15,7	1,35
T max [°C]	27,7	29,3	30,0	27,7	26,6	26,0	25,0	25,5	27,1	28,2	26,6	26,0	27,1	1,51
Rs [MJ/m².dag]	24,37	25,62	23,40	20,72	19,76	18,46	15,66	19,05	21,44	21,14	21,14	21,86	21,1	2,69
n/N [-]	0,82	0,84	0,71	0,60	0,61	0,57	0,40	0,54	0,63	0,68	0,64	0,70	0,6	0,12
U mean [m/s]	2,3	2,5	2,5	2,2	2,6	2,6	2,8	3,1	2,8	3,2	2,6	2,8	2,7	0,29

Table 3.1: Climatic data Kitui Agriculture station, Kitui District, Kenya (Source: FAOCLIM v2.01, 2000).

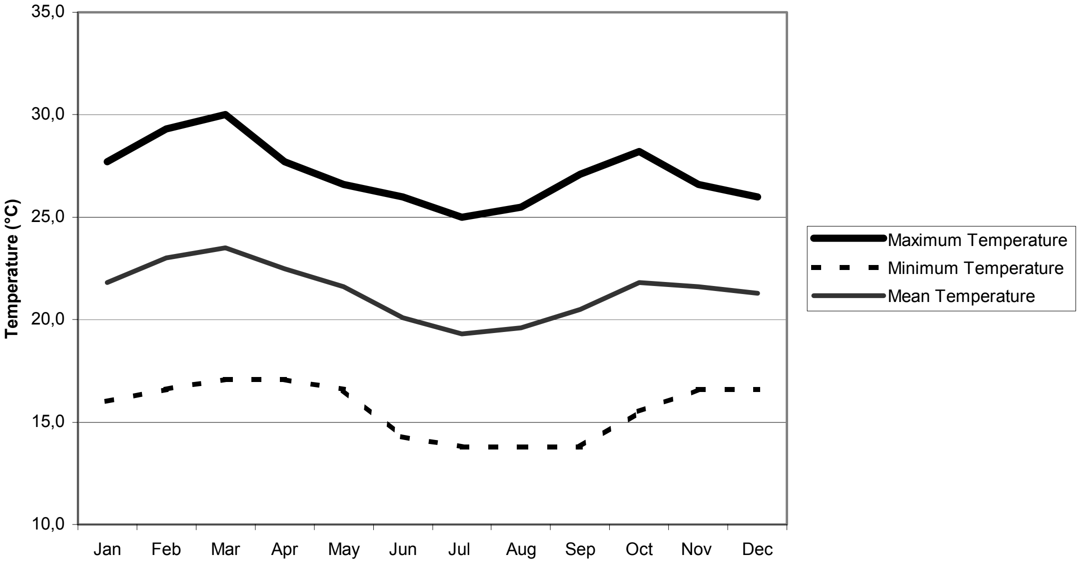

Figure 3.5: Graphical presentation of the mean maximum, the mean minimum and the overall mean temperature, Kitui Agriculture station, Kitui District, Kenya (Source FAOCLIM v2.01, 2000).

3.2.2. Analysis of the rainfall data

Semi-arid areas are characterised by a high temporal and spatial variation in rainfall (Rockström et al., 2002), it is important to develop a dataset that incorporates or bypasses most of its variation. To incorporate the temporal variation, the dataset should cover enough records separated by a sufficiently small time step. With a dataset that contains 20 to 30 years of rainfall data, a frequency analysis can provide reliable results on rainfall probabilities. To bypass the spatial variation, the dataset has to originate from the nearest meteorological station to the place of interest. A time step of a decade is chosen. Daily time steps give to much temporal variation, which would diminish the usefulness of the frequency analysis. Monthly time steps would be too long in comparison with the growth period of the crops.

Next to the temporal and spatial variation, variation of other sources can enter the dataset. For example a change in sampling method, use of other sampling materials, change of sampler and replacing the sampling materials. This variation is decisive for the homogeneity of the dataset.

In order to make predictions on future rainfall, a homogenous rainfall dataset has to be developed out of the available historical rainfall data and the dependable rainfall has to be determined through calculation of the rainfall probability. Dependable rainfall is defined as the rainfall that can be expected a set number of years out of a total number of years, for example 4 out of 5 years or 80% of the years. The percentage gives the probability that the dependable rainfall will be exceeded. The determination of the probability level is related to the risk, one wants to accept. For agriculture the risk involved is the reduction in or the loss of the yield once in so many years (Raes, 1995). For the development of irrigation charts the information on the amount of rainfall which one can expect in a specific period (mostly decades) under different conditions of wetness is important for predicting the amount of water that has to be irrigated. The three probability values that are distinguished are shown in Table 3.2 (Raes *et al.*, 1996).

Condition	*Prob. of exceedance*
Wet	20% (1 out of 5 years)
Normal	50% (1 out of 2 years)
Dry	80% (4 out of 5 years)

Table 3.2: Three useful probability values for irrigation planning and management (Source: Raes, 1995).

To test the homogeneity of the dataset and to make a frequency analysis, a software tool called RAINBOW is used (Raes, 2000b).

The frequency analysis is based on ranking. After ranking the data values in a descending order and assigning a serial rank number to each value, a plotting position is obtained using the Weibull relationship. A normal distribution is assumed. If the plotted data do not fall in a reasonable alignment, the software offers transformation possibilities to convert the distribution to normal (Raes *et al.*, 1996).

In RAINBOW the theorem of total probability is used to analyse a set of data with zero and non-zero values,

$$G_X(x) = p + (1 - p)\, F_X(x)$$

With:

G(x): cumulative probability distribution of all X [prob($X \leq x \mid X \geq 0$)]

p: probability that X is zero

F(x): cumulative probability distribution of the non-zero values of X [prob($X \leq x \mid X \neq 0$)]

Through the specification of nil values, the software excludes very small, although not zero events from the probability plot. These values are treated as zero values events (Raes *et al.*, 1996).

In RAINBOW the homogeneity test is based on the adjusted partial sums or cumulative deviations from the mean,

$$S_k = \sum_{i=1\ldots k} (X_i - X_m) \quad \text{and} \quad k = 1\ldots n$$

With:

S_k: cumulative deviations from the mean

X_i: records of the partial duration series ($X_1, \ldots X_n$)

X_m: mean of records of the partial duration series

For a homogeneous record one may expect that the S_k's fluctuate around zero since there is no systematic pattern in the deviations of the X_i's from there average value. In RAINBOW the cumulative deviations are rescaled by dividing the S_k's by the sample standard deviation (σ_k). Statistics used for testing homogeneity are the maximum cumulative deviation (Q) and the range (R),

$$Q = \max \mid S_k / \sigma_k \mid$$
$$R = \max \mid S_k / \sigma_k \mid - \min \mid S_k / \sigma_k \mid$$
$$\text{and} \quad k = 1\ldots n$$

High values of Q are an indicator for a change in the mean level. Shifts in the mean usually give rise to high values of the range. Values for Q and R presented by Buishand are used to decide whether or not to reject the hypothesis of homogeneity of the data (Raes *et al.*, 1996).

3.2.3. Reference evapotranspiration

A consultation of experts organized by the Food and Agriculture Organisation of the United Nations (FAO) in 1990 recommended the adoption of the Penman-Monteith combination method as a new standard for computing reference evapotranspiration and advised on procedures for calculation of the various parameters. The method uses a hypothetical crop with an assumed height of 0.12 m having, a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered. The reference evapotranspiration (ET$_0$) provides a standard to which evaporation at different periods of the year or in other regions can be compared and evaporation of other crops can be related (Allen *et al.,* 1998). The reference evapotranspiration equation is (Allen *et al.,* 1998),

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Where,

ET$_0$: reference evapotranspiration [mm/day^{-1}]

R$_n$: net radiation at the crop surface [MJ m^{-2} day^{-1}]

G: soil heat flux density [MJ m^{-2} day^{-1}]

T: mean daily air temperature at 2 m height [°C]

U$_2$: wind speed at 2m height [m s^{-1}]

e$_s$: saturation vapour pressure [kPa]

e$_a$: actual vapour pressure [kPa]

(e$_s$ – e$_a$): saturation vapour pressure deficit [kPa]

Δ : slope vapour pressure curve [kPa °C^{-1}]

γ : psychrometric constant [kPa °C^{-1}]

The dataset of the Kitui Agriculture station, derived from the FAOCLIM CD-ROM (2000), only provides mean monthly values. However, for irrigation planning, reference evaporation is used on decadal level. Before calculation of the reference evapotranspiration all average monthly data can be transformed to 10-day data by the following formula (Gommes, 1983),

$$D_1 = \frac{5M_{prev} + 26M_{act} - 4M_{next}}{27}$$

$$D_2 = \frac{-M_{prev} + 29M_{act} - M_{next}}{27}$$

$$D_3 = \frac{-4M_{prev} + 26M_{act} + 5M_{next}}{27}$$

With

D_1: 10-day value for the first decade of the actual month

D_2: 10-day value for the second decade of the actual month

D_3: 10-day value for the third decade of the actual month

M_{prev}: mean monthly value of the previous month

M_{act}: mean monthly value of the actual month

M_{next}: mean monthly value of the next month

For the calculation of the reference evapotranspiration, the ET_0 software (Raes, 2000a) was used. Because humidity data are missing, the ET_0 software estimates this data from the minimum temperature.

3.2.4. Onset, cessation and duration of the growing period

The rainfall and ET_0 data can provide information on reference growing periods. The growing period defines the period of the year when both moisture and temperature conditions are suitable for rainfed crop production. Here, the length of the growing period is not limited by temperature and only the ratio of precipitation over reference evapotranspiration determines the start, end and type of growing period. Because the climate follows a bimodal pattern, two distinct growing periods are observed (FAO, 1996).

The length of the growing period is a continuous period during the year with precipitation greater than half the reference evapotranspiration, calculated by the Penman-Monteith method, plus a number of days required to evapotranspirate another 100 mm of soil water stored at the end of the rains (De Pauw, 1989).

Since the decadal reference evapotranspiration data are derived from monthly values, recalculating these data to daily values is considered not appropriate to make prediction on one-day events like onset and cessation. Therefore, duration, onset and cessation of the growing periods were determined on a decadal level for the dataset. To avoid a false onset by early showers, onset dates before the second decade of October and March are rejected. This data are analysed using the RAINBOW software (Raes, 2000b) giving the 20, 50 and 80 percent probability of exceedance values for the parameters analysed.

3.3. Crop data and cropping practices

The driving force for water transport, from the soil through the plant to the atmosphere, is the gradient in energy level of the water over this pathway. In the soil, this energy level is expressed by the water potential of the soil in the root zone. The vapour pressure of the air represents the energy level of the water vapour in the atmosphere. In order to simulate the processes related to water transport from a cropped or bare soil to the atmosphere, crop and management parameters have to be collected. Location specific information like cropping patterns, irrigation management and harvest were collected during field interviews while other more intrinsic crop parameters were derived from literature.

3.3.1. Farming systems in the Ukambani region

In the Ukambani region (largely contained within the Machakos and Kitui District of Kenya) biophysical agricultural potential is a function of soil characteristics and moisture availability, both of which are largely controlled by elevation and topography. Jaetzold and Schmidt (1983) mapped agricultural potential in Kenya using a modified version of the FAO Agro-ecological Zone system (see Figure 3.6). They calculated that 64.7 percent of the Kitui District falls into agro-ecological zones IV (UM: Upper Midland) and V (LM: Lower Midland), with 50.7 percent falling in zone V. The Upper Midland zone is classified to be suitable for maize production, the Lower Midland zone is suitable for livestock keeping and cultivation of millet and sorghum (Nix, 1985). The 1980 development plan for Kitui classifies 2 percent of the district as having a high potential, 37 percent as medium potential, and 61 percent as low potential.

Landholdings in most households in agro-ecological zone IV and V are respectively 2-10 ha and 2-15 ha. As land is subdivided and allocated or sold to the rising generation, however, farm sizes of 0.5-1 ha have become commonplace in zone IV. Among all holdings in the Kitui District (all zones), 17 percent are less than 0.9 ha in size.

The most common food crops in the Ukambani region are maize, beans, cowpeas, pigeon peas, pumpkins, sweet potatoes, green gram, and bananas. Farmers intercrop maize, beans, bananas, potatoes, sweet potatoes, pumpkins, and sometimes coffee in the wet uplands. Many upland coffee farmers also grow other tree crops, including macadamia nuts, mango, papaya, timber, and fuel wood. Cash crops as cabbages, tomatoes, onions, red peppers and greens are usually limited to river flood plains or poorly drained valley sites. Greens are referred to as sukuma wiki in Kiswahili. In this study the local name will be used because there exists some uncertainty about the name. The FAO links two crops with the Kiswahili name, marrow-stem kales and collard greens.

The survey area is situated in the drier parts of the Ukambani region where most farmers grow maize, beans, cowpeas, pigeon peas, and sometimes green gram and cotton. Sorghum and millet, once the staple grains, are found in small patches in croplands, but have been largely replaced by maize. From the Kenya land use map (Scale 1:3.000.000, Kenyan government, 1985) it is clear that the Kisayani area has a maize and beans based agriculture. Sweet potatoes, pumpkins, and bananas are cultivated on the wetter sites in the field, along the base of terrace walls, in deep pits (1 m^3) with fruit trees, on termite mounds, or in gardens near the home. Increasingly, farmers in agro-ecological zone IV are also intercropping papaya, citrus, and some fodder or timber trees with their field crops.

The typical crop mix raised by a farm household still varies substantially between agro-ecological zones but also varies between households and between more localized landscape niches determined by topographic location, soil type, soil moisture, and proximity to water points and to forest. Whereas single households (usually extended families sharing production and consumption) once maintained a number of fields, across agro-ecological zones, most farm households are now reduced to nuclear families or smaller extended family units cultivating a single plot or a cluster of similar plots in one agro-ecological zone. Moreover, most households in the past relied on a regular supplement of food supply from wild and semi-domesticated plants in forests, hedgerows, rangelands, and fallows (Rocheleau *et al.*, 1995).

The farming systems in the Kitui District can be classified as mainly permanent upland cultivation. Permanent upland cultivation is characterized by clearly demarcated fields, a predominance of annual and biennial crops and permanent housing. At least 2/3 of the land is used for arable land, not leaving a lot of plots to be taken into cultivation. Consequently the fallow is short and limited to the dry season resulting in a rapid fertility decline. Production is at low level of output with high drought risks and a lot of erosion. Provided land is scarce and labour ample. Mixed intercropping, as yield increasing, moisture saving, risk reducing, fertility and power saving but labour demanding techniques are very common. The crop rotation patterns are of confusing varieties with rainfall and population densities as major determining factors (Swennen, 2001).

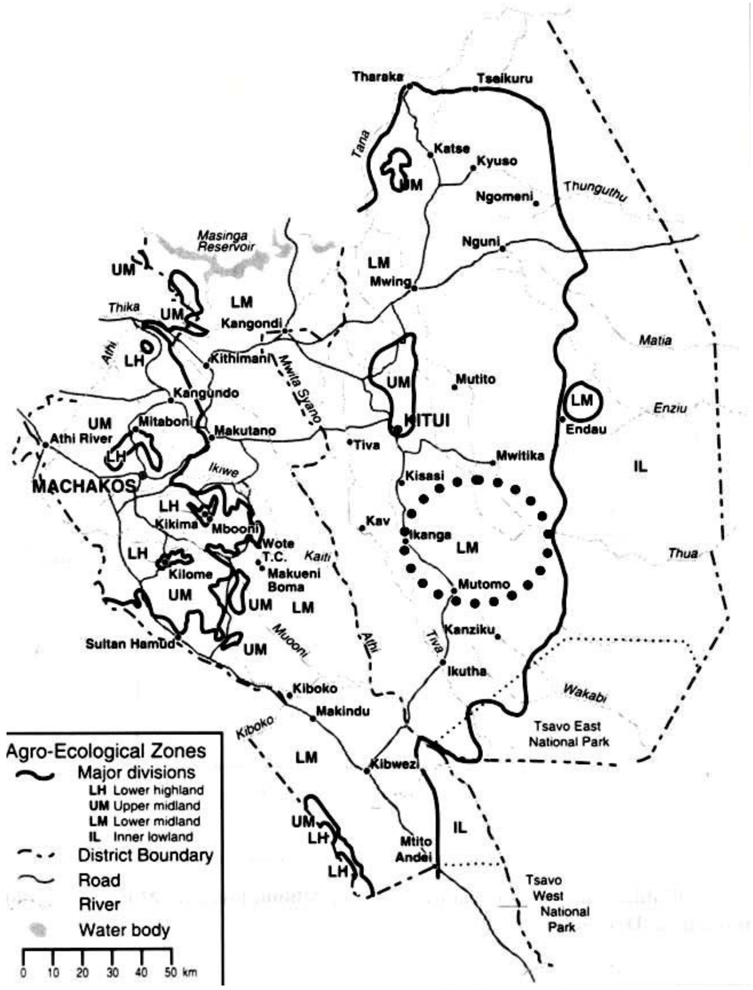

Figure 3.6: Agro-ecological zones of the Ukambani region. The survey area is encircled. (Source: Jaetzold and Schmidt, 1983).

As already mention in this paragraph cash cropping is limited to the river flood plains or poorly drained valley sites. This could be an indication that the system is going through an evolution to irrigated farming. However, irrigation can only be extended to plots more uphill if enough water is present. Sand-storage dams could act as a catalyst in this evolution.

3.3.2. Crop data collection

Relevant crop parameters for the simulation of crop growth and yield response to water were derived from two main sources, interviews with local farmers and literature.

3.3.2.1. Interviews with local farmers

To get a better understanding of the local farming practices, an interview technique called participatory rural appraisal (PRA) was used to gather necessary information from local farmers (Bolt *et al.*, 2001). PRA consists of a series of techniques for quick research of information that generate results of apparently less precision, but greater evidential value, then classic quantitative survey techniques. It emphasizes the importance and relevance of situational local knowledge, and the necessity to identify rightly key elements rather than achieving spurious statistical accuracy. It is based on listening research and on a creative combination of iterative methods and verification, including triangulation of data from different sources. The main PRA techniques used were the transect walk, seasonal calendar, problem listing, time trends and semi-structured interviews (Mergeai *et al.*, 2001). The interview sessions were conducted at the end of the long dry season (August-September) of 2003.

3.3.2.2. Crop parameters from literature.

The BUDGET model (paragraph 3.1.2) describes the effect of external environmental conditions on the crop's yield. To simulate the reaction of crops on the atmospheric water demands and water deficits or water logging in the root zone, the model needs empirical parameters that can be calculated from literature values. Most of the literature data is derived from the irrigation and drainage papers no. 33 and 56, respectively by Doorenbos *et al*. (1979) and Allen *et al*. (1998). All parameters mentioned in this part are summarized per crop in crop files.

Length of crop development stage (L_i)

The FAO Irrigation and drainage paper 33 provides general lengths for the four distinct growth stages and the total growing period for various types and locations. The rate at which vegetation cover develops and the time at which it attains effective full cover are affected by weather conditions in general and by mean daily air temperatures in particular. It will also vary with crop variety (Allen *et al*., 1998). The lengths of growth stages listed in the crop files are the values presented by Allen et al. (1998) modified for the local practices. This modification was based on the cropping calendar derived from the interviews with the local farmers.

Soil water depletion fraction for no stress (p)

The soil water depletion fraction for no stress (p) is the fraction [0-1] of the total available soil water (TAW) that the crop can extract from its root zone without experiencing water stress. The readily available soil water (RAW) is the amount of soil water that can be extracted from the root zone without experiencing water stress.

$$RAW = p\ TAW$$

The p-fraction depends on the sensitivity of a crop to water stress, the soil type and the evaporating power of the atmosphere. The listed values should be reduced or increased by 5-10%, respectively for fine and coarse textured soils. The soil water depletion fraction will be up to 20% less or more when the crop evapotranspiration is respectively above or under 5 mm per day (Allen *et al.*, 1998).

Crop evapotranspiration (ET_c)

Crop evapotranspiration (ET_c) under standard conditions means that there are no limitations placed on crop growth and evapotranspiration from soil water by salinity stress, crop density, pests and diseases, weed infestation and low fertility. It is the upper envelope of crop evapotranspiration. ET_c is determined by the crop coefficient (K_c) approach, whereby the effect of the various weather conditions is incorporated in the potential Penman-Monteith evapotranspiration (ET_0). The effect of both crop transpiration and soil evaporation are integrated into a single crop coefficient (Allen *et al.*, 1998).

$$ET_c = K_c\ ET_0$$

Crop type, changing characteristics of the crops during the growing season and conditions affecting soil evaporation will have an influence on the crop coefficient. Due to differences in albedo, crop height, aerodynamic properties and leaf and stomata properties, the evaporation from full grown, well-watered crops differs from the Penman-Monteith ET_0. The crop coefficient also has a dependency on the climate, because aerodynamic propreties can differ per crop (Allen *et al.*, 1998).

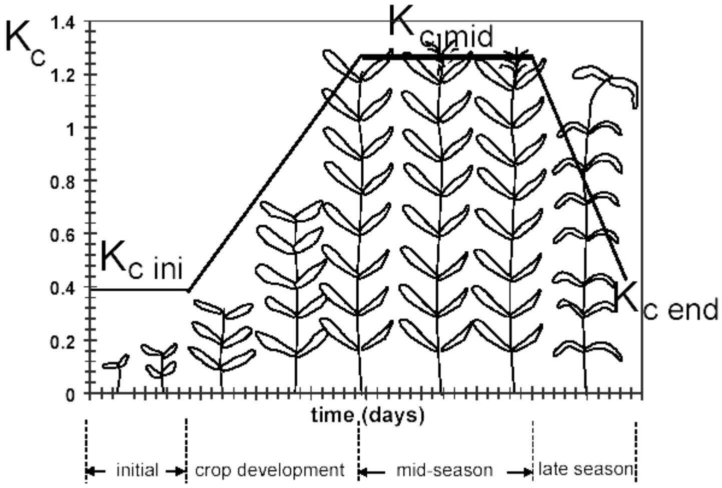

Figure 3.7: Crop coefficient curve (Source: Allen *et al.*, 1998).

The trends in K_c during the growing period are represented in the crop coefficient curve (Figure 3.7). Only three values for K_c are required to describe that curve, the initial, mid-season stage and end of the late season stage crop coefficient respectively $K_{c\ ini}$, $K_{c\ mid}$ and K_{cend} (Allen *et al.*, 1998).

In the initial growing stage the ground cover is very low so ET_c will largely be dependent on the soil evaporation. Drier soils will give lower K_c values. The tabulated $K_{c\ ini}$ values in literature are only approximations and should be corrected for the interval between and magnitude of the wetting events (irrigation and rainfall) and the evaporation power of the atmosphere during the specific stage. If heavy rainfall (more than 40 mm per event) is assumed during the rainy season on a medium textured soil with an average interval of 4 days, $K_{c\ ini}$ will be close to 1. For irrigation a medium application dept of 20 mm per event can be assumed with an interval of 2 to 4 days, which gives a $K_{c\ ini}$ of 0.7 to 0.8 as result. For irrigation this values have to be adjusted if there is only a partial wetting of the soil surface (Allen *et al.*, 1998). For sukuma wiki, a fraction of surface wetted by irrigation of 0.5 was determined from field observation. By multiplying this fraction with the $K_{c\ ini}$, an effective K_{cini} of 0.35 to 0.45 is derived. In the same way the wetted surface fraction of tomatoes was observed to be also 0.5.

For the mid-season and end of the late season stage the crop coefficient will mainly be influenced by the difference in aerodynamic properties of the vegetation. The effect of the difference in aerodynamic properties between the grass reference and agricultural crops is not only crop specific but also varies with the climatic conditions and crop height. The tabulated data are values of $K_{c\ mid}$ and $K_{c\ end}$ for a relative minimum humidity of 45% and wind velocity of 2 m/s. Since the estimations of the climatic data of the survey area are in the same range, respectively 49% and 2.6 m/s, the tabulated $K_{c\ mid}$ and $K_{c\ end}$ values are considered correct (Allen *et al.*, 1998).

Water, management and environmental stress coefficient (K_S)

Factors such as soil salinity, water stress, poor land fertility, limited application of fertilizers, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evaporation. If nessecary, ET_c can be adjusted for non standard conditions by multiplying it with an adjustment factor (K_S).

$$ET_{c\ adj} = K_S\ \ K_C\ \ ET_0$$

Calculation procedures for K_S for water and salinity stress are presented by Allen *et al.* (1998).

Yield response to water

The response of yield to water supply is quantified through the yield response factor (K_Y), which relates relative yield decrease to relative evapotranspiration deficit. This can be represented for a whole growing season or for the separate growth stages.

$$\left(1-\frac{Y_a}{Y_m}\right)=K_Y\left(1-\frac{ET_{c\,adj}}{ET_m}\right)$$

With,

Y_a: actual yield

Y_m: maximum yield

$ET_{c\ adj}$: actual adjusted crop evaporation

ET_m: maximum evaporation (ET_c)

The K_Y values for most crops are derived on the assumption that the relationship between relative yield decrease and relative evapotranspiration deficit is linear and is valid for water deficits of up to about 50 percent. The values for K_Y are derived from Doorenbos and Kassam (1979). The missing values for the establishment stage were taken as 1.0 (sensitive to water stress).

So under conditions of limited water distributed equally over the total growing season, involving crops with different K_y values, the crop with the higher K_y value will suffer a greater yield loss than the crop with a lower K_y value (Doorenbos *et al.*, 1979).

As an example, seasonal yield response factors determined in an irrigation scheme in a semi-arid region in Kenya (Kipkorir *et al.*, 2002) deviated by 16% for onions and only 3% for maize from the published values. A sensitivity analysis by Kipkorir indicated that by adjusting the published K_Y values for sensitive growth stages by ± 10%, the difference in simulated yields for various crops remained smaller than ± 5%. This implies that in the absence of locally determined K_Y values, the values presented by Doorenbos and Kassam (1979) can be used as good indicative values (Raes et al., 2003).

Intercropping and mulching

The field campaign results report the intercropping of mostly maize and beans or maize and cowpeas. Because of their long growing period, pigeon peas are only intercropped during the rainy seasons and remain as pure stand during the short dry season (February-March). For intercropping of a contiguous vegetation with different ground cover the K_C of the intercropped field can be estimated by weighting the K_C values for the individual crops (K_{C1}, K_{C2}) according to the fraction (f_1, f_2) of the area covered by each crop and by the height (h_1, h_2) of the crop (Allen *et al.*, 1998).

$$K_{C\ field} = \frac{f_1\ h_1\ K_{C1} + f_2\ h_2\ K_{C2}}{f_1\ h_1 + f_2\ h_2}$$

Using this formula for a maize and beans intercropped field with a single 1 m wide row of maize for every 2 m of beans, the $K_{C\ \mathrm{field}}$ values for the mid stage and end of late stage season are 1.14 for the mid stage and 0.67 and 0.35 for the end of the stage with respectively green and dry harvest. Because no solutions are offered for the calculation of the soil water depletion fraction for no stress (p) and the rooting depth, assumptions will have to be made. The soil water depletion fraction for no stress will be taken the least of the two crops in order not to stress the most sensitive crop. The rooting depth can be taken as the weighted mean of the two crops taking into account the fraction of the field planted with each crop. The yield response to water will not be considered during intercrop simulations

To reduce evapotranspiration from the soil surface an organic mulch layer can be applied. Other advantages of a mulch layer are reduced erosion risks and weed control. The layer may consist of unincorporated plant residues or foreign material imported to the field such as straw. The dept and fraction of the soil surface covered will affect the amount of reduction in evaporation from the soil surface. Allen *et al.* (1998) estimated that during the initial growth stage the soil water evaporation is reduced by about 5% for each 10% of soil surface that is effectively covered by and organic mulch. For later stages the crop cover becomes more important and the effect of the organic mulch layer on the evaporation from the soil surface will be lost very rapidly (Allen *et al.*, 1998).

3.4. Soil data

The soil is a very complex system, made up of a heterogeneous mixture of solid, liquid, and gaseous material. The liquid phase consists of soil water, which fills part or all of the open spaces between the solid particles. The water phase contains solutes that may have been dissolved from the soil mineral phase or may have entered through the soil surface. The water phase is held in the soil matrix by forces and varies significantly in mobility depending on its location. The soil solid phase has a dominant influence on many water, heat and solute transport and retention processes. Therefore, characterizing the physical properties of the soil solid phase is essential to an understanding of many of the practical agricultural problems (Jury *et al.*, 1991).

3.4.1. Geology of the Kitui District

The greater part of the Kitui District is underlain by the Basement System, which is generally considered to be of lower Precambrian (Archean) age. Originally, this Basement System consisted of sedimentary rocks. These rocks were metamorphosed. Some were granitized and, in some places, invaded by basic igneous rocks prior to metamorphism. A wide variety of gneisses and schists make up the Basement System underlying the Kitui District. The granitoid gneisses, which are more resistant to erosion than banded gneisses, form most of the hills and the mountains. Most of the survey area is a peneplain. Most of this peneplain is a dominantly undulating to hilly planation surface of post-Miocene age (Republic of Kenya, USDA, 1978).

3.4.2. Soils of the Kitui District

The general pattern of soils in the Kitui District is chiefly determined by the kind of bedrock and the climate. The soils in most of the area developed on the Basement system rocks. On the granitoid gneisses, which are quarts rich, the soils are sandy. These soils are very poor from a chemical standpoint but are very porous and have good workability.

On the undifferentiated Basement rocks, mainly banded gneisses, quite a variety of soils have developed, partly because of the variety in composition of the bedrock. The red soils that developed on these rocks are, in general, clayey. The brown soils are less clayey, probably because they developed on rocks that contain more quartz. The soils in substantial area over undifferentiated Basement rocks are shallow and stony. On the gneisses that are rich in ferromagnesian minerals (e.g. hornblende), deep, red clays and deep, black, cracking clays developed.

In the area of highest rainfall the northwestern part of the Kitui District, soils are generally friable and porous, have high infiltration and permeability rates, and are relatively resistant to erosion. In the drier areas to the east and the south, the soils tend to be more compact in the subsoil, and sealing of the upper few centimetres of the profile is substantial, giving rise to slower infiltration and permeability rates. These soils are less resistant to sheet erosion.

There is a spatial variability in soil chemical characteristics. However, most soils are slightly to strongly acid. The base saturation on the average is 50 percent. Exchangeable aluminium is absent. The organic matter content of most topsoils is low, generally about 1 percent. Available potash status is fair except in the sandy soils and some Black cotton soils. The reserve of minerals particularly potassium and phosphorus, is generally very low (Republic of Kenya, USDA, 1978).

3.4.3. Data collection and processing

Soil hydraulic parameters are crucial input data for modelling water movement in the unsaturated zone of the soil. Different techniques are available to measure these characteristics both in the laboratory and in the field.

Soil water parameters were collected from literature as well as from field measurements and disturbed and undisturbed samples, analysed in the laboratory. The general philosophy is to match the literature values and the parameters that were derived from sample analysis and field measurements in order to get a broader spectrum of parameters for a specific sample.

A lot of soil surveys in the Kitui District report detailed profile descriptions with analytical data. The reports that are used in this study are “Reconnaissance Soil Survey, Machakos-Kitui-Embu” (Republic of Kenya, USDA, 1978), “Detailed soil survey of the Voo research substation, Kitui District” (Gachene *et al.*, 1986) and “Preliminary evaluation of the soil of the Ukamba agricultural institute (UKAI) site, Kitui District” (Mugai, 1978). Included in the “Reconnaissance Soil Survey, Machakos-Kitui-Embu” is a soil map of the study area on a scale of 1:250.000.

3.4.3.1. Literature data of the survey area

From the soil map (Republic of Kenya, 1978) 2 major soil units can be distinguished around Kisayani village (see Figure 3.8). Table 3.3 gives a description of the map units in the survey area together with their classification according to the FAO/UNESCO system of 1974, U.S. Soil Taxonomy and the World Reference Base for soil resources (WRB).

Because of their steep slopes and stony subsurface, the Lithosols are not suitable for agriculture and are not taken into account in this study. The soil map's large scale does not permit to identify smaller inclusions of different soil types. After land evaluation in the Kisayani area, three soils types mentioned in Soil Survey report of the Voo research substation are added to the list. "Black Cotton Soils" (WRB: Black cotton soils) and Arenosols are present as little inclusions in the lower parts of the land. Fluvisols or alluvial soils can be found as 10-40m wide strips along the riverbed. These soils are very important from the irrigation perspective, because most irrigated farming is today being done on these grounds.

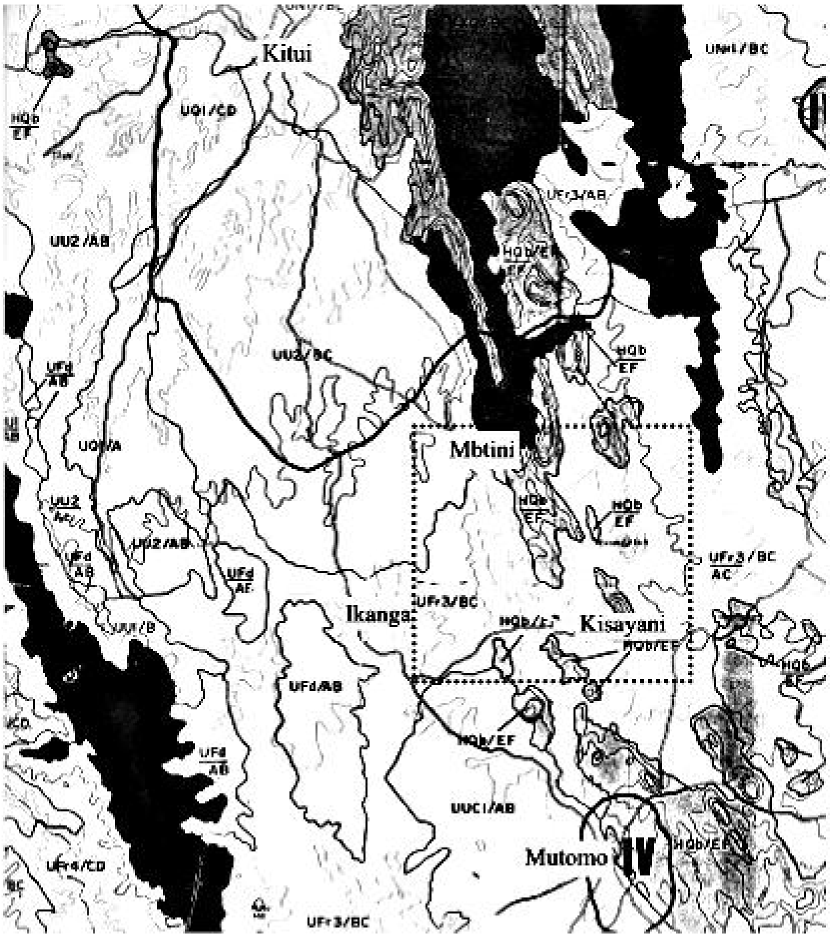

Figure 3.8: Extract from soil map (scale 1:250000) around Kisayani village, Kitui District, Kenya (Source: Republic of Kenya, 1978).

Map unit	*Description*	*Classification*		
		FAO/UNESCO	*U.S. Soil Tax.*	*WRB*
HQb/EF	Somewhat excessively drained, shallow, reddish brown, stony and rocky sandy clay loam to clay, slope: 16-50%	Lithosols; Humic Cambisol, lithic phase	Udorthents and Humitropepts, lithic subgroup	Lithic Leptosol
UFr3/BC	Well drained, moderately deep to very deep dark red to red friable to firm sandy clay to clay, slope: 2-8%	Chromic Luvisol	Fine, kaolinitic, isothermic Typic	Lixisol

Table 3.3: Description of the soil map units around Kisayani village, Kitui District, Kenya (Source: Republic of Kenya, 1978 and Driessen *et al.*, 2001).

3.4.3.2. Sample analysis

Three Kopecky rings were taken from each horizon layer of the nine profile pits. These pits with a depth of 1 metre were dug in the neighbourhood of the “proposed dam site” and more uphill in order to find profiles that are representative for a certain place along the catena. The soil water characteristics of these undisturbed samples were analysed in the laboratory. Derived parameters were the saturated conductivity (K_{sat}), bulk density, soil water content at saturation (θ_{SAT}, pF 0), field capacity (θ_{FC}, pF 2.3) and wilting point (θ_{WP}, pF 4.2) and the total available water content (TAW). The former two points of the soil water retention curve were determined by putting the samples in a water bath at ambient temperature and saturating them from the bottom up. The water content at saturation is the difference between the weight of the dry sample (oven dry, 105°C) and the weight of the completely saturated sample. After 24 hours of draining, the sample is reweighed and the water content at field capacity can be calculated. The water content at permanent wilting point was measured by placing smaller sub samples of the original ones in a high pressure ceramic plate extractor and applying a pressure of 1500 kPa (COFORD, 2000).

The total available water content is defined as the water content available between field capacity and permanent wilting point and can be calculated as,

$$\boxed{\mathrm{TAW}_{[\mathrm{mm/m}]} = 10(\theta_{\mathrm{FC}\,[\mathrm{vol\%}]} - \theta_{\mathrm{WP}\,[\mathrm{Vol\%}]})}$$

The saturated hydraulic conductivity was measured and calculated using the constant head method described by Klute and Dirksen (1986). The bulk density is the weight of the oven dry sample divided by its volume. Three undisturbed samples were taken per horizon, per parameter that was determined the average value is used in further analysis.

In contrast to the direct measurement of hydraulic parameters which is time consuming and relatively expensive, indirect methods are developed to predict those parameters from more easily measured and less costly soil data such as texture, organic matter content and bulk density. These indirect methods are also referred to as pedotransfer functions. Within these functions a subdivision is made between class and continuous pedotransfer functions. A class pedotransfer function predicts the hydraulic characteristics of a texture class. A continuous pedotransfer function predicts the hydraulic characteristics using the actually measured particle distribution. Needless to say that the former method is less expensive but at the same time less accurate than the latter (Wösten *et al.*, 1995).

In order to make use of the continuous pedotransfer functions, the disturbed samples were analysed to determine the textural parameters. This was done by sieving and sedimentation following the international standard (ISO 11277, 1998).

Early forms of pedotransfer functions are regression equations that predict specific points of interest of mainly the water retention characteristics, e.g. Rawls *et al.* (1982). The advantage of this method is that fairly accurate predictions can be made for specific points along the water retention curve. Clear disadvantages are that a large number of regression equations are required to quantify the complete soil moisture retention characteristics and that the output tends to be tabular. The latter format is generally more limited as it may hamper the efficient inclusion of hydraulic characteristics in simulation models (Wösten et al., 2001).

Saxton *et al.* (1986) used the results of broad based regression equations that predict specific points (e.g. Rawls *et al.*, 1982) to derive equations to estimate continuous relationships of soil water moisture content to potentials and hydraulic conductivity from soil textures, as defined by de USDA (United States Department of Agriculture Soil Conservation Service). These so called pedotransfer functions provide good computational efficiency for model applications and the textures can be used as calibration parameters where field or laboratory soil water characteristic data are available. The complete "water potential (Ψ/h) – water content (θ)" relationship or pF curve is represented by three equations for the ranges of (i) saturation to air entry, constant; (ii) air entry to 10 kPa, linear; and 10 kPa to 1500 kPa and greater, curvilinear. The used equations are shown in Table 3.4.

The coefficients of the linear and curvilinear part of the curve were determined using respectively linear regression and stepwise multiple non-linear regression techniques. The results of this regression analysis are presented in Table 3.4 (Saxton *et al.*, 1986).

The SPAW-hydrology software, which integrates the equations of Table 3.4, is available as freeware (Saxton, 2003). The primary input consists of the sand and clay content of the soil. It is possible to define secondary parameters as organic matter content, salinity, gravel content and degree of compaction. The output consists of a numerical presentation of the most important soil water characteristics. The software facilitates greatly the estimating of the most important soil water characteristics from the texture analysis.

Tension range (kPa)	*Equation*	*Coefficient equations*	*N, R²*
>1500 to 10	$\Psi = A\theta^{B}$	$A = \exp[a + b(\%C) + c(\%S)^2 + d(\%S)^2(\%C)]100$ $B = e + f(\%C)^2 + g(\%S)^2(\%C)$ With, a=-4.396; b=-0.0715; c=-4.880^{E}-04; d=-4.285^{E}-05; e=-3.140; f=-2.22^{E}-03; g=-3.484^{E}-05	44; 0.99 44; 0.99
10 to Ψ_e	$\Psi = 10 - \frac{(\theta - \theta_{10})(10 - \Psi_e)}{(\theta_{sat} - \theta_{10})}$	$\theta_{10} = \exp[2.302 - \ln A)/B]$ $\Psi_e = 100[m + n\theta_{sat}]$ $\theta_{sat} = h + j(\%S) + kLOG_{10}(\%C)$ With, h=0.332; j=-7.251^{E}-04; k=0.1276; m=-0.108; n=0.341	10; 0.94 10; 0.99
Ψ_e to 0.0	$\Theta = \Theta_{sat}$		
>1500 to 0.0	$K_{sat} = 2.778\,E - 06 \quad \exp\left[\frac{p + q(\%S) + [r + t(\%S) + u(\%C) + v(\%C)^2]}{\theta_{sat}}\right]$ With, p=12.012; q=-7.55^{E}-02; r=-3.8950; t=3.671^{E}-02; u=-0.1103; v=8.7546^{E}-04		230;0.95

Table 3.4: Equations used to estimate soil water characteristics from texture. Ψ: water potential [kPa]; Ψ_e: water potential at air entry [kPa]; θ water content [m³/m³]; θ_{sat}: water content at saturation [m³/m³]: θ_{10}: water content at 10 kPa [m³/m³]; K_{sat}: saturated hydraulic conductivity [m/s]; (%S): percent sand; (%C): percent clay; N: number of sets of variables; R²: goodness of fit (Source: Saxton et al., 1986).

Another type of pedotransfer functions are models with no physical background but which have emphasis on a sufficiently accurate description of soil water characteristics. These types of functions predict parameters in models describing the complete pF-curve (Ψ-θ) or the K-θ relationship. This approach is more straightforward than the point prediction procedure since the results are directly applicable in simulation models.

The “Van Genuchten” model (1980) is an example of the last type of pedotransfer functions. By combining the “Van Genuchten model” with Mualem’s pore-size model, an expression for K(θ) can be derived. Table 3.5 gives the analytical functional forms for h(θ) and K(θ).

The residual water content refers to the water content where the gradient dθ/dh becomes zero (for h→ -∞). In practice, θ_r is the water content at some large negative value of the soil water pressure head. The parameters α, n and L determine the shape of the curve. The parameter α equals approximately the inverse of the pressure head at the inflection point where dθ/dh has its maximum value. The dimensionless parameter n determines the rate at which the S-shape retention curve turns towards the ordinate for large negative values of h, thus reflecting the steepness of the curve. The dimensionless parameter L determines the slope of the hydraulic conductivity curve in the range of more negative values of h (Wösten, 1995).

Function	*Mathematical form*
Matric potential – water content	$\theta(h) = \theta_r + \frac{\theta_{sat} - \theta_r}{\left[1 + (\alpha h)^n\right]^{(1-1/n)}}$
Hydraulic conductivity – water content	$K(\theta) = K_0 \, S_e{}^L \left[1 - \left(1 - S_e{}^{\frac{n}{(n-1)}}\right)^{1-1/n}\right]^2$ $S_e = \frac{\theta(h) - \theta_r}{\theta_{sat} - \theta_r}$

With,

h: pressure head [>0 for increasing suctions, cm]

θ (h): water content at suction h [m³/m³]

θ_{sat}: water content at saturated [m³/m³]

θ_r: residual water content [m³/m³]

α: parameter [>0, cm^{-1}]

n: parameter [>1, -]

K(θ): hydraulic conductivity [cm/day]

K_0: fitted matching point at saturation [cm/day]

S_e: effective saturation [-]

L: empirical parameter, mostly taken equal to 0.5 [-]

Table 3.5: The analytical functional forms of the “Van Genuchten” model for h(θ) and K(θ) (Source: Schaap *et al.*, 2001).

Schaap et al. (1999) used neural network analysis to estimate "Van Genuchten" water retention parameters and saturated hydraulic conductivity. An advantage is that neural networks require no a priori model concept. The optimal, possibly non-linear, relations that link input data to output data are obtained and implemented in an iterative calibration procedure. More detailed explanations of neural network analysis is however beyond the scope of this study. To facilitate the practical use of the pedotransfer functions, they designed a hierarchical structure to allow input of limited and more extended sets of predictors.

While neural network-based pedotransfer functions provide relatively accurate estimates, they contain a large number of coefficients that do not permit easy interpretation or publication in explicit form. Therefore the hierarchical models of Schaap and Leij are integrated in the ROSETTA software (Schaap, 1999). Software input can vary from a soil textural class to measured values of particle size distribution in combination with measured values of bulk density and water content at field capacity and permanent wilting point (Schaap et al., 2001). The ROSETTA model is integrated in the HYDRYS-1D software (Simunek *et al.*, 1998).

In this study both the SPAW software and the ROSETTA software will be used to estimate the soil water characteristics. This estimates will be used in the simulations with BUDGET and UPFLOW in order to get an idea of the uncertainty of the output when making use of soil water parameters that were estimated with more easily measured and less costly soil data.

3.4.3.3. Field measurements

The saturated hydraulic conductivity at the surface was tested following the double ring infiltration method. For the field measurement of the saturated hydraulic conductivity at 1 m depth the inversed auger hole method also known as the Porchet method is used (Figure 3.9).

The inversed auger hole method consists of drilling a hole to a certain depth, saturating it with water and measuring the drop of the water with time. This method was used because at the time of sampling the groundwater table often was 3 m deep.

The saturated hydraulic conductivity can be calculated by (International institute for land reclamation and improvement, 1974),

$$K_{sat} = 1.15\, r \tan\alpha$$

$$\tan\alpha = slope(t, \log(h(t_i) + r/2)) = \frac{\left[\log(h(t_i) + r/2) - \log(h(t_n) + r/2)\right]}{t_n - t_i}$$

With,

$h(t_i)$: initial wetting depth

$h(t_n)$: final wetting depth

t_i: initial time

t_n: final time

r: radius borehole

Figure 3.9: Methods for measuring the saturated hydraulic conductivity. The inversed auger hole method (left) and the double ring infiltrometer method (right).

The double ring infiltrometer is used to measure the K_{sat} of the soil surface. Infiltration is modelled by the Kostiakov equation,

$$I = A.t^{B}$$

Where I is the cumulative amount of infiltration between time zero and the final time. A and B are constants that have no particular physical meaning and that are evaluated by fitting the model to experimental data by,

$$Log(I) = Log(A) + B\ Log(t)$$

Where Log(A) and B will be respectively the intercept and the slope of the linear relationship between Log(I) and Log(t) (Jury et al., 1991).

The infiltration rate (i) can be modelled by differentiating the Kostiakov equation in time,

$$i = \frac{dI}{dt} = AB.t^{(B-1)} = a.t^{b}$$

The coefficients can be calculated from the already determined constants A and B. The soil is assumed to be saturated after 2 hours, hence the saturated hydraulic conductivity can be assumed equal to the infiltration rate after 2 hours (Feyen, 2002).

It has to be mentioned that the first method measures the horizontal and the vertical hydraulic conductivity at the same time, while the last method measures only the vertical hydraulic conductivity.

3.5. Capillary rise

Capillary rise is the water movement from a saturated zone upwards into the vadose zone of the soil profile by surface tension. In the presence of a shallow water table, the upward water movement by capillary rise from the groundwater table to the root zone is an important incoming flux at the bottom boundary of the root zone. Since the upward transported water can cover part of or even the total crop water requirement, the flux should not be neglected when estimating the irrigation requirement (Raes *et al.*, 2002c).

3.5.1. The UPFLOW-model

3.5.1.1. Generalities about the model

UPFLOW (Raes, 2001) is a software tool developed to assess steady state upward flow of water and salts from a shallow water table to the topsoil during a specific period and for the given environmental conditions. The environmental conditions are specified in the program by the average evapotranspiration demand of the atmosphere during the period under consideration, the average soil water content that is maintained in the topsoil during that period (upper boundary), the depth of the water table below the soil surface (lower boundary), the water extraction pattern of the plant roots, the thickness of the successive layers of the soil profile and the salt content of the water table (Raes *et al.*, 2002c). Additionally, the software displays the deficient aeration conditions in the root zone and its effects on crop evapotranspiration when the groundwater is close to the soil surface (Raes et al., 2003). Guidelines for estimating evapotranspiration from a cropped and a non-cropped surface are given by Allen *et al.* (1998).

Former simulations were in line with indicative values presented in literature (Raes *et al.*, 2003). Field measurements in Brazil, Senegal (Raes et al., 2002c) and Belgium (Raes *et al.*, 2003) have proven that the model simulates in the correct order of magnitude.

The model estimates the average capillary rise that can be expected during a period (typically 10 days) in which the specified environmental conditions are valid. Although daily values might fluctuate around the average value it is believed that the fluctuations will be small as long as the environmental conditions do not change drastically (Raes *et al.*, 2003).

3.5.1.2. The calculation procedure

Steady state upward flow from a shallow water table is estimated by means of a calculation procedure presented by De Laat (1980, 1995). By assuming a constant flux from a shallow water table to the top soil, De Laat rewrote and integrated the Buckingham-Darcy equation as,

$$z = -\int_0^h \frac{K(h)}{q + K(h)}\, dh$$

With,

z [m]: height from the water table to the surface (taken positive)

q [m/day]: constant upward flux

h [m]: the soil matric potential per unit weight of water (head)

K(h) [m/day]: the hydraulic conductivity. The K-h relation is given by Mualem's model if the parametrical estimation of the Θ-h curve is chosen.

By means of the equation of De Laat and the K-h relationship, the matric potential can be calculated at specific points above the water table for particular steady state upward flows. Using the soil water characteristics curve (Θ-h) this pressure profile can be transformed into moisture profiles. So, given the K-h and Q-h relationships for the various soil layers of the profile above the water table, UPFLOW is able to determine the maximum flux that can flow to the topsoil by checking that the simulated soil water content remains below the specified mean water content of the topsoil (Raes *et al.*, 2002c).

Since steady state conditions are assumed, the upward flux has to be equal to the amount of water that can be extracted by soil evaporation or root water uptake. Root water extraction is determined by the root extraction rate (S_{max}) and the degree of water logging of the root zone. The software determines that point in the root zone where the integrated root water extraction is equal to the upward flux. If the soil is not cultivated, the extraction point is located at the soil surface, where all the upward transported water evaporates. The closer the water table is to the surface, the more the root zone is waterlogged. Water logging will result in deficient aeration conditions that will hamper root water uptake. This is simulated in UPFLOW by multiplying S_{max} with a water stress coefficient (K_S). Once aeration conditions in the root zone are deficient, K_S decreases exponentially from 1 to 0. This anaerobis point (K_S=0) is plant specific and is expressed as a certain deviation in volumetric water content from soil saturation (Raes *et al.*, 2003).

3.5.2. Determination of the relevant conditions for modelling capillary rise

The topographic map of the survey area (Appendix 4) shows that the Ngunga river incises the survey area quite roughly, resulting in locally very steep slopes (40-60%) in the outer parts of the river bends. At the inner part of the river bends, the incision is more moderate with slopes of 0-5%. The slope map for the survey area is given in Appendix 4. The soil that developed on the riverbanks at the inner parts of the river bends are very deep, reaching a dept of up to 3.80 m. The depth of the soil profiles decreases quickly, with the rock layer at the depth of 0.70 m within a 100 m from the river. This topographic and pedologic arguments lead to the conclusion that it is most likely that capillary rise only takes place in the deep soils at the inner parts of the river bends.

The parts of the land where capillary rise is most likely to occur coincide with the plots that will be used for cultivating irrigated cash crops. Taking in account the soil and crop data that were collected during the field campaign it is most relevant to simulate capillary rise for the cash crops, cultivated on a black cotton soil or a deep sandy loam soil (riverbank) with a well watered topsoil because irrigation can be assumed. During the field campaign several farmers were reported cultivating their cash crops in the riverbed during the dry season. Therefore the coarse sand soils are also taken into account during the simulations for capillary rise.

The drop of the groundwater table during the dry season is aquifer specific and the initial depth after the rains also depends on the prevailing climatic conditions. Since data on the depth of the groundwater table at specific times during the dry season are lacking, it is not possible to predict that depth for certain prevailing climatic conditions. However these predictions would not be applicable for farmers in different aquifers. Giving guidelines for irrigation in relation to the actual monitored depth of the groundwater table in the field is more flexible and more widely applicable.

3.5.3. Abstraction of the crop and soil parameters

In order to facilitate the further use of the results of the simulations a few abstractions are made. First of all the potential evapotranspiration is assumed to be the mean yearly value (4.55 mm/day) all year long. The use of a mean value can be justified by the small standard deviation (0.5 mm/day) in decadal potential evapotranspiration through the year. Another abstraction made is the use of three hypothetical crops representing the shallow, medium and deep-rooted crops. The shallow rooted crop group represents crops like sukuma wiki, cabbages, onions and spinach with roots up to 0.75 m. The medium-rooted crops, like tomatoes, have a maximum rooting depth of 1.00 m. An example of a deep-rooted crop is pigeon peas having a root system up to 2 m deep. These crops are assumed to be perennial with an active ground cover, a canopy cover of 50% and a root water uptake pattern that is similar to that of deciduous trees. All parameters of the hypothetical crops are based on the crop parameters, described in paragraph 3.3.2.2, and are summarized in Table 3.6.

Shallow rooted crops:				
Growth stage	*Initial*	*Development*	*Mid-stage*	*End of late-stage*
K_C (-)	0.75	>>	1.05	0.90
ET_C (mm/day)	3.20	>>	4.80	4.10
Rooting dept (m)	0.25	>>	0.5	0.5
Medium rooted crops:				
Growth stage	*Initial*	*Development*	*Mid-stage*	*End of late-stage*
K_C (-)	0.75	>>	1.10	0.80
ET_C (mm/day)	3.20	>>	5.20	3.65
Rooting dept (m)	0.25	>>	1.00	1.00
Deep rooted crops:				
Growth stage	*Initial*	*Development*	*Mid-stage*	*End of late-stage*
K_C (-)	0.80	0.80	0.80	0.80
ET_C (mm/day)	3.65	3.65	3.65	3.65
Rooting dept (m)	2.00	2.00	2.00	2.00

Table 3.6: The crop parameters used to simulate capillary rise.

The evaporation from a bare soil surface is said to be equal to the evapotranspiration for the initial growth stage of the shallow to medium rooted crops (Allen *et al.*, 1998).

The Van Genuchten parameters for the water retention curves of the different soil layers that were explained in paragraph 3.4 will be inputted in the model. The measured saturated hydraulic conductivity values were used to simulate the water flow through the profile. Since there is an uncertainty on the saturated hydraulic conductivity, the sensitivity of the model for this parameter will be examined. The soil profile of the riverbanks (sandy loam) is assumed to have a depth of 3.50 m with the lowest analysed layer extending up to that depth. For the Black Cotton Soil (sandy Clay Loam) the field research showed a less deep profile of 1.70 m with a clay layer until a depth of 1.00 m followed by a weathered limestone layer. This layer is assumed to have similar properties as the top layer of the riverbank (sandy loam). Capillary rise in the riverbed is also investigated for a profile with a depth of 2.30 m.

3.6. Guidelines for irrigation: development and use

This study will follow the method for the development of irrigation calendars presented by Raes *et al.* (2002d). The farmers are given simple guidelines on how to adjust irrigation to the actual weather conditions, the presence of a shallow water table (capillary rise) and when shortage in the supply of irrigation water occurs. The developed guidelines are presented in irrigation charts for a specific crop and for a particular region, soil type and growing season. The development of irrigation charts requires a good knowledge of the regional climatic conditions, physical soil parameters, capillary rise as a function of the depth of the water table, crop characteristics, and the ongoing irrigation practices (Raes et al., 2002d).

3.6.1. Concepts

3.6.1.1. Procedure for developing irrigation charts

Since the objective of the irrigation chart is to give farmers guidelines for the adjustment of their irrigation calendars to the actual weather conditions, the development requires information on rainfall and evapotranspiration levels that can be expected with various probabilities. The rainfall probabilities will be derived statistically as explained in paragraph 3.2.2 from 10-day rainfall records by means of a frequency analysis. The 10-day reference evapotranspiration values of semi-arid regions can be assumed to have little variation over all the years. The 10-day evapotranspiration values are calculated from mean monthly data using the Penman-Monteith equation. The rainfall probability levels distinguish three weather conditions, dry, normal and wet, as explained in paragraph 3.2.2. Irrigation scheduling during the short rainy season includes an extra very dry condition with no rainfall at all. This condition is not present in other irrigation charts since here the dry conditions already receive no or almost no rainfall.

Irrigation calendars are developed by means of a soil water balance technique. It consists in calculating the net irrigation requirement, which is obtained by subtracting from the crop water requirement (ET_C) the expected gains of water through rainfall. Given the fixed net irrigation application depth, the irrigation interval can subsequently be derived by plotting the root zone depletion along the time axis. As shown in Figure 3.10 each time irrigation water is applied, the root zone depletion decreases with the applied net irrigation depth.

To avoid water stress, the root zone depletion should not exceed the threshold value for no stress (RAW). The resulting yield decrease depends on the severity of the stress and sensitivity of the crop at the particular growth stage. On the other hand, to avoid water losses due to deep percolation, the soil water content in the root zone after an irrigation event should not exceed field capacity. By alternating the irrigation interval or the irrigation depth during the season, one is able to keep the root zone depletion between the lower (RAW) and upper (Field Capacity) boundary. With the help of the BUDGET model alternative solutions can be quickly developed and evaluated.

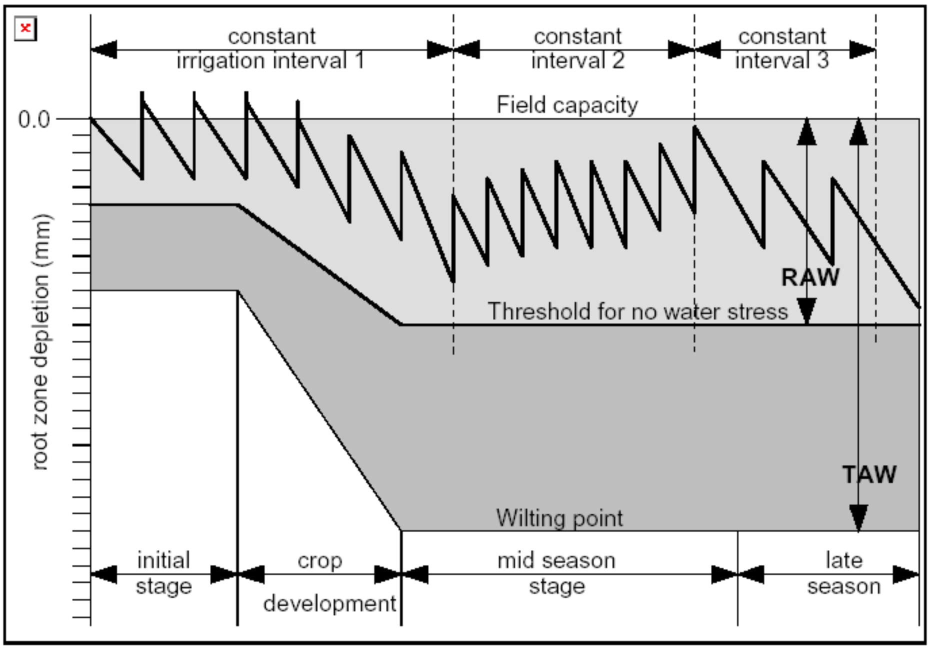

Figure 3.10: Root zone depletion (broken line) for a schedule with a fixed irrigation application depth (Source: Raes et al., 2002d).

In case of a shallow water table the contribution of capillary rise to the soil water balance can be considered as well by developing irrigation guidelines in the case where the water table is in a certain, in advance determined, depth interval. Capillary rise data can be taken into account during simulations with BUDGET by lowering the reference evapotranspiration of a time step with the capillary rise during the same time step. For vegetable crops this results in little over- and underestimation of the irrigation requirements in respectively the initial and the mid stage of the growing season because this correction should be done on the crop evaporation and not on the reference evaporation. Up to today BUDGET offers no alternative for considering capillary rise. The relation between the depth of the water table and the capillary rise, as will be determined in paragraph 4.4, is used to define values for capillary rise which are representative for a certain depth interval. For shallow rooted crops the curve that represents the mid stage is used, since the differences between the different growth stage curves are minimal. Only the maximum capillary rise is different, which is taken into account when making further calculations. For the medium rooted crops, the initial and the mid stage curves are used, because the rooting depth and subsequently capillary rise differs significantly between the respective growth stages. As mentioned above, the values for capillary rise are used to lower the reference evapotranspiration. The derived series of reference evapotranspiration records are loaded into the BUDGET software and the soil water balance method is used the develop irrigation charts. The guidelines for the different values of capillary rise developed are represented in irrigation charts. The charts including includes the capillary rise only present guidelines for one crop, one soil type and one rainfall scenario.

3.6.1.2. Working with irrigation charts in the field

Indicative values for irrigation intervals for the four considered weather conditions in a particular period of the growing season are presented in the front of the irrigation charts as show in Table 3.7.

For *no and insignificant* rainfall, indicative intervals are given respectively in line 1 and 2. When rainfall of one or successive days is *significant*, the interval between the irrigations can be stretched. Expected mean intervals for rainy period are given in line 3 (normal weather) or line 4 (wet weather). The adjustments of the irrigation interval during periods of rainfall should consider the amount of rainfall that is recorded.

If the rainfall is *equal or higher* than the irrigation application depth then rainfall will replace irrigation. Once the rains are over, guidelines for the irrigation interval/dose are given in line 1 and 2.

If the rainfall is *smaller* than the recommended application depth, the irrigation can be delayed with a number of days by multiplying the advised interval (in line 1 or 2) with a delay factor. This factor is equal to the rainfall amount divided by the net irrigation application depth. It is good practice to compare the stretched irrigation interval during rainy periods with the guidelines in line 3 or 4. If the stretched interval is on average much smaller than the advised interval, it is likely that one is over-irrigating. If the interval is larger, one is likely to under-irrigate and the crop might experience some water stress.

At the bottom of the table of the irrigation interval on the front of the chart, users can find information about crop sensitivity to water stress at the various growth stages. In case of water shortage, these references are useful to further adjust irrigation scheduling while still maximizing production. Some water savings can be made by delaying irrigation during periods of low to moderate water stress. A slight to moderate increase of the interval will not strongly affect crop yield. Water savings should be avoided when the crop is sensitive to very sensitive to water stress.

Month		**October**		**November**			**December**			**January**		
Decade		2	3	1	2	3	1	2	3	1	2	3
Meteo conditions	**No rainfall**	3days			5	4days		5	4days			5
	Dry	3days			5	6days		5	4days			5
	Normal	3days		No irrigation				5days		4days		5
	Humid	4days		No irrigation							5days	
Growth period		Establishment		Vegetative		Flowering		Yield formation		Ripening		
Sensitivity to water stress		Very (a)		Moderate (b)		Extremely (c)		Very (a)		Moderate (b)		

Table 3.7: Irrigation interval table for a tomato crop cultivated during the short rains with a net application depth of 20mm.

The charts still provide valid guidelines for irrigation planning when farmers prefer to adjust both the application depth and the interval as long as a proportional change between application and interval is respected. However these variations should remain moderate. Indeed, if the application becomes to small, the water distribution on the field will not be uniform. If, on the other hand the application depth is much larger than the advised depth, large volumes will be lost by deep percolation.

As a reference, 10 day rainfall amounts expected during dry, normal and wet weather conditions are plotted on the back of the chart. Crop evapotranspiration expected under average meteorological conditions for each decade of the growing period are also presented at the backside of the irrigation chart. With the help of this table and information on the actual rainfall, enterprising managers and farmers with a good knowledge of the characteristics of their irrigation system can develop their own irrigation calendars.

Month		May			June			July			August	
Decade		1	2	3	1	2	3	1	2	3	1	2
Depth of water table	**>1.6 m from surface (no capillary rise)**	4days		5days					4	5days		
	1,4-1,6 m from surface e	4days		5days				6days				
	1,0-1,4 m from surface	5days		6days			No irrigation					
	<1,0 m from surface	5days		7days		No irrigation						
Growth period		Establishment		Vegetative		Flowering		Yield formation		Ripening		
Sensitivity to water stress		Very (a)		Moderate (b)		Extremely (c)		Very (a)		Moderate (b)		

Table 3.8: Irrigation guidelines for a tomato crop on a sandy loam soil cultivated in the dry season with a net application of 20 mm, taking into account capillary rise for different depths of the water table.

The presentations of the guidelines that incorporate capillary rise are somewhat different (see Table 3.8). They don not incorporate the variability of the weather conditions. When able to measure the depth of the water table (from a scoop hole), the farmer can determine the irrigation interval from the table presented in the front of the charts. The first line shows the situation were the water table is at a depth were no capillary rise will occur, the following lines present indicative intervals when the contribution of capillary rise becomes significant. The back of the charts contains the same information as the charts that take into account the variability of the rainfall. An extra graph is added to presents the relation between the capillary rise and the depth of the water table. When using this graph in combination with the crop evaporation table and the rainfall distributions farmers can make their on irrigation calendars. Also when able to derive the capillary rise from this graph, the farmer can manipulate the intervals as described earlier in this paragraph for rainfall.

The irrigation requirements indicated in the charts are only net requirements. Since irrigation is never 100 percent efficient, allowance must be made for losses during conveyance and application of water. However, due to the application method (jerry cans or buckets), water can be applied only where needed and the irrigation can be assumed very efficient. Moreover, since the water source is mostly close to the fields, conveyance losses can be minimized.

A simple formula to calculate how much buckets of water the farmer has to apply per bed of plants, given the dimensions of the plots and volume of the buckets is given in Appendix 8.

3.6.2. Practical approach

For the construction of the irrigation interval tables, a fixed application depth is selected in function of local practices, soil and crop parameters and irrigation method

The mean number of rainfall events during a decade on a monthly basis, as asked in the BUDGET software, is calculated from the 21-year new dataset of the Mutomo agriculture station, constructed in paragraph 4.1.1. Per decade the number of wet days with rainfall higher than 3 mm is calculated and an average is taken for the particular month over the 21 year. These data are needed in the runoff procedure of the BUDGET model. The more rainfall events will take place in a decade, the smaller the runoff will be.

The charts will be developed strictly following the guidelines presented by Raes *et al.* (2002d). When SASOL decides to introduce these charts among the local farmers, simplifications could be considered. For example, the no rainfall scenario in Table 3.7 could be simplified to an initial thirty-day period with a time interval of 3 days, followed by a 4-day interval for the rest of the season. When simplifying the charts care must be taken not to under- irrigate.

3.6.2.1. Cash crops

During simulations it was assumed that the soil reached field capacity at the sowing date. This can be achieved by pre-irrigation of the plots. As seen in the field, the fraction of the soil surface wetted during irrigations is taken to be 50%.

Irrigation charts will be developed for sukuma wiki and cabbage, tomato, onion and spinach traditionally cultivated in the dry season (from June until the end of September). Since there is no rainfall during these months only the no rain scenario can be simulated. Simulations will be done for the four soils selected in paragraph 4.3 and summarized in one irrigation chart per crop. Since in the dry season water is scarce and most water is lost by deep drainage in the initial stage, these irrigation charts indicate different intervals in combination with different applications depths in order not to waste water in the initial stage and not to waste time in the later stages. For tomatoes and sukuma wiki, cultivated on a Sandy loam soil (riverbank) and a coarse sand soil (riverbank) in the dry season, irrigation charts will be developed that include capillary rise.

Next to these traditional cropping patterns a few other scenarios will be worked out for growing seasons during the short and long rains and in between. This was done for sukuma wiki and cabbage, tomato and onion, all cultivated on the sandy loam soils of the riverbanks. For every season, the ideal sowing date is determined by minimizing the net irrigation requirements. Because of the long growing period, one onion rotation can make use of rainfall of both short and long rains.

3.6.2.2. Food crops

Irrigation charts are developed for maize cultivated during the short and the long rains on the sandy clay loam soils of the uplands with a net application depth of 20 and 40 mm. The same will be done for a maize and beans intercrop and a maize and cowpea intercrop cultivated during the short rains. The crops are assumed to be sown or planted at the same time and to occupy an equal fraction of the planted area. The crop coefficient for the intercropped field is calculated using the formula explained in paragraph 3.3.2.2. The rooting depth is assumed to be 1 metre and the soil water depletion fraction for no stress to be the smaller of the two crops.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Climatic data

4.1.1. Development of a homogenous rainfall dataset

Because time steps of decades are preferred above monthly time steps and the dataset should contain records for 20 to 30 years, data of only four of the fourteen meteorological stations could be used. The completeness of this data for a period from January 1979 to December 1999 is shown in Table 4.1.

Figure 3.4 indicates that the Mutomo Agriculture station is closest to Kisayani. To avoid special variability this dataset will be used in further analysis. To determine if the dataset can be completed with data from nearby stations, the relationship between different datasets is investigated. Table 4.2 gives the results of the comparison of couples of datasets. Different scenarios are taken into account:

1. ER-ER: number of days with empty records in the two datasets

2. ER-VR: number of days with empty records in the first dataset and valid records in the second
3. VR-ER: number of days with valid record in the first dataset and empty records in the second
4. VR-VR: number of days with valid records in the two datasets

Station	*Valid records*	*Completeness (%)*
Kitui Agriculture station	5228	68.2
Ithookwe Agriculture station	6783	88.4
St. Angelas school Mutunie	2374	31.0
Mutomo Agriculture station	6389	83.3

Table 4.1: Completeness of datasets with daily records from 1979-1999, the total possible number of records is 7670.

The datasets with the most overlapping valid records are Ithookwe Agriculture station and Mutomo Agriculture station (Table 4.2: VR-VR scenario). If a satisfying relationship between these two datasets can be found, the completeness of the Mutomo Agriculture station dataset could be raised with 13% (Table 4.2: VR-ER scenario).

	Kitui-Ithookwe		Kitui-Mutomo		Kitui St. Angelas		Ithookwe-Mutomo		Ithookwe-St. Angelas		Mutomo-St. Angelas	
	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.
ER-ER	4%	277	14%	1067	10%	763	4%	278	11%	826	7%	518
ER-VR	28%	2165	18%	1375	22%	1679	8%	609	1%	61	10%	763
VR-ER	8%	610	3%	214	**59%**	4533	13%	1003	**58%**	4470	**62%**	4778
VR-VR	**60%**	4618	**65%**	5014	9%	695	**75%**	5780	30%	2313	21%	1611

Table 4.2: Results of the comparison of couples of datasets, each dataset contains 7670 records. ER: empty record; VR: valid record. Numbers indicated in bold represent the scenarios with the most overlapping records for a certain comparison.

To investigate the relations between the datasets an overlap/goodness of fit (R^2) table (Table 4.3) is constructed. The number of days with valid records in the two data sets (VR-VR scenario) was copied from Table 4.2. The goodness of fit is tested by linear fitting of the overlapping valid records.

The correlation between the datasets is very poor. The best fit can be made between the Ithookwe Agriculture station data and the Kitui Agriculture station data but these stations are both located too far from Kisayani. The goodness of fit between Ithookwe Agriculture station data and the Mutomo Agriculture station data doesn't permit a transfer of records between the two datasets.

	Kitui Agric.		*Ithookwe Agric.*		*Mutomo Agric.*	
Ithookwe Agric.	60%	0,4696				
Mutomo Agric.	65%	0,10674	75%	0,10201		
St. Angelas sch.	9%	0,23363	30%	0,3169	21%	0,05772
	Overlap	*R^2*	*Overlap*	*R^2*	*Overlap*	*R^2*

Table 4.3: Overlap/goodness of fit (R^2) table.

Another option is to analyse the rain or no-rain events of the datasets (see Table 4.4). Again couples of datasets are compared internally. Only the overlapping valid records are taken into account this time. Again different scenarios are analysed:

1. NR-NR: number of days with no rain in the two datasets
2. NR-R: number of days with no rain in the first dataset and rain in the second
3. R-NR: number of days with rain in the first dataset and no rain in the second
4. R-R: number of days with rain in the two datasets

	Kitui - Ithookwe		*Kitui - Mutomo*		*Kitui - St. Angelas*		*Ithookwe-Mutomo*		*Ithookwe-St. Angelas*		*Mutomo-St. Angelas*	
	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.
NR-NR	79,5%	3670	80,5%	4034	75,7%	526	77,5%	4477	73,9%	1709	69,8%	1125
NR-R	5,0%	233	4,4%	221	12,1%	84	3,8%	220	8,3%	192	16,8%	271
R-NR	5,3%	245	9,5%	477	3,5%	24	10,6%	614	5,3%	122	4,4%	71
R-R	10,2%	470	5,6%	282	8,8%	61	8,1%	469	12,5%	289	8,9%	144
Total:	100%	4618	100%	5014	100%	695	100%	5780	100%	2312	100%	1611

Table 4.4: Results of the comparison of the valid couples of records. NR: no rain; R: Rain.

From Table 4.4 it is possible to calculate the probability on rainfall in station A if there is rainfall in station B (Table 4.5). Table 4.5 shows that for each couple there is less than 50% probability for rain in one station if there is rain in the other. Though, the certainty of no rainfall in station A if there is no rain in station B is a lot bigger, more or less 80% (Table 4.6). Interchanging data between Ithookwe Agriculture station and Mutomo Agriculture station can only be done for days with no rainfall. By filling up the Mutomo dataset with data from the Ithookwe dataset the number of empty records is reduced to 4.7% in comparison with 16.7% in the original Mutomo dataset.

	Kitui Agric.	*Ithookwe Agric.*	*Mutomo Agric.*
Ithookwe Agric.	49,6%		
Mutomo Agric.	28,8%	36,0%	
St. Angelas sch.	36,1%	47,9%	30%

Table 4.5: Chance for rain in the one station if there is rain in the other

	Kitui Agric.	*Ithookwe Agric.*	*Mutomo Agric.*
Ithookwe Agric.	88,5%		
Mutomo Agric.	85,2%	84,3%	
St. Angelas sch.	83,0%	84,5%	77%

Table 4.6: Chance for no rain in the one station if there is rain in the other.

The new dataset is used in this thesis and is given in Appendix 2. The daily records are changed into decadal records by calculating the sum of the daily records that make up the decade of interest.

The homogeneity was tested per decade on the 21-year dataset as described in paragraph 3.2.2. In none of the test the cumulative deviation exceeds the confidence level at which homogeneity should be rejected with a 90% probability. Therefore the dataset is assumed to be homogenous.

The method to fill up empty records used in this paragraph was not described in literature. The somewhat pragmatic approach is followed because no satisfying applicable method to solve this particular problem was found in literature.

4.1.2. Frequency analysis of the new rainfall dataset

For every decade, a frequency analysis was conducted using the RAINBOW software. For every dataset a Weibull plotting position together with a normal distribution was assumed. The transformation use varied between lognormal and square root. The goodness of fit (R^2) after the transformation of the data never was less than 0.90.

Because RAINBOW needs at least 3 non zero events for a 21-year dataset, the dependable rainfalls of the dry season could not be determined for some of the decades. In what follows, it will be assumed that the not analysable records are zero. This can lead to an overestimation of the irrigation requirements of the crops. However, less than 4 non-zero events on a 21-year time span means a probability 86% on a no rain event. A graphical representation of the dependable rainfall for different probabilities of exceedance and the probabilities for no rain events are given in Figure 4.1. Detailed results are included in Appendix 2.

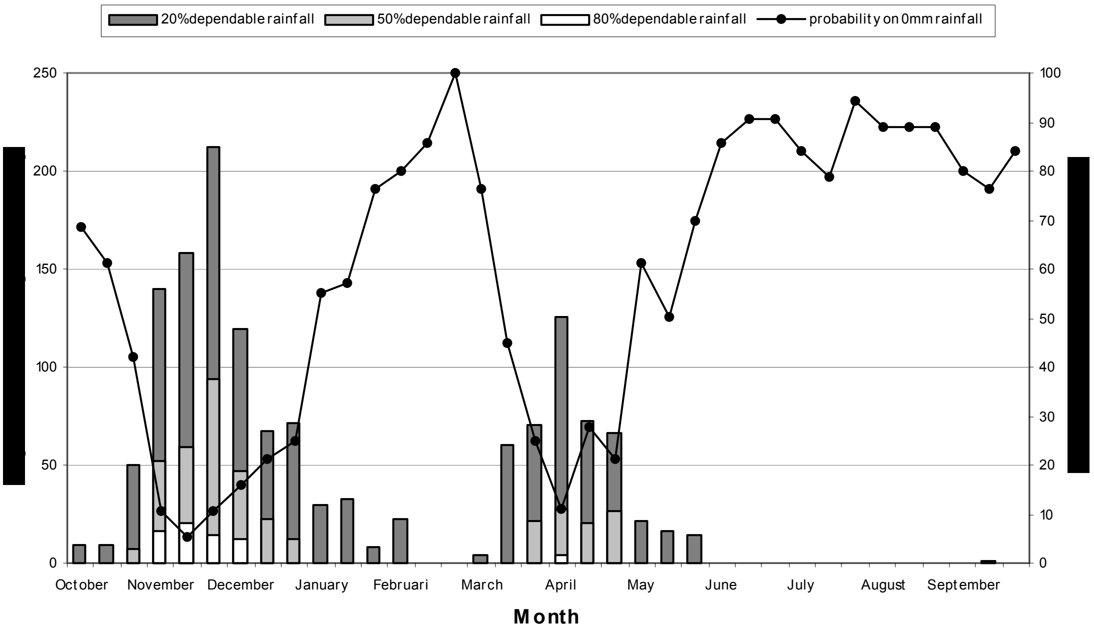

Figure 4.1: 20, 50 and 80% dependable 10 day rainfall levels and probability on 10 day lasting no rain events, Mutomo Agriculture station, Kitui District, Kenya.

4.1.3. Calculation of the 10-day reference evaporation

The mean monthly data are converted into decadal values as mentioned in paragraph 3.2.3. These values are inputted in the ET_0 software. The output is given in Appendix 3. A graphical representation of the decadal reference evapotranspiration is given in Figure 4.2.

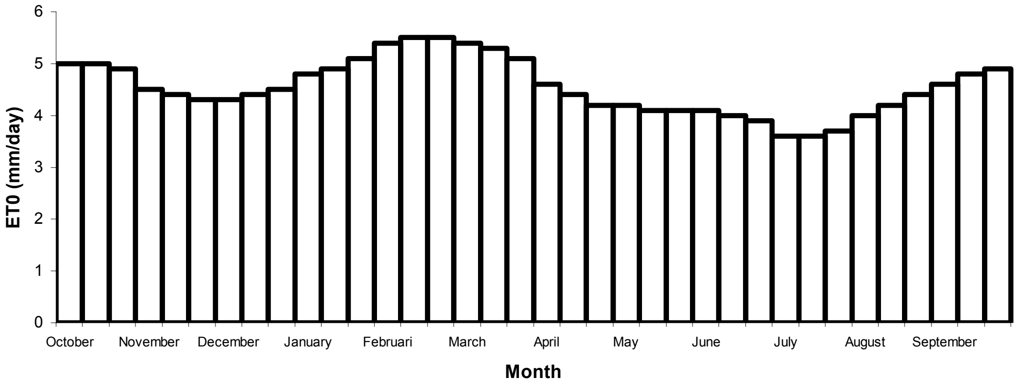

Figure 4.2: 10 day reference evapotranspiration (ET_0), Kitui Agriculture station, Kitui District, Kenya.

4.1.4. Discussion of the climatic data

Figure 4.1 and Figure 4.2 are brought together in Figure 4.3. The units of the reference evapotranspiration are converted to millimetres per decade to simplify the comparison with the rainfall data. As explained in the next paragraph the $ET_0/2$-curve can be used to determine if a certain decade belongs to the growing season. The mean reference evapotranspiration calculated with the mean monthly values is 46 mm/decade with a standard deviation of 5.6 mm/decade. Mean rainfall during the short rains (October-February) is 530 mm with a standard deviation of 320 mm. For the long rains there is a mean rainfall of 219 mm with a standard deviation of 150 mm. The high standard deviations indicate a high inter annual variation in rainfall. On a yearly basis, mean rainfall is 780 mm with a standard deviation of 324 mm. The moisture index, defined in paragraph 1.6.1, is more or less 45%. According to Table 1.1 the Kisayani area can be classified as semi-humid to semi-arid.

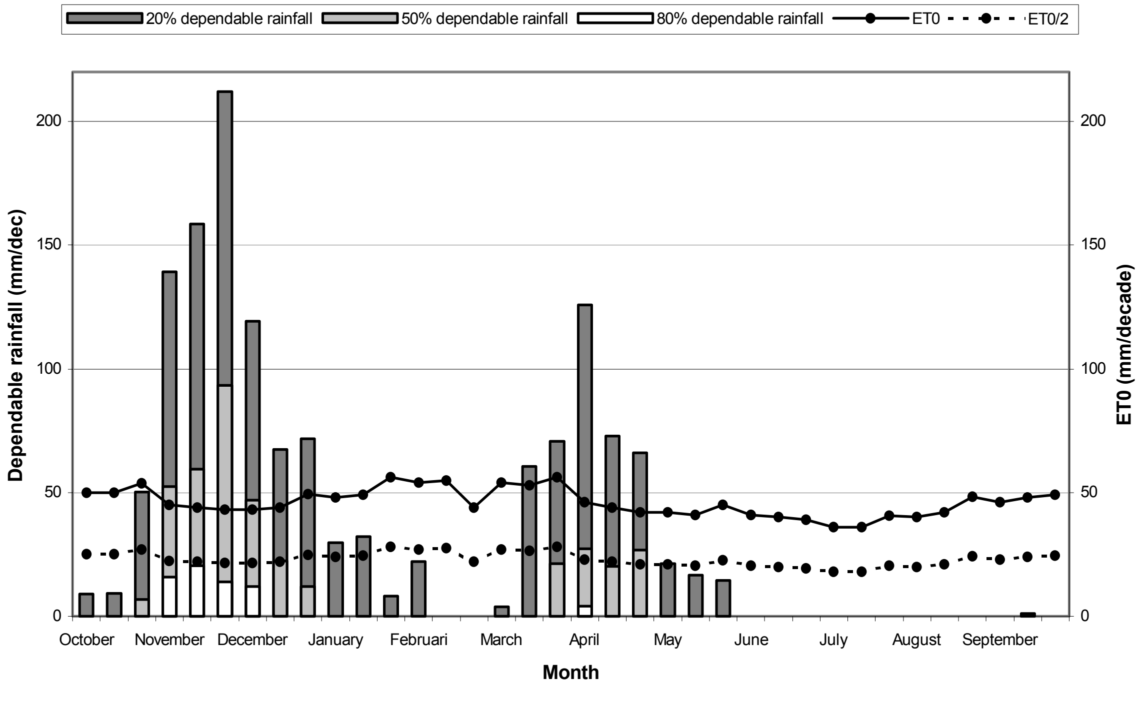

Figure 4.3: 20, 50 and 80% dependable 10 day rainfall levels and reference evapotranspiration per decade, Kitui Agriculture station, Kitui District, Kenya.

The yearly rainfall varies from 1092 mm in a wet year (20% probability of exceedance) to 346 mm in a dry year (80% probability of exceedance). These yearly values were derived from a frequency analysis on a dataset with the ten full-year records available. The same was done for the yearly values of the Machakos and Kitui Agriculture station. A comparison of the dependable rainfall results of the three stations is shown in Figure 4.4.

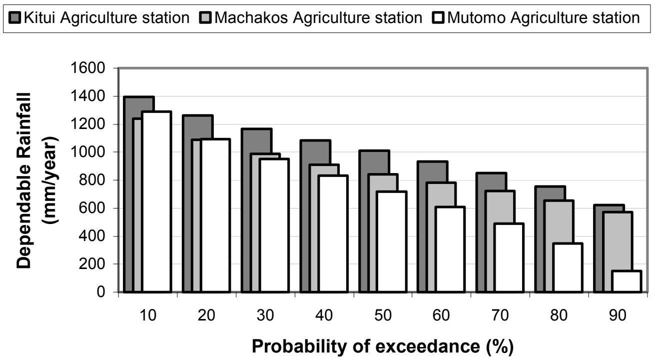

Figure 4.4: Dependable rainfall for various probabilies of exceedance for the Kitui, Machakos and Mutomo agriculture station.

Figure 4.4 shows that the spatial variation in rainfall decreases from very dry years (90% probability of exceedance) to very wet years (10% probability of exceedance). Locations of the Kitui and Mutomo Agriculture stations, which are approximately 60 km away from each other, are shown in Figure 3.4. The Machakos station is situated 85 km more west of the Kitui station (Figure 1.6).

4.1.5. Onset, cessation and duration of the growing period

The results of the frequency analyses on the duration, the onset dates and the cessation dates are shown in Table 4.7.

Prob. exeedance	*Short rains*			*Long rains*		
	Duration (days)	*Onset (month/decade)*	*Cessation (month/decade)*	*Duration (days)*	*Onset (month/decade)*	*Cessation (month/decade)*
20%	101	11/02	01/03	75	04/02	06/01
50%	77	10/03	01/01	51	03/03	05/01
80%	57	10/02	12/02	33	03/02	04/03

Table 4.7: Duration and onset and cessation of the growing periods of the analysed climatic data.

Apparently, there is an anomaly in the names of the rainy seasons. The duration of the short rains is longer than that of the long rains and the amount of rainfall during the short rains is higher than during the long rains. No explanation could be found in literature for this apparent anomaly. A possibility is that the names of the season refer to the duration of the single rainfall events.

The results on the duration match the data of "the length of growing season in Sub-Saharan Africa" map (FAO, 2001). As shown in Figure 4.5 within one year no relation can be found between the duration of the short rains and the long rains. Figure 4.6 shows the poor regression results for the relation between onset and the cessation of the growing periods. Neither a relation can be found between the onsets of the growing seasons of the short rains and the long rains. The same can be concluded for the cessation (Figure 4.7).

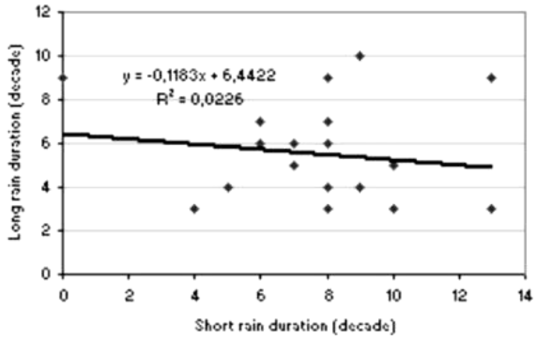

Figure 4.5: Long rain growing period duration as a function of the short rain growing period duration.

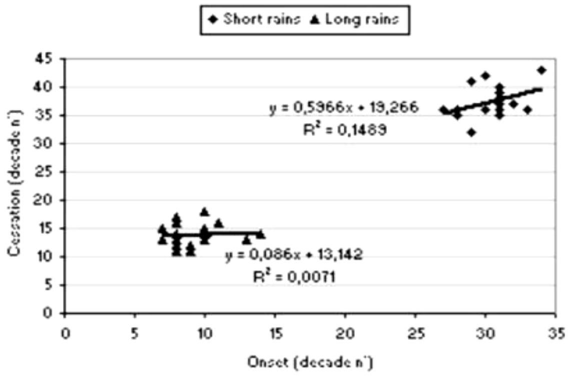

Figure 4.6: Cessation of the growing period as a function of the onset for the long and the short rains.

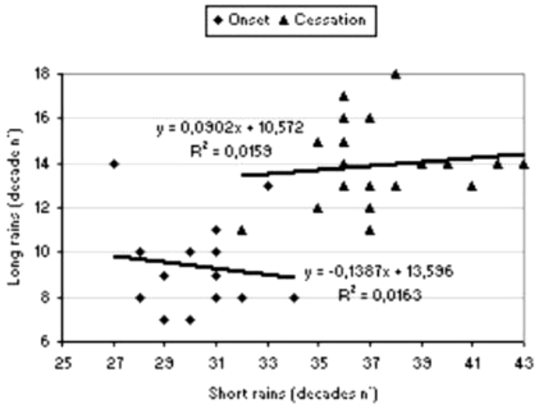

Figure 4.7: Onset and cessation of the long rains as a function of respectively the onset and the cessation of the short rains.

4.2. Crop data and cropping practices

4.2.1. Results of the interviews with the local farmers

Ten local farmers were interviewed in order to get an idea of the crops they grow, the area of the irrigation plot, the cropping calendar, the irrigation schedules and the yield. Seven of the farmers lived in the Kitui Central Division and all of them had access to irrigation water from a sand-storage dam. The age of the sand-storage dams was between 1 and 14 years. Three farmers were interviewed in the neighbourhood of Kisayani village. Two of them only cultivated rainfed crops because they didn’t have access to irrigation water. One of the fields was situated next to the proposed dam site in the Ngunga river, while the other field was situated next to the Kamunyuni dam in the same river. The latter dam was already present at the time of the interview but had not yet filled up with water. The third farmer lived next to a natural barrier in the riverbed and could enjoy the availability of irrigation water the whole year through. This farmer had 28 years of farming experience. The experience of the other nine farmers was between 1 and 18 years.

The farming area, cultivated by one family, is between 0.5 and 4 hectares. Irrigated plots within these fields only occupy 0.04 to 0.5 hectares or 2 to 25 percent of the total farming area. These plots are located in 50 meter wide strips along the river. Irrigated farming is done on small-scale and has more resemblances with horticulture than with arable farming. According to the farmers, the main reasons for the location of the irrigated plots are the fertility and the distance to the water source. Rainfed crops are cultivated on the slopes to the river or more uphill. When there is no source of irrigation water present, farmers only cultivate traditional rainfed food crops like maize, beans, pigeon peas, cow peas and to a minor extend cassava, millet and sorghum. When a source of irrigation water (e.g. a sand-storage dam) is present in the direct neighbourhood of the field, most farmers start cultivating irrigated cash crops. Most popular crops are tomatoes and sukuma wiki. These crops were cultivated among all interviewed farmers that had access to irrigation water. Three farmers cultivated cabbage and spinach, two farmers cultivated onions and carrots. Paprikas and sweet potatoes were cultivated by only one farmer. Most farmers who have access to irrigation water also cultivate fruits like bananas, mangos, avocados and papayas. Some grow passion fruit and citrus fruits. Although these crops are not irrigated, they benefit from the irrigation of other crops.

In situ rainwater harvesting and erosion control techniques as contouring, terraces and strip cropping were observed during the field campaign.

4.2.1.1. Cropping calendars

Except for pigeonpeas there are two harvests per year at the end of each rainy season. Sowing of the crops happens at the start of each rainy season. Only pigeonpeas are sown at the beginning of the short rains (October-February) and harvested after the long rains.

For irrigated crops, the findings of the field research are less straightforward. Most farmers report not to cultivate cash crops during the rainy seasons because of the pests and diseases. However two of the three farmers most experienced with irrigation claim to cultivate tomatoes, greens, cabbage and spinach during the short rains. Probably, they attained a higher financial status and were able to buy chemicals for pest and disease control. Their fields are located in the Kitui Central division, near to local markets, so they surely have access to the chemicals. Both farmers report the need for more information about the quantity of pesticides and fertilisers to be applied on their fields.

One farmer was reported to do phased planting, planting tomatoes at six different times from October to January in order to spread the work peaks and keep an constant harvest. Greens, if cultivate, are also important food crops and are grown continuously for one year.

4.2.1.2. Irrigation schedules

During the field campaign, one farmer was reported using irrigation by pumping the irrigation water with a food pump in an uphill basin and leading the water to the terraces in tubes. All other farmers execute bucket irrigation in jerry cans of approximately 20 litres.

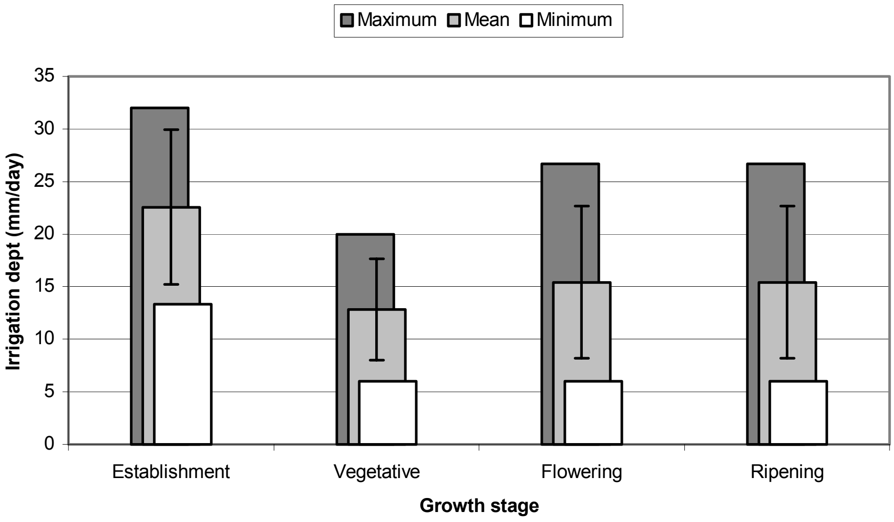

Figure 4.8: Irrigation quantities (mm/day) for tomatoes (7 farmers).

The mean irrigation quantities and their standard deviation per development stage derived from the interviews for the most popular cash crops are given in Figure 4.8 to Figure 4.11. The minimum-maximum ranges are indicated as well. The establishment stage is the stage from sowing in the seedbed until transplantation. For tomatoes, sukuma wiki and cabbages a planting density of 4 plants per square meter was observed. Spinach was observed to be planted with a density of 20 plants per square meter. A general trend is that an average irrigation depth of 25 mm/day is given as long as the crops are in the seedbed. The least irrigation is done during the vegetative stage that is most tolerant for water deficits, while during the flowering and the ripening the irrigation depth is higher and remains more or less constant. However, these trends are not visible for the irrigation pattern of spinach. Here the irrigation dose is the highest during the vegetative stage. With a plant density that is 5 times higher compared to the other crops, the irrigation depth is more or less 4 times higher after transplantation.

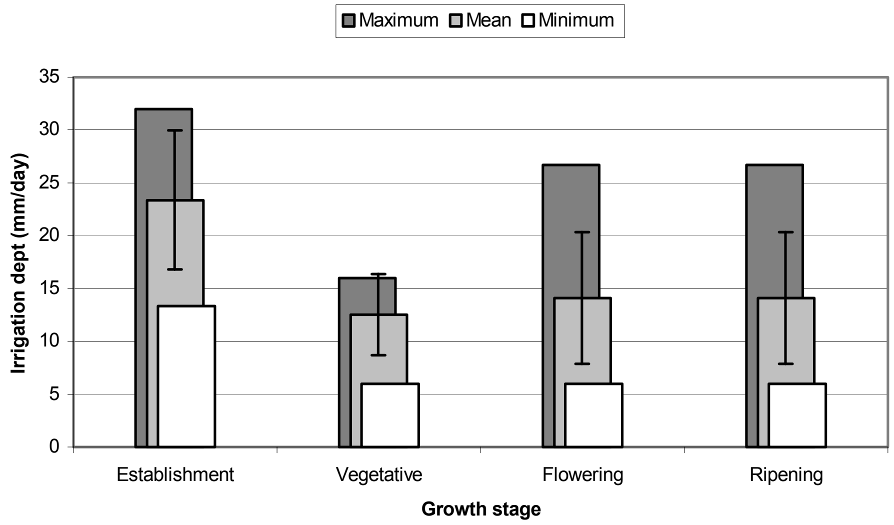

Figure 4.9: Irrigation quantities (mm/day) for sukuma wiki (7 farmers).

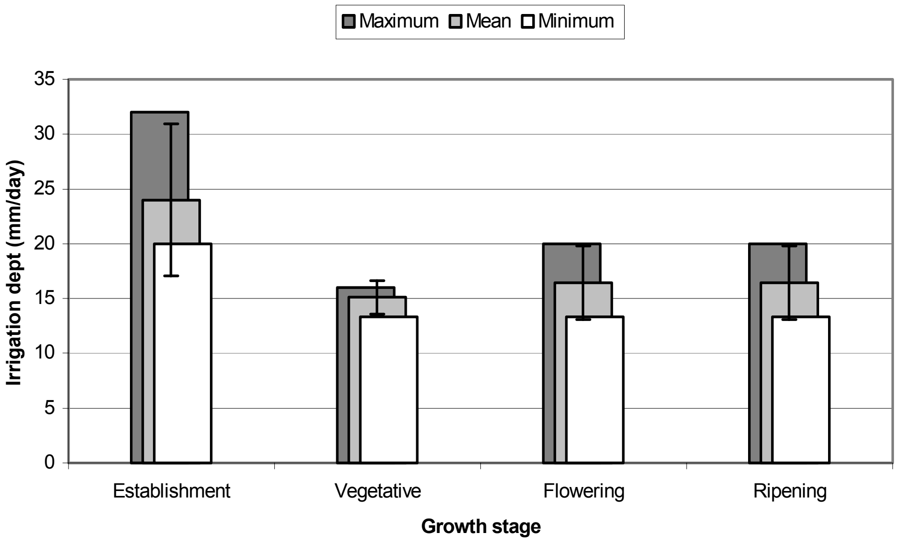

Figure 4.10: Irrigation quantities (mm/day) for cabbage (3 farmers).

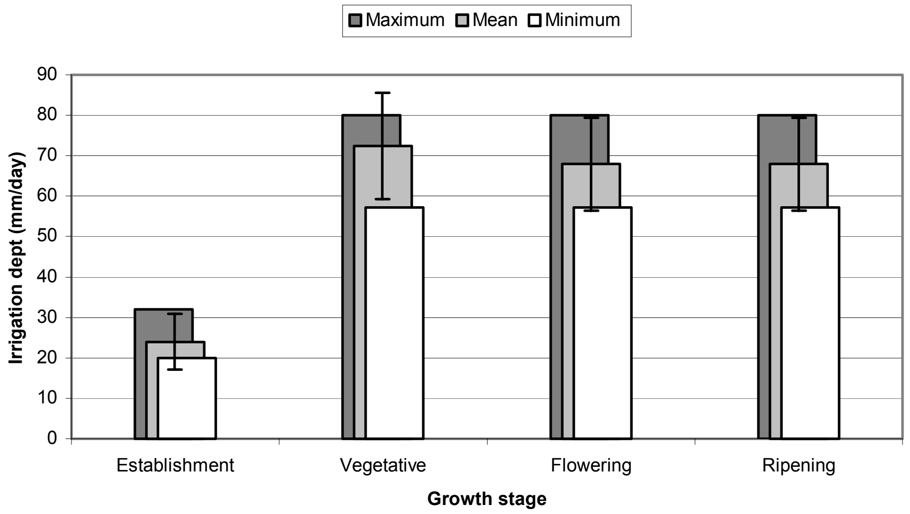

Figure 4.11: Irrigation quantities (mm/day) for spinach (3 farmers).

4.2.1.3. Achieved yields

Since food crops are intercropped or cultivated in different patches of the field, it is difficult to calculate the yield per unit of area for one specific crop. Moreover, since the interviews took place at the end of the dry season, no food crops where in the fields, so the results are only based on the interviews. In Table 4.8 the calculated yields per crop are presented together with the total yield of food crops per hectare. A weight of 90 kg per bag of harvested food crop was assumed to transform the yield from number of bags per year to weight per year. It has to be noticed that for very dry growing seasons many farmers do not have any yield at all.

Name Farmer	*Maize*	*Beans*	*Cow peas*	*Pigeon peas*	*Sorghum*	*Millet*	*Green grams*	*Total (ton)*	*Area (ha)*	*TOTAL YIELD*
Monica	0,55	-	0.18	0.37	-	-	-	1,1	0,5	1,102
Micheal Mutia	1,35	0,50	0.12	-	-	-	-	2,0	4,0	1,965
Peter Nzau	0,18	0,04	-	0.08	-	-	-	0,3	2,0	0,292
Angelinah	0,86	0,05	0.08	0.11	0,03	0,09	0,04	1,2	3,0	1,242
Peter Mutie	1,08	0,04	0.24	0.05	-	-	0,20	1,6	2,5	1,620

Table 4.8: The seasonal yields (ton/ha) for the individual food crops, the total harvest weight and plot surface of all cultivated food crops, and the total food crop yield per farmer interviewed.

The reported cash crop yields per hectare are given in Table 4.9. In the interviews the farmers where asked to give the tomato and sukuma wiki yield in respectively crates and leaves per unit of time. This data were transformed to weight per unit of area by making a few assumptions. A crate of tomatoes was assumed to have a weight of 64 kg and a bag of sukuma wiki was assumed to have a weight of 50 kg. These estimations were concluded out of conversation with local farmers and local market traders. Making a yield estimation for cabbages and spinach was not possible with the collected data. For cabbages one farmer reports that 75% of the originally transplanted plants go to the market. The reason for the higher yields of sukuma wiki is that once this crop is mature, its leaves are harvested for the rest of the year while tomatoes are mostly harvested continuously for only one month.

	Tomatoes	*Sukuma Wiki*
Mean	0,861	5,743
Maximum	2,276	11,110
Minimum	0,171	0,830
St. Dev.	0,676	4,281

Table 4.9: Cash crop yields (ton/ha.season).

In Table 4.10 the mean yields for the most relevant food crops are given for Kenya and the Kitui District. Also included are the food crop yields of two other districts with an arid to semi-arid climate. These last values were also derived from participatory rural appraisal. Table 4.8 to Table 4.10 show that except for maize the yield estimates of the interviewed farmers are below the mean yield values of the country and the district. It has to be noticed that the yields derived from the interviews have to be multiplied by two to compare with the values from Table 4.10 because there are two cropping season per year. Possible reasons for the difference could be that only small-scale farmers were interviewed and the mean values of the country and the districts also include large-scale irrigated farming. In the Makueni and Mbeere district 70% of the farmers own an ox-plough for land preparation. Most interviewed farmers of the Kitui District prepare their fields manually. Another reason could be that small-scale farmers mostly do not keep detailed records of their crop yields because most of them are illiterate, so the yields derived from the interviews are only rough estimates. It can also indicate that the proposed assumptions for the transformation of the preliminary data are not optimal.

Crop	Production (ton/ha.year)					
	National 1994-2002 (FAOSTAT)		*National 1994-1999 (Kiilu et al.)*	*Kitui District 1994-1999 (Kiilu et al.)*	*Makueni Districts (Mergeai et al.)*	*Mbeere District (Mergeai et al.)*
	Mean prod.	*St. Dev.*	*Mean prod.*	*Mean prod.*	*Mean prod.*	*Mean prod.*
Maize	1,6	0,2	-	-	1,2	1,4
Beans, Dry	0,3	0,2	-	-	-	-
Beans, Fresh	3,3	0,6	-	-	-	-
Beans general	-	-	-	-	0,9	0,6
Cow Peas	0,3	0,2	-	-	0,8	1,0
Pigeon Peas	0,3	0,2	-	-	0,8	1,0
Green Grams	-	-	-	-	1,1	0,6
Millet	0,5	0,1	-	-	1,1	-
Sorghum	0,8	0,1	-	-	1,4	1,7
Tomatoes	16,5	0,6	15,9	21	-	-
Sukuma wiki	-	-	13,5	26,3	-	-
Cabbages	14,5	0,7	13,3	1,3	-	-
Spinach	-	-	-	0,3	-	-
Carrots	-	-	9,5	2,5	-	-
Sweet Potatoes	9,5	0,7	-	-	-	-
Onions	9,0	2,2	10,8	11,7	-	-
Cassava	8,6	1,1	-	-	-	-
Sugar Cane	78,7	7,7	-	-	-	-
Avocados	-	-	13,5	13,7	-	-
Pawpaws	-	-	10,3	3,7	-	-
Bananas	2,9	0,3	14,0	34,8	-	-
Oranges	5,9	0,1	-	-	-	-
Mangoes	9,2	1,4	10,4	13,5	-	-

Table 4.10: Mean yield values for crops cultivated in Kenya and Kitui (Source: FAOSTAT, 2004; Mergeai et al., 2001; and Kiilu *et al.*, 2002).

4.2.2. Presentation of crop data in crop files

The parameters that were derived from the field and literature research are summarized per crop in Appendix 5 for tomato and sukuma wiki, crop files of other crops can be found on the CD-ROM attached to this thesis. These crop files consists of three parts (i) the agronomic data (ii) the yield response to water and (iii) some irrigation guidelines. The part with the agronomic data shows the reported growing period from the field research and the crop coefficients for the relevant growth stages. The rooting depth, possible yields, spacing information and the soil water depletion fraction for no stress (p), all derived from literature, are also mentioned here. The second part gives the yield response factors (K_Y) values for the different growth stages. The yield response factors for some crops (cowpea, pigeonpea and spinach) could not be found in literature. The irrigation guidelines for these crops will only be based on the reduction of the root zone depletion during the growing season. The guidelines cannot take into account the yield optimisation. To simulate the situation of an intercropped field with the BUDGET model, the crop coefficients can be calculated using the crop coefficients of the individual crops. However, assumptions will have to be made on the rooting depth and the soil water depletion fraction for no stress.

4.3. Soil data

The results of the soil sample analyses per horizon are given in Appendix 6. The soil profile images of the soils that were sampled can be found on the CD-ROM attached to this document. The calculated (Saxton *et al.*) soil water characteristics are calculated from textural data with the SPAW-Hydrology software. All soil surveys report organic mater contents between 0.4 and 1.3%. Literature data show that an organic matter content of 0.5% can be used for all soils. The calculated (Schaap *et al.*) parameters of the “Van Genuchten” model are estimated with the ROSETTA software that is included in the HYDRUS-1D software. As input data the results of the particle distribution analysis in combination with the bulk density and the measured water content at field capacity and permanent wilting point are used.

Out of all the analysed soil profiles, four soils are selected for further use. Most important criteria are data availability and place in the toposequence. The chosen soil samples, situated in the toposequence are indicated in Figure 4.12. The sample numbers match the sample numbers in Appendix 6.

To get an idea of the variability amongst the measured and estimated points of the pF-curve and the values for the saturated hydraulic conductivity, mean values with the standard deviations are given per soil layer for the four selected soils in Table 4.11. To derive these statistic values the estimated values of the Van Genuchten and the Saxton model are used together with the individual measured values. For the upper two layers of the riverbed profile only the estimated values are used because coarse soil texture did not permit to take undisturbed samples for these horizons. A standard deviation of 1 vol% in the water content is equal to 10 mm of water in a profile of 1 meter. In irrigation scheduling this can result in a reduction of the application events. So a lot of variability exists among the soil water content data. Even more variability exists among the saturated hydraulic conductivity data. Standard deviations that exceed the mean values are not unusual.

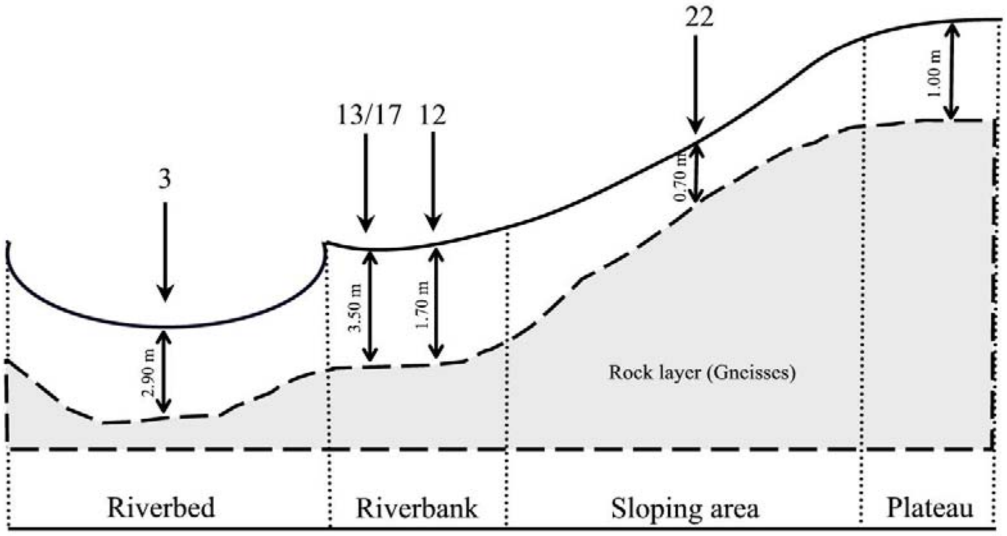

Figure 4.12: Chosen soil profile data for further use situated in the toposequence. The depth of the profile is indicated. The sample numbers match the sample numbers in Appendix 6.

Profile	*Depth (cm)*	*n*	θ_{WP}*(Vol%)*		θ_{FC}*(Vol%)*		θ_{SAT}*(Vol%)*		K_{SAT}*(mm/dag)*		
			Mean	*St. Dev.*	*Mean*	*St. Dev.*	*Mean.*	*St. Dev.*	*n*	*Mean*	*St. Dev.*
Riverbed	0-10	2	5,36	0,09	14,72	4,56	34,01	0,01	2	1515,25	497,73
	10-90	2	5,35	0,07	14,62	4,41	33,61	0,55	2	1439,70	604,58
	90-230	5	5,94	1,66	11,81	2,51	35,68	3,64	5	5723,00	8641,98
Riverbank	0-30	5	8,83	1,23	19,03	4,37	40,87	4,62	6	4486,45	3129,42
	30-60	5	7,03	2,00	14,44	3,67	41,90	1,50	6	4890,50	3168,53
	60-110	5	9,24	1,17	18,89	0,85	41,85	2,50	6	2078,69	3349,99
Sloping area	0-17	5	7,94	1,95	20,21	5,23	40,43	5,41	6	7358,98	7045,52
	17-52	3	11,94	2,31	24,27	4,64	40,16	5,31	3	849,40	544,39
	52-70	5	9,06	4,06	19,94	4,41	35,36	7,07	4	638,25	511,89
Black cotton soil	0-55	8	20,35	2,68	34,63	5,78	47,08	3,46	8	977,12	1938,06
	55-85	5	21,34	3,15	34,90	4,71	46,94	2,09	5	506,66	862,25
	85-100	4	22,70	2,42	39,64	6,02	52,28	3,10	4	49,35	60,88

Table 4.11: Mean and standard deviation of measured and estimated points of the pF-curve. n is the number of points in the dataset.

The main reason for the variability in the measured values is the possible presence of voids, made by roots or worms in the undisturbed samples and suboptimal sampling materials. The variation between the estimated values and measured values could be caused by the limited data input. The Van Genuchten model, which includes more measured parameters, generally gives results that better match the measured values than the Saxton model. Organic matter content was not included in neither of the two models, however this can have an effect on the model output. Another reason for variation in the estimated values could be the original datasets on which the models are based. The regression analyses are based on datasets of soil parameters poor on tropical and subtropical soil records.

The results in Table 4.11 show a variability that could be significant in the perspective of irrigation scheduling. In further analyses the parameters, derived from laboratorial analyses, will be used to simulate the soil behaviour. These parameters are mean values of three repetitions per soil layer and are considered to be quite representative.

4.4. Capillary rise

The results of the simulations with the UPFLOW software are represented graphically in Appendix 7. Per figure the capillary rise is plotted against the depth to the water table for the four different growth stages. This is done per soil type and per crop type. These graphs are a user-friendly tool to determine the capillary rise in the field if the soil type, the crop type, the growth stage of the crop and the depth of the water table can be determined. These graphs will be simplified in the when developing irrigation guidelines. They will be used to determine contribution of the capillary rise to the soil water balance.

The capillary rise to a bare surface is equal to the evapotranspirative demand of atmosphere (ET_C) if the water table comes within a critical distance of the soil surface. This critical depth depends on the soil type. The curve for the initial stage shows a similar progress as the curve for the bare surface until there are deficient aeration conditions in the waterlogged root zone. At this depth the capillary rise for the initial stage will decrease fast with decreasing depths of the water table. From the time of sowing on until the end of the initial stage (10% ground cover) capillary rise will be equal to the evaporative demand of the atmosphere if the water table is below the critical depth, otherwise capillary rise will have a value somewhere between the curve for a bare surface an the curve for the initial stage depending on the root development and the depth of the water table.

Because the rooting depth of the mid stage and the end of the late stage are equal, their curves are similar up to a certain capillary rise and from a certain value for the capillary rise on. They form a peak that is cut off at a maximal capillary rise (ET_C) that can take place in that stage. If there are no restrictions on the atmospheric demands, the peak can reach its maximum value for capillary rise under the given soil parameters and rooting depth.

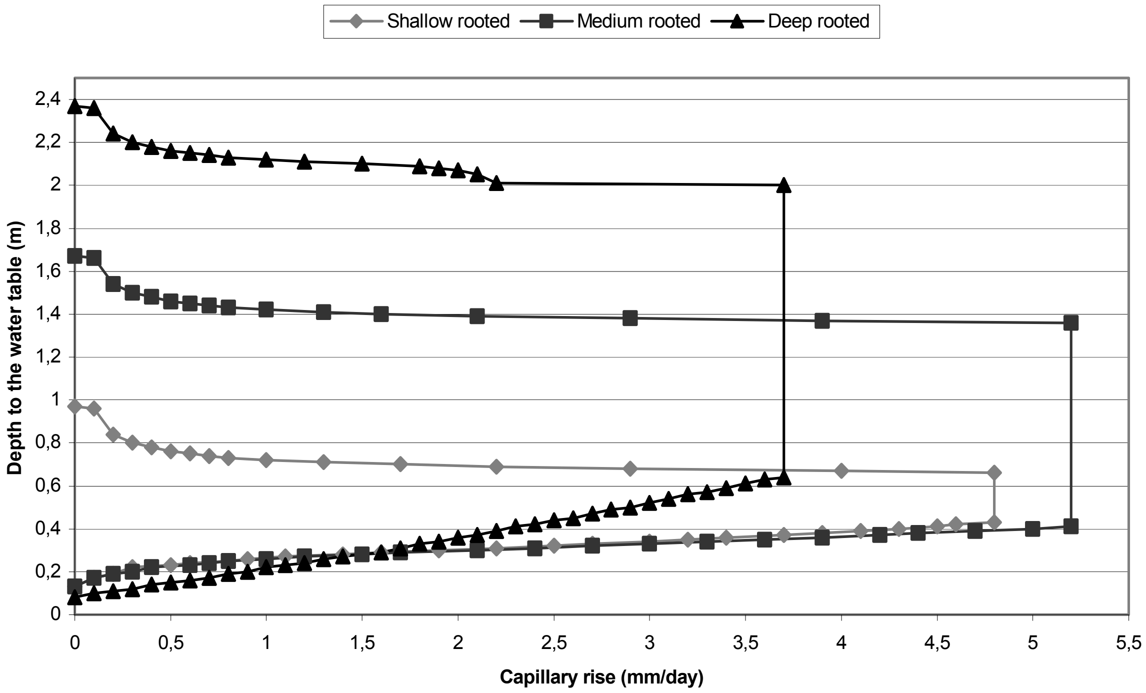

Figure 4.13: Capillary rise in relation to the depth of the water table for different crop types in their mid stage, growing in a sandy loam soil.

4.4.1. The effect of the rooting depth

In Figure 4.13 the relation between the upflow and the depth to the water table is plotted for different crop types. The deeper the roots, the deeper the water table can be situated to get the same capillary rise. This can be expected because the root system is the transfer system of the atmospheric suction. From the critical depth on to the topsoil, the curves are quite similar for the medium and shallow rooted crops. This part of the deep-rooted crop curve is somewhat different because in this case another root uptake pattern and another condition for water logging was chosen (deciduous trees). Another reason is that the software does not allow different soil layers in the root zone. If a root zone contains different layers they have to be merged together as also the parameters.

The soil profile of the Black Cotton soil consists of two very distinct materials. Merging those two layers would not give accurate results since the hydraulic properties and water characteristics of the layers are too different. For this reason the curve for the deep-rooted crops growing in a Black Cotton soil was not constructed with the UPFLOW software. A model that takes smaller discretisations of the soil profile could give a more satisfying result in this last case. However, probably the deep-rooted crops will not penetrate in the coarse limestone layer underlaying the Black Cotton Soil so that the simulated values for a medium rooted crop can be used.

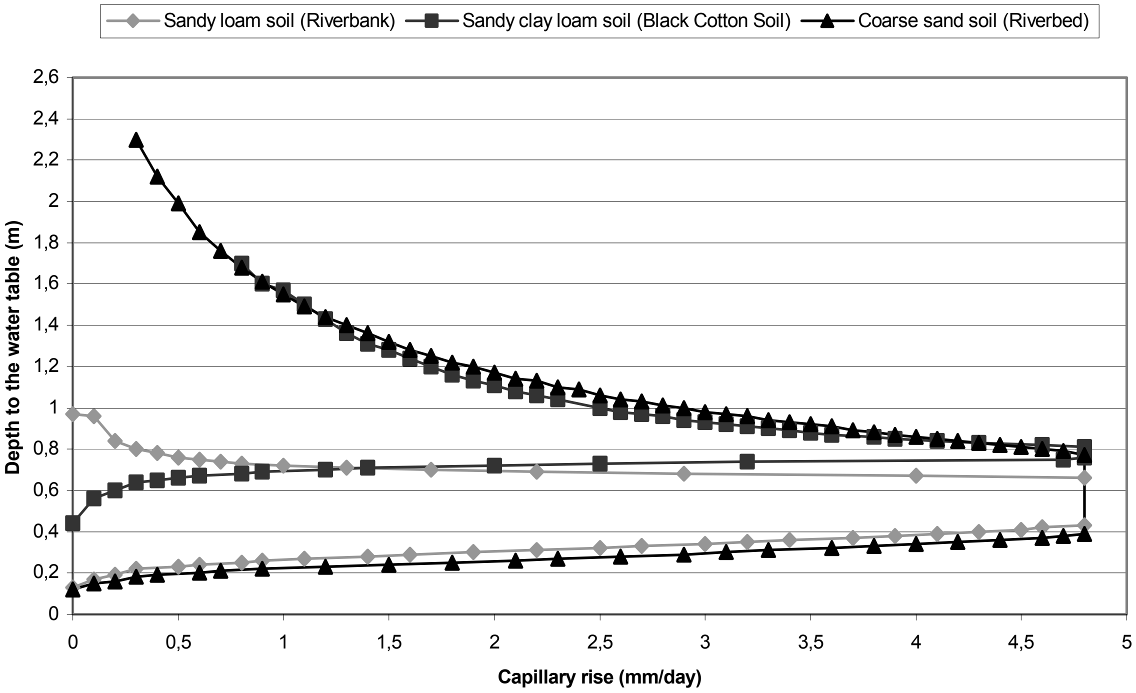

Figure 4.14: Capillary rise in relation to the depth of the water table for shallow rooted crops in their mid stage, growing in different soil types.

4.4.2. The effect of the soil types

Results are shown in Figure 4.14. Because of their narrow pores in which water rises higher, the Black cotton soils will give the highest values for capillary rise for the greater depths of the water table. Also, as a consequence of the narrow pores, these soils reach deficit aeration conditions before the water table reaches the root zone. In contrary, coarse sand soils have wide pores and very large hydraulic conductivities resulting in a severely aerated topsoil and upflow from deep water tables. The sandy loam soils of the riverbanks have well aerated topsoils but the combination of medium pore size and medium hydraulic conductivities results in a fast decreasing value of capillary rise with decreasing depths of the water table.

In paragraph 3.4 it was shown that the saturated hydraulic conductivity was the soil parameter with the largest variability. The sensitivity of the model to the K_{SAT} is investigated in Figure 4.15. Using the K_{SAT} values calculated with the Saxton model, the simulated results show a fairly good resemblance to the results that were derived from the simulations with the measured K_{SAT} values. Only under conditions near to maximum capillary rise, deviations from the other results are quite large. The K_{SAT} values that where estimated with the ROSETTA model give better results.

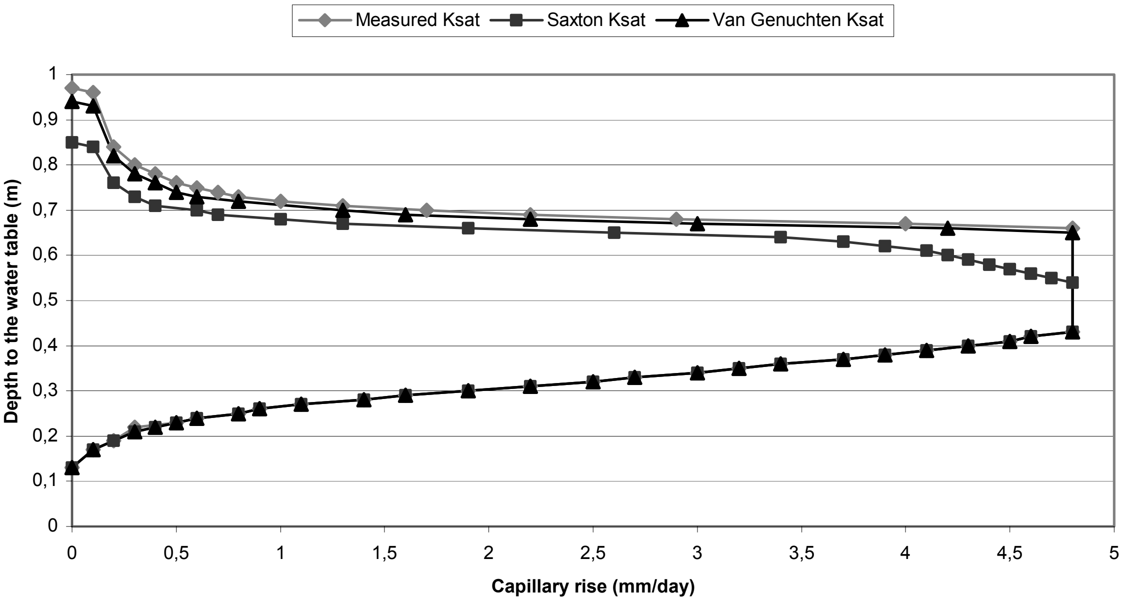

Figure 4.15: Capillary rise in relation to the depth of the water table for shallow rooted crops in their mid stage, growing in a sandy loam soil, simulated using different saturated hydraulic conductivities.

However, the variation in simulation results is only visible for situations where the water table is below the zone with deficient aeration conditions. The uniformity of the data in the zone with deficient aeration conditions is due to the fact that here the processes of capillary rise are mainly determined by the stress conditions and to a minor extent by the conductivity.

When the depths with equal capillary rise are plotted against each other for simulations that make use of the measured and the simulated K_{SAT}, this difference can be quantified. These plots are shown in Figure 4.16. The simulation results in the deficient aeration condition zone are not significantly influenced by the K_{SAT}. The regression analysis gives a factor of more or less 1 in the depth between the simulation results that make use of the measured and the estimated K_{SAT} values. If the water table drops below the critical depth for aeration deficit, this factor decreases to 0.98 and 0.90 for simulations using the K_{SAT} estimated with respectively the Van Genuchten model and the Saxton model. The regression analysis between the simulation results using the measured K_{SAT} and the Saxton K_{SAT} gives a goodness of fit of 0.8964.

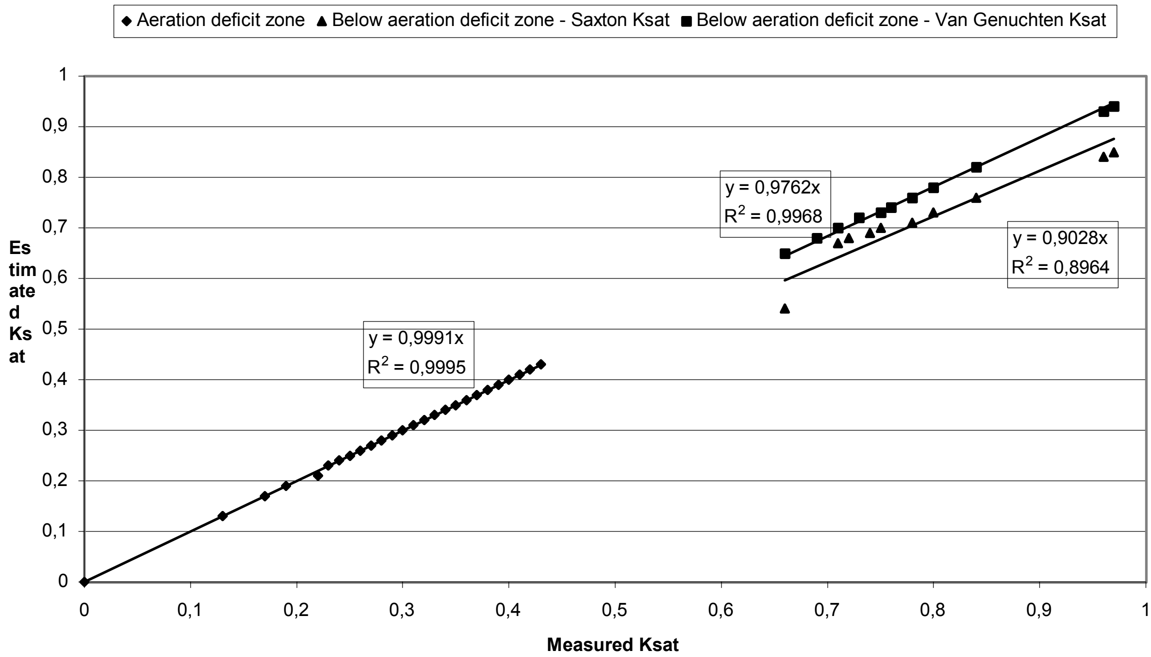

Figure 4.16: Depths with equal capillary rise plotted against each other for the different K_{SAT} simulations.

Compared to the evaporation from a bare soil surface, the cumulative evapotranspiration of a soil surface with a canopy cover will be higher because in the mid en the end stage of plant growth the crop evapotranspiration is higher. On the other hand water that would otherwise just evaporate can be used to grow crops. A hypothetical example is worked out for shallow rooted crops like sukuma wiki and medium rooted crops like tomatoes, cultivated in the riverbed during the dry season under optimal conditions and having the same growth cycle. The depth of the water table is assumed to drop in discrete steps of 0.50 m per growth stage, starting at a depth of 0.50 m after the rains and ending at 2.00 m at crop harvest. In the example of the shallow rooted crops 57% more water will be evapotranspirated in comparison with a bare surface, which will evaporate 125 mm over the growing period. For the medium rooted crops 108% more water will be brought up to the surface.

4.5. Guidelines for irrigation

4.5.1. Development of the irrigation charts

The results of the PRA interviews with the local farmers show there is a wide range of application depths used to irrigate cash crops (paragraph 4.2.1.2). The field campaign also showed that irrigation was done with jerry cans of approximately 20 litres. Therefore, a net application depth of 20 mm was chosen to facilitate the implementation of the irrigation charts. The losses due to deep drainage for some of the schedules were high, therefore, alternative schedules were developed using a net irrigation depth of 10 mm.

Simulations with the BUDGET model show that when every decade of the growing season of maize during the short rains would be wet (above 20% of dependable rainfall), still only 70% of the possible yield under full water supply would be harvested. This percentage drops to 35% of the possible yield during the long rains. If every decade of the growing season would be dry (under 80% of dependable rainfall), there would be no yield at all. This can also be concluded out of the frequency analysis on the duration of the growing period in paragraph 4.1.5. Even the longest growing seasons (20% probability of exceedance) are not long enough for optimal rainfed production of maize. Supplemental irrigation is necessary to meet the crop's water requirements. Irrigation charts for these food crops cultivated in the upland soils were developed using net application depths of 20 mm and 40 mm. Using the upland soil profile that was observed in the survey area (Sandy clay loam, sample number 22 in Appendix 6) water logging was simulated because of the shallow soil profiles with an impermeable rock layer beneath it. For the further simulations it will be assumed that there is free drainage out of the soil profile.

Some irrigation charts that were developed for tomatoes are shown in Appendix 8. Two charts gives guidelines for the current practices in the dry season, one chart shows the guidelines for different soils and another chart shows guidelines when a shallow water table is present (capillary rise) The last chart gives guidelines for cultivation of tomatoes during the short rains, including guidelines for different climatic conditions. The rest of the charts can be found on the CD-ROM attached to this document. An overview of the developed charts can be found in Appendix 8.

4.5.2. Interpretation of the water efficiency of the irrigation charts

The water efficiency of the developed irrigation schedules can be compared by analysing the effect of sensitive parameters in the development of guidelines on the net irrigation requirements, evaporation and the losses due to deep percolation, which should be minimized. It is not appropriate to quantify the water efficiency of the irrigation guidelines if the climate trajectory and the drop of the water table through the growing season are unknown, since an infinite number of decadal combinations are possible. However a frequency analysis could be made on seasonal net irrigation requirements by making day-to-day irrigations decisions using historical rainfall data. This would be time consuming.

When there is no rainfall (dry season) and no capillary rise from a shallow water table, water efficiency can be discussed quantitatively, because the trajectory through the growing season will be fixed.

4.5.2.1. The effect of the sowing date

Figure 4.17 shows that the seasonal cumulative net irrigation requirement for a tomato crop is always smaller for a 10 mm net application depth. Cultivating crops in the short rainy season (sowing date 2nd decade of October) generally requires less water than cultivating them during the long rains or in between the two rainy seasons. Obviously for drier meteorological conditions, more irrigation water is needed. It has to be noticed that the net irrigation requirements from Figure 4.17 are calculated assuming that every decade of the growing season belongs to the same probability of rainfall exceedance level. So, Figure 4.17 does not show the probability of exceedance levels for the net irrigation requirements.

As can be seen from Figure 4.18 the losses due to deep drainage for the 20 mm scenario are generally higher than those of the 10 mm scenario if the results of the same sowing dates are compared. The mostly shallow root systems of the vegetable crops, especially in the initial growth stage, and their small soil water depletion fraction for no stress (p, see paragraph 3.3.2.2) give, in combination with the soil properties, allowable root zone depletions smaller than the net application depth of 20 mm. The high values for deep drainage indicate that a lot of rainfall or irrigation is concentrated in a too small time step. During this time steps the soil water content is above field capacity and all excess water infiltrating in the root zone will drain to lower soil layers. The high values for deep drainage are concentrate to the wetter rainfall scenarios (20% probability of rainfall exceedance) and to the wetter periods of the year (short rains).

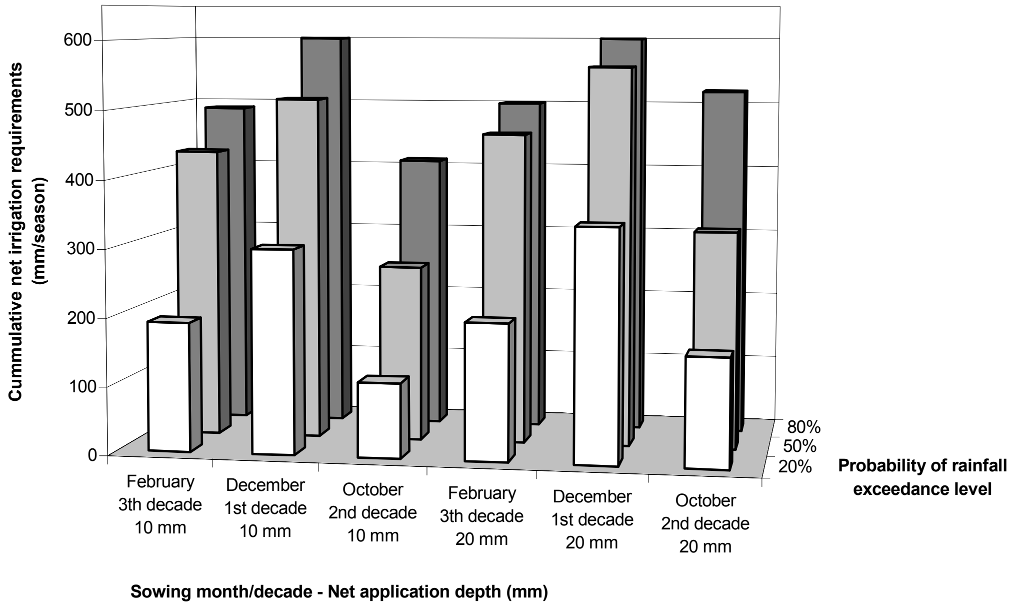

Figure 4.17: Cumulative net irrigation requirements over the whole growing cycle of tomatoes, cultivated on a Sandy loam soil as a function of different sowing dates through the year, different net application depths and different climatic conditions.

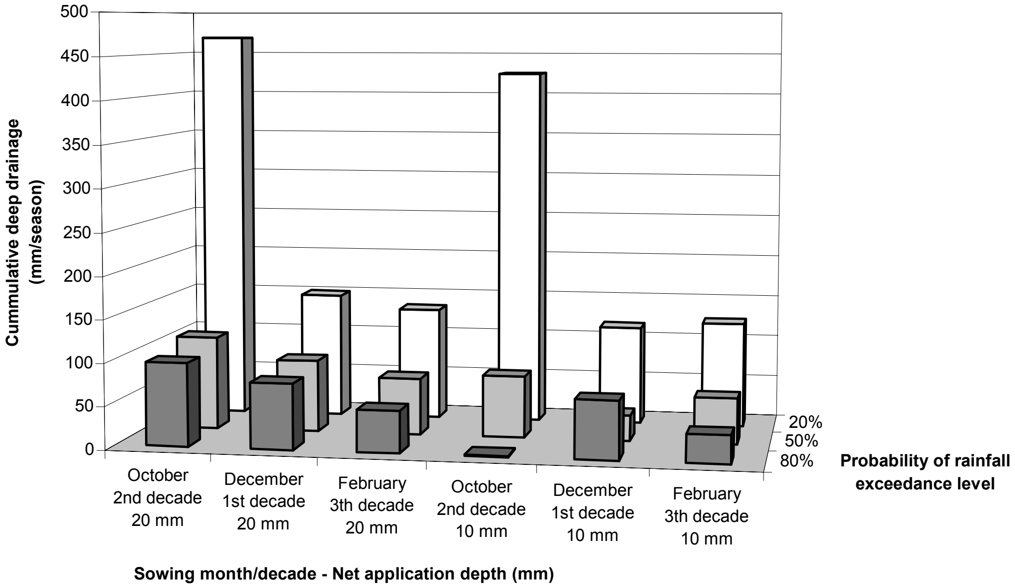

Figure 4.18: Cumulative deep drainage (mm) over the whole growing cycle of tomatoes, cultivated on a Sandy loam soil as a function of different sowing dates through the year, different net application depths and different climatic conditions.

Figure 4.17 and Figure 4.18 show that the use of a 10 mm application depth is more water efficient because less water is used by reducing the losses due to deep percolation. However, if the application depth becomes to small, the uniformity of the water distribution on the field is endangered. Using the 10 mm scenario also means accepting more frequent irrigating and subsequently more work. Also, when irrigating more frequently, the soil surface gets wet more frequently, this means that there will be higher soil evaporation. This was not observed in the simulations because the difference between intervals of the charts using a 20 mm and a 10 mm applications depth is too small. The same conclusions can be made after analysing net irrigation requirements and the losses due to deep percolation of the sukuma wiki crops.

4.5.2.2. Effect of the crop and the soil type

Figure 4.19 shows that onions are the most water demanding crops. From the irrigation charts it is clear that onions, together with spinach need frequent irrigation. The longer growing period of onions (210 days) results in highest seasonal water requirements. Tomatoes need less irrigation water because of the shorter growing season.

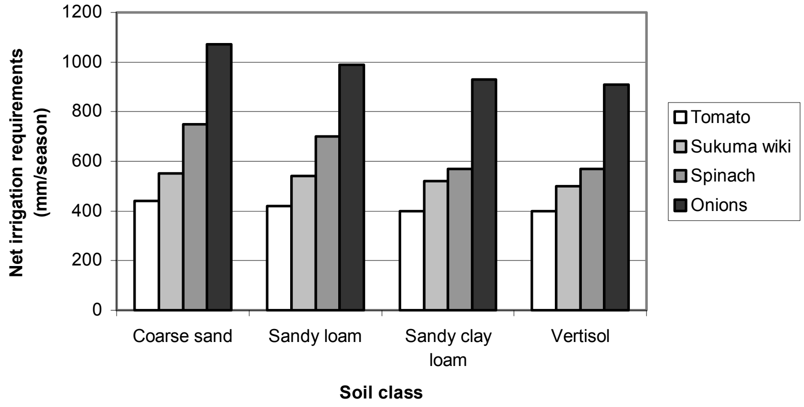

Figure 4.19: Net irrigation requirements for different crops as a function of the soil under no rain climatic conditions.

Cultivated in a coarse sand soil, the crops generally have the highest irrigation demands. Crops cultivated in a Black cotton soil have the least irrigation requirements. This can be expected since the Black cotton soil combines good soil water properties with a low hydraulic conductivity when going to deeper layers. The reverse is expected for coarse sand soils. Comparing crops, cultivated in the Sandy clay loam soil and the Black cotton soil, there is a minor difference in irrigation demands. These two soils show small differences in soil water properties. For tomatoes and sukuma wiki the differences in seasonal water demands does not differ greatly with the soils, the difference between the maximum and minimum seasonal irrigation demands are respectively 40 mm and 50 mm. However, for spinach and onions these differences are respectively 180 mm and 160 mm.

Figure 4.20 shows that the losses due to deep drainage are the smallest for the tomato crops. This is because of the deep roots that can intercept water that drains through the profile for a longer time. In the coarse sand soils and the sandy loam soils losses are very high for the crops other than tomatoes. The highest losses (200 mm) are generated for spinach, the most shallow-rooted crop, cultivated in the coarse sand soils of the riverbed. These differences become very small for the sandy clay loam soil and the Black cotton soil. Water travels very slowly through their profile what reduces the water losses to a maximum of 53 mm per season for sukuma wiki cultivated on a sandy clay loam soil.

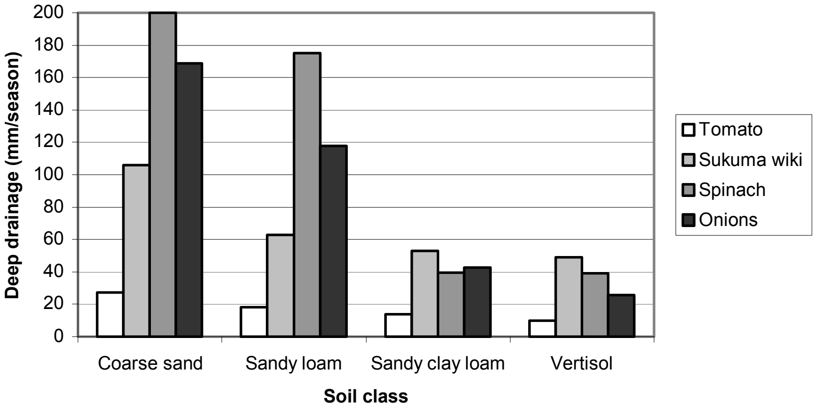

Figure 4.20: Losses due to deep drainage for different crops as a function of the soil under no rain climatic conditions.

4.5.2.3. The effect of intercropping food crops

If the water efficiency of the irrigation charts for maize and its intercrops are compared in terms of net irrigation requirements (Figure 4.21), it can be concluded that there is no significant difference in water demand between the different crops. Again, the assumption is made that the growing season consists of decadal rainfall values of the same probability of rainfall exceedance value. If the depth of the sandy clay loam soil is taken to be 0.50 m with a lower impermeable boundary, as determined in the field, there will be a yield decline because of water logging.

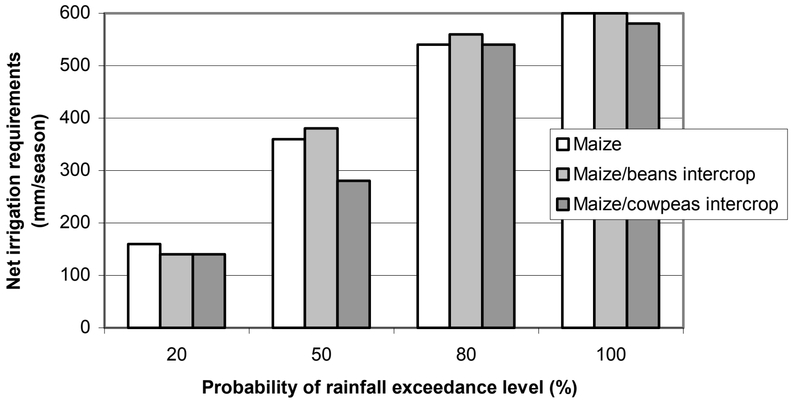

Figure 4.21: Cumulative net irrigation requirements over the whole growing cycle of food crops, cultivated during the short rains on a Sandy clay loam soil under different climatic conditions.

4.5.2.4. The effect of the estimated soil parameters

To get an idea about the effect of the uncertainty of the soil data on the final output, the BUDGET model was run with soil water parameters that were estimated in paragraph 4.3 with the Saxton and Van Genuchten model. Another run was done assigning to each soil layer the textural default values included in the BUDGET model.

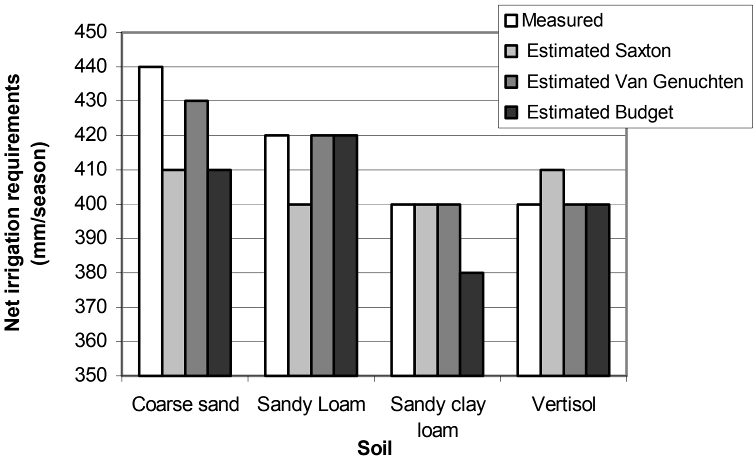

Figure 4.22: Cumulative net irrigation requirements for tomato crops cultivated under no rain climatic conditions on different soils of which the parameters were measured and estimated using various methods.

Irrigation calendars were constructed and their net irrigation requirements were determined. Figure 4.22 shows a maximal seasonal deviation of 20 mm in net irrigation requirements between the runs that make use of the different estimation methods and the measured data. The soil water parameters estimated with the Van Genuchten model give results that show the best resemblance with the results that make use of the measured soil data. This is evident because this model uses most of the measured soil water parameters to estimate the soil water retention curve.

Comparing the cumulative net irrigation requirements associated with the different soil inputs as was done in Figure 4.22 gives no indication about the eventual water shortage during certain growth stages. The irrigation calendar for tomatoes under no rain conditions, constructed earlier in this paragraph, was used in combination with the estimated soil water parameters and the subsequent yield decline was simulated. There was only a minor yield decline of 2 percent in the riverbed using the soil water parameters estimated with the Saxton and the Van Genuchten model.

4.5.2.5. The effect of including capillary rise in the soil water balance

As can be seen from Figure 4.23 the net irrigation requirements will be lower if the water table is closer to the surface. Care has to be taken that no water logging problems occurs when the water table is too close to the surface.

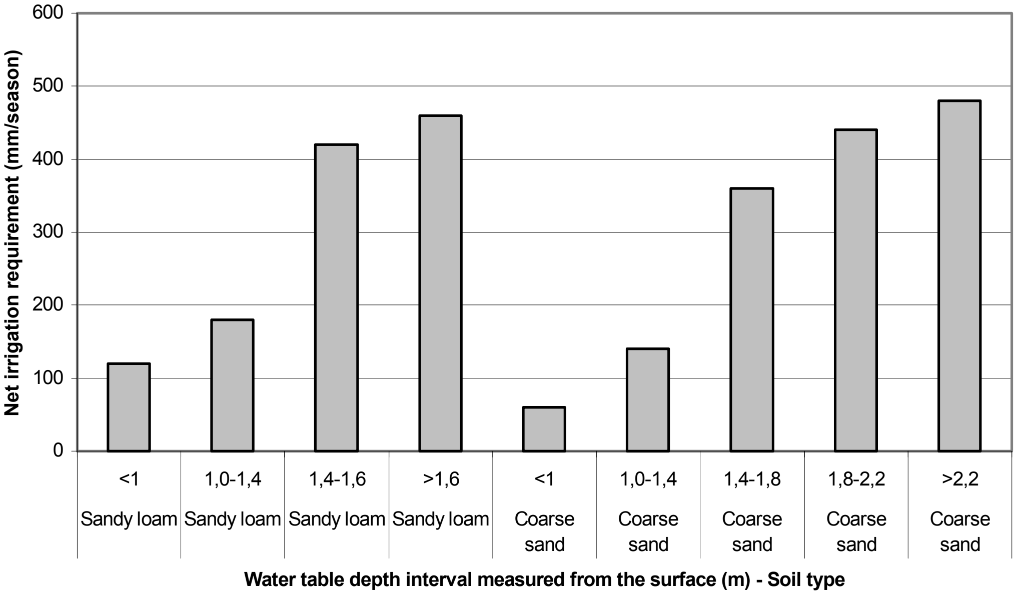

Figure 4.23: Cumulative net irrigation requirements for tomato crops cultivated under no rain climatic conditions for different depth intervals of the water table and different soil types.

From Figure 4.14 it was concluded that in the coarse sand soils the effect of capillary rise can be observed until deep under the soil surface. In the sandy loam soils of the riverbanks, this effect is less pronounced. The capillary rise in the coarse sand soils (riverbed) is still significant at a water depth that would not lead to capillary rise in the riverbank soils.

Traditionally the irrigated crops are planted at the end of the rainy seasons, so when the water table is high and the capillary rise is at its maximum. So, in the beginning of the growing season, after the long rains, capillary rise will have a significant influence on the irrigation requirements of the crops. When the dry season proceeds, the water table drops and subsequently the irrigation requirements of the crops will rise. So, when the growing season proceeds, the farmer will have to move downward from the first line in Table 3.8 to the following lines as a function of the drop of the water table through the season.

In the Kisayani study area the difference in elevation between the lower banks and the riverbed was estimated to be between 0.50 m and 1.00 m. From the graphs for capillary rise in sandy loam soils (riverbanks) presented at the back of the irrigation charts, it can be seen that capillary rise for shallow rooted crops like sukuma wiki, cultivated on the riverbanks decreases very fast if the water table drops from 0.50 to 1.00 m. So if the water table is below 1 m depth in the sandy loam soil profile, the contribution of capillary rise to the water requirement of the crops, cultivated on the riverbank will be limited. This is realised almost immediately after the end of the rainy season.

Medium rooted crops like tomatoes enjoy the capillary rise in a sandy loam soil for water tables down to a depth of 1.6 m. The capillary rise in the Black cotton soils is still significant at a water table depth of 1.70 m for both shallow and medium rooted crops (respectively around 1 and 5 mm/days) as can be seen in the graph shown in Appendix 7.

4.5.3. The presented irrigation guidelines versus the current practices

Figure 4.24 shows that the current irrigation practices lead to tremendous over-irrigation of the crops.

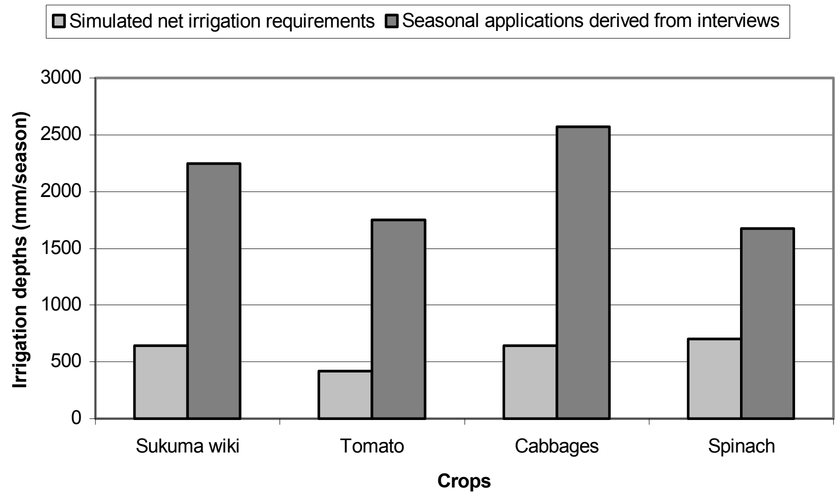

Figure 4.24: The simulated net irrigation requirements versus the current irrigation practices under no rainfall scenarios, derived from the interviews with the local farmers.

Following the simulated guidelines, cabbages and tomatoes are given four times more water than necessary. Sukuma wiki and spinach are given respectively 3,5 and 2,5 times more water than required according to the guidelines.

The current application doses were calculated using the PRA results on daily irrigation per growth stage (Figure 4.8 to Figure 4.11) and the lengths of those growth stages. The simulation results in Figure 4.24 are calculated from the developed irrigation charts that do not take into account capillary rise. Comparing the simulated guidelines that include capillary rise with the current practices would result in even higher factors of over-irrigation.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Climatic data

The meteorology of the Kisayani survey area was studied using rainfall data from the closest meteorological station, the Mutomo Agriculture station. Other climatic parameters like mean, minimum and maximum temperature, global radiation, wind speed and relative sunshine fraction, used for the estimation of the reference evapotranspiration, were collected from the Kitui Agriculture station, approximately 50 km away from Kisayani. The reference evapotranspiration, estimated with the ET0 software (Raes, 2000a) that makes use of the Penman-Monteith equation, showed little variation during the year.

In the Mutomo Agriculture rainfall dataset, the missing records were partly filled up with zero rainfall events from the Ithookwe Agriculture dataset, reducing the number of empty records with 12%. This was justified statistically. The frequency analysis on the rainfall dataset, performed with the RAINBOW software (Raes, 2000b), showed a high temporal variation in rainfall. When the results of the frequency analysis on the yearly data of different station are evaluated, spatial variation is seen to be the highest for the drier years.

The resulting rainfall and evaporation dataset are given in respectively Appendix 2 and Appendix 3.

The onset, cessation and duration of the growing season were determined for the 21-year dataset, using the criteria presented by De Pauw (1989). Analysing the duration of the long and short rains and the onset and cessation dates, a great variability was observed. The onset, cessation and duration of the growing season were analysed on a 20, 50 and 80% probability of exceedance level showing that monthly differences between early and late onset or cessation are not rare. The results also show a difference of approximately 40 days in the duration of the growing period comparing 80% (short growing period) and 20% (long growing periods) probability of exceedance values

5.2. Crop data and cropping practices

Relevant crop parameters for the simulation of crop growth and yield response to water were derived from two main sources, literature and interviews with local farmers. The parameters that were derived from the field and literature research are summarized for each crop in Appendix 5 for tomato and sukuma wiki, crop files of other crops can be found on the CD-ROM attached to this thesis. These crop files consists of three parts (i) the agronomic data (ii) the yield response to water and (iii) some irrigation guidelines. The part with the agronomic data shows the reported growing period from the field research and the crop coefficients for the relevant growth stages. The rooting depth, possible yields, spacing information and the soil water depletion fraction for no stress (p), all derived from literature, are also mentioned here. The second part gives the yield response factors (K_Y) values for the different growth stages.

The field campaign was conducted during the end of the dry season when all crops were harvested. This gives the interviewer no visual proofs of the data he wants to collect and leaves only the interviews with the farmers to make conclusions on the cropping practices.

Parameters for various crops could not be found in literature. More research is needed on crops like cowpeas, pigeonpeas, spinach and sukuma wiki in order to facilitate the development of irrigation guidelines for these crops. Also, parameters for simulating the water requirements of an intercropped field should be examined more extensively. A formula is provided by Allen *et al.* (1998) for the calculation of the crop coefficients, however, assumptions have to be made on the rooting depth and the soil water depletion fraction for no stress (p). A lot of problems with simulating intercropped fields deal with the use of a point simulation approach instead of a multiple dimension approach.

5.3. Soil data

The most important soil profiles, used for further analyses were selected in paragraph 4.3 and presented in Appendix 6. The soil water parameters were determined in three different ways. First of all parameters were derived from laboratorial analyses of the disturbed and undisturbed samples. Secondly parameters were estimated by using the textural data derived from the analysis of the disturbed samples in combination with the Saxton pedotransfer functions and thirdly parameters were estimated using the textural data and the measured soil water properties in combination with the Van Genuchten pedotransfer functions. For the estimation of the soil parameters with the Saxton pedotransfer functions, the SPAW hydrology software was used (Saxton, 2003), the ROSETTA model (Schaap *et al*., 2001) was used to estimate the parameters using the Van Genuchten functions. Field measurements were done in order to determine the saturated hydraulic conductivity for some profiles. The method of the double ring infiltrometer and the Porchet method were used

The results of the measured (in the laboratory and the field) and estimated (by pedotransfer functions) parameters showed a variability that could be significant in the perspective of irrigation scheduling. The saturated hydraulic conductivity was identified as the parameter having the largest variability. Because of this variability, the effect of the relevant soil parameters on the UPFLOW and BUDGET outputs was tested.

5.4. Capillary rise

The results of the simulations with the UPFLOW software (Raes, 2001) were presented graphically (Appendix 7). Per figure the capillary rise was plotted against the depth to the water table for the four different growth stages. This was done per soil type and per crop type. These graphs are a user-friendly way to determine the capillary rise in the field if the soil type, the crop type, the growth stage of the crop and the depth of the water table can be determined. The graphs were used later to determine the contribution of capillary rise to the soil water balance when developing irrigation guidelines.

The simulation results indicate that cultivating irrigated crops in the riverbed can be water efficient since the water that otherwise would be evaporated from a bare riverbed, can be used for plant growth. Though, the cumulated evapotranspiration will be higher compared to the

bare surface scenario because in the mid en the end stage of plant growth the crop evapotranspiration is higher. The capillary rise will result in less frequent irrigation events or a smaller irrigation depth per event, what results less labour input.
The sensitivity of the UPFLOW model to the saturated hydraulic conductivity was tested. The results that made use of the K_{SAT} estimated with the Van Genuchten model showed the best resemblance with the results that made use of the measured soil parameters.
More optimal use of the capillary rise potential can be made by intercropping plants with a different rooting depth. The deeper rooting system that has developed to the end of the dry season will still be able to use the water of the deeper water table.

5.5. Irrigation guidelines

This study followed the method for the development of irrigation calendars presented by Raes *et al.* (2002d). The farmers were given simple guidelines on how to adjust irrigation to the actual weather condition, to the presence of a shallow water table (capillary rise) and when shortage in the supply of irrigation water occurs. The developed guidelines are presented in irrigation charts for a specific crop, a particular region, soil type and growing season. A list of all the charts developed in this study can be found in Appendix 8. Some irrigation charts can be found in Appendix 8, the rest was put on the CD-ROM attached to this study. A simple formula for the farmers to transform the net application depth of the charts to the number of buckets that have to be applied per growing bed is also given in Appendix 8.

Irrigation calendars were developed by means of a soil water balance technique. The soil water balance was simulated with the BUDGET model (Raes, 2002).

For cash crops guidelines were developed for the current field practices, observed during the field campaign. These practices are mainly limited to irrigated farming in the long dry season (June-September). Next to the traditional field practices, irrigation charts for the cultivation of cash crops during and between the short and long rains were presented.
The irrigation charts for cash crops were developed for a 10 mm and a 20 mm net application depth. A comparison was made between the irrigation charts that use a different net application depth. When following the charts using a 10 mm net application depth, the seasonal cumulative net irrigation requirements of the crops were observed to be lower than those when following the chart using 20 mm net application depth. The small allowable root

zone depletions of the cash crops make the full use of the 20 mm applications impossible, which results in deep drainage. In order to optimise the water efficiency of the applications, one could choose to use the irrigation charts with the least net application depth (10 mm). However, if the application depth becomes too small, the uniformity of the water distribution on the field is endangered. Using the 10 mm scenario also means accepting more frequent irrigation events and subsequently more work.

Onions have the highest seasonal water requirement because of the combination of a frequent irrigation demand and a long growing season what gives a high risk for crop failure. A possible solution was presented by developing irrigation guidelines for cultivating onions from the beginning of November until the end of May, in other words by including the two rainy seasons into the growing season.

Tomato and sukuma wiki need the least irrigation water of the traditionally cultivated crops what makes them useful in the dry season. Moreover, tomato crops have limited losses due to deep drainage because of their deeper root system.

The crops cultivated on the medium light to light textured soils of the riverbed and the riverbank have the highest water requirements because of the soil is not able to keep up water. Consequently a lot of water is lost to deep drainage. However, part of this lost water will recharge the reservoir of the sand-storage dam. As expected the water efficiency is higher when cultivating crops on a heavier textured soil like the soils more uphill and the Black cotton soils.

For the traditionally rainfed food crops, irrigation charts were developed in order to get higher yields. Because of the deeper rooting system, 20 mm and 40 mm were chosen as net application depths. Irrigation guidelines were developed for maize (pure stand) and an intercrop of maize and beans and an intercrop of maize and cowpeas. To run simulations for the intercrops, assumptions had to be made for the rooting depth and soil water depletion fraction for no stress (p). Results did not show a difference in irrigation requirements between maize and the intercrops. The reason why the farmers cultivate intercrops is probably more due to the better fertility then to the water efficiency.

The soil parameters estimated with the Van Genuchten model and the Saxton model and the default soil parameters of the BUDGET model were used to run some simulations and the results were compared with the results that make use of the measured soil parameters. The differences in output of the model were small with a maximum seasonal deviation of 20 mm.

After incorporating capillary rise in the soil water balance, irrigation requirements became gradually smaller for higher water tables. In the situation where no sand-storage dam is present, the effect of the capillary rise on the irrigation requirements of crops cultivated on the riverbank is assumed to have a fast decline as the dry season proceeds. If the difference between the topsoil and the water table is more than 1 m, the effect of capillary rise on the irrigation requirements were estimated to be minimal for the shallow rooted crops cultivated on the riverbank. Medium rooted crops like tomatoes can enjoy capillary rise for a water table depth down to 1.6 m. When growing crops in the riverbed the contribution of capillary rise to the soil water balance in the root zone is significant until a depth of 2.2 m for both shallow rooted and medium rooted crops. For the Black cotton soils capillary rise is still significant at the lower boundary of the profile (1.7 m). Simulating capillary rise in the upland soils was considered irrelevant since no water table was present in the profile.

Finally the simulated guidelines were compared with the irrigation calendars derived from the interviews with the local farmers. The simulated irrigation requirements were 2.5 to 4 times lower than the seasonal irrigation depth currently applied by the interviewed farmers.

5.6. General conclusions and recommendations

Kenya is faced with a problem of economic water scarcity. Sufficient water resources are present but there is a necessity to increase water supplies through conveyance and regulation systems. On the other hand, the country deals with severe water poverty, which means that the country cannot support the costs of a sustainable clean supply for its inhabitants. Intensification of human activities and population growth will only contribute to these problems. The parts of the country struck the hardest by water poverty and water scarcity are the poor, rural arid and semi-arid regions. One of these regions is the Kitui district. To abate water poverty in these areas it is important that low priced and sustainable solutions are found. A promising technology for semi-arid regions of Sub Saharan Africa is rainwater harvesting. Sand-storage dams, storage systems for rainwater, are constructed in the Kitui district as a local initiative and offer the land users a tool to control water stress and dry spell mitigation. The construction of these small water-retaining structures in the ephemeral rivers has a major impact on the communities, on agriculture and on the environment. The time and water that becomes available because of the sand-storage dams is used to start growing irrigated cash crops for local markets. Irrigated farming is done on a small-scale on the riverbanks and has more resemblances with horticulture than with arable farming.

The unreliability of rainfall in the semi-arid regions, and the absence of guidelines at a short time-step often complicate decision making during the irrigation season. At small farmers' level, guidelines for scheduling are rarely available or require expensive monitoring equipment and data processing. As such small farmers follow often a rather fixed irrigation calendar with or without some empirical adjustments to the actual weather conditions. The corresponding irrigation applications are mostly characterised by periods of over- and under-irrigation.

In this study, guidelines for irrigation were developed giving farmers simple indications on how to adjust their irrigation to the actual weather condition, to the presence of a shallow water table (capillary rise) and when shortage in the supply of irrigation water occurs. The guidelines are presented in irrigation charts that can be used by the farmers to determine the irrigation requirements of their crops in real time. To implement these charts, it is important that SASOL starts sessions in the field to teach the farmers how to use the charts.
Irrigation charts were developed for the traditionally irrigated cash crops like tomato, sukuma wiki, cabbage, spinach and onions. This was done for the current sowing dates but also new dates are presented to the farmers. To optimise the yield of the traditionally rainfed food crops, supplemental irrigation for those crops is considered as well.

Crop water requirements were simulated by means of a soil water balance technique. The soil water balance was simulated with the BUDGET model (Raes, 2002). In order to solve the water balance, BUDGET needs parameters to calculate the incoming and outgoing fluxes. A field campaign was conducted to collect relevant data and report current cropping practices. Climatological data were collected in order to make predictions on the probability of future rainfall and to estimate the evapotranspiration. The deep percolation is estimated by the BUDGET model and depends on amount of water that a soil can retain in the root zone. The soil water characteristics were determined by field experiments and by collecting samples in the field and by subsequently analysing them in the laboratory. Two types of pedotransfer functions were used to estimate soil water properties in order to determine whether soil data collection can be less costly and less time consuming. The UPFLOW software (Raes, 2001) was used to simulate the capillary rise from a shallow water table. The output of the UPFLOW model was taken into account in the soil water balance of the BUDGET model. The sensitivity of the BUDGET and UPFLOW output towards the measured and estimated soil parameters was analysed and observed to be minimal. Hence in later studies, less costly and time consuming soil data collection techniques like textural analysis can be used.

From the engineering perspective it would really facilitate the simulations if all programs used in this thesis were merged into the BUDGET model. This would lead to a significant reduction of the time spend on data input. On the other hand the model has to be kept user-friendly in order to stay useful for less specialised users who get their ready-to-use input data from meteorological research centres or stations.

Water in the sand-storage dam reservoir can be used more efficient in the perspective of irrigation. Since the current seasonal application depth differs a factor 2.5 to 4 with the simulated crop water requirements, the farmers have the possibility to enlarge the area allocated to cash crops with approximately the same factor. An alternative a higher number of crop yields per year for the same area. Here, the developed guidelines for cash crops cultivated during and in between the short and the long rains can be used to determine the crop water requirements. A last possibility is to start irrigating the traditionally rainfed food crops.

Without supplemental investments, the use of the water from the sand-storage dams can be intensified giving a higher crop yield per unit of water provided by the dam. The analysis of the water efficiency was done without taking capillary rise into account, doing this would only increase current over-irrigation of crops.

The irrigation doses used to develop the irrigation charts were 10 and 20 mm for cash crops, and 20 mm and 40 mm for the food crops. Generally, using the lower doses, the losses will be less, because the smaller losses due to deep drainage. However, these losses are very small compared to the losses when using the traditional irrigation calendar.

If no sand-storage dam is present the contribution of the capillary rise to the soil water balance of the riverbanks (sandy loam), which are mostly used for cash cropping, will be minimal. The riverbed and the Black cotton soil have better soil properties to enjoy capillary rise. An extra advantage of the cultivation of cash crops in the riverbed is that the excess irrigation water, otherwise lost by deep drainage, will directly recharge the water reservoir of the sand storage dam.

In the scenario where a sand-storage dam is present, the capillary rise will become more significant, since a sand-storage dam has the characteristic to maintain a high water table for a longer time. However, a lot of research still has to be done. The REAL project started up a network of piezometers in the Ngunga river between the Kamunyuni dam and the Ngunga Kwoko dam. Currently SASOL people are monitoring them. In order to analyse the effect of a sand-storage dam on the contribution of capillary rise in the root zone, measurements of the water table fluctuations through the growing season before and after a dam is constructed are needed.

Despite of the fact that the cash crops generally do not experience water stress because they are well watered, low yields were reported during the interviews with the local farmers. The good drainage properties of the soil exclude water logging as a reason for the low yield. Probably no or limited fertiliser application and disease control are the main reasons for the low yields. The farmers should be better informed about these subjects. Here, SASOL can play an important role using their communal approach.

Probably, the low reported yields for the food crops are in the first place due to their dependency on the climatic conditions. They experience a high risk for water stress during the growing period since they are cultivated rainfed. As mentioned, farmers should take into account the possibility to start irrigating part of their food crops in order to reduce the risk on crop failure. This does not happen at present due to mainly financial and social arguments, for example the higher labour input involved with irrigating the larger areas using the traditional way or the higher costs for other less labour demanding irrigation methods. The fact that a farmer can earn more money irrigating an extra area of cash crops than by irrigating food crops with the same amount of water, probably will make the farmer buy food crops with the extra money he gets from cultivating more cash crops.

The objective to suggest guidelines on the optimal size of the irrigated area in relation to the amount of water in the dam could not be realised because it was not possible to analyse the variability of the volume of water that a dam can provide through the year. The problem was the lacking data on the water taken from the dams for domestic use and cattle, the runoff from upstream areas and the seepage to the banks. If these data would be present a local water balance could be constructed for one or more sand-storage dams also integrating possible irrigation events, rainfall on the riverbed surface and outflow of the reservoir. Per season of the historical data the optimal irrigated area can be determined with the local water balance by keeping water available for cattle and domestic use during the year. Using the results, guidelines on the optimal plot size for irrigation can be given to farmers at the beginning of the dry season in relation to the amount of water that is stored behind the dam during the last rainy season. The constructed soil and topographic maps (Appendix 4) can contribute in the calculation irrigation requirements because area where there is an effect of capillary rise can be estimated and the surface occupied by a soil type can be taken into account. Neesen (2004) created a local water balance in his study on the regional water balance of the Ngunga river. In the local water balance the runoff from the catchment upstream of the proposed dam site was simulated using the AV-SWAT model (ArcView-Soil and Water Analysis Tool). By integrating the irrigation requirements, seepage and water use by humans and animals in this local water balance as explained above, this last objective could realised in the future. To validate this local water balance model, the depth of the water table should be monitored for several years. Therefore the piezometer network that was installed by the REAL project should be maintained and monitored at a regular time step.

Since the farming systems in the Kitui District are situated in between permanent upland cultivation and irrigated farming, the possibility that the system evolves to a largely irrigation-based system has to be taken into account in future studies. Irrigation guidelines will have to be developed for more advanced irrigation techniques like sprinkler irrigation or drip irrigation.

Finally, it has to be stressed that nevertheless this study tries to provide guidelines with the best reliability, it always stays a preliminary simulation of the reality. The simulations only take into account the crops’ reaction to water, the fertility aspects are neglected. The time reserved for data collection was too ample to collect a sufficiently large dataset to perform a validation of the guidelines. Therefore, it is advised to evaluate the guidelines in this study some years after their implementation. By then a temperature and rainfall dataset will be available from the Kisayani primary school and the Mbtini secondary school where a meteorological station was started up during the field campaign. A more extensive soil parameter dataset can be developed, however it was seen that soil parameters does not have a large effect on the BUDGET output as long as the textural classes are chosen well. Another topic that should be addressed is the salinity problems that could arise when using saline irrigation water. In this thesis building up of salt in the root zone was assumed to be negligible. Future data collection should therefore include research on the salinity of the potential irrigation water in the sand storage dam reservoir and building up of salts in the soil.

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Appendix 1 Rainfall data summarised per meteorological station

Appendix 1 Rainfall data summarised per meteorological station

Station	**Station ID**	**Source**	**Lat (S)**	**Lat Y**	**Long (E)**	**Long X**	**Alt (m)**	**Daily/Monthly Records**	**Time series**
Kitui agricultural station	9138000	1	1°40'	-1,37	38°01'	38,02	1177	Monthly	1904-1990
	9138000	3	1°40'	-1,37	38°01'	38,02	1177	Monthly	1926-1954; 1958-1971;1973-1974; 1976-1980
	9138000	2	1°40'	-1,37	38°01'	38,02	1177	Daily	1979-1994; 1999
Ithookwe Agriculture substation	9137095	2	1°22'	1,37	37°59'	37,98	975	daily	1979-1991; 1993-1999
Mutomo Agriculture station	9138001	3	1°51'	1,85	38°12'	38,20	914	Monthly	1957-1982
	9138001	2	1°51'	1,85	38°12'	38,20	914	Daily	1979-1999
St. Angelas school Mutunie	9138035	2	1°19'	1,32	38°01'	38,02	1280	Daily	1979-1980; 1987; 1989-1991; 1993-1999
Kitui Voo Dispensary	9138007	3	1°40'	1,67	38°20'	38,33	610	Monthly	1957-1980
Ikanga chief camp	9138013	3	1°43	1,72	38°04'	38,07	610	Monthly	1960-1978; 1980
Mutha chief camp	9138010	3	1°47	1,78	38°25'	38,42	610	Monthly	1979-1980
Kyatune subchief camp	9138019	3	1°46'	1,77	38°07'	38,12	853	Monthly	2003
Mbtini secundary school	/	5	/	-1,59	/	38,12	/	Daily	2002-2003
Kisayani prim school	/	6	/	-1,69	/	38,19	/	Daily	2001-2002
Mutomo: Gabriel Ndetei	/	4	/	/	/	/	/	Monthly	2001-2002

	/	4	/	/	/	/	/	Daily	2001-2002
Mutomo: Manundu Nyamai	/	4	/	/	/	/	/	Monthly	2001-2002
	/	4	/	/	/	/	/	Daily	2001-2002
Mutomo: Bartholomew Mutia	/	4	/	/	/	/	/	Monthly	2001-2002
	/	4	/	/	/	/	/	Daily	2001-2002
Mutomo: Stephen Mulatya	/	4	/	/	/	/	/	Monthly	2001-2002
	/	4	/	/	/	/	/	Daily	2001-2002

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4. SOFEM: Kenya Social forestry extension model development. [http://www.kefri.org/kitui/]
5. Mbtini Secondary school
6. Kisayani Primary school

Appendix 2   Rainfall dataset

	January			**Februari**			**March**			**April**			**May**			**June**		
Maand/decade	**1 / dec 1**	**1 / dec 2**	**1 / dec 3**	**2 / dec 1**	**2 / dec 2**	**2 / dec 3**	**3 / dec 1**	**3 / dec 2**	**3 / dec 3**	**4 / dec 1**	**4 / dec 2**	**4/dec/03**	**5 / dec 1**	**5 / dec 2**	**5 / dec 3**	**6 / dec 1**	**6 / dec 2**	**6 / dec 3**
1979	30,6	40,5	94,8	26,1	0	0	0	-999	-999	102,3	56	55,7	55	0	89,1	22,1	0	0
1980	0	0	0	0	0	0	0	0	25	-999	-999	-999	-999	-999	0	0	0	0
1981	0	0	0	0	0	0	0	68	74	73	47	0	15	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	1,5	41,3	160,7	20	3,5	8	0	0	0	6,5
1983	0	22,5	0	0	0	0	0	0	0	0	0	52,5	0	0	0	0	0	0
1984	23	0	0	0	0	0	0	13	0	0,9	23,5	1,8	0	2	0	0	0,5	0
1985	0	0	12	25	13	0	0	0	0	25	0	16	23,2	0	0	0	0	2,5
1986	0	0	0	0	0	0	3,8	31,5	8,5	24,5	86	72	0	22	52	0	0	0
1987	12	0	0	0	0	0	0	0	0	9	24	34	27	31	0	0	0	0
1988	65,5	9	0	0	0	0	0	43	38,5	74	4	17,6	0	0	0	19,5	0	0
1989	1,2	76,1	0	0	0	0	0	1	19	150	101	68	8	0	0	0	0	0
1990	0	12,3	16,5	-999	0	-999	65	122,8	27,5	191,5	48,5	41,5	48	14,5	4	0	0	0
1991	0	0	0	0	0	0	0	0	124	56	10	0	0	9,5	24	0	0	0
1992	0	0	0	0	0	0	0	0	0	72,5	0	116,5	0	0	0	0,5	0	0
1993	60,5	170,5	123,5	45	0	0	0	5	5	0	0	0	0	0	0	0	6	0
1994	3	4,5	0	0	48,5	0	0	67	26,5	9,5	1,5	8	0	28,5	0	0	0	0
1995	0	8	0	33	0	0	101	0	27	6	46	18	0	7	0	0	0	0
1996	0	0	0	0	0	0	0	110	114	-999	-999	0	0	14	31	0	0	0
1997	26,5	0	0	0	0	0	0	0	22	379	40	79	-999	-999	-999	0	0	0
1998	439,9	229,5	60	0	117	0	12	0,5	137	-999	-999	-999	-999	-999	0	0	0	0
1999	-999	0	0	0	0	0	14	115	66,5	21,5	0	65	0	0	8,5	0	0	0
Standard deviation	245	61	34	220	27	218	25	228	230	393	373	313	362	361	221	6	1	1
10% DR	108,1	95,3	65,8	46,5	n.a.	0	30	106,5	103,6	271,4	107,6	91,1	40,5	25,5	46,9	n.a.	n.a.	n.a.
20%DR	29,8	32,3	8,2	22,1	n.a.	0	3,7	60,7	70,8	125,8	72,9	66,1	21,3	16,7	14,6	n.a.	n.a.	n.a.
50%DR	0	0	0	0	n.a.	0	0	0	21,3	27,2	20,2	26,7	0	0	0	n.a.	n.a.	n.a.
80%DR	0	0	0	0	n.a.	0	0	0	0	4,1	0	0	0	0	0	n.a.	n.a.	n.a.
90%DR	0	0	0	0	n.a.	0	0	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.
0mm-events	11	12	16	16	18	20	16	9	5	2	5	4	11	9	14	18	19	19
# non valid record	1	0	0	1	0	1	0	1	1	3	3	2	3	3	1	0	0	0
# valid records	20	21	21	20	21	20	21	20	20	18	18	19	18	18	20	21	21	21
Probability 0mm (%)	55	57	76	80	86	100	76	45	25	11	28	21	61	50	70	86	90	90
Distribution	normal	normal	normal	normal	/	/	normal	normal	normal	normal	normal	normal	normal	normal	normal	/	/	/
Plotting position	Weibull	Weibull	Weibull	Weibull	/	/	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	/	/	/
Transformation	log	log	sq root	sq root	/	/	log	sq root	sq root	log	sq root	sq root	sq root	sq root	sq root	/	/	/

(n.a. : not analysable; -999: no data)

	July			August			September			October			November			December			
Maand/decade	**7 / dec 1**	**7 / dec 2**	**7 / dec 3**	**8 / dec 1**	**8 / dec 2**	**8 / dec 3**	**9 / dec 1**	**9 / dec 2**	**9 / dec 3**	**10 / dec 1**	**10 / dec 2**	**10 / dec 3**	**11 / dec 1**	**11 / dec 2**	**11 / dec 3**	**12 / dec 1**	**12 / dec 2**	**12 / dec 3**	**Total**
1979	0	0	0	0	0	0	0	0	0	0	0	0	97,7	29	0	0	35,4	128,4	-999
1980	0	0	0	10	10	0	0	0	0	0	0	0	118,2	20	5	25	80	5	-999
1981	0	0	0	0	0	0	0,2	0	0	3	4	10	60,7	37,5	101	20,5	10,5	30	277
1982	0	0,5	0	0	0	0	1,5	0	30	8	41,4	17,4	10	44,3	30,7	69,2	15,3	3	241,5
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	10,1	44,3	91,4	0	5	75
1984	12	1	0	0	0	0	0	0	0	50,6	10	150	350	290	190	0	10	15	64,7
1985	3	0	0	0	0	0	0	0	0	44	2	87	23	82,9	84,1	191,2	13	2,8	116,7
1986	0	0	7	0	0	7	11	0	0	0	2	5	84	76,5	420	127,4	14	0	300,3
1987	0	8	0	20	0	0	0	0	0	0	0	0	90	25	21,5	16	0	0	137
1988	0	0	0	0	0	21	25,5	19,5	0	0	0	19,5	168,5	193,5	89,7	78,5	23	232,5	271,1
1989	0	0	0	0	0	0	0	1	0	9,5	0	49,7	13,2	213,5	367	149	0	0	424,3
1990	0	0,5	0	0	0	0	0	0	8,5	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999
1991	0	0	-999	0	49	0	0	5	0	0	0	23	96,5	155,5	80,5	-999	-999	0	223,5
1992	-999	-999	-999	-999	-999	-999	0	0	0	0	0	146	203,5	27	141,5	24,5	241	44	189,5
1993	0	0	0	0	0	0	0	0	0	0	0	0	54,5	44	117,5	105	117	9,5	415,5
1994	8,5	0	0	-999	-999	-999	0	9	0	0	36	9	67	158,5	106	174	15	45	197
1995	-999	-999	-999	-999	-999	-999	0	0	0	-999	-999	-999	0	27	58	24	29	20	246
1996	0	0	0	0	0	0	0	84	107,3	0	0	0	25	84	107,3	0	0	0	-999
1997	0	0	0	0	0	0	0	0	-999	18	34	42,5	-999	-999	-999	170	104,5	122,5	-999
1998	0	0	-999	0	0	0	-999	0	-999	0	-999	0	58	0	0	24	34	25	-999
1999	0	0	0	0	0	0	0	0	0	0	0	0	25	293,5	277	36	55	246	-999
Standard deviation	301	301	402	359	360	359	218	19	304	303	361	313	335	341	354	327	318	240	599
10% DR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	14,6	n.a.	27,1	28	104,1	228,1	262,3	290,2	188,2	114,1	165,4	1287,1
20%DR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1,1	n.a.	9,1	9,2	50,1	139,3	158,5	212,2	119,2	67,3	71,8	1092,1
50%DR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	n.a.	0	0	6,8	52,3	59,5	93,4	47	22,3	11,9	719,5
80%DR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	n.a.	0	0	0	15,9	20,6	13,8	11,9	0	0	346,8
90%DR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	n.a.	0	0	0	0	10,1	0	0	0	0	151,9
0mm-events	16	15	16	16	16	16	16	16	16	13	11	8	2	1	2	3	4	5	0
# non valid record	2	2	4	3	3	3	1	0	2	2	3	2	2	2	2	2	2	1	7
# valid records	19	19	17	18	18	18	20	21	19	19	18	19	19	19	19	19	19	20	14
Probability 0mm (%)	84	79	94	89	89	89	80	76	84	68	61	42	11	5	11	16	21	25	0
Distribution	/	/	/	/	/	/	/	normal	/	normal	normal	normal	normal	normal	normal	normal	normal	normal	normal
Plotting position	/	/	/	/	/	/	/	Weibull	/	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull
Transformation	/	/	/	/	/	/	/	log	/	log	log	log	log	log	sq root	sq root	log	log	lineair

(n.a. : not analysable; -999: no data)

Appendix 3   ET$_0$ dataset

Appendix 3 ET$_0$ dataset

	January			Februari			March			April			May			June			July
Mont / decade	**1 / dec 1**	**1 / dec 2**	**1 / dec 3**	**2 / dec 1**	**2 / dec 2**	**2 / dec 3**	**3 / dec 1**	**3 / dec 2**	**3 / dec 3**	**4 / dec 1**	**4 / dec 2**	**4 / dec 3**	**5 / dec 1**	**5 / dec 2**	**5 / dec 3**	**6 / dec 1**	**6 / dec 2**	**6 / dec 3**	**7 / dec 1**
T mean [°C]	21,53	21,77	22,10	22,70	23,03	23,27	23,56	23,56	23,39	22,82	22,50	22,19	21,99	21,62	21,19	20,50	20,07	19,73	19,40
T min [°C]	16,02	15,96	16,02	16,41	16,60	16,78	17,01	17,12	17,17	17,17	17,12	17,01	17,03	16,67	16,10	14,80	14,23	13,87	13,89
T max [°C]	27,15	27,70	28,25	28,90	29,33	29,67	30,21	30,11	29,68	28,29	27,66	27,16	26,89	26,58	26,33	26,26	26,02	25,73	25,11
Rs [MJ/m².dag]	23,72	24,42	24,97	25,72	25,75	25,39	24,21	23,42	22,57	21,36	20,66	20,15	20,13	19,77	19,38	19,12	18,52	17,75	15,68
n/N [-]	0,79	0,82	0,84	0,86	0,85	0,82	0,75	0,71	0,67	0,62	0,60	0,59	0,61	0,61	0,60	0,60	0,58	0,53	0,41
U mean [m/s]	2,36	2,27	2,26	2,46	2,51	2,53	2,54	2,51	2,44	2,20	2,17	2,23	2,53	2,62	2,66	2,57	2,59	2,64	2,72
Eto [mm/day]	4,80	4,90	5,10	5,40	5,50	5,50	5,40	5,30	5,10	4,60	4,40	4,20	4,20	4,10	4,10	4,10	4,00	3,90	3,60
#days/decade	10	10	11	10	10	8	10	10	11	10	10	10	10	10	11	10	10	10	10
ET0 Decade (mm/dec)	48,00	49,00	56,10	54,00	55,00	44,00	54,00	53,00	56,10	46,00	44,00	42,00	42,00	41,00	45,10	41,00	40,00	39,00	36,00

	July		August			September			October			November			December				
Mont / decade	**7 / dec 2**	**7 / dec 3**	**8 / dec 1**	**8 / dec 2**	**8 / dec 3**	**9 / dec 1**	**9 / dec 2**	**9 / dec 3**	**10 / dec 1**	**10 / dec 2**	**10 / dec 3**	**11 / dec 1**	**11 / dec 2**	**11 / dec 3**	**12 / dec 1**	**12 / dec 2**	**12 / dec 3**	**Mean**	**St. dev.**
T mean [°C]	19,26	19,24	19,41	19,58	19,81	20,14	20,49	20,87	21,59	21,86	21,96	21,68	21,60	21,52	21,28	21,27	21,35	21,38	1,29
T min [°C]	13,78	13,73	13,80	13,80	13,80	13,55	13,74	14,11	15,02	15,52	15,96	16,40	16,64	16,76	16,69	16,62	16,49	15,65	1,33
T max [°C]	24,94	24,94	25,17	25,46	25,87	26,64	27,12	27,54	28,23	28,30	28,07	26,99	26,56	26,25	25,86	25,92	26,23	27,14	1,49
Rs [MJ/m².dag]	15,43	15,87	18,07	19,09	20,00	21,04	21,54	21,74	21,20	21,13	21,10	21,03	21,11	21,27	21,36	21,79	22,43	21,05	2,65
n/N [-]	0,39	0,40	0,50	0,54	0,58	0,61	0,63	0,65	0,68	0,68	0,68	0,64	0,64	0,65	0,67	0,70	0,73	0,65	0,12
U mean [m/s]	2,80	2,89	3,09	3,12	3,09	2,80	2,77	2,83	3,22	3,24	3,15	2,68	2,57	2,55	2,84	2,83	2,74	2,67	0,29
Eto [mm/day]	3,60	3,70	4,00	4,20	4,40	4,60	4,80	4,90	5,00	5,00	4,90	4,50	4,40	4,30	4,30	4,40	4,50	4,55	0,54
#days/decade	10	11	10	10	11	10	10	10	10	10	11	10	10	10	10	10	11		
ET0 Decade (mm/dec)	36,00	40,70	40,00	42,00	48,40	46,00	48,00	49,00	50,00	50,00	53,90	45,00	44,00	43,00	43,00	44,00	49,50	46,05	5,56

Appendix 4 Construction of a topographic, soil and land use map of the survey area.

Introduction

Geographical data were collected for the survey area in order to construct a topographic, a soil and a land use map. These maps were used to visualise the survey area between the Kamunyuni dam and the proposed dam site. Based on this map the distance between the dams could be estimated, together with the corresponding surface of the riverbed. This information was used to estimate the volume of the river basin between the dams. The topographic map was used in combination with the soil map to determine areas were irrigated farming could take place. The same maps can be used to determine areas where capillary rise can be important. The land use map was constructed for future projects that intend to assess the impact of a sand-storage dam on the farming area. For future analysis, the piezometers that where installed also integrated in the dataset.

Material and methods

Together with the elevation, the polar coordinates of 313 point in the riverbed and on the banks were measured with an optical teodolite (SOKKIA). These polar coordinates were entered in the AUTOCAD 2002 software to determine the Cartesian coordinates.

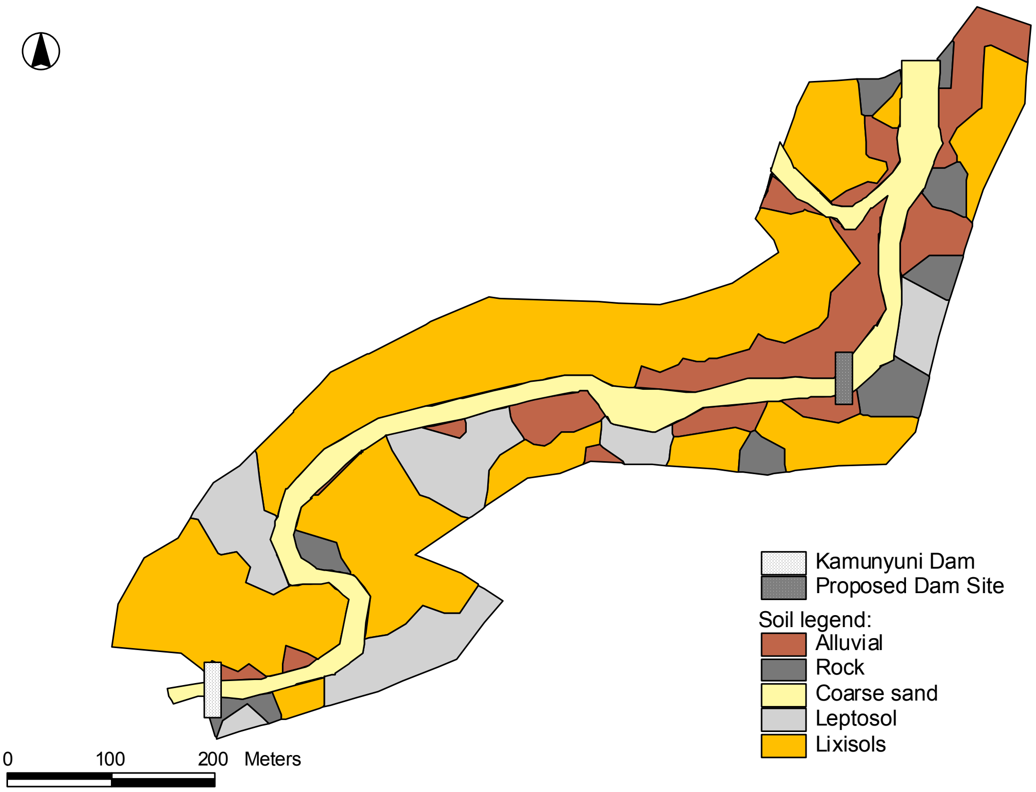
The derived XY coordinates are stored into a database, together with the elevation data, piezometer data, soil data and land use data of the specific points. The database was used as input for geographical analysis with the ARVIEW-GIS 3.2 software.

The topographic map was constructed by interpolation of the elevation values of the point data. For each point a fixed radius of 60 m was taken for the interpolation. To take into account the steep topography of the outer riverbanks, the river edges were inputted as barriers. The proposed dam site is the reference point, having an elevation of 0 m and Cartesian coordinates of 0,0.

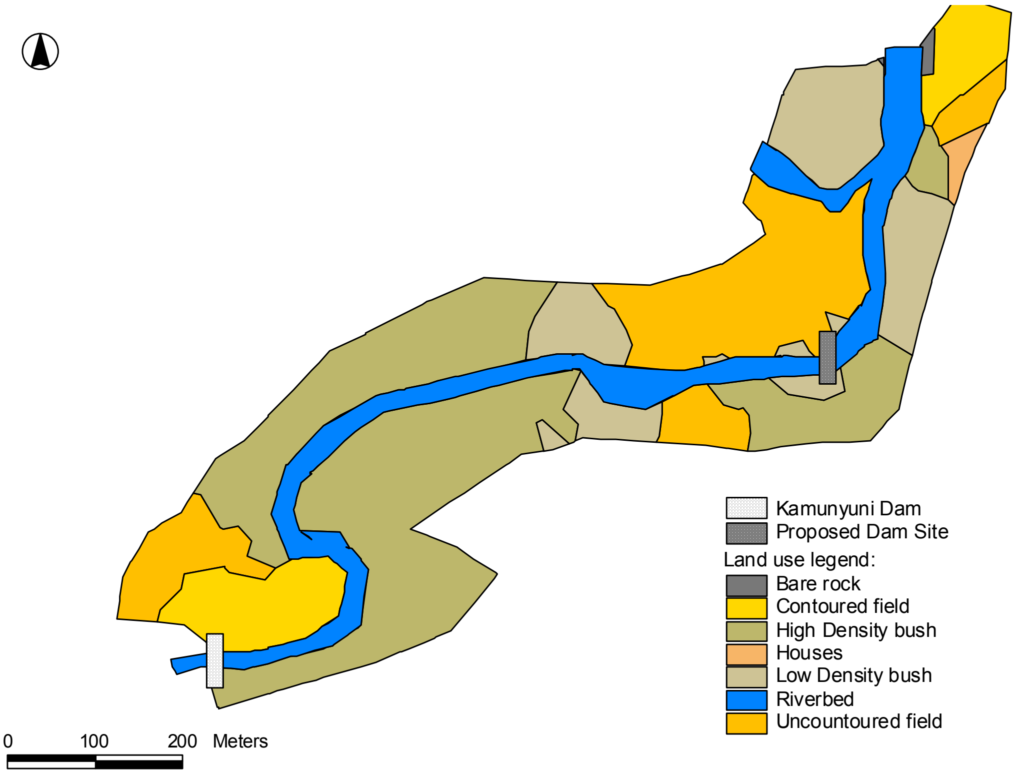
For the construction of the land use and soil map the same procedure was followed. Thiessen polygons were constructed around each point, based on land use data or soil data of that particular point. Afterwards the boundaries of polygons with equal values were dissolved.

Appendix 4 Construction of a topographic, soil and land use map of the survey area.

Soil map

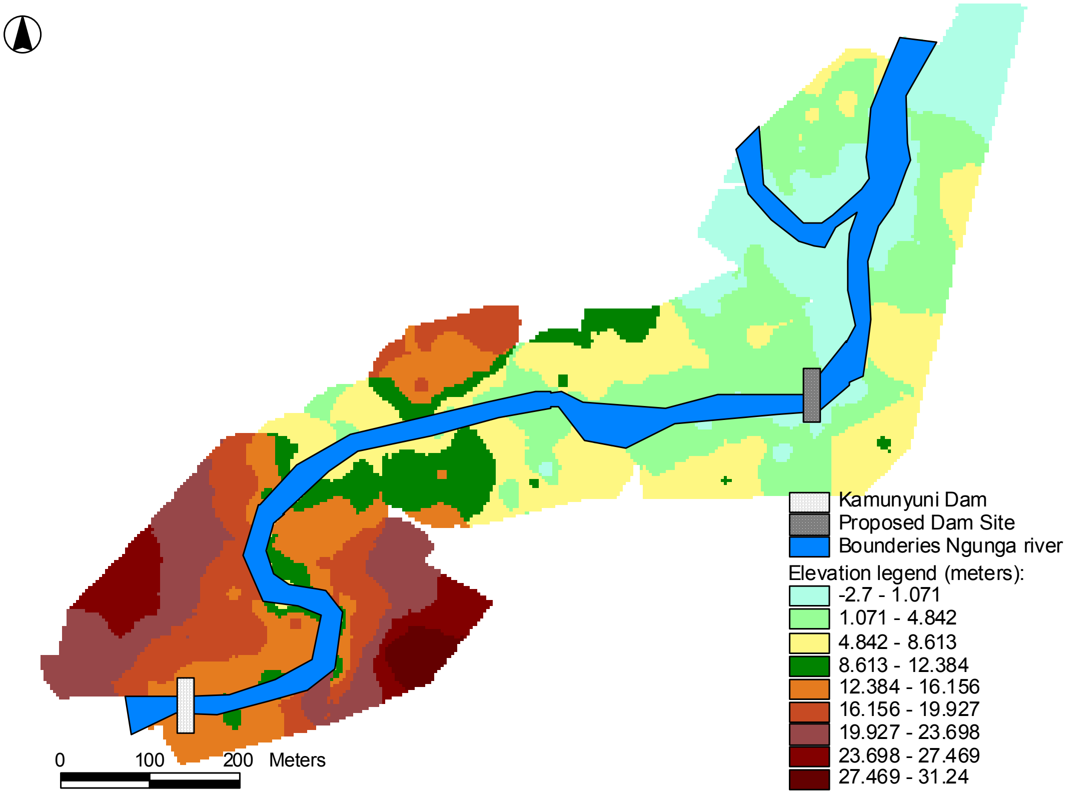


Land use map



Appendix 4 Construction of a topographic, soil and land use map of the survey area.

Topographic map



Slope map

Appendix 5 Crop files

Crop files of the other crops mentioned in this study can be found on the CD-ROM attached to this document. The total content of the CD-ROM can be found in Appendix 9.

SUKUMA WIKI

* Ecocrop (http://ecocrop.fao.org) gives two matching scientific names (Brassica oleracea var. acephala and Brassica Integrifolia var. cartina)

Agronomic data:

Growing period within the year:

Sowing time: May-June or January

Harvest time: After 3 months continuously for 1 year

Crop coefficient and rooting depth per growth stage:

	Initial	*Development*	*Mid*	*Late*	*Total*
Length (days)	20	35	25	10-270	90-360
K_c-factor*	0.70	>>	1.05	0.95	-
Rooting depth (m)*	0.25	>>	>>	0.50	-
Depletion factor (p)*	-	-	-	-	0.40

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

Yield per hectare: 13.5 ton/ha (Kenya, national average, FAOSTAT), 26.3 ton/ha (Kitui, Kiilu *et al.*)

Spacing, sowing depth and density:

Spacing within the row: 30 cm

Spacing between the rows: 60 cm

Sowing depth: /

Plant density: 30000-40000 plants/ha

Soil and fertility requirement for optimal growth:

- Apply two handfuls of manure in each planting hole. When plants are 20 cm high, apply 1 teaspoon of calcium ammonium nitrate (CAN) per 3 weeks (KARI).
- 100-150 kg/ha N, 50-65 kg/ha P and 100-130kg/ha K (FAO values for cabbage, Brassica oleracea var. capitata).
- Moderately sensitive to soil salinity. 0% yield decrease at EC_e 1.8 mmhos/cm and 100% at EC_e 12.0 mmhos/cm. (FAO values for cabbage, Brassica oleracea var. capitata).
- Always practice rotation to reduce incidence op black rot. Use related plants e.g. onion or tomatoes (KARI).

Yield response to water:

Moderately sensitive to water stress

	Establishment	*Vegetative*	*Flowering*	*Yield formation*	*Ripening*	*Total*
Length, fresh (days)*	-	-	-	-	-	90-360
K_y-factor, fresh*	1	0.20	-	0.45	0.60	1.15

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

Most sensitive stages for water deficits: Yield formation and ripening

Most tolerant stages for water deficits: slow development in the vegetative stage

Guidelines for irrigation:

- Transplant plants after 3 week in 30 cm deep holes (for irrigation purposes)
- Water requirements vary from 380 to 500mm depending on climate and length of growing season

References:

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56.* Rome, Italy: FAO - Food and Agriculture Organization of the United Nations. [14.03.2004, http://www.fao.org/docrep/X0490E/X0490E00.htm]

Doorenbos, J., Kassam, A.H. (1979). *Yield Response to Water - Irrigation and Drainage Paper No 33.* Rome, Italy: FAO - Food and Agriculture Organization of the United Nations. [14.03.2004, http://www.fao.org/ag/agl/aglw/cropwater/parta.stm].

FAOSTAT. (2004). *FAO statistical databases, agricultural production (last update 03.02.2004).* [13.03.04, http://faostat.fao.org].

KARI (Kenyan Agricultural Research Institure). Production of Kales (Sukuma Wiki) and onions using bucket drip irrigation. Machakos, Kenya: KARI publications unit.

Kiilu, F.M., Muhammad, L., and Wambugu, S.M. (2002). Market survey report on market opportunities for fruits and vegetables processing in Ukambani, Eastern Kenya. FOODNET. [12.03.2004, http://www.foodnet.cgiar.org/Projects/Fnetrep1.htm].

Personal communication. Field campaign August-September 2003 in the Central and Mutomo Division of the Kitui District, Kenya.

TOMATO (LYCOPERSICON ESCULENTUM)

Agronomic data:

Growing period within the year:

Sowing time: April-May-June

Harvest time: After 2 months continuously for 4-5 weeks

Crop coefficient and rooting depth per growth stage:

	Initial	*Development*	*Mid*	*Late*	*Total*
Length (days)	20	35	25	30	110
K_c-factor*	0.60	>>	1.15	0.7-0.9	-
Rooting depth (m)*	0.25	>>	>>	1.0	-
Depletion factor (p)*	0.30	>>	0.40	0.50	0.30

* Modified values for tomatoes (FAO irrigation and drainage papers)

Yield per hectare (FAO): 45-65 ton/ha (80-90% moisture) for a well managed crop

Spacing, sowing depth and density:

Spacing within the row: 30-60 cm

Spacing between the rows: 60-100 cm

Sowing depth:

Plant density: 40000 plants/ha

Soil and fertility requirement for optimal growth:

- The crop grows on a wide range of soils, preferably on a well drained, light silty loam soil with pH of 5 to 7.
- The crop should be grown in rotation with maize, cabbage and cowpea to reduce pests and disease infections
- The crop is moderately sensitive to soil salinity. 0% yield decrease at EC_e 2.5 mmhos/cm and 100% at EC_e 12.5 mmhos/cm. Most sensitive is during germination and early plant development.

Yield response to water:

Sensitive to water stress

	Establishment	*Early vegetative*	*Flowering*	*Yield formation*	*Ripening*	*Total*
Length (days)	25-35	20-25	20-30	20-30	15-20	100-140
K_y-factor*	1	0.40	1.10	0.80	0.40	1.05

* Modified values for tomatoes (FAO irrigation and drainage papers)

Most sensitive stages for water deficits: immediately after transplantation, during flowering and yield formation.

Most tolerant stages for water deficits: vegetative period (enhances root growth) and ripening.

Guidelines for irrigation:

- The crop is sensitive to water logging, because of the higher risk for incidence diseases such as bacterial wilt
- 100-150 kg/ha N, 65-110 kg/ha P and 160-240 kg/ha K.
- Pre-irrigation is necessary to leach the salts.
- Highest yield of tomatoes are obtained by frequent light irrigations.
- The crop needs a relatively high soil water content achieved without leaf wetting, so drip irrigation or surface irrigation are preferred.

References:

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56.* Rome, Italy: FAO - Food and Agriculture Organization of the United Nations. [14.03.2004, http://www.fao.org/docrep/X0490E/X0490E00.htm]

Doorenbos, J., Kassam, A.H. (1979). *Yield Response to Water - Irrigation and Drainage Paper No 33.* Rome, Italy: FAO - Food and Agriculture Organization of the United Nations. [14.03.2004, http://www.fao.org/ag/agl/aglw/cropwater/parta.stm].

Personal communication. Field campaign August-September 2003 in the Central and Mutomo Division of the Kitui District, Kenya.

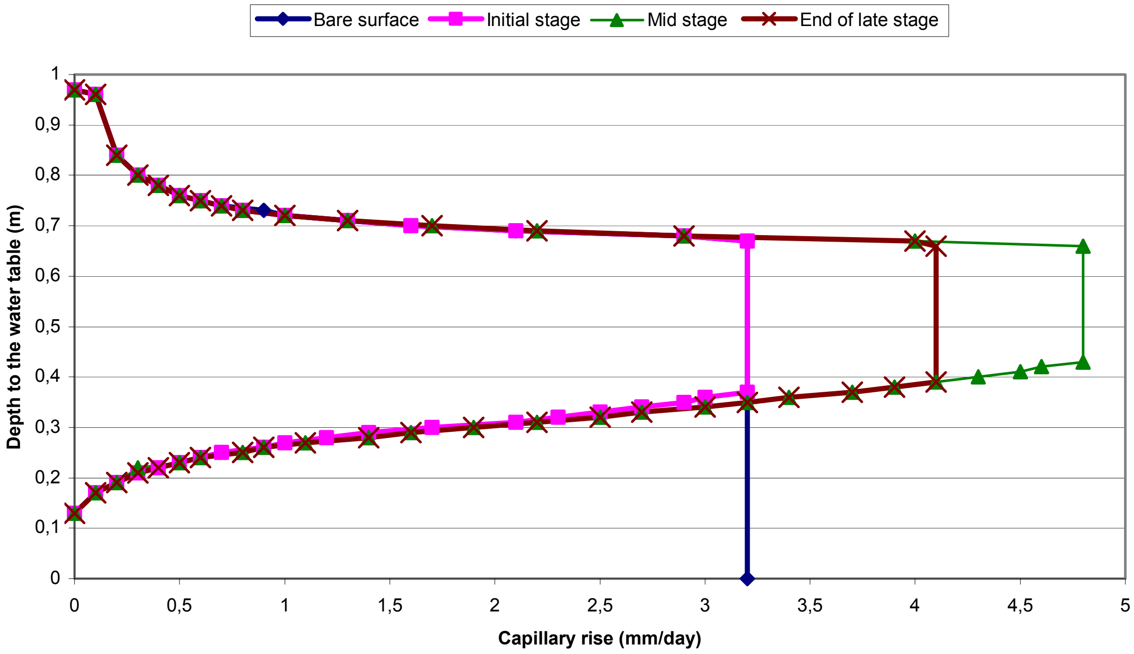
Appendix 6   Soil profile data

Sample no.		3			21	8	11			15/16		
Soil sampling site		**Riverbed**			**Sandy riverbank**	**Red soil (bush)**	**Riverbank (bush)**			**Plateau Kisayani village (Bush/Old field)**		
Dept (cm)		**0-10**	**10-90**	**90-230**	**0-5**	**0-100**	**0-25**	**25-65**	**65-100**	**0-10**	**10-60**	**60-100**
Texture	Texture class	**Sand**	**Sand**	**Sand**	/	**Sandy clay loam**	**Loamy sand**	**Loamy sand**	**Sand**	/	/	/
	Sand (vol%)	97,44	99,03	90,42	/	63,3	87,06	82,19	95,07	/	/	/
	Clay (vol%)	1,8	0,5	9,08	/	28,96	6,15	4,34	2,4	/	/	/
	Silt (vol%)	0,77	0,47	0,5	/	7,74	6,79	13,47	2,53	/	/	/
Measured	Bulk Density (g/cm³)	/	/	1,64	1,39	1,43	/	/	/	1,61	1,66	1,46
	Saturation Point pF 0,0 (vol%)	/	/	35	38,7	41,7	/	/	/	34,2	29	36,2
	Field Capacity pF 2,3 (vol%)	/	/	10,1	8,9	24	/	/	/	18,4	15,7	18,5
	Wilting Point pF 4,2 (vol%)	/	/	5,5	4,7	15,2	/	/	/	9	8,2	8,8
	TAW (mm/m)	**/**	**/**	**46**	**42**	**88**	**/**	**/**	**/**	**94**	**75**	**97**
Calculated (Saxton *et al.*)	Bulk Density (g/cm³)	1,74	1,74	1,62	/	1,41	1,69	1,71	1,73	/	/	/
	Saturation Point pF 0,0 (vol%)	34	34	38,9	/	46,9	36,3	35,6	34,7	/	/	/
	Field Capacity pF 2,3 (vol%)	11,5	11,5	15,4	/	25,6	13,8	14,3	11,9	/	/	/
	Wilting Point pF 4,2 (vol%)	5,3	5,3	8,4	/	16,8	6,3	6	5	/	/	/
	TAW (mm/m)	**62**	**62**	**70**	**/**	**88**	**75**	**83**	**69**	**/**	**/**	**/**
Calculated (Schaap *et al.*)	Residual water content (vol%)	2,8	2,76	3,23	/	/	/	/	/	/	/	/
	Water content at saturation (vol%)	34,02	33,22	34,57	/	/	/	/	/	/	/	/
	alpha (cm-1)	0,0505	0,0496	0,057	/	/	/	/	/	/	/	/
	n (-)	1,4681	1,464	1,6322	/	/	/	/	/	/	/	/
Ksat (mm/day)	Ksat Porchet method	/	/	/	/	2430,2	/	/	/	/	/	/
	Ksat Double Ring infiltrometer	/	/	/	/	/	/	/	/	/	/	/
	Ksat estimated (Van Genuchten)	1163,3	1012,2	1295,5	/	/	/	/	/	/	/	/
	Ksat estimated (Saxton)	1867,2	1867,2	691,2	/	57,6	1370,4	1476	1984,8	/	/	/
	Ksat measured in laboratory	/	/	8876,1	47173,2	791,45	/	/	/	1144,13	58888,7	4388,49
	Ksat mean	**1515,25**	**1439,70**	**3620,93**	**47173,20**	**1093,08**	**1370,40**	**1476,00**	**1984,80**	**1144,13**	**58888,70**	**4388,49**

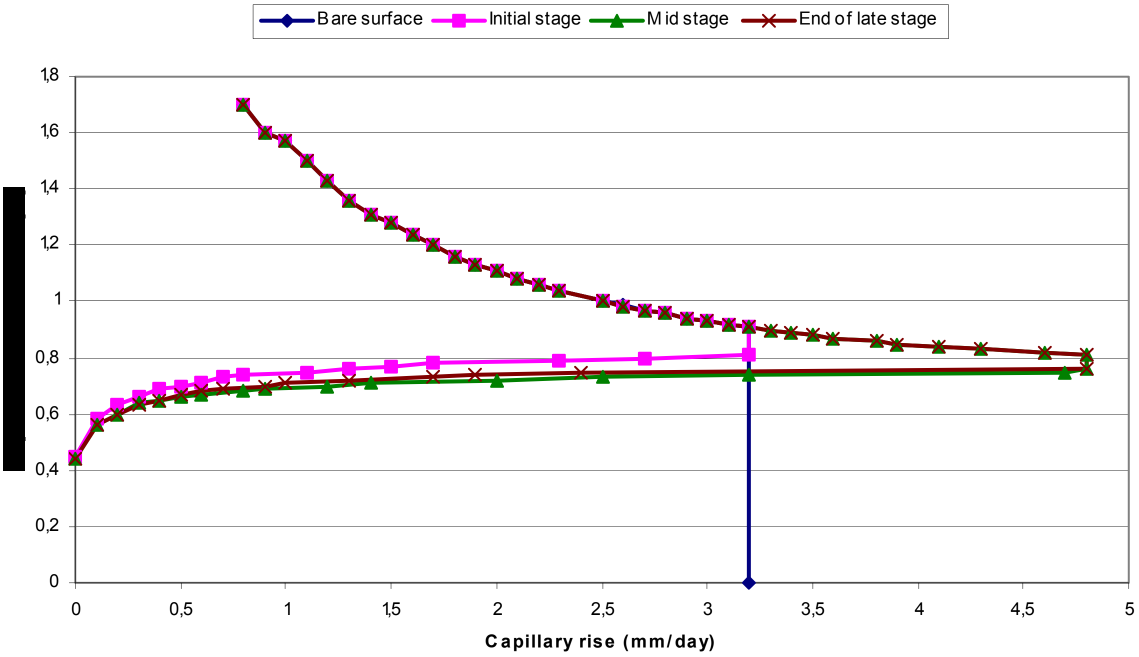
Sample no.		**13/17**			**2/18**		**14**			**20**		
Soil sampling site		**Riverbank (field)**			**Riverbank (bush)**		**150 m from riverbank (field)**			**Downslope area (cleared bush)**		
Dept (cm)		**0-30**	**30-60**	**60-110**	**0-5**	**5-90**	**0-10**	**10-50**	**50-70**	**0-20**	**20-60**	**60-100**
Texture	Texture class	**Sandy loam**	**Sandy loam**	**Sandy loam**	**/**	/	**Loamy sand**	**Sandy clay loam**	**Sandy clay loam**	**/**	**/**	**/**
	Sand (vol%)	75,17	73,3	70,46	/	/	81,67	66,58	67,87	/	/	/
	Clay (vol%)	13,26	14,29	16,35	/	/	7,2	21,68	22,56	/	/	/
	Silt (vol%)	11,56	12,41	13,19	/	/	11,13	11,73	9,57	/	/	/
Measured	Bulk Density (g/cm³)	1,39	1,33	1,36	1,39	1,28	/	/	/	1,41	1,54	1,56
	Saturation Point pF 0,0 (vol%)	42,2	42,6	40,2	40,6	47,1	/	/	/	37,9	37,1	35,6
	Field Capacity pF 2,3 (vol%)	18,6	11,8	16,7	17,3	18	/	/	/	15,1	16,2	18
	Wilting Point pF 4,2 (vol%)	8,6	5,8	8	8,1	9,6	/	/	/	8	9,3	11,2
	TAW (mm/m)	**100**	**60**	**87**	**92**	**84**	**/**	**/**	**/**	**71**	**69**	**68**
Calculated (Saxton et al.)	Bulk Density (g/cm³)	1,55	1,53	1,51	/	/	1,66	1,46	1,45	/	/	/
	Saturation Point pF 0,0 (vol%)	41,5	42,1	43,1	/	/	37,5	45,1	45,3	/	/	/
	Field Capacity pF 2,3 (vol%)	18,6	19,2	20,3	/	/	15,2	22,6	22,9	/	/	/
	Wilting Point pF 4,2 (vol%)	10	10,4	11,3	/	/	7	13,8	14,3	/	/	/
	TAW (mm/m)	**86**	**88**	**90**	**/**	**/**	**82**	**88**	**86**	**/**	**/**	**/**
Calculated (Schaap *et al.*)	Residual water content (vol%)	3,57	3,42	4,78	/	/	/	/	/	/	/	/
	Water content at saturation (vol%)	42,39	39,55	39,5	/	/	/	/	/	/	/	/
	alpha (cm-1)	0,063	0,363	0,363	/	/	/	/	/	/	/	/
	n (-)	1,3435	1,3381	1,3381	/	/	/	/	/	/	/	/
Ksat (mm/day)	Ksat Porchet method (mm/day)	/	6431,685	8880,235	/	972,2	/	/	978,44	/	/	/
	Ksat Double Ring infiltrometer	6316,22	/	/	18761,5	/	/	/	/	8117,93	/	/
	Ksat estimated (Van Genuchten)	1201,1	3116,6	548,3	/	/	/	/	/	/	/	/
	Ksat estimated (Saxton)	379,2	326,4	244,8	/	/	1058,4	115,4	103,2	/	/	/
	Ksat measured in laboratory	6558,34	6489,44	715,336	7692,35	10000,1	/	/	/	6583,55	980,21	15154,8
	Ksat mean	**3613,72**	**4091,03**	**2597,17**	**13226,93**	5486,15	**1058,40**	**115,40**	**540,82**	**7350,74**	**980,21**	**15154,80**

Sample no.		12			22			M			Kit	
Soil sampling site		**Black cotton soil (field)**			**Sloping area (bush)**			**Pit for brick making (bush)**			**Pit for brick making (bush)**	
Dept (cm)		**0-55**	**55-85**	**85-100**	**0-17**	**17-52**	**52-70**	**0-45**	**45-55**	**55-100**	**0-40**	**40-100**
Texture	Texture class	**Sandy clay loam**	**Sandy clay loam**	**Sandy Clay**	**Sandy loam**	**Sandy clay loam**	**Sandy clay loam**	**Loamy sand**	**Sandy clay loam**	**Sandy Clay**	**Loamy sand**	**Sandy loam**
	Sand (vol%)	52,71	49,33	45,99	74,36	66,9	64,75	84,24	62,53	49,96	80,04	72,21
	Clay (vol%)	28,05	31,2	35,8	12,26	22,65	22,51	10,38	28,79	43,98	10,12	20,14
	Silt (vol%)	19,24	19,47	18,2	13,37	10,45	12,74	5,39	8,68	6,06	9,84	7,65
Measured	Bulk Density (g/cm³)	1,46	1,47	1,27	1,34	1,49	1,71	/	/	/	/	/
	Saturation Point pF 0,0 (vol%)	47,64	47,46	54,8	39,3	34,7	32,3	/	/	/	/	/
	Field Capacity pF 2,3 (vol%)	35,36	35,8	41,15	17,8	20,4	17,5	/	/	/	/	/
	Wilting Point pF 4,2 (vol%)	21,12	22,8	24,8	7,2	10,2	10,1	/	/	/	/	/
	TAW (mm/m)	**142,4**	**130**	**163,5**	**106**	**102**	**74**	/	/	/	/	/
Calculated (Saxton *et al.*)	Bulk Density (g/cm³)	1,39	1,37	1,34	1,56	1,45	1,44	1,61	1,41	1,32	1,6	1,48
	Saturation Point pF 0,0 (vol%)	47,5	48,3	49,4	41,2	45,3	45,5	39,4	46,9	50,2	39,7	44,2
	Field Capacity pF 2,3 (vol%)	26,6	28,4	30,9	18,4	23	23,2	16,2	25,6	33,3	16,7	21,4
	Wilting Point pF 4,2 (vol%)	16,2	17,5	19,9	9,5	14,3	14,2	8,5	16,8	23,8	8,5	13,1
	TAW (mm/m)	**104**	**109**	**110**	**89**	**87**	**90**	**77**	**88**	**95**	**82**	**83**
Calculated (Schaap *et al.*)	Residual water content (vol%)	6,19	6,52	7,39	2,97	4,46	4,8	/	/	/	/	/
	Water content at saturation (vol%)	43,3	43,5	50,02	43,13	40,47	34,34	/	/	/	/	/
	alpha (cm-1)	0,0097	0,0123	0,0081	0,0385	0,0305	0,0389	/	/	/	/	/
	n (-)	1,2914	1,2521	1,3028	1,3407	1,336	1,3461	/	/	/	/	/
Ksat (mm/day)	Ksat Porchet method	/	/	1217,08	/	/	/	/	/	/	/	/
	Ksat Double Ring infiltrometer	/	/	/	7055,11	/	/	/	/	/	/	/
	Ksat estimated (Van Genuchten)	83	71,7	166,1	1467	762,8	451,5	/	/	/	/	/
	Ksat estimated (Saxton) (mm/day)	72	57,6	43,2	439,2	103,2	105,6	648	57,6	26,4	626,4	144
	Ksat measured in laboratory	1276,99	25,93	69,06	12077,6	641,992	2237,8	/	/	/	/	/
	Ksat mean	**477,33**	**51,74**	**92,79**	**5259,73**	**502,66**	**931,63**	**648,00**	**57,60**	**26,40**	**626,40**	**144,00**

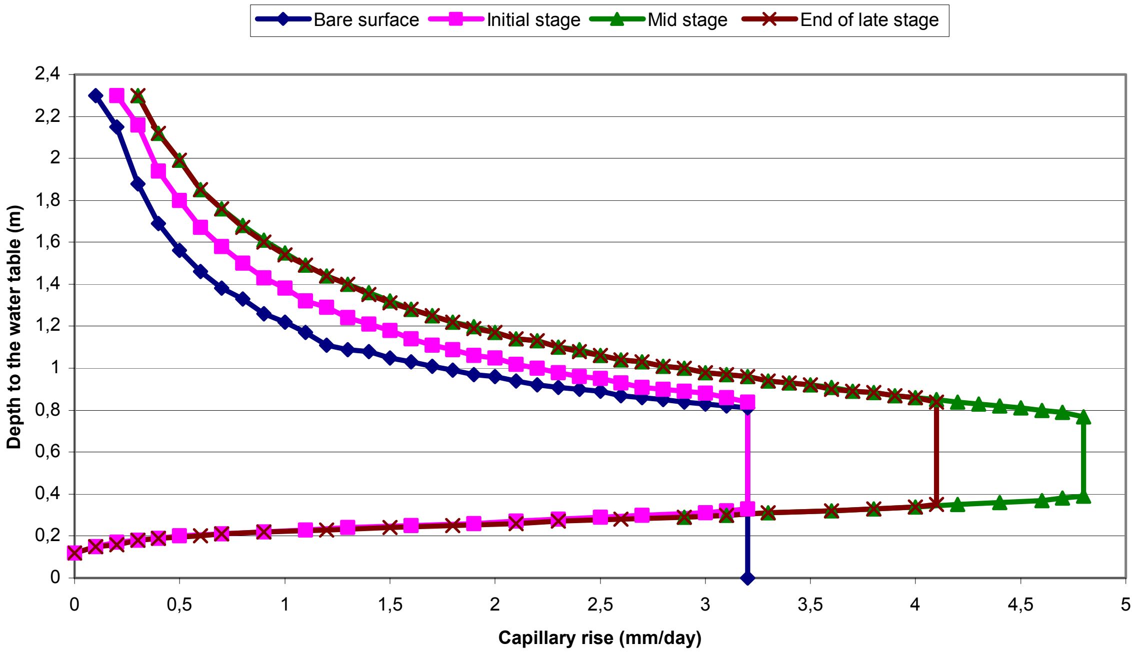
Appendix 7 Capillary rise



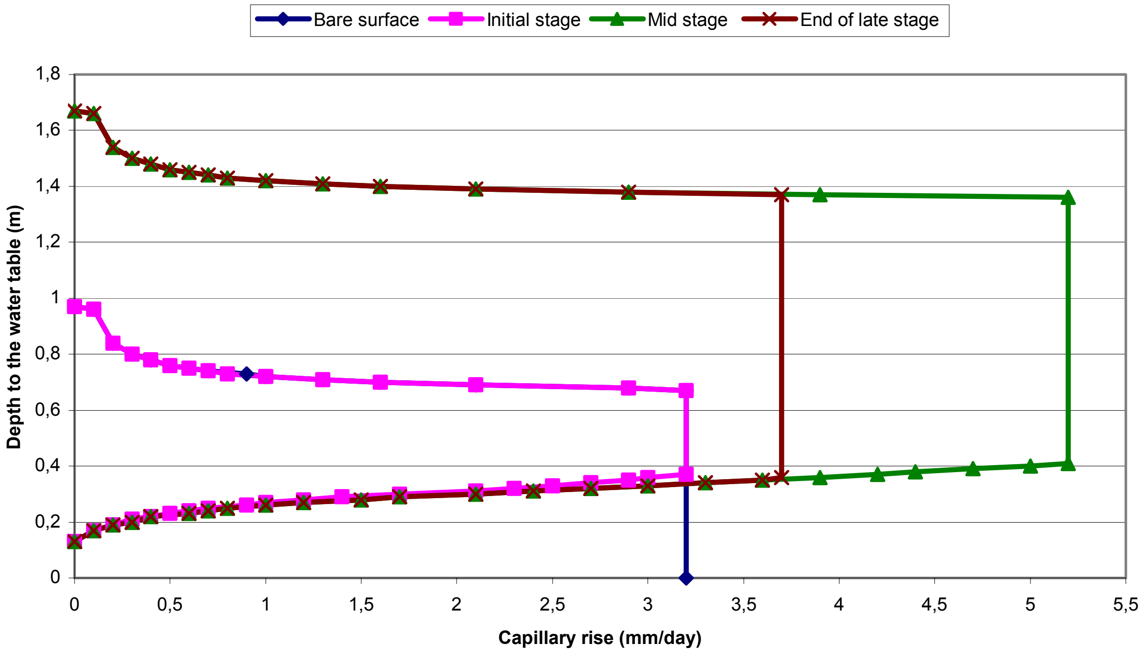
Capillary rise per growth stage in relation to the depth to the water table in a sandy loam soil (Riverbanks) with shallow rooted crops.



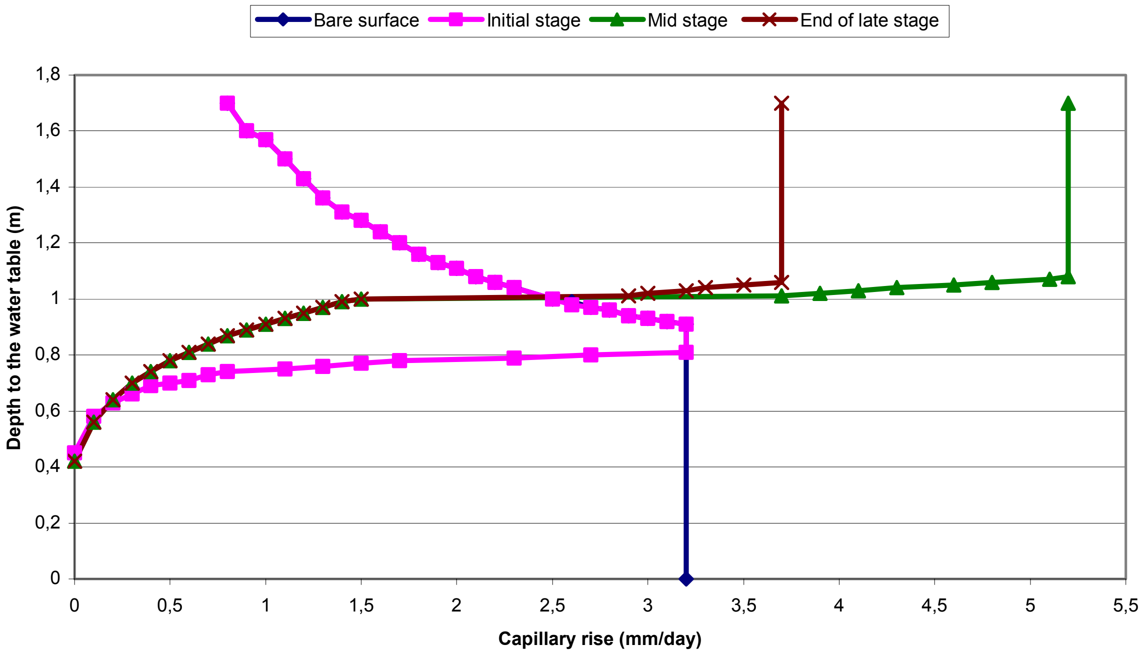
Capillary rise per growth stage in relation to the depth to the water table in a sandy clay loam soil (Black cotton soil) with shallow rooted crops.



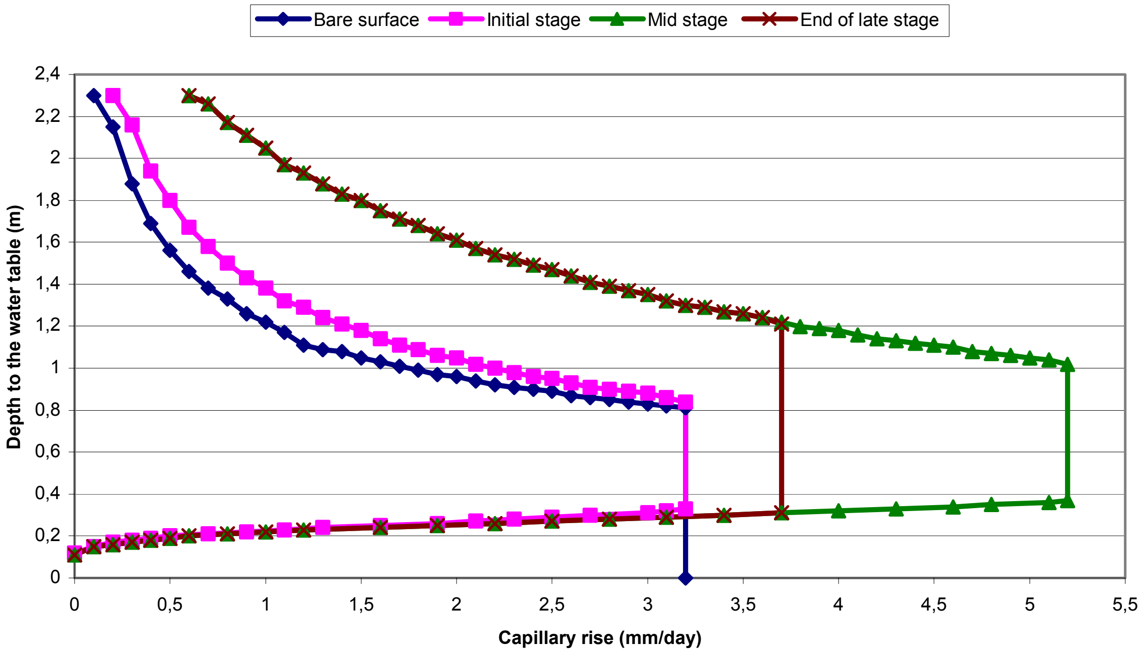
Capillary rise per growth stage in relation to the depth to the water table in a sandy soil (Riverbed) with shallow rooted crops.



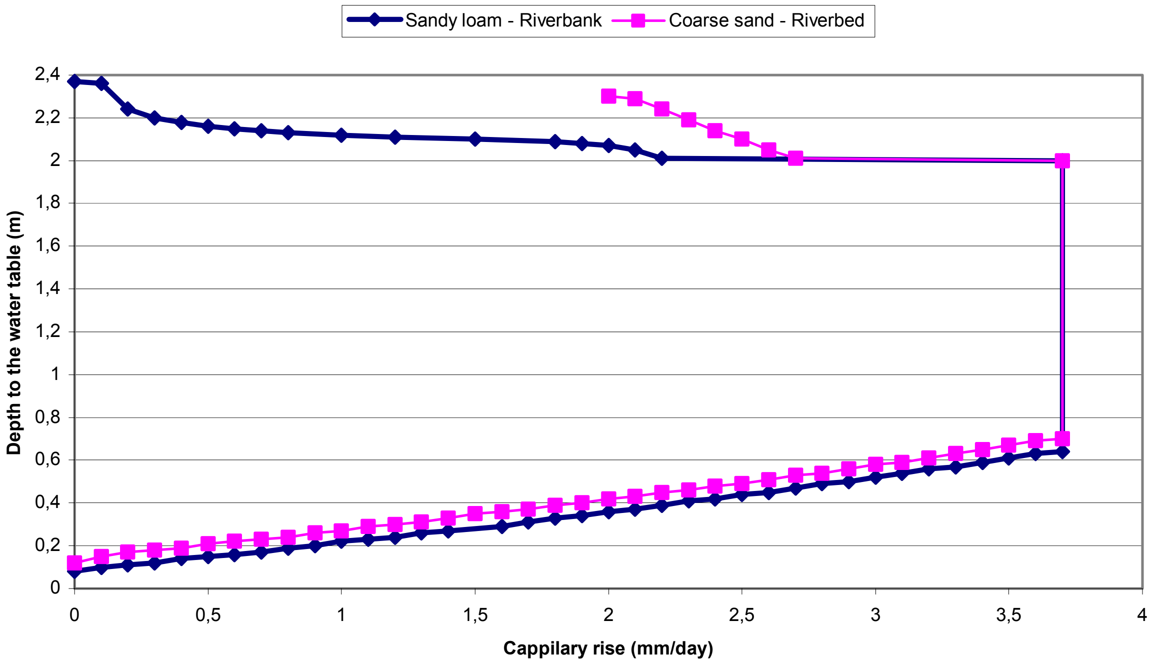
Capillary rise per growth stage in relation to the depth to the water table in a sandy loam soil (Riverbank) with medium rooted crops.



Capillary rise per growth stage in relation to the depth to the water table in a sandy clay loam soil (Black cotton soil) with medium rooted crops.



Capillary rise per growth stage in relation to the depth to the water table in a sandy soil (Riverbed) with medium rooted crops.



Capillary rise per soil type in relation to the depth to the water table for deep-rooted crops.

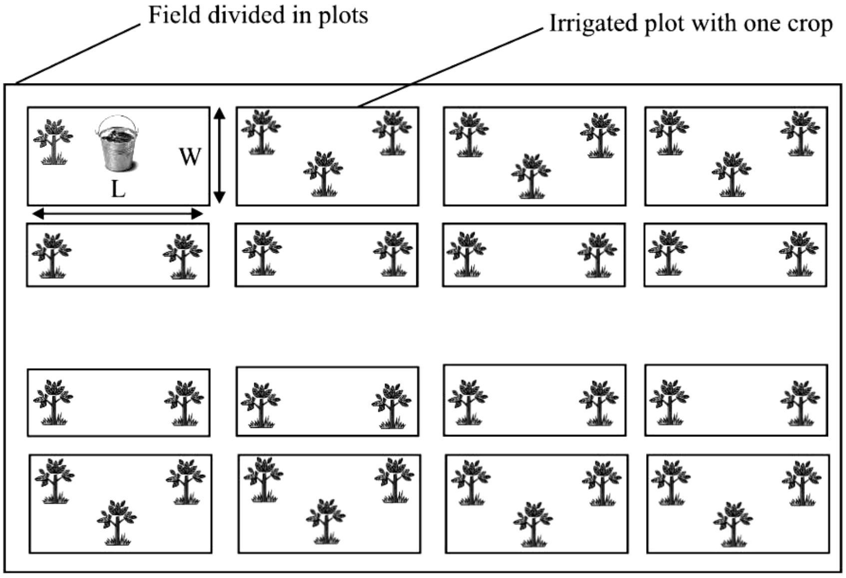
Appendix 8 Irrigation charts

All irrigation charts that were developed are shown in the following table and can be found on the CD-ROM that is attached to this document. The total content of the CD-ROM can be found in Appendix 9.

Crop	*Net appl. depth [mm]*	*Soil*	*Sowing date*	
			Decade	*Month*
Sukuma wiki	10-20	Coarse sand	1	May
	10-20	Sandy loam	1	May
	10-20	Sandy clay loam	1	May
	10-20	Black cotton soil (Vertisol)	1	May
	20 + capillary rise	Sandy loam	1	May
	20 + capillary rise	Coarse sand	1	May
	20	Sandy loam	1	October
	20	Sandy loam	1	December
	20	Sandy loam	3	February
	10 + capillary rise	Sandy loam	1	May
	10	Sandy loam	1	October
	10	Sandy loam	1	December
	10	Sandy loam	3	February
Tomato	10-20	Coarse sand	1	May
	10-20	Sandy loam	1	May
	10-20	Sandy clay loam	1	May
	10-20	Black cotton soil (Vertisol)	1	May
	20 + capillary rise	Sandy loam	1	May
	20 + capillary rise	Coarse sand	1	May
	20	Sandy loam	2	October
	20	Sandy loam	1	December
	20	Sandy loam	3	February
	10 + capillary rise	Sandy loam	1	May
	10	Sandy loam	2	October
	10	Sandy loam	1	December
	10	Sandy loam	3	February

Onions	10-20	Coarse sand	1	January
	10-20	Sandy loam	1	February
	10-20	Sandy clay loam	1	March
	10-20	Black cotton soil (Vertisol)	1	April
	20	Sandy loam	1	November
Spinach	10-20	Coarse sand	1	May
	10-20	Sandy loam	1	May
	10-20	Sandy clay loam	1	May
	10-20	Black cotton soil (Vertisol)	1	May
Maize	20	Sandy clay loam	2	October
	40	Sandy clay loam	2	October
	20	Sandy clay loam	2	March
	40	Sandy clay loam	2	March
Maize/Beans	20	Sandy clay loam	2	October
Maize/Cowpea	40	Sandy clay loam	2	October

Formula for calculating the number of buckets that have to be applied per plot:



$$N = \frac{W * L * A}{20}$$

With,

N: number of buckets (20 Litres) that have to be applied uniformly over the plot

W: Wide of the bed in metres as indicated in the figure

L: Length of the bed in metres as indicated in the figure

A: Net application depth in millimetres as indicated in the irrigation charts that is being followed (e.g. 10 mm, 20 mm or 40 mm)

This formula was derived by assuming that one bucket has a volume of 20 Litres (=20 mm), as observed in the field. If the bucket used to irrigate has another volume, than this formula can easily be adapted by replacing the denominator by the real volume (Litres) of the bucket.

Example: An irrigated plot of tomatoes has a length of 2 metres and is 1.5 metres wide. The farmer follows the irrigation scheme with a net application dose of 10 mm. By following the above formula the farmer can calculate that he has to apply 1.5 bucket uniformly over the plot.

$$N = \frac{1.5 * 2 * 10}{20} = 1.5\, buckets$$

Irrigation chart for tomato

Sowing date: End of rain season, no rainfall

Region: Mutomo Division, Kitui District, Kenya

Irrigation type: Bucket irrigation

Irrigation interval in days/application depth in mm

Month		May			June			July			August	
Decade		1	2	3	1	2	3	1	2	3	1	2
Soil conditions	**Coarse Sand**	3/10			5days/20mm				4/20		5/20	
	Sandy loam	3/10		5days/20mm					4/20	5days/20mm		
	Sandy clay loam	3/10		5days/20mm							6/20	
	Vertisol	3/10		6days/20mm				4/20		5days/20mm		
Growth period		Establishment		Vegetative		Flowering		Yield formation		Ripening		
Sensitivity to water stress		Very (a)		Moderate (b)		Extremely (c)		Very (a)		Moderate (b)		

(a) The crop is very sensitive to water stress during establishment. Therefore, irrigate every three days during the first decades. Also during yield formation water shortage should be avoided because it will result in high losses of yield.

(b) During the vegetative stage, the crop is moderate sensitive to water stress and root development is encouraged by limited water supply. Also during ripening the crop is moderate sensitive to water stress.

(c) The highest demand for water is during flowering. However, withholding irrigation during this period is sometimes recommended to force less mature plants into flowering in order to obtain uniform flowering and ripening. Care should also be exercised in this to avoid damage to the mature plants.

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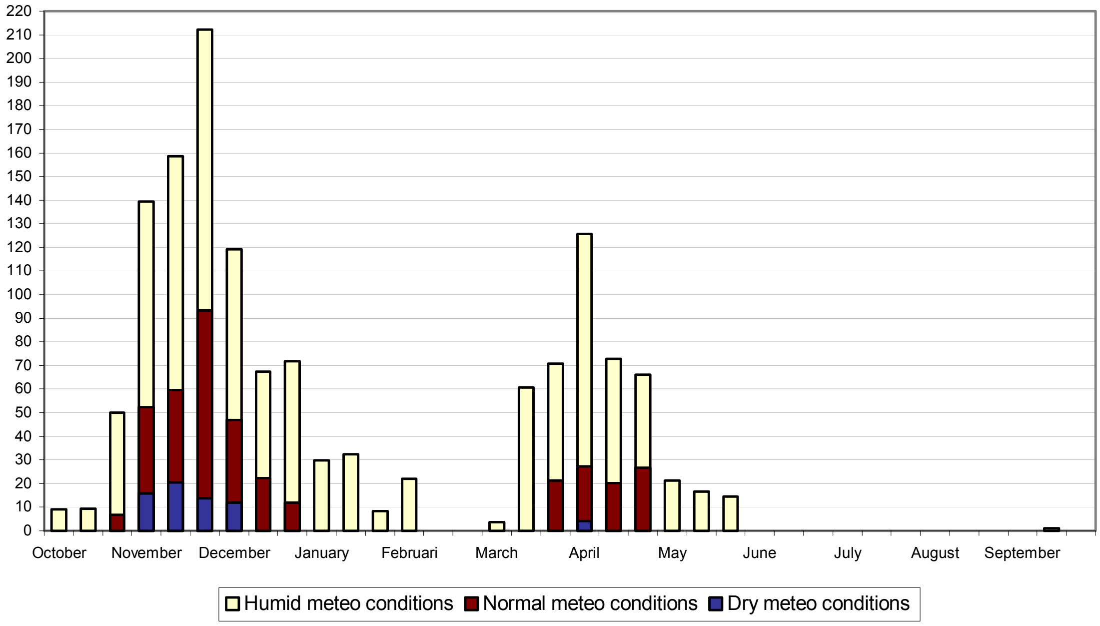
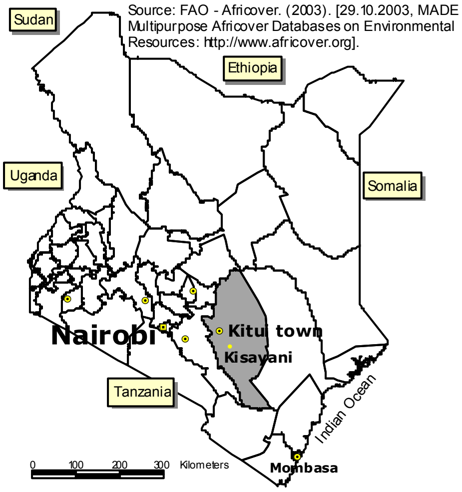
Climate – Rainfall (mm/decade)



Crop evapotranspiration (mm/decade)

Month	May			June			July			August	
Decade	1	2	3	1	2	3	1	2	3	1	2
Tomato	25	28	35	36	39	45	41	41	43	39	38
Growth period	Establishment		Vegetative		Flowering		Yield formation		Ripening		

Source: www.fao.org/docrep/w6974t/ w6974t03.htm



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

Irrigation chart for tomato

Sowing date:	Second decade of October, short rains
Soil type:	Sandy loam
Region:	Mutomo Division, Kitui District, Kenya
Irrigation type:	Bucket irrigation
Net application depth:	20 mm

Irrigation interval in days

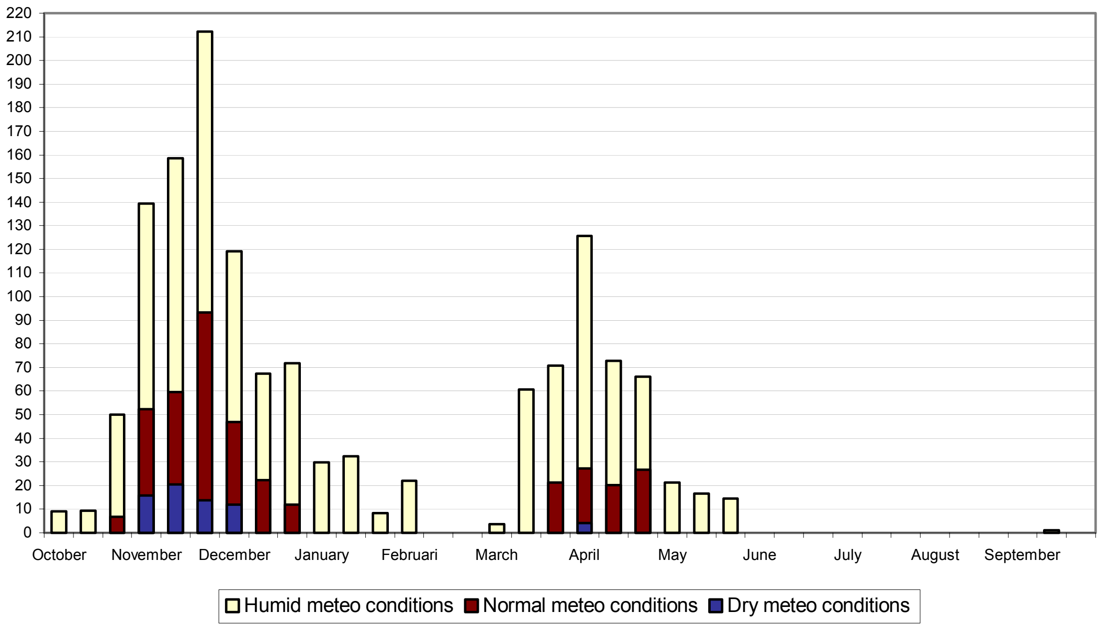
Month		October		November			December			January		
Decade		2	3	1	2	3	1	2	3	1	2	3
Meteo conditions	**No rainfall**	3days			5	4days		5	4days			5
	Dry	3days			5	6days		5	4days			5
	Normal	3days		No irrigation				7days		4days		5
	Humid	4days		No irrigation							5days	
Growth period		Establishment		Vegetative		Flowering		Yield formation		Ripening		
Sensitivity to water stress		Very (a)		Moderate (b)		Extremely (c)		Very (a)		Moderate (b)		

(a) The crop is very sensitive to water stress during establishment. Therefore, irrigate every three to four days during the first decades. Also during yield formation water shortage should be avoided because it will result in high losses of yield.

(b) During the vegetative stage, the crop is moderate sensitive to water stress and root development is encouraged by limited water supply. Also during ripening the crop is moderate sensitive to water stress.

(c) The highest demand for water is during flowering. However, withholding irrigation during this period is sometimes recommended to force less mature plants into flowering in order to obtain uniform flowering and ripening. Care should also be exercised in this to avoid damage to the mature plants.

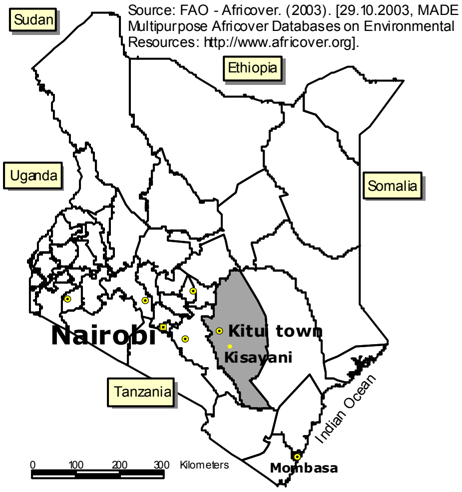
Climate – Rainfall (mm/decade)



Crop evapotranspiration (mm/decade)

Month	October			November			December			January		
Decade	1	2	3	1	2	3	1	2	3	1	2	3
Tomato		30	35	42	39	43	49	49	51	53	47	44
Growth period		Establishment		Vegetative		Flowering		Yield formation		Ripening		

Source: www.fao.org/docrep/w6974t/ w6974t03.htm



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

Irrigation chart for tomato

Sowing date: Beginning of May
Soil type: Coarse sand (**with capillary rise**)
Region: Mutomo Division, Kitui District, Kenya
Irrigation type: Bucket irrigation
Net application depth: 20 mm

Irrigation interval in days

Month		May			June			July			August	
Decade		1	2	3	1	2	3	1	2	3	1	2
Depth of water table	**>2,2 m from surface (no capillary rise)**	4days			5days				4days		5days	
	1,8-2,2 m from surface	4days			5days				6days			
	1,4-1,8 m from surface	4days			5days		7days		10days			
	1,0-1,4 m from surface	4days			No irrigation							
	<1,0 m from surface	5days		No irrigation								
Growth period		Establishment		Vegetative		Flowering		Yield formation		Ripening		
Sensitivity to water stress		Very (a)		Moderate (b)		Extremely (c)		Very (a)		Moderate (b)		

(a) The crop is very sensitive to water stress during establishment. Therefore, irrigate every four to five days during the first decades. Also during yield formation water shortage should be avoided because it will result in high losses of yield.

(b) During the vegetative stage, the crop is moderate sensitive to water stress and root development is encouraged by limited water supply. Also during ripening the crop is moderate sensitive to water stress.

(c) The highest demand for water is during flowering. However, withholding irrigation during this period is sometimes recommended to force less mature plants into flowering in order to obtain uniform flowering and ripening. Care should also be exercised in this to avoid damage to the mature plants.

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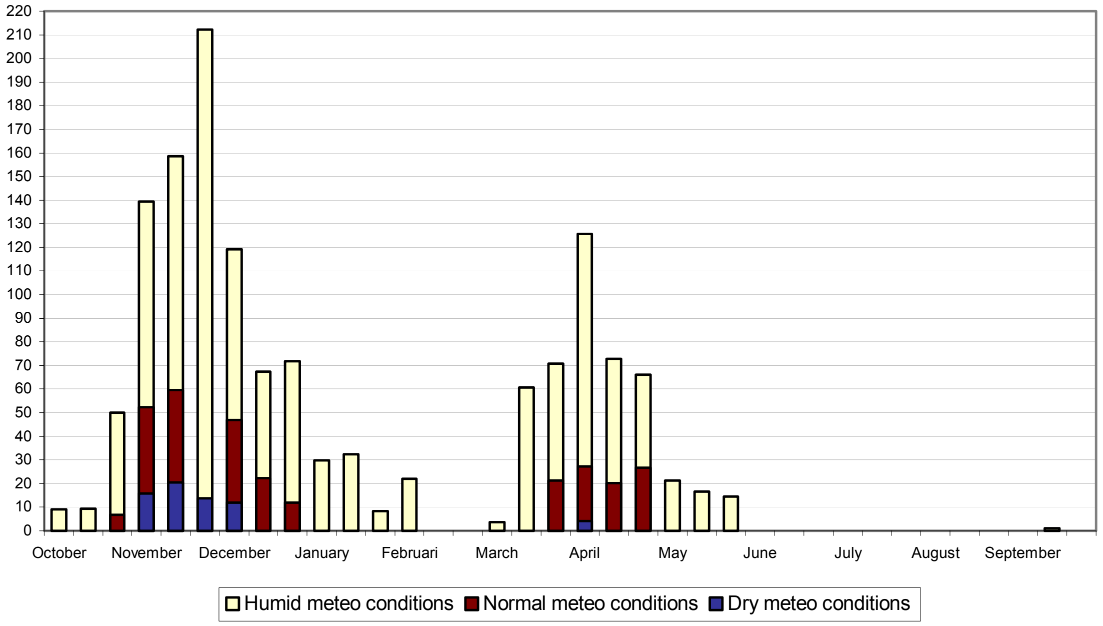
Department of land management

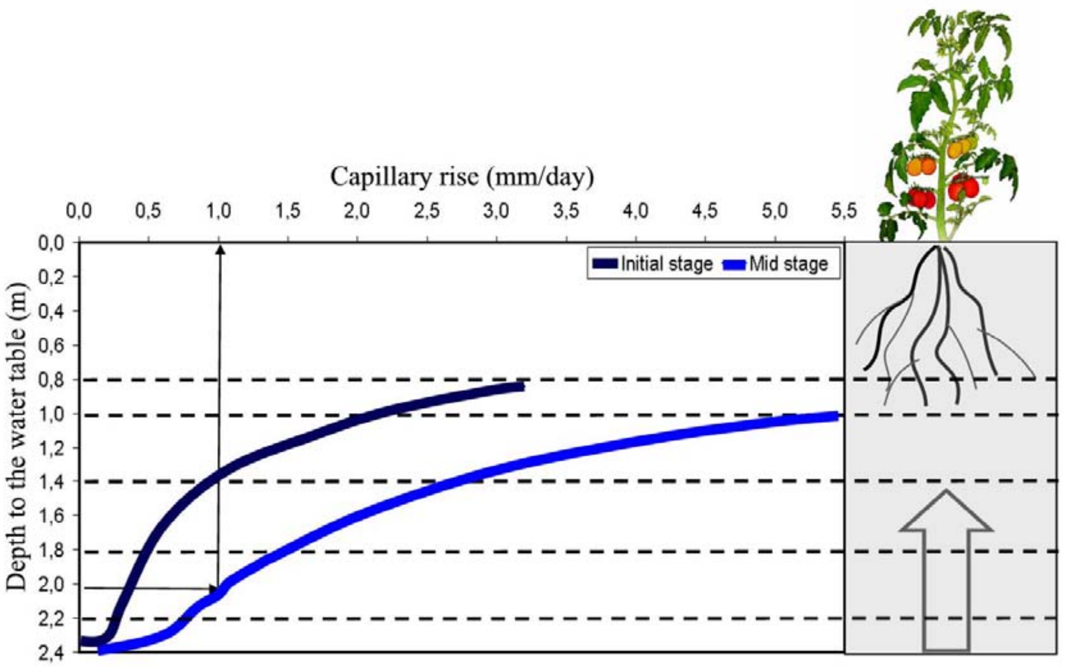
Climate – Rainfall (mm/decade)



Crop evapotranspiration (mm/decade)

Month	May			June			July			August	
Decade	1	2	3	1	2	3	1	2	3	1	2
Tomato	25	28	35	36	39	45	41	41	43	39	38

Capillary rise (mm/day) for different depths of the water table



Appendix 9 CD-ROM: Table of contents

Main map	Submap 1	Submap 2	File name
CROP FILES			Beans (doc/pdf) Cowpeas (doc/pdf) Maize (doc/pdf) Onions (doc/pdf) Pigeonpeas (doc/pdf) Spinach (doc/pdf) Sukuma wiki (Cabbage) (doc/pdf) Tomatoes (doc/pdf)
IRRIGATION CHARTS	Maize	Short rains Long rains	Files can be found listed in Appendix 8
	Maize-Beans	Short rains	
	Maize-Cowpea	Short rains	
	Onion	Short-long rains Dry season	
	Spinach	Dry season	
	Sukuma wiki (Cabbage)	Dry season Short rains Long rains Short-Long rains	
	Tomato	Dry season Short rains Long rains Short-Long rains	
MAPS			Ngunga Cartesian dataset.dbf Kenya.wmf Ngunga land use.wmf Ngunga slopes.wmf Ngunga soil.wmf Ngunga topography.wmf Weather station Kitui.wmf
SOFTWARE	BUDGET	ZIP UNZIP MANUAL	
	ET0		
	RAINBOW		
	UPFLOW		
SOIL PROFILE IMAGES			Soil Profile Images (doc/pdf)
STUDY			Study (doc/pdf)