Water as a constraint on food production in the Sahel

Influence of rainfall scenarios and crop densities on production and the water-use efficiency of millet

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ABSTRACT

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Until now problems with food production consists in the Sahel. Because of the unreliable climate farmers are sowing widespread to reduce risks. This gives low yields. To increase the yield it is an option to increase the crop density. By modelling, the optimum crop density is determined at 75 to 100 cm. This is slighty closer than there is sown now. This optimum is determined by varying crop densities with several rainfall scenarios in the TRIGGER model. The crop density is spread between a maximum density (50 cm) and 150 cm. At this density the crop grows like individual plants. Rainfall scenarios are varied between 128 mm and 1474 mm.

Keywords: crop production, millet, rainfall scenarios, sahel, soil moisture

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Contents

Preface

This report contains the results of a research carried at the DLO Winand Staring Centre in Wageningen, at the department Agrohydrology. It was carried out as graduation of the Master of Sciences programme Land & Water management, specialisaiton Natural Resources Management at the Larenstein College.

The present study is a part of a larger research, which aims at understanding the reasons for a decline in rainfall and the need to predict climate changes in the future, either in response to external factors such as global CO_2 increase. A number of research projects are developed all over the world, in order to achieve this objective. One of these projects is the Hydrologic Atmospheric Pilot EXperiment in the Sahel (HAPEX-Sahel). In order to get information about climate, soil properties and vegetation a Intensive Observation Period (IOP) was carried out in Niger in 1992. This research has been a cooperation of several international institutes, including the DLO Winand Staring Centre in Wageningen (SC-DLO). Results of this IOP are used for the present study, which is more an applied scientific subject and contributes to solutions for sustainable agriculture in Niger and the Sahel.

The report was mainly written for specialists who are occupied with basic research to plant behaviour and hydrological processes, but can also be used by specialists who are occupied with sustainable farming system research.

For the kind support and valuable assistance during this project I would like to express my gratitude to the supervisors of the DLO Winand Staring Centre, Pavel Kabat, Jan Elbers, Jaap Huygen, Barend van den Broek, Cees van Diepen and the supervisors of the International Larenstein College, Jan Palte, Jack Schoenmakers, David Alexander.

List of abbreviations

AMAXTB	:	Maximum CO2 ASSIMILATION Rate as a Function of Development Stage of the Crop
CGM	:	Crop Growth Monitoring System
CWDM	:	Cumulative actual weight of above ground biomass
CWSO	:	Cumulative actual weight of storage organ biomass
DTSMTB	:	Daily Increase in Temperature Sum as a function of Average Temperature
EC	:	European Community
EFF	:	Light Use Efficiency of a Single Leaf
FAO	:	Food and Agricultural Organisation
HAPEX	:	Hydrologic Atmospheric Pilot EXperiment
HYV	:	High Yielding Varieties
IOP	:	Intensive Observation Period
ITCZ	:	Intertropical Convergence Zone
KDIF	:	Extinction Coefficient for Diffuse Visible Light
LAI	:	Leaf Area Index
LAIEM	:	Leaf Area Index at Emergence
NRM	:	Natural Resources Management
QPW	:	Quattro Pro for Windows
RV	:	Rainfall Variability
SC-DLO	:	Agricultural Research Department, Winand Staring Centre for Integrated Land, Soil and water Research
SPA	:	Specific Pod Area
SSA	:	Specific Stem Area
SWAP	:	Soil-Water-Atmosphere-Plant
TDWI	:	Initial Total Crop Dry Weight
TSUMAM	:	Temperature Sum from Anthesis to Maturity
TSUMEA	:	Temperature Sum from Emergence to Anthesis
WUE	:	Water Use Efficiency

Summary

Introduction

Arid and semi-arid lands occupy approximately one third of the world's land surface. The Sudano-Sahelian zone is one of them. This zone has a harsh climate, with low, but highly variable rainfall, high soil and air temperatures, high evaporative demands and poor soils. As a consequence the natural vegetation is sparse and will only grow during a short period, the rainy season. Rainfall is influenced by the intertropical convergence zone (ITCZ). It is accepted that the rainfall has been declining over the last two decades.

Niger policy

Niger is one of the countries situated in the Sahelian zone. Like other Sahelian countries it has problems with food production, population growth and degradation of its natural resources.

After the famine of 1973-1974 the Niger government decided to aim at food self-sufficiency. As a result of this policy the production of millet and sorghum, the main food crops, increased to a reasonable extent. This increase was mainly brought about by means of increasing the agricultural area. However, production is still highly dependent on rainfall. Further expansion of the agricultural area is hardly possible, because only a small zone of Niger can be used for agriculture. Hence, to achieve a further increase in agricultural production other solutions should be found.

Farming system

The farming system is evolving from a shifting cultivation system towards a permanent system. As a consequence, natural resources are used more intensively, although the investments required to sustain the resources cannot be made. This results in soil degradation and decreasing yields. This trend is accentuated by a declining rainfall.

Study is required to find solutions in order to arrest this downward movement. This report is a description of one of these studies, it is focused on the influence of different crop densities of millet as well as different rainfall scenarios at both biomass production of millet and millet water use efficiency (WUE).

Methodology

The TRIGGER model was used to research the effects of both rainfall and crop densities on production and WUE. Data required for this model were derived from HAPEX-Sahel measurements, done during the Intensive Observation Period(IOP) in Niger, and literature.

During modelling a calibration was first carried out, whereafter a simulation could be done. During calibration most attention was paid to the hydrological processes. During simulation, in which both crop density and rainfall scenarios were varied, crop density was varied between 50 cm and 150 cm, while the rainfall scenarios were based upon rainfall variability and length of the rain season.

Model & data requirements

The TRIGGER model describes crop growth and soil moisture flow in the unsaturated zone. A waterbalance is the basis for the description of the climatological and hydrological processes. The plant growth is based upon the process of assimilation and dry matter partitioning over the different plant parts.

Soil moisture flow in the unsaturated soil is described by the Richards' equation. This equation is based on Darcy's flux equation and the humidity equation. And additional sink term accounts for uptake of water by the roots. These processes are calculated per soil compartment for each timestep.

Evapotranspiration is described by the Penman-Monteith approach.

Plant dry matter production originates from the process of photosynthesis. CO_2 from the air is converted into carbohydrates. This process is the CO_2 assimilation. The rate of CO_2 assimilation depends on the radiation energy absorbed by the canopy, which is a function of incoming radiation and crop leaf area. Carbohydrates are mainly used for dry matter production and partly for maintenance respiration and growth respiration. The dry matter produced is partioned over the different plant parts: roots, stem, leaves and storage organs.

Results

Calibration

The calibration could not be fulfilled satisfactorily, because the calibrated soil moisture content could not accurately be fitted with the soil moisture content. During the rainy season the measured points and calibration results showed the same trends in soil moisture changes, though the calibration results overestimated the soil moisture content. At the end of rain season the soil moisture data still remained water, while the calibration results showed a quick dehydration. Two reasons could be suggested for the differences:

- Due to crust formation a large part of the rainfall is running towards the valley and so will not infiltrate at the millet plot. The TRIGGER model does not describe this until the required detail, this results in an overestimation of the soil moisture content.
- Processes such as evapotranspiration in the vapour phase play a role during the dehydration, but can not be described within the TRIGGER model.

The quick dehydration of the soil in the model affected the crop growth as well. The result of this quickly decreasing soil moisture content is that it becomes difficult for the plant to extract moisture, hence the plant becomes stressed and production will leave behind or even stop. This process occured during calibration. For this reason only trends can be taken into account during simulation.

Simulation
The results of the simulation were focused on trends and relations, a quantitative analysis was of marginal importance.

Out of the simulations can be concluded that the optimum crop density lays between a density of 75 cm x 75 cm and 100 cm x 100 cm. With this crop space even in a relative dry year a reasonable yield can be achieved. Hereby, it is expected that rainfall ranges between 420-780 mm.

Both the actual transpiration and water use efficiency (WUE) is an linear function of crop production and rainfall, this means that the photosynthesis efficiency is independent of crop production and rainfall. The latter is rather unexpected, because it is expected that the plant senses stress with low rainfall amounts.

The actual evaporation showed to be independent of crop density, this is rather unexpected as well, because it is expected that actual evaporation decreases with an increasing crop density. This decrease is a consequence of shading effects of the soil by the plant.

Conclusions

The present study can support to the research which aims at the development of a sustainable agricultural system in the Sahel. Though this study showed trends in crop production with different rainfall scenarios and crop densities, further field research will be required to analyse the detailed effects of a crop density increase on for instance production of intercrops and nutrient depletion.

1 Introduction

1.1 Context

The present study is a part of a larger research, which aims at understanding the reasons for a decline in rainfall and the need to predict climate changes in the future, either in response to external factors such as global CO_2 increase (Goutorbe et al.,1994). A number of research projects are developed all over the world, in order to achieve this objective. One of these projects is the Hydrologic Atmospheric Pilot EXperiment in the Sahel (HAPEX-Sahel). In order to get information about climate, soil properties and vegetation a Intensive Observation Period (IOP) was carried out in Niger in 1992. This research has been a cooperation of several international institutes, including the DLO Winand Staring Centre in Wageningen (SC-DLO).

1.2 Background

Arid and semi-arid lands occupy approximately one third of the world's land surface and accommodate about 600 million inhabitants. The Sudano-Sahelian (semi-arid) zone of West-Africa has a harsh climate, with low rainfall which is highly variable, high soil and air temperatures, high evaporative demand and poor soils. The production of adequate and renewable supplies of food, fodder and firewood in this zone is severely limited by the scarcity of water (Van Zanten, 1992). The situation in Niger, one of the countries situated in this zone, will be used as reference for this study.

Niger policy

Despite the unfavourable climatological circumstances, the development policy of the Niger government is to make the country self-sufficient in food production. During the last twenty years food production increased to a reasonable extent. The increasing national income due to uranium exports has made it possible to focus the agricultural production on food and to minimize cash production of groundnuts. At the same time, in the seventies, the government had a realistic price policy. The high price for food crops stimulated farmers to produce millet and sorghum. This policy was given up in 1986, under pressure from the Worldbank. As a consequence, the production of cash crops increased.

In 1984 the policy of a self-sufficient food production was upset by droughts and a collapsing uranium price, that was due to a decreasing interest in nuclear energy in the world and, later, to the aftermath of the 'Chernobyl accident'. In 1985 the Niger government introduced an 'off-season' growing programme which was intended to compensate for the cereals deficit and which represented a distinct change from traditional methods of food-crop cultivation. The programme consists mainly of a large number of small-scale operations using manually-provided irrigation (Hodgkinson, 1995) and is mainly focused on vegetables and fruits. Some large irrigation project, supervised by the FAO and EC, have also been developed to increase food production. These projects have been developed, in an attempt to become less dependent on the unreliable climate.

Despite these efforts, food production increases were mainly a consequence of an expanding agricultural area and less the consequence of yield increase per hectare. The production area for millet increased by 6.5% in one year (1979/'80), while the production area for sorghum increased by 40% in two years (1979/'80-1980/'81). However, the millet production has increased with only 0.7% per year during the last two decades (Spencer and Sivakumar, 1987). The reason for this slow increase can be carried back from abiotic as well as biotic constraints. Gradually, agricultural land is becoming more sparse, partly due to the small zone of Niger which can be used for agriculture. If the government wants to continue the policy of self-sufficiency, it should search for methods to increase the production per hectare (Van Dijk and Bremmers, 1987).

Farming system

The traditional farming system in Niger is shifting cultivation. In this system a part of land is used for agriculture for some years. This agricultural use is followed by a fallow of several years. During this fallow period soil and vegetation have a chance to rehabilitate. During the last thirty years this system has been under more and more pressure, because of a quickly growing population and declining rainfall. The steadily population growth is the result of decreasing child mortality and the increasing age of the population. The declining rainfall has several, interrelated, causes, which are focused on albedo, soil moisture and atmospheric dust (Goutorbe et al., 1994).

The agricultural system is therefore evolving towards a more permanent system. This transition will ultimately results in a system which is to a larger extent based upon economics and will become less dependent on labour. In order to attain this system, investments are required in for example chemical fertilizer and equipment. Until now most Sahelian farmers have not been sufficiently creditworthy to invest in their farming system. Despite, this, they start to use natural resources permanently, with soil degradation among the consequences. Because of this, yields will decrease (Stoop,1991).

As above described the more intensive use of land causes soil degradation. Natural grasses and shrubs become rare. This makes that wind and water can gather the relatively fertile upper layer of the soil, so that yields are declining again.

Another reason for a low yield is the sowing density. In general farmers sow their crops broadcasted, so that even in a dry year water and nutrient competition will be minimized and a certain crop yield is guaranteed. According to Brouwer et al. (1993) the subsistence farming communities are looking for a good minimum yield, a satisfactory level of 'assured' production, so that there will be no hardship; high average yields are of secondary concern. In general rainfall is divided over four relative wet years, four average years and two extremely dry years per decade (Van Dijk and Bremmers, 1987).

Production improvement
In order to improve yields, several measures can be taken, such as water harvesting, the improvement of fertilizer use, the planting of trees to protect the soil against wind and water erosion, planting crops in higher density. The last option will be examined in this report, whereby most attention will be paid to the water use by the plant. This is one of the most limiting factors for crop growth in the north of the Sahel. Other important plant growth factors are the amount of available nutrients, the amount of available radiation and the air temperature. Nutrients are also a limiting factor for plant growth in the Sahel, but are less limiting than water. Radiation and temperature are no limitations in this case.

It has been argued by Hudson that high yield varieties (HYV) should be used. These varieties can be sown in high density without exhausting soil moisture. The water consumption of a crop is determined more by climatic factors like income radiation than by the density of the crop, and a high yielding crop is the result of using water more efficiently rather than in greater quantity (Hudson, 1981). Because of the higher yield, the cost of fertilizer, which is required to grow HYV, can be subsidized.

1.2.1 Formulation of the main objective

On the basis of this description the following objective was formulated:

To establish the influence of different millet densities and different rainfall scenarios on millet production and millet water-use efficiency.

As above described the increase of crop density can be one of the solutions to improve the agricultural system in the Sahel. Until now there was not carried out a lot of model research to the influence of crop density and rainfall on crop production. As reference crop millet is used, because millet is one of the most important crops in the semi-arid zones of the world. Niger was taken as an example for a country situated in the semi-arid zone, because all required measurements were carried out to fulfill this study during the HAPEX-Sahel project.

1.2.2 Research questions

The objective was translated into a number of research questions. These questions concern the following subjects:
— the relationship between plant growth and moisture availability;
— the relation between crop density and biomass production;
— the influence of both rainfall scenarios and climate on evapotranspiration as well as crop growth.
These subjects are elaborated below.

Plant growth and moisture availability
The research questions concerning the relationship between plant growth and moisture availability simultaneously examine the ability of millet to extract moisture from the soil and the water use efficiency (WUE) of the plant. Within this framework the following questions were important:

— How did transpiration influence crop growth?
— What climatological, hydrological and plant growth factors influence the WUE?

Crop density and biomass production
This subject is focused on the question:
— What is the optimum crop density for a guaranteed production?

Rainfall scenarios and climate influences
In order to forecast trends for optimum millet densities under different rainfall scenarios, a range of rainfall scenarios was tested. On the one hand, the influence of rainfall on plant growth should be analysed:
— Did the optimum crop density change under different rainfall scenarios? If so, what reasons could be given for the changes?
— Did rainfall influence evapotranspiration? If so, to what extent?
On the other hand, the rainfall unreliability in Niger should be analysed:
— Do certain rainfall patterns exist in the Sahel, which return regularly?
— What method should be used to determine these rainfall patterns statistically?
Besides this specific subjects, the main question which was asked is the following:
— Is crop density increase a solution to improve and develop a sustainable agricultural system in the Sahel?

Besides these questions which should answer the main objective, a last question can be posed:
Until what amount can an increased crop density be solution for food shortage problems in the Sahel?

1.3 Methodology

To achieve the objective a model study was carried out. The choice to use a model is ambiguous. Firstly, field research would have taken to much time. To carry out a field research for an equivalent study, a period of three years is required. Secondly, the present study has not been carried out yet with the aid of a model. The SWAP model (Soil-Water-Atmosphere-Plant model), which is developed by SC-DLO could be tested, whether it is sufficiently sensitive and whether the right processes are incorporated to model extreme circumstances like in the Sahel. The latter reason was an additional objective of the present study.

Ultimately there was chosen not to use the SWAP model, but the TRIGGER model (TRIGGER is a combiantion of the SWAP and the WOFOST model). It is a combination of a one-dimensional unsaturated hydrological model and a mechanistic crop growth model. The TRIGGER model requires an extensive data set to simulate hydrological and plant growth processes. This data set was derived from two types of source: measurements and literature. All required data were measured during the Intensive Observation Period (IOP) of the HAPEX-Sahel project in Niger, 1992. A variety of literature was used to complete the variable set.

After the data set collection, modelling could start. During the modelling two steps were carried out:

- Fitting, containing a model calibration, a validation and a sensitivity analysis. During this phase the accuracy degree of the fitting was the major point of attention, because this would determine the accuracy of the simulation results. If the accuracy of the calibrations are low, the interpretation of the simulations should mainly be based on trends and less on a quantitative analysis. The results and interpretation of the calibration answered the additional objective. Depending on the calibration results more or less attention will be paid to the simulation.
- Simulation. During this phase the model was used for predictions. Rainfall scenarios and crop densities of millet were varied to establish the influence of both on biomass production and on the water use efficiency of millet. The results and interpretation of the simulations answered the main objective.

1.4 Structure of the report

In Chapter 1 the framework is explained for the study described in this report. Out of this background the objectives were formulated. In Chapter 2 a short overview will be given of the study area. This view is mainly focused on four subjects:

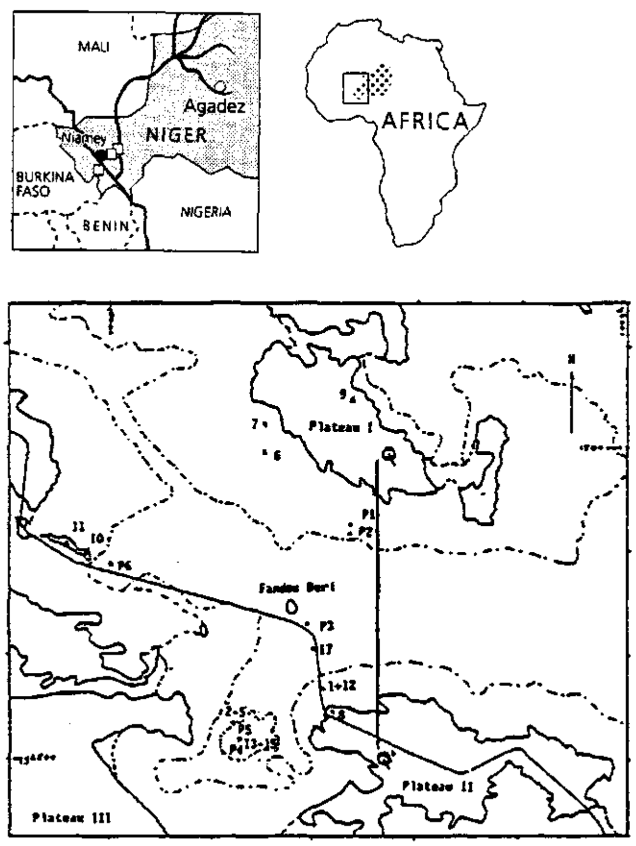
- Research place used for the millet measurements during the IOP of the HAPEX-Sahel project.
- Climate. Some general information is given about the specific climatological circumstances which consists in the Sahelian zone are described. The influence of the climatological circumstances on vegetation is also shortly mentioned.
- Growth of pearl millet. The importance of pearl millet for the food supply in West-Africa is described. Some attention is also paid to the botany and cropping of millet.
- Hydrology. The major soil types of the Sahelian zone are mentioned briefly. The sandy loam soil is some more extended mentioned, because this soil is the main soil for this study. This Chapter is a physical introduction used as justification for the data requirements description of Chapter 5.

Chapter 3 examines the model choice and gives a description of the most important processes described by the model. To firm the model choice, the concepts of the considered models, SWAP, WOFOST and TRIGGER, are described as well. The more detailed model description regards the processes of the TRIGGER model.

In Chapter 4 the methodology of the fitting, simulation and interpretation are discussed. A fitting consists of three parts: calibration, validation and sensitivity analysis. The function of every part is shortly described. The methodology of the simulations are focused on the preparation of the simulation input data, especially crop density and rainfall scenarios are described. In the section concerning the interpretation both interpretations are discussed of the calibration and simulation.

Chapter 5 gives a description of the input data set. Only the most important parts of the data set are discussed, because the data set is too extended for a full description. The description of the climatological data is focused on the choice of the set and the place of measurement of this set, which do not correspond with the measurement place of the other data. The data set description of the crop growth processes is focused on the data required for phenology, initial situation, CO_2 assimilation and partitioning. To describe the hydrological data set, special attention was paid on the retention and conductivity curves and sink term.

In Chapter 6, both the results and discussing concerning the results are described. The first section describes and discusses the results of the fitting. Most attention will be paid to the calibration of the hydrological processes, because these results largely influences the study. Less attention is paid to crop growth processes, validation and



Legend:

	Boundary plateau	————————
	Boundary or eroded plateau	— — — — —
	or middle terrace	—·—·—·—·—
	Boundary depression	························
	Location profile pits	P1, P2, P3
	Location samples	1,2,3
	Location cross section of Figure 10	Q ______ Q'

Fig. 1 Overview of the research place (Central-West super-site)

sensitivity analysis. The second section describes and discusses the results of the simulation. The influence of crop density and rainfall scenarios on millet production and on WUE is described. In this Chapter the discussion continues at the right pages, while the left pages are used to show the supporting Figures.

In Chapter 7, conclusions and recommendations, the results of the study are discussed and, in the recommendations, suggestions are given for further research. These suggestions concerning further research for the development of the agricultural system in the Sahel and the extension of the model. The terminology, list of abbreviations and symbols can be found after references and literature.

2 Area description

2.1 Research place

The research place is situated in Niger, approximately 60 km from the capital Niamey at the 2-3° East Longitude and 13-14° Northern Latitude square (see Fig. 1).Within this 100 km × 100 km region three super-sites were defined between 10 km × 10 km and 20 km × 20 km. Within these super-sites sub-sites in each of the three principal vegetation types were intensively monitored: open woodland (tiger bush), fallow savannah and millet (Kabat and Elbers, 1992). Data used during the present study were measured at the millet plot of the Central-West super-site. Fig. 1 shows the shape of the Central-West super-site. It is considered that most millet is grown between P3 and P6, located between the plateaus and valleys (see Figure 2).

The plateaus and the valleys have discontinuous hardened plinthite layer and hardened plinthite rock outcrops at the escarpments. The valley slopes consists of reddish brown loamy sand. In the valley bottom yellowish brown to completely bleached white sandy soils occur. At the one place of the valley bottom which is devoided of aeolian deposits, very compact, strongly weathered and leached kaolinitic sandy clay soils are found (Legger and Van der Aa, 1994).

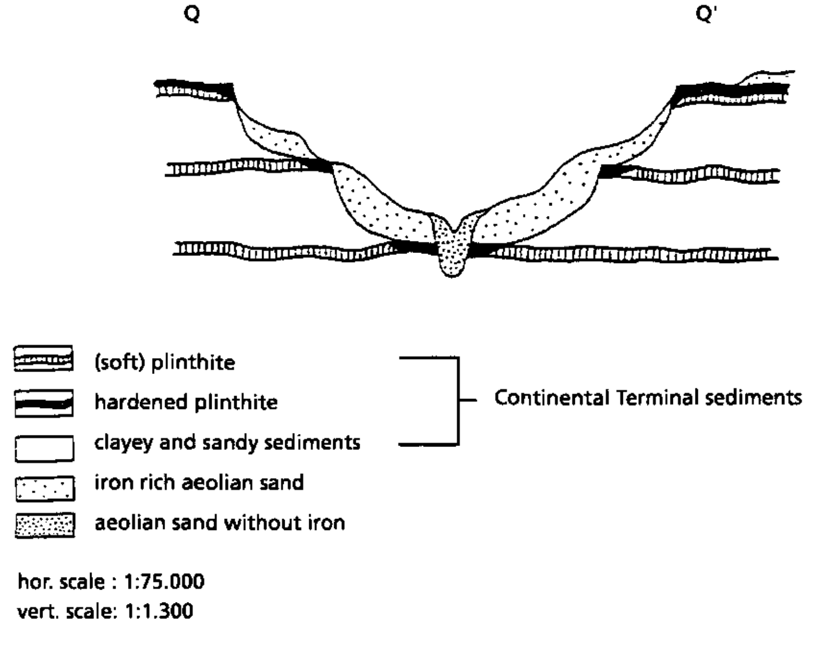


Fig. 2 The geological transverse alongtransect Q-Q' of Fig. 1

2.2 Climate

The Sahel comprises an area of some 3106 km^2 lying between the wet, humid, equatorial zone of Africa to the south, and the Sahara desert to the north. This result in a strong north-south rainfall gradient and a climate with a notoriously unreliable rainfall. The rainfall is now generally accepted to have been declining for the past two decades (Nicholson, 1989). The decline of rainfall in the Sahelian zone has several causes, which are, however been interrelated. The causes are focused on albedo, soil moisture and atmospheric dust (Goutorbe et al., 1994).

ITCZ
The north-south migration of the intertropical convergence zone (ITCZ) is related to the seasonal shifts in the relative positioning of the sun (see Fig. 4). During June and July a large part of West Africa is under the influence of moist southwesterly air masses, giving rise to the rainy season. The maximum northward extent of the ITCZ is reached in August, when the maximum rainfall occurs in the Sahel. The duration of the wet season decreases from about 5 months in the south of the Sahel (12°N) to 3 months in the north (18°N). The annual rainfall is closely related to the duration of the rainy season, varying from 800 mm in the south to 200 mm in the north, following a regular gradient of 1 mm/km (Goutorbe et al., 1994).

Climate influence on vegetation
The highly variable and unreliable rainfall governs the growth and distribution of the vegetation. Total rainfall is everywhere less than potential evaporation, which is in the order of 2000 mm/year. This results in a highly sparse vegetation cover with large areas of bare soil. The predominantly vegetation consists of large woody perennials (e.g. *Combretum micranthum*) and trees (e.g. *Combretum nigricans*).

2.3 Growth of pearl millet

Importance
In all the major African millet producing countries, the crop is of considerable importance in the agricultural system, and accounts for over one-third of total cereal output. It is grown primarily for human consumption. Pearl millet (*Pennisetum americanum*) is the main millet sort grown in Africa. It is traditionally grown as an intercrop with a legume such as cowpea or groundnut. In such situations economic returns are much higher than for a pure crop millet, though moving northwards, through the Sudan to the Sahel zone, the proportion of sole cropping increases. The bulk of African pearl millet is grown in the regions with annual rainfall ranging from 200-800 mm (Spencer and Sivakumar, 1987).

Botany & cropping
Pearl millet is an erect annual grass 0.5-5.0 m tall. The stem is solid and plant has a variable capacity to produce tillers. Most of them produce an inflorescence. There

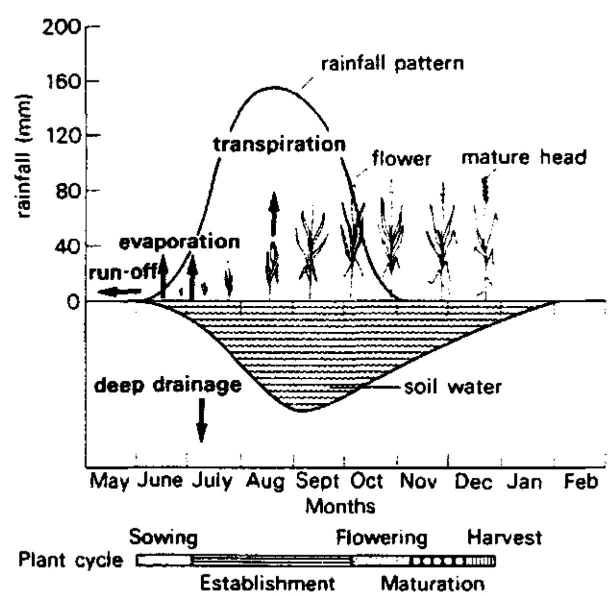


Fig. 3 Growth of a cereal crop in relation to moisture availibility (Gibbon and Pain 1985)

exist both day length dependent and day-length independent cultivars. The growth season ranges between 90 and 150 days of the different cultivars.

As a rainfed crop, pearl millet is sown with the first rains during the growth season. It is even often dry planted, before the rains arrive, in order to take advantage of the flush of nitrogen in the soil that occurs with the first rains (Gibbon and Pain, 1985). The crop is sown in April-May in the Southern zone and in June-July in the Northern zone. The choice of the appropriate variety in a given zone is didacted by the available length of the growing season. In Fig. 3 a review is shown of the relation of the crop cycle and the moisture availability.

Millet is sown in hills 45 cm x 45 cm to 100 cm x 100 cm apart. Spacings of 100 cm x 200 cm or even 200 cm x 200 cm are sometimes used. The number of seeds sown in each hill varies enormously. The stand is progressively thinned during weedings once the plants have reached 15 cm (Spencer and Sivakumar, 1987). Yields are highly variable and range from 250 to 3000 kg ha^{-1} (Gibbon and Pain, 1985).

2.4 Hydrology

The Sahel is a rather flat area with field slopes of 1-3%. The major part of the Sahel has no external drainage system and run-off therefore leads to a non-uniform infiltration pattern on slopes and depressions. In the north a limited number of (temporary) river beds feed (temporary) lakes. In the south some areas have a discharge towards major rivers such as the Senegal, Niger, Volta's and Chari (Hoogmoed and Stroosnijder, 1984).

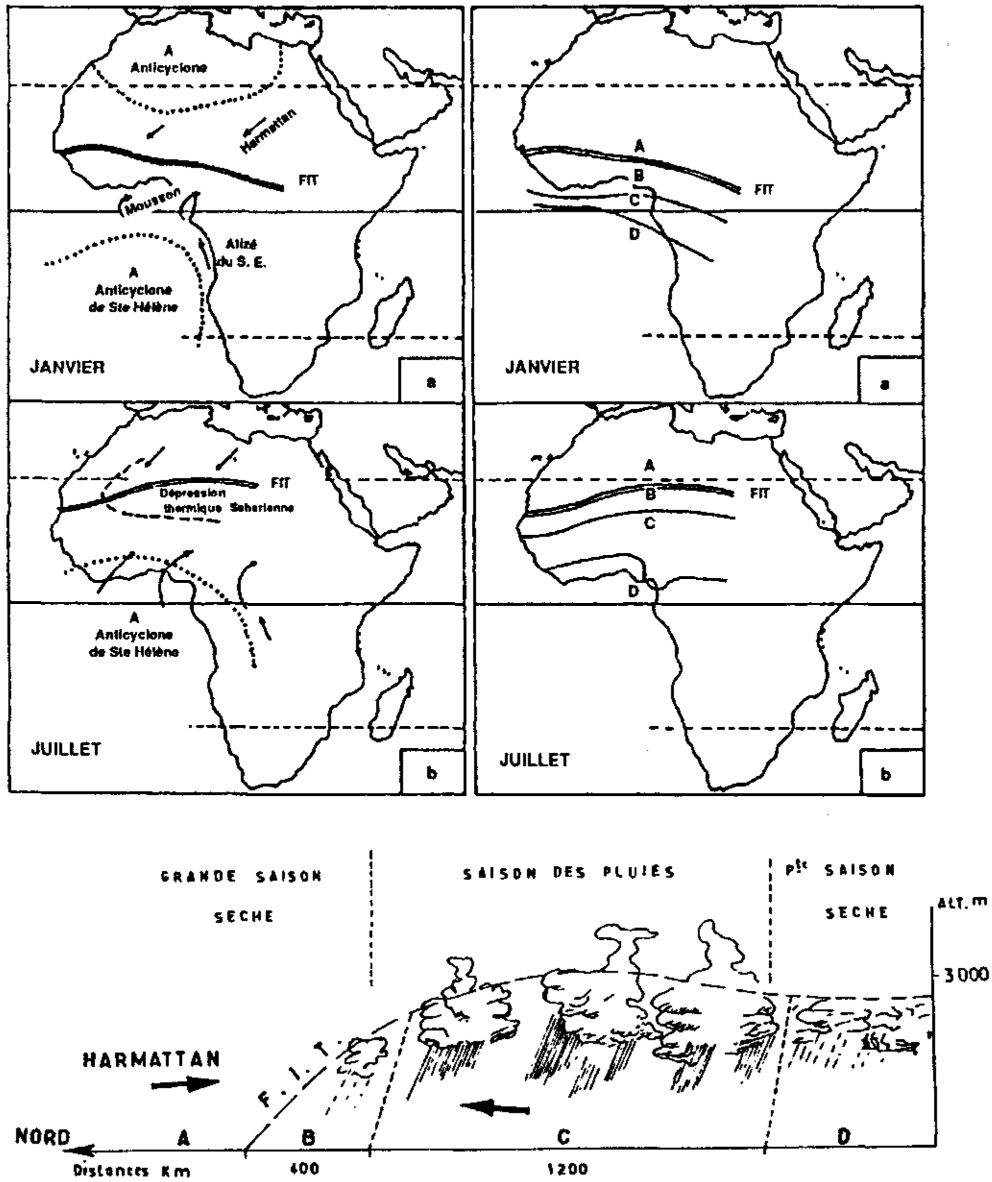


Fig. 4 ITCZ movement (Casenave and Valentine, 1989)

Three types of soil/landscape combinations can be distinguished:

— Deep sandy soil either in the form of pronounced dunes or eroded dune fields.
— Deep clay soils, recent of fossil river and lake deposits.
— Shallow or stony soils on laterite or sandstone (Hoogmoed and Stroosnijder, 1984). During this study the deep sandy soil play a dominantly role (see for its properties Table 1).

Major soil type

Most millet is grown at Arenosols (Legger and Van der Aa, 1994), this is a sandy loam, without specific soil horizonts. Though the individual sand grains have not seldom a coating of (brownish) clay and/or carbonates, gypsum or goethite. Due to the low coherence, Arenosols are sensitive for compaction, but this do not hinder tillage or rooting. However the soil is very permeable, a conductivity of 300 until 30,000 cm d^{-1} may occur (Driessen and Dudal, 1989).

Table 1 Profile description of a Arenosol

Horizont	Depth	Description
C	0-10	light brown (7.5YR 6/4) dry, strong brown (7.5YR 5/8) moist, single grain, loose, fine sand; very fine, common pores; gradual, smooth boundary; pH 5.7. Lighter coloured sandy surface has a pH of 6.1
2Ah	10-35	light brown (7.5YR 6/4) dry, strong brown (7.5YR 5/6) moist, single grain, loose, fine sand; pockets with light red (2.5YR 6/6) sand; very fine, common pores; pH 4.5; diffuse, smooth boundary to:
2B	35-480	light red (2.5YR 6/6) dry, yellowish red (5YR 5/8) single grain, loamy fine sand; pockets with reddish yellow (7.5YR 6/6) sand; pH 4.75
3B	480-520+	fine sandy loam; hard, firm, slightly sticky, non plastic consistence; common, medium, soft yellow (10YR 7/8), very pale brown (10YR 8/4) and red (2.5YR 4/8) iron nodules; pH 4.7 (Legger and Van der AA, 1994)

Soil moisture content

Soil moisture decreased rapidly after the end of the rainy season. It is also relevant to note that the soil moisture dynamics in the short term heavily influences the run-off and infiltration behaviour of the soils. The low water holding and high infiltration capacity of the soils lead to very short time scales of infiltration; often within 3 or 4 hours after the storm, water had drained through a substantial part of the profile.

3 Model description

3.1 Model choice and model concepts

A literature study led towards a model choice, which will be described in this paragraph. In order to justify the choice, the concepts of the models are described as well. In first instance it was suggested to use the SWAP model. When knowledge about plant growth processes extended, there was concluded that the SWAP model was not the best model to use for reasons explained below.

Concept SWAP

The SWAP model is based upon the classical theory and principles underlying soil water flow in the unsaturated zone, the Richard's equation. The model simulates transient vertical flow in a heterogeneous soil profile. It considers soil water movement in response to soil water pressure head gradients in accordance to the Darcy and continuity equations. Water extraction by roots is accounted for by a sink term. The approach requires specification of the soil water retention and hydraulic conductivity curves, crop characteristics, a lower boundary condition (e.g. a specified soil water pressure head or flux) and is driven by meteorological data (i.e. upper boundary conditions of precipitation and potential evapotranspiration) (see Fig. 5). The crop growth rate is defined as a hyperbolic function of transpiration with the maximum growth rate as the upper limit and water-use efficiency as the initial slope. When the crop is well supplied with nutrients, weather conditions (in particular solar radiation and temperature) determine the maximum growth rate (Kabat et al., 1992).

The plant growth part of the SWAP model is relative simple. Especially the options to change crop density and the possibility to see changes in spike production are limited. Only leaf area index (LAI) production can be changed, but not the sowing density. Total biomass production is given as output, while also spike production is required to tackle the research problem. So there was looked for another plant growth model. A choice was made to use the WOFOST model.

Concept WOFOST

WOFOST 6.0 is a mechanistic model that explains crop growth on the basis of the underlying processes, such as photosynthesis and respiration, and how these processes are influenced by environmental conditions. Dry matter accumulation of a crop can thus be calculated as a function of meteorological parameters such as irradiation, temperature, windspeed etc. and crop characteristics (Supit et al., 1994) (see Fig. 5).

For photosynthesis water is required. This water will be extracted out of the soil. The plant has an optimal range to extract soil moisture without sensing stress. A crop growth simulation model must therefore keep track of the soil moisture potential to determine when and to what degree a crop exposed water stress. This is commonly

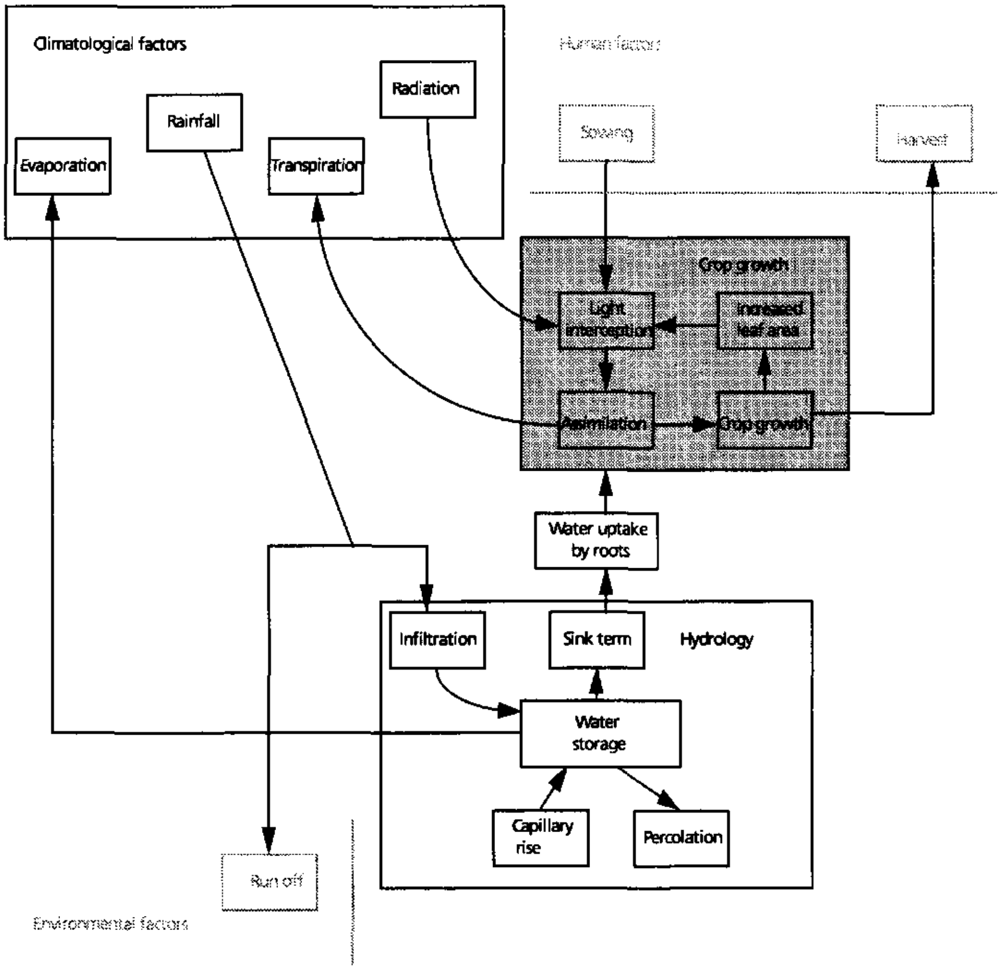


Fig. 5 Overview of the TRIGGER model in relation with external factors

done with the aid of a water balance equation, which compares for a given period of time, incoming water in the rooted soil with outgoing water and quantifies the difference between the two as a change in the amount of soil moisture stored (Supit et al., 1994).

As above mentioned WOFOST 6.0 is a rather expanded crop growth model, but simulates soil hydrology in a relative simple way. This model consumes a homogeneous soil profile and a fixed drying pattern of the profile, while these processes are variable in the SWAP model. This makes a combination of the two models most suitable for the simulation of different crop densities and several rainfall scenarios. Working with this combination became possible, because the SWAP and WOFOST model were linked into the TRIGGER model. This simplified the choice for a model, because in the TRIGGER model strong parts of both models were taken to carry out the simulations.

Concept TRIGGER

TRIGGER is a combination of SWAP and WOFOST whereby different complexities of simulations can be carried out. Depending on the complexity of the research problem, a choice can be made between simple or detailed soil and plant growth processes. In Table 2 an overview is given of the model used for different complexities.

Table 2 Use of SWAP and WOFOST for different situations

	Simple model	Detailed model
plant growth processes	SWAP	WOFOST
hydrological processes	WOFOST	SWAP

The SWAP and WOFOST model have recently been linked (December 1994) into the TRIGGER model, so it has not been tested sufficiently yet. Though both parts of the TRIGGER model, SWAP and WOFOST have already shown their power.

To solve the research problem the SWAP concept will be used to calculate soilmoisture content, while the WOFOST concept will be used to calculate biomass production, this option gives the most detailed information about plant growth and the behaviour of the soil. This detailed information is required, because of the extreme circumstances, for plant and soil, in the Sahel.

In Table 3 a summary is given of the reasons to choose the TRIGGER model.

Table 3 Summary of reasons to use the TRIGGER model

— WOFOST analyses variability and trends in crop yields, such as growth determination, sowing strategies, while other crop growth models are empirically based. In general the application of these models are limited until one area

— WOFOST is an international validated programme used for yield simulation fit in the Crop Growth Monitoring System (CGMs) project, developed for the European Union

— SWAP and WOFOST have been developed within the Winand Staring Centre, so all the SC-DLO experts were easy to consult during the study

— Generally the SWAP model performed better as other unsaturated flow models such as LEACHW, SWASIM, especially over limited ranges of space and time

— WOFOST is strong in simulating plant growth processes, while SWAP is works well for the simulating of hydrological processes. In the TRIGGER model both models are linked

— SWAP model should be tested in order to show whether the model is sufficiently sensitive to simulate Sahelian circumstances

3.2 Setting the model

In this section the most important theories are described per process. There are three overall processes which are important for this simulation: climatological processes, hydrological processes and plant growth processes (see Fig. 5).

3.2.1 Climatological processes

Potential evaporation and transpiration are influenced by climatological factors, such as temperature, radiation, wind speed, air humidity and rainfall. In the TRIGGER model the Penman-Monteith approach (Smith, 1991) is used to calculate potential evapotranspiration. This approach requires daily measurements data of solar radiation, minimum temperature, maximum temperature, air humidity, rainfall and windspeed (SC-DLO, 1994) (see for equation Annex A).

The Penman-Monteith formula is an update of the Penman formula. The Penman-Monteith formula calculates evapotranspiration more accurately in comparison with the Penman formula[1].

3.2.2 Crop growth processes

The development of a crop depends on a number of processes. The major processes are the rate of phenological development, CO_2 assimilation, transpiration, respiration, partitioning of assimilates to the various organs and dry matter formation (see Fig. 6) (Hijmans et al., 1994). Most of the processes are driven by weather, or more specific radiation, temperature and rainfall. For this study crop density was an important factor. So some additional attention will be paid to this factor.

Phenological development

Phenological development, or plant growth, can be controlled by day length or temperature. In the model before anthesis, both factors, temperature and day length can be active. After anthesis only temperature influence is possible (Supit et al., 1994).

CO_2 assimilation

The CO_2 assimilation is the process where CO_2 from the air is converted into carbohydrates $(CH_2O)_n$ according to the overall reaction:

$$CO_2 + H_2O + solar\ energy \rightarrow CH_2O + O_2 \quad (1)$$

The rate of gross CO_2 assimilation is dependent on the radiation energy absorbed by the canopy, which is a function of the absorbed radiation and the photosynthesis-light response of individual leaves. This response is dependent on temperature, leaf age and plant type, C3 or C4 plant (Hijmans et al., 1994).

Part of the carbon fixed by the assimilation process is respired to provide energy for biological functioning of the organism (maintenance respiration). The remaining

[1]The Penman-Monteith formula has a regression coefficient of 1.01 for regression through the origin of lysimeter versus equation estimates, while the Penman formula has a regression coefficient of 1.04. Both regression calculations are specific for the arid zone (Smith, 1991).

carbohydrates are converted into structural plant dry matter. In this conversion some of the weight is lost as growth respiration (see Fig. 6).

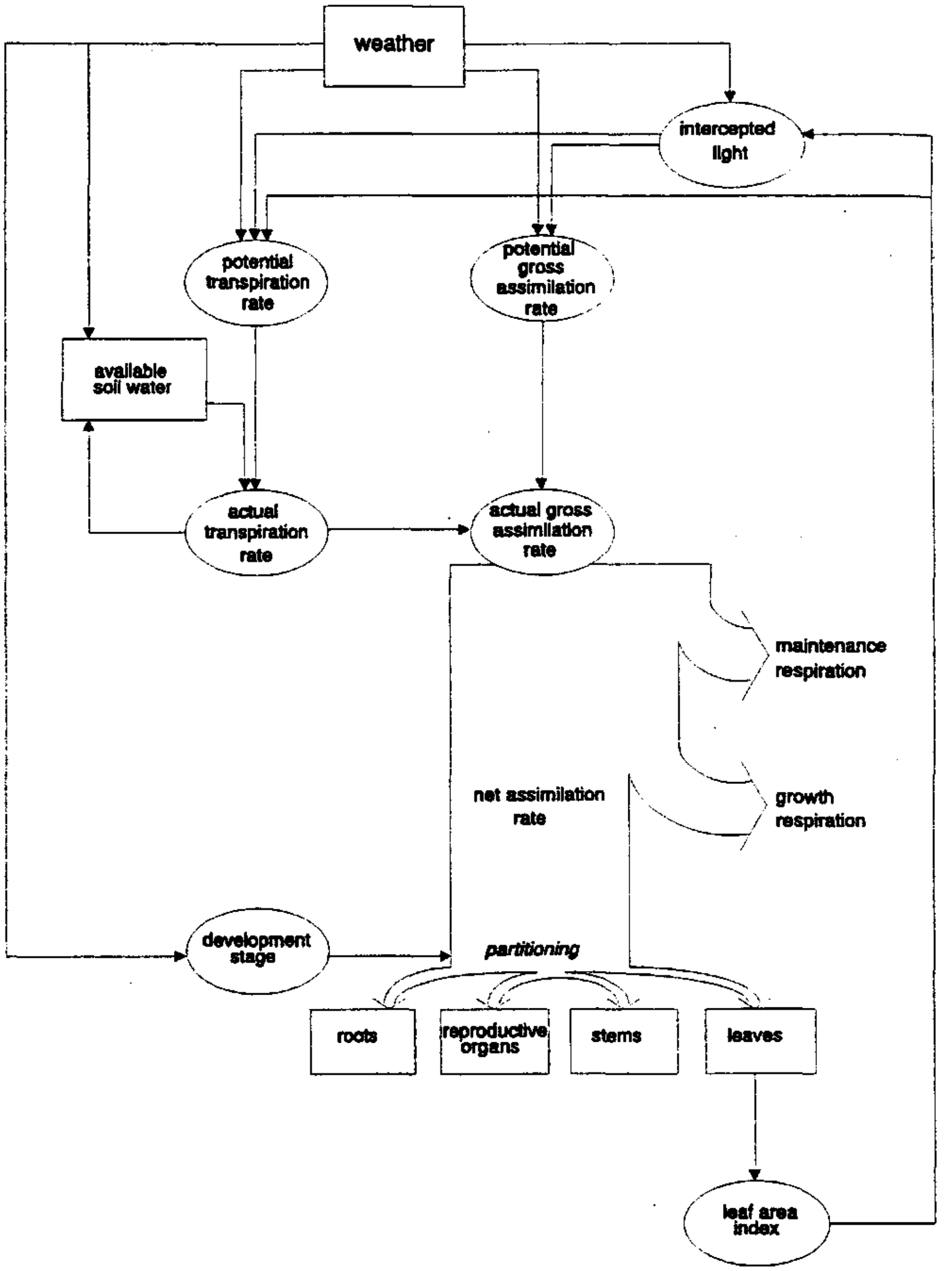


Fig. 6 Simplified general structure of a dynamic explanatory crop growth model (Kropff and Van Laar, 1993)

Partitioning

The produced dry matter is partitioned amongst the various plant organs such as roots, leaves, stems and storage organs, using partioning factors that are a function of the phenological development stage of the crop (Supit et al., 1994).

Crop density

Crop density is mainly determined by the used amount of seed. However this is not a variable input. To vary crop densities during the simulation, derived input variables were changed. These are initial dry weight and leaf area index at emergence (LAIEM). Initial dry weight depends on both the plant weight at emergence and the number of plants per hectare. LAIEM depends on the initial dry weight, the amount of dry matter partioned to the leaves at emergence and the specific leaf area (personal command Van Diepen).

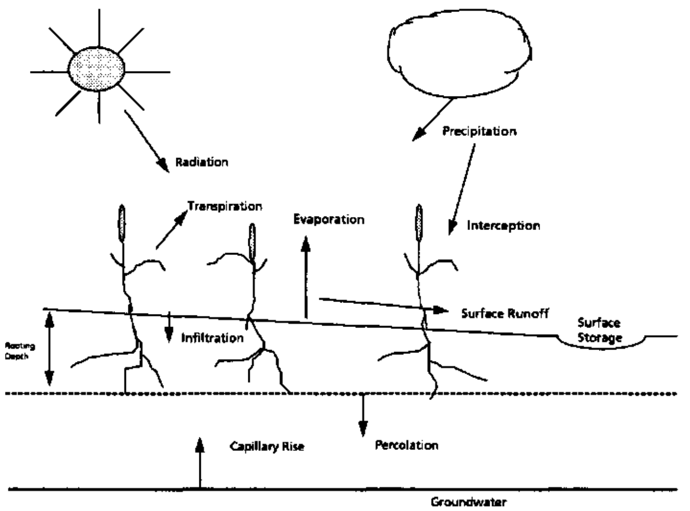


Fig. 7 Schematic representation of water storage and flow in a plant-atmosphere system (Van Keulen and Wolff, 1986)

3.2.3 Hydrological processes

The major hydrological processes can be derived out of the water balance (see Fig. 7). The water balance should be solved to calculate the soil moisture content. Soil moisture is required to continue evaporation and transpiration and so the dry matter production. The actual water storage change can be established according to:

$$\Delta W = I + Q - (E_a + T_a) \tag{2}$$

where:

$$I = P + SS - (SR + IC) \tag{3}$$

and:

$$Q = CR - Perc \tag{4}$$

where:

ΔW	: water storage change over a given time period	cm d^{-1}
I	: infiltration	cm d^{-1}
Q	: net upward flow through the bottom of the profile	cm d^{-1}
T_a	: actual transpiration rate of a crop	cm d^{-1}
P	: precipitation rate	cm d^{-1}
E_a	: actual evaporation rate of a soil	cm d^{-1}
SS	: surface storage	cm d^{-1}
SR	: rate of surface run-off	cm d^{-1}
IC	: interception	cm d^{-1}
CR	: rate of capillary rise[2]	cm d^{-1}
$Perc$	: percolation rate	cm d^{-1}

Table 4 is a reproduction of the equations (2) to (4) and shows that I, Q and E_a are partly or totally influenced by hydrological processes. These parts of the water balance are described in this section. The actual transpiration (T_a) depends, via the uptake of water by the roots, on the sink term and is described in this form in this section as well.

Table 4 The influence of different processes on different parts of the waterbalance

	Climatological processes	Hydrological processes	Crop growth processes
I		*	
Q		*	
E_a	*	*	
T_a	*		*

Soil water flow

The soil water flow depends on the pores fraction, soil conductivity and the storage capacity. These factors are determined by soil properties. In general soil properties are described by a retention and conductivity curve. The reduction of the soil moisture content, caused by transpiration, is described by a sink term.

In the SWAP model the basic equation for soil water transport is the Richard's equation, which describes the liquid phase of the soil water flow. This equation has the advantage of being applicable for saturated and unsaturated flow, and in layered soils, where the pressure head remains continuous at the boundaries between the layers (Feddes et al., 1978).

[2]Not applied, freely draining profile

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)} \times \frac{\partial}{\partial z} (k(h) \, (\frac{\partial h}{\partial z}+1)) \, \frac{S(h,z)}{C(h)} \qquad (5)$$

where:

h	: pressure head	kPa
t	: time	d
$C(h)=d\Theta/dh$	: differential soil moisture capacity	cm^{-1}
$k(h)$	: hydraulic conductivity-pressure head relationship	$cm\ d^{-1}$
$S(h,z)$	: sink term for water uptake by roots	$cm\ d^{-1}$
z	: depth below the soil surface	cm

This equation, which is solved for the unsaturated zone in this study, will be explained in steps. The $C(h)$ term will be described under catchword retention curve even as $k(h)$. $S(h,z)$ will be described under the catchword sink term. Factor z implies that the Richards' equation is solved per compartment. A maximum of forty compartments and four soil types can be used in the SWAP model. The different terms of the Richard's equation are solved per compartment for each time step (the time step of a day is divided into discrete time steps).

Retention & conductivity curve

As above mentioned, the retention and conductivity curve, better known as pF curve and K-h relation are used to describe the soil properties. The form of both curves symbolizes the infiltration rate and water retention capability. To calculate the pF curve and K-h relation the Van Genuchten formulas were used (see Annex A). For the calculation of the retention and conductivity curve the model requires: Θ_r, Θ_s, α, n, K_s and l. The influences of the different variables on both curves are shown in Annex B.

Sink term

The concept of a sink term to describe the actual water uptake by roots has been introduced by Feddes et al. (1978) and is subsequently used for crops growing in mainly salt free environments and moderate climates (Bastiaanssen, 1994). The sink term requires critical pressure heads, h_1 to h_4 to be specified for each crop in order to prescribe the actual transpiration behaviour (Fig. 8). The critical pressure heads can be further elaborated as:

h_1	: pressure head at near-saturation below which oxygen persists;
h_2	: pressure head at near-saturation at which air enters the soil without any flow resistance;
h_3^l	: pressure head at which stomata starts to close since the amount of easily available moisture is consumed; the evaporative demand of the atmosphere is relative low(1 mm/d);
h_3^h	: pressure head at which stomata starts to close in order to prevent the crop from cell moisture depletion; the evaporative demand of the atmosphere is extremely high (10 mm/d);
h_4	: pressure head at which stomata are completely closed and transpiration is entirely ruled out (wilting point, 0 mm/d) (Singh et al., in prep.).

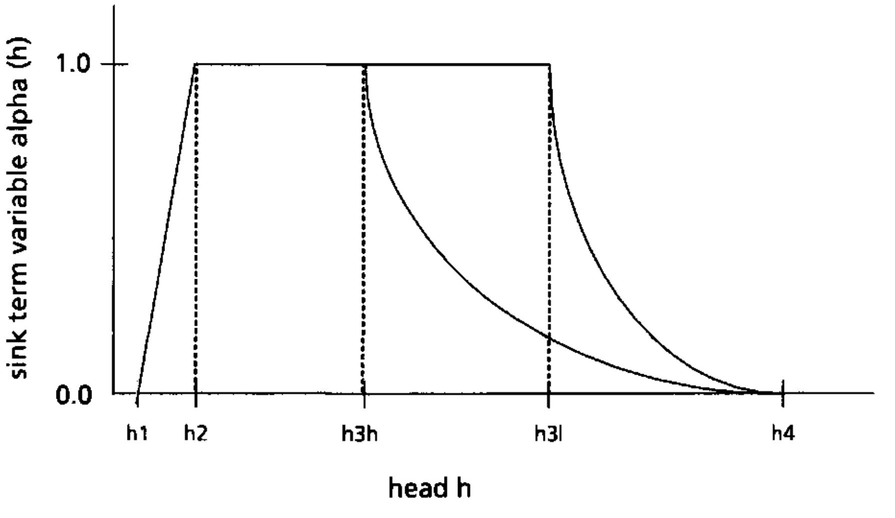


Fig. 8 General shape of the sink term for transpiration responds to available soil moisture. The sink term is a function of the total soil pressure head i.e. $\alpha(h)$ relationship (Bastiaanssen, 1994)

4 Applying the model

4.1 Calibration

The calibration of a model is a process of trial and error. Measured data and calculated model output should fit, whereby the maximum ranges of variation of the variables should be taken into account. The following three steps should be taken during the calibration process:

Fitting
Import measured data into the model and compare the calculated output with the measured data set. If the measured data and calculated output do not sufficiently correspond there are two possibilities:
— input data has been imported into a wrong unit;
— variables values are not right.
In order to check the above, after every run a decision should be taken whether:
— to rerun with other data within the fixed range;
— to adapt the range.
If there is a sufficient correspondence between the measured data and calculated output, a start can be made with the validation.

The accuracy of the model simulation depends on the accuracy of the calibration results. If the results of the calibration are weak, simulation results should be analysed with reservations. This meant only trends out of the simulation results can be discussed, while a quantitative analysis should be left out of the discussion.

Validation
After the model calibration, a verification should take place with another measured data set. This data set should, until a certain extent, correspond to the set used for the calibration. Verification of a model shows the reliability of the model.

Sensitivity analysis
A sensitivity analysis is carried out, in order to analyse the effects of value changes of variables on value changes of the output. A model is less sensitive if large ranges are possible for a variable without changes in the result. This makes a model less reliable. In general a sensitivity analysis for complex models, like the TRIGGER model, is carried out during special studies. These studies show which parameters are most sensitive and thus show the sensitivity and reliability of the model. The results of the sensitivity analysis of Clemente et al. (1993) can be found in Chapter 6.

4.2 Simulation

Preparation of an input data set is required, before a simulation can be carried out. For this study several rainfall scenarios and several plant densities were required.

Rainfall scenarios

In the Sahel rainfall patterns and amounts are very unreliable. A method should be used which can cover different patterns and amounts of rainfall, because both can influence crop growth. To determine different rainfall scenarios, rainfall variability (RV) as well as a variation of the duration of the rain season were chosen. The rainfall season was divided into three time periods: the start of the rainy season, mid rainy season and late rainy season. It was assumed that the mid rainy season was ensured with rainfall. The start and end of the rain season were again divided in an early, mid, late season. The rainfall period were linked with RV. Every time period would be classified: dry (90% RV), wet (10%) or average (50%) (see Table 5).

Table 5 Rainfall scenarios

Start rain season *(April-June)*				Mid season *(July-Augustus)*			End rain season *(September-October)*			
Rainfall regime		Period	RV	Rainfall regime	Period	RV	Rainfall regime		Period	RV
early	dry	April	90%	dry	-	90%	early	dry	September	90%
early	average	April	50%	average	-	50%	early	average	September	50%
early	wet	April	10%	wet	-	10%	early	wet	September	10%
mid	dry	May	90%				mid	dry	Sept/Oct	90%
mid	average	May	50%				mid	average	Sept/Oct	50%
mid	wet	May	10%				mid	wet	Sept/Oct	10%
late	dry	June	90%				late	dry	October	90%
late	average	June	50%				late	average	October	50%
late	wet	June	10%				late	wet	October	10%

All possible combinations of Table 5 were worked out into rainfall input files. Links between 90% RV and 10% RV were smoothed via 25% RV, 50% RV and 75% RV. Firstly simulations were carried out with minimum, maximum and average rainfall. Whereafter simulations were carried out with intermediate values, whereby relationships between the three parts of the rainy season and RV were taken into account.

RV data was used from Sivakumar et al. (1987), whereby Ouahigouya was used as reference. This place is situated at a latitude of 13°35′ in Burkina Faso. The mean annual rainfall is 649 mm and ranges between 413 and 971 mm. More than 90% of the rain falls between April and October, whereby July and August are the wettest months. The rainfall data have been analysed from 60 years of data collection.

Table 6 Rainfall quantity per decade and linked to the number of events

Rainfall	Number of events per decade
< 5	1
5-20	2
20-40	3
40-80	4

In Sivakumar rainfall data are described per decade. For this study the rainfall data were divided into one to five rainy events per decade (see Table 6), depending on the amount of rainfall. In general one or two storms contributed to 70-80% at the total quantity of rainfall per decade. Hence, it can be concluded from rainfall analysis that there are one or two major storms and some smaller storms per decade (see Annex C).

According to Lebel et al. (in prep.) the main source of rainfall deficit is more due to a smaller number of rainy events than to a variation of the efficiency of these events. This was overcome by using a fixed number of events for fixed ranges of rainfall amounts.

Plant density
Minimum millet density is around 50 cm x 50 cm patterns (personal remarks Van Diepen), because millet will not continue spike production with a higher plant density. So for the simulation 50 cm x 50 cm patterns were used as minimal crop density, while the maximum millet density used, were 150 cm x 150 cm patterns. At lower densities, millet will no longer grow like a crop, but like individual plants. Because crop density is not an input variable, crop densities were converted to the derived input variables TDWI and LAIEM. For values and the calculation method see Annex D.

4.3 Interpretation

4.3.1 Calibration

The acceptable ranges of deviation for the calibration was determined on approximately 10%. Within this range there can be concluded that the calibration was successful. This percentage was more a guideline than a fixed value. Beside, this, the form of both the measured and calibrated curve should have the same development. During this calibration soil moisture content was principally used to calibrate the hydrological processes, while dry matter increase was used to calibrate the crop growth processes. The curves of the calibrated results and the measured data were compared with the aid of the spreadsheet programme Quattro Pro for Windows (QPW).

Rainfall was taken into account during the comparison of the hydrological processes so that the reaction from both types of curves on rainfall could be considered. For the comparisons of the crop growth processes especially the potential productions were used, because these show the crop growth calibrated by the model without any limitations from external factors.

4.3.2 Simulation

The interpretation of the simulation results consisted of two steps:
— processing the simulation results;
— draw to conclusions.

Processing
The processing was carried out with the aid of QPW. Required results, concerning total crop production (CWDM), total spike production (CWSO), actual evaporation and actual transpiration were taken from the output files of the TRIGGER model (see for an example of the output files Annex E). These results were reorganised in the QPW programme. The rainfall amount and crop density were taken as basis, because these were the main subjects of the present study. After the reorganisation the actual evapotranspiration and the WUE could be calculated. The WUE was calculated with the aid of the following equation:

$$WUE = \frac{ET_a}{CWDM} \tag{6}$$

or:

$$WUE = \frac{T_a}{CWDM} \tag{7}$$

where:

WUE	: water use efficiency	kg ha^{-1} m^{-1}
Et_a	: actual evapotranspiration[3]	cm
T_a	: actual transpiration[7]	cm
CWDM	: cumulative actual weight of aboveground biomass	kg ha^{-1}

It is a calculation method to compare the performance of crops in different dry land situations or soil moisture regimes.

Concluding
To got a clear idea about relationships the reorganised results are converted into graphs. The graphs used in order to find relations are showed in Table 7.

The upper graph shown in Table 7 indicated: the influence of crop density and rainfall quantity on millet production; the behaviour of evaporation and transpiration with an increasing rainfall quantity; and the influence of crop production on evaporation and transpiration. The second graph indicated the relation between dry

[3]There is no consensus whether Et_a or T_a should be used

matter production and WUE and the relation between dry matter production and transpiration. The third graph indicated the relation between rainfall quantity and WUE.

Table 7 Overview of the graphs used to draw conlusions

X-axis	First Y-axis	Second Y-axis	Commands
rainfall	dry matter production	evaporation and transpiration	per crop density only for CWSO
dry matter production	WUE	transpiration	for ET_a and T_a
rainfall	WUE		per crop density, for both WUE for ET_a and T_a

5 Data requirements

5.1 Climatological data

During the IOP several climatological factors were measured. The model requires daily climatological data of minimum temperature (°C), maximum temperature (°C), solar radiation (J m^{-2}), mean air humidity (kPa), mean windspeed (m s^{-1}), rainfall (mm) and, if available, reference evapotranspiration (mm). At the Central-West super-site, where the used millet pilot is situated, not all required data were measured for the whole of 1992. Only rainfall data measured at the Central-West super-site could be used. Other climatological data were taken of the Central-East super-site.

5.2 Crop growth data

Especially phenology, initial growth situation, specific pod and stem area, assimilation and partitioning influence crop growth. These processes and variables will thus be described below. Variables which hardly influences crop growth will not be mentioned.

Phenology
Growth speed is determined by phenology. It can be controlled by day-length or temperature (see Chapter 3). During this study a choice was made to make the plant growth temperature influenced, because most millet varieties are not dependent on day-length.

By changing the temperature sum for and after anthesis (TSUMEA an TSUMAM) the amount of growth days can be influenced. TSUMEA and TSUMAM are dependent on the number of growth days until anthesis or until maturity and the optimum growth temperature. The latter is described in the Table for daily increase in temperature sum (DTSMTB). DTSMTB is plant dependent and ranges from a threshold temperature via an optimum to a maximum temperature for growth. For millet the minimum temperature for growth is approximately 10 °C, the optimum 28 °C and the maximum 45 °C. The more the air temperature approaches the optimum temperature the shorter the growth cycle. Crop development is restricted if the air temperature is far below or above the optimum temperature.

It was hard to quantify the optimum growth rate and temperature sums, because these are strongly dependent on millet varieties. However, several varieties are mixed within a field in order to reduce risks.

Initial situation
Crop growth is strongly determined by initial situation. To determine the initial situation, data about initial crop dry weight (TDWI) and LAI at emergence (LAIEM) are required. Accurate measurement methods of TDWI an LAIEM are difficult to determine, because of an irregular emergence pattern and low initial values. For this reason, instead of using initial IOP data, TDWI and LAIEM were estimated on the basis of the expected seeding density.

CO_2 assimilation
Millet is a C4 plant, which implies that it has another photosynthetic pathway than C3 plants. This is expressed in a higher CO_2 assimilation in comparison with C3 plants under the same circumstances. In general C4 plants have an extinction coefficient of 0.56 (KDF), while the light use efficiency of a single leaf is around 0.45 kg ha^{-1} h^{-1} J^{-1} m^{-2} s^{-1} (Van Heemst, 1988) (EFF) and the CO_2 assimilation rate ranges between 30-90 kg ha^{-1} h^{-1} (Van Keulen et al., 1986) (AMAXTB). For AMAXTB Van Heemst (1988) gave a value of 85 kg ha^{-1} h^{-1} over the whole growth season. In general a maximum value of 70 kg ha^{-1} h^{-1} is taken for C4 plants (personal remarks Van Diepen), while towards the end of the growth season the CO_2 assimilation slightly decreases. The assimilation value influences photosynthesis and so biomass production. The biomass production will increase with an increase of the maximum CO_2 assimilation value.

Partitioning
The use of factors taken from the dry matter accumulation measured during the IOP was considered, but ultimately Van Heemst (1988) values were used. The partitioning factors extracted from the measurements show a pattern which noticeably deviated from the Van Heemst (1988) values. In first instance too much dry matter was partioned to the roots, while the dry matter increase of the parts of the plants above the ground remained behind. At the end of the growth season the leave and stem growth continues too long and for this reason only a small part was partioned to the storage organs. Consequently the spike production could hardly be developed (personal remarks Van Diepen).

5.3 Hydrological data

The Van Genuchten variables should have the properties of a permeable sandy loam. This can be translated into a soil with a high conductivity and a quick dry dout. The top of the soil should be a layer where infiltration decreases quickly from 100 mm h^{-1} to 30 mm h^{-1} during a rainstorm, and which is sensitive to crust formation. Hence, the soil can be very open after tillage and will close rapidly after some rainstorms.

Because the model cannot compose an irregular K-h relation, a mix of the properties named above were used to describe the top layer.

The measurements of the soil moisture content were carried out at twelve depths. The total depth of the profile is 170 cm, while the thickness of the measured compartments ranges between 5 and 20 cm. For the calibration was chosen to use

Table 8 Ranges of Van Genuchten variables used for the sensitivity analysis

Θ_r	0.01	$cm^3 cm^{-3}$
Θ_s	0.35	$cm^3 cm^{-3}$
α	0.03-0.015	$m s^{-1}$
K	10-240	$cm d^{-1}$
l	3-2	-
n	3.5-2	-

smaller compartments than measured. The thickness of the used compartments ranges between 1 and 10 cm. This choice was made, because smaller compartments give a better soil moisture division over the depth over the profile. As mentioned in Chapter 3, soil moisture content is calculated per compartment. With an increase of compartments soil moisture jumps are less expected.

Retention and conductivity curve

Soil moisture content is very sensitive for changes in the Van Genuchten parameters *n*, *k* and *l*. The factor α determines the shape of the wet side of pF curve and is less important for this study. The measured soil moisture content ranges between 0.038 $cm^3 cm^{-3}$ and 0.135 $cm^3 cm^{-3}$, while the saturated soil moisture content equals 0.35 $cm^3 cm^{-3}$. A sensitivity analysis was carried out for the Van Genuchten variables. Every variable was changed, within a certain range (see Table 8), but none of the tests gave a satisfying result (see Chapter 6). During this analysis, there was considered that the soil consists of a single layer[4]. Subsequently several tests were taken with a double soil layer, to improve the calibration results. The soil consisted of a top layer of 25 cm which hardly contains any moisture and is strongly influenced by climatological changes and a deeper layer with a thickness of 150 cm, which has a general soil moisture content of 0.10 $cm^3 cm^{-3}$ (see above)[5].

Sink term

To calculate the sink term, h_1 to h_4 should be given. All pressure heads are soil dependent, while h_3 and h_4 are also crop dependent. In general h_1 equals pF 1, h_2 equals pF 1.7, h_4 is 4.2: wilting point and h_3 are determined by the equation:

$$\Theta_{crit} = \Theta_{pF2.3} - p(\Theta_{pF2.3} - \Theta_{pF4.2}) \qquad (8)$$

[4]As described in Chapter 2 the common soil in the millet area is the Arenosol without any specific soil horizont. For this reason the calibration was in first instance carried out with a single soil layer. When this did not gave satisfying results it was considered to use a top layer which is very sensitive for crust formation and dehydration. These phenomena are rather common in the Sahel. This double soil layer was an improvement.

[5]In every soil layer the pF curve and K-h relation can be changed, so that conductivity can not take place totally independently as may be suggested. Affection of a layer will always influence the soil moisture content in the other layer.

where:

Θ_{crit}	: critical soil moisture content	$cm^3\ cm^{-3}$
$\Theta_{pF2.3}$	: soil moisture content at pF = 2.3	$cm^3\ cm^{-3}$
$\Theta_{pF4.2}$	: soil moisture content at pF = 4.2	$cm^3\ cm^{-3}$
p	: fraction of available soil water[6]	-

[6]The crop factor is 0.55 for sorghum (Bastiaanssen, 1994). The crop factor for sorghum was used, because the crop factor for millet is not determined and millet and sorghum have a similar growth pattern.

6 Results and discussion

6.1 Calibration

During the calibration the calculated soil moisture content could not be fitted satisfactorily with the soil moisture content data. In the rainy season the soil moisture content was overestimated by the model, while at the end of the rainy season the soil moisture content was underestimated.

The following comments can be made with regard to the calibration results:

— Due to crust formation a large part of the rainfall runs off towards the valley (see Fig. 2) and so will not infiltrate on the test field. The TRIGGER model does not simulate this until the required detail.

— Processes such as evapotranspiration in the vapour phase, which play a role and cannot be described within the TRIGGER model.

6.1.1 Results of hydrological calibration

In first instance the hydrological calibration was carried out with a homogeneous soil profile, a single layer soil. When this did not give satisfying results the hydrological calibration was carried out with a double layer soil, a top soil of 25 cm and a deeper layer of 150 cm (see for more information Chapter 5).

Figures 9, 12 and 13 show the results of the soil moisture calibration. Three of the best single layer soil calibrations, respectively two of the best double layer soil calibrations are compared with soil moisture content data. In Table 9 and Annex H the Van Genuchten variables and curves shown are belonging to the best calibrations for the single soil layer and the best for the double soil layers.

Both types of calibration results, the single and double soil layer, give a similar view of the soil moisture development over the calibration period. In the rainy season(August-September) the measurements and calibration results had rather similar line patterns, though the calculated lines had derivations ranging from 16% (Try34) to 53% (Top106).The measured points and calibration results, react strongly to rainfall. Rainfall resulted in an immediate increase in soil moisture. Though on some days measured soil moisture decreased, while it rained as well. If this consists it was considered that soil moisture was measured before rainfall, for instance in the morning. However, the calibration results do react at rainfall, because the model shows the soil moisture content at the end of the day.

At the end of the rainy season the measured points bore no resemblance to the model results. While the measured data show a slow decrease of moisture, the model results show a fast dehydration. The soil moisture even approached zero.

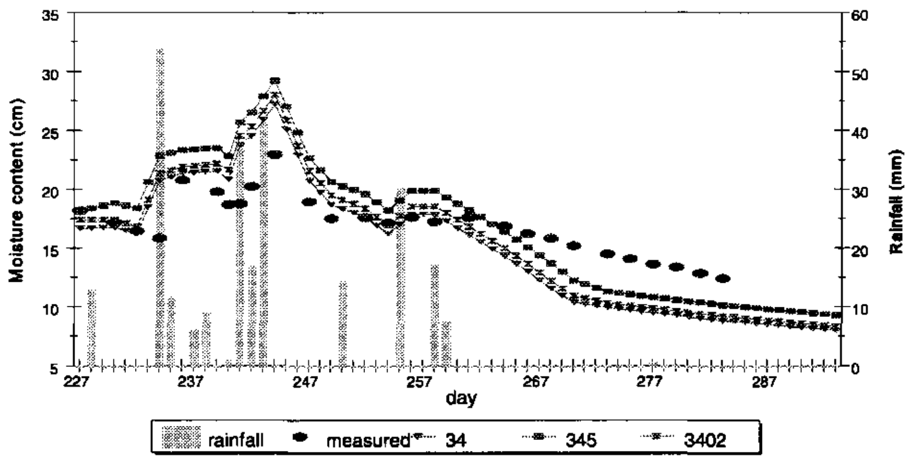


Fig. 9 Comparison of measured and calibrated data applying to the total moisture content (cm) in time. For the calibration a one layer soil was used

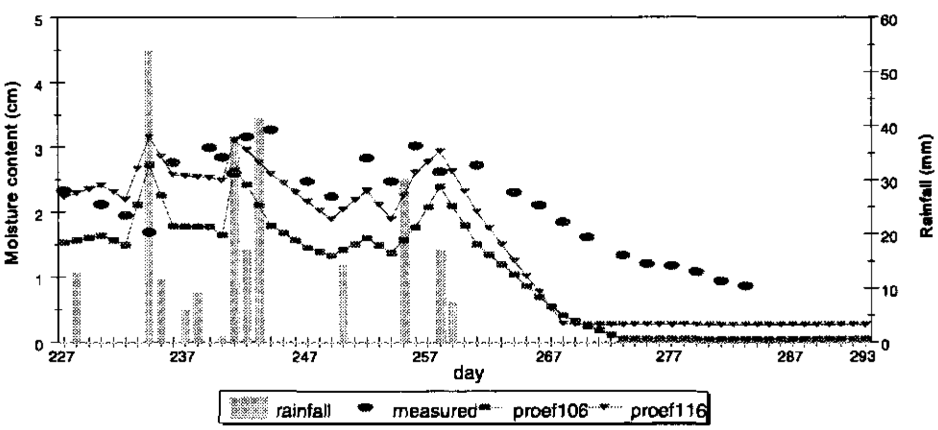


Fig. 10 Comparison of measured and calibrated data, applied to moisture content (cm) in time. For the calibration a two layer soil was used, this concerns the top layer from 0-25 cm

Calibration of single layer soil

At the start of the calibration (mid August) the measured data showed a quite erratic course, while the calibration results had a smoother course. At the end of the rainy season (mid September) the calibration results reacted adequately to the last rainfall, while the measured points hardly show any reaction. After the last rainfall the calibration results show a quick dehydration of 6.4 mm d^{-1} in the period from 14 September to 27 September, whereafter dehydration dropped to a moisture loss of 0.9 mm d^{-1}. The soil moisture loss of the soil moisture data was 3.1 mm d^{-1} over the total dehydration period.

Table 9 Van Genuchten variables used for the best calibration results

Calibration	Θ_r	Θ_s	K_s	α	l	n
34	0.01	0.35	240	0.03	2	3
345	0.01	0.35	240	0.03	2.5	3
3402	0.01	0.35	200	0.03	2	3
top10	0.0001	0.1	240	0.03	11	4.5
top11	0.0001	0.1	240	0.005	11	1.5
deep6	0.01	0.35	100	0.03	4	3.5

Calibration of double layers soil

In general the top layer reacted stronger to rainfall than the deeper layer, but on the other hand the deeper layer did not dry out as quick as the top layer. The calculated moisture of top layer shows a rather erratic pattern, though it was smoother than the measured points. From October onwards the calibrated soil moisture in the top layer fell quickly to almost zero. However, the measured points of the top layer still contained a substantial amount of water at the end of the IOP.

Though the calibration results of the top layer were slightly similar to the measurements, some reservations should be made. Extreme pF and K-h relations were used, to calibrate the top layer (see Table 9 and Annex H). More common retention curves led towards output twice the soil moisture data.

The calibrated courses of the deeper layer rose until a peak at the end of August, whereafter the soil dehydrated with a moderate density (4.5 mm d^{-1}). The measured points of the deeper layer show a rather constant soil moisture content with some small peaks. After the rainy season a slow dehydration took place (1.5 mm d^{-1}).

6.1.2 Discussion concerning hydrological calibration

Crust formation

A regular wetting of the soil in August-September, means that processes described in the TRIGGER model are sufficient for correct calibration, though the whole calculated profile retains too much moisture. The large retention of moisture can be explained by the following two points:

- Run-off. Time intervals used in TRIGGER affect the existing run-off amounts. The TRIGGER model considers a time interval of one day, with rainfall distribution over a period of 24 hours, while in reality most rain storms are of short duration and have high rainfall intensities;
- Variable infiltration rates. Variable infiltration rates affect soil moisture retention. The TRIGGER model considers a homogeneous infiltration pattern over a season, while in reality infiltration rates vary with the actual structure, an open structure directly after tillage and a silted structure after some rain storms.

Run-off

The infiltration rate is soil dependent and can reach 100 mm h^{-1} at the start of a rainstorm and decrease to 30 mm h^{-1} for sandy loam soil after some minutes (Hoogmoed et al., 1991) (see Fig. 10). Rain rates distribution research has shown that 50% of the precipitation falls at rain rates larger than 35 mm/h, and 33% falls

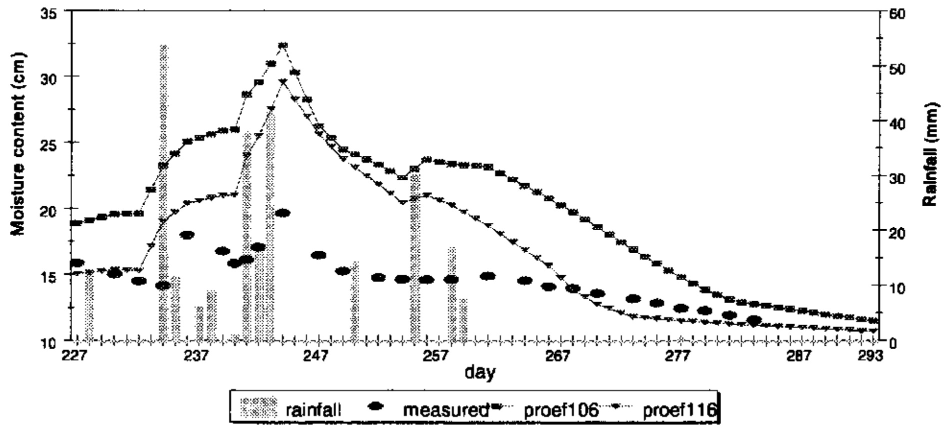


Fig. 11 Comparison of measured and calibrated dates, applied total moisture content (cm) in time. For the calibration a two layers soil was used, this concerns the deeper layer from 25-170 cm

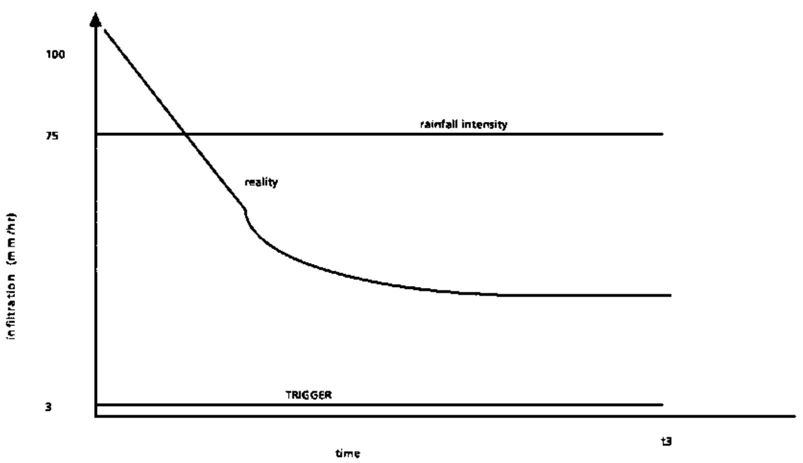


Fig. 12 Comparison of the actual and calculated transpiration rate as a function of time under a simulated rainfall of 75 mm/h

at rain rates larger than 50 mm/h (Lebel et al., in prep). So, almost half of the rainy time rain rates exceed infiltration rates, this will led to run-off. Also Fig. 11 shows this phenomena.

It shows the four phases in the development of infiltration and run-off. In the first phase infiltration exceeds rainfall intensity: all rainfall infiltrates. At the end of this phase, surface storage appears and some run-off takes place towards depressions. In phase two, infiltration decreases and rainfall intensity exceeds the infiltration intensity, the whole field participates in run off. In phase three, both rainfall intensity and infiltration, are minimised: a balance is found between infiltration and run-off.

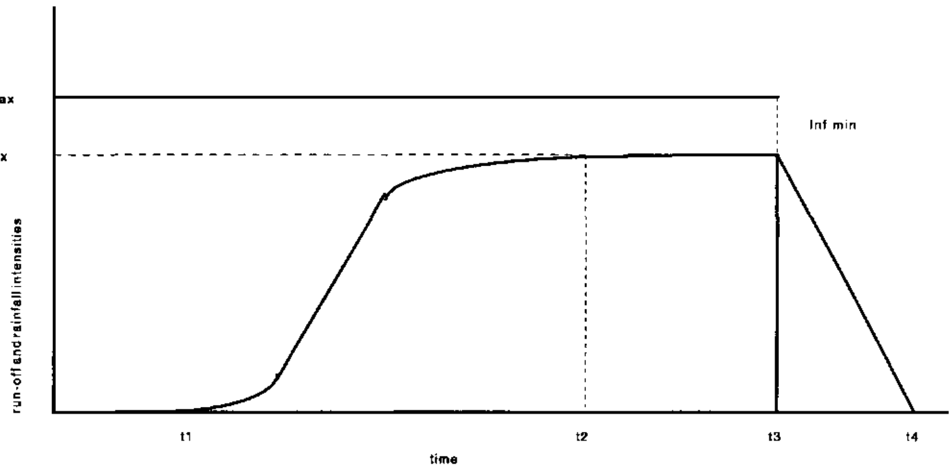


Fig. 13 Theoretical hydrogramme describing the run off during a rainstorm with a constant intensity (Casenave and Valentin, 1989)

In phase four rainfall stopped, but run off continues until the field does not contain any water.

Hence, rainfall can be totally infiltrated for only a few minutes in reality, whereafter rainfall intensity exceeds the infiltration rate of the soil. This results in run-off[7].

However, the TRIGGER model spreads a storm over one day. As a consequence rainfall intensities decrease until 0 to 5 mm/h. This is only a fraction of the maximum infiltration rate of the soil (see Fig. 10). This results in a full infiltration of rainfall into the soil and causes a calculated soil moisture content which is noticeable larger compared with the soil moisture data.

Variable infiltration rates

After sowing[8] the fields are weeded two or three times during the growing season. This minimizes pests and opens the soil, what increases infiltration, but only temporarily.

In a tilled soil, due to rainfall, the crust is gradually restored. Thus, the infiltration rate is not only a function of the actual moisture condition at the soil surface and of the initial soil wetness, as for instance in the TRIGGER model, but also of the crust history (Hoogmoed, 1981). In Fig. 14[9] a first wetting takes place directly after tillage, a second wetting takes place one day after the first wetting and a third wetting

[7]Annex I shows run-off of more than 50% of the total rainfall. This water balance is a rough estimation and was calculated with the aid of one-day or two-days simulation periods. At the start of every new period, measured soil moisture contents were used as the initial value. The transpiration was estimated, based on calibrated biomass production similar to the measured biomass production.

[8]In general the field is not preparated before sowing

[9]During this test an artificial rain was applied at a constant rate of 0.82 mm min^{-1}

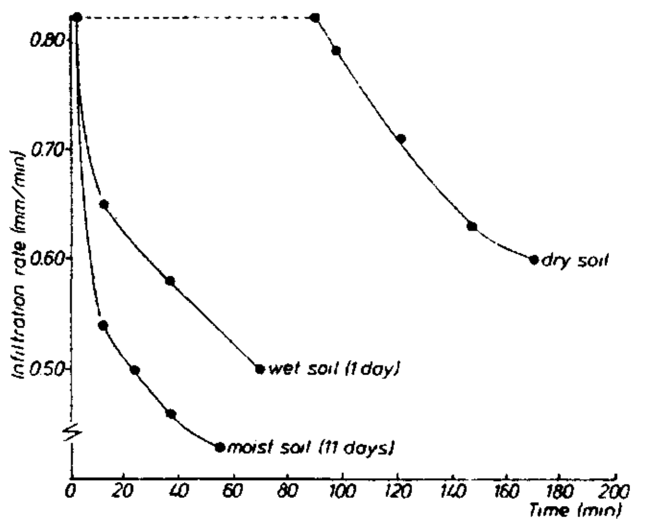


Fig. 14 Measured infiltration rates (IR) as a function of time of wetting for different conditions of tilled (and recrusted) soil (Stroosnijder and Hoogmoed, 1984)

11 days after the second. From the curves of these three wettings, it can be concluded that each shower contributed to the build up of a new crust and that at the third wetting the effect of ploughing had almost disappeared. The infiltration rate decreased to 10 mm h^{-1} (Hoogmoed and Stroosnijder, 1984).

As stated above the infiltration rate in the TRIGGER model is dependent on the initial and actual soil moisture content and the saturated conductivity. During the simulation, one K-h relation is used to describe the soil moisture, saturated conductivity[10] dependency of the soil. Hence, it is considered that soil properties will not change during the growing season. However, Figure 14 shows infiltration curves, which are not homogeneous during the growing season and which are crust formation dependent. It indicates a change of soil properties during the growth season. Hence, more K-h relations are required to describe the change in top soil properties.

After tillage actual K_s values correspond to the values used during the calibration. If the recrustation of the top soil starts, infiltration quickly decreases. Hence, K_s values used during the calibration are no longer representive and should be minimalised. As described above there are no possibilities within the TRIGGER model to adjust K_s during modelling. Besides, crusts strongly decrease infiltration, also soil moisture content decreases. In a study by Hoogmoed and Kievit (1981) it was found that in the crusted soil the soil moisture content just below the crust was only 15-20%, while in a non-crusted soil values occur of 30-35%. This difference is due to the large drop in pressure head over the depth of the crust; below the crust it has already reached a significant negative value. Thus, in the subsoil, where the soil moisture content will never exceed the observed values of 15-20%, the infiltration of water is in fact an unsaturated infiltration. During the simulation the decreased

[10]It is considered that the saturated conductivity equals the steadily infiltration level

soil moisture content was taken into account, a saturated soil moisture content of 0.1 cm^3 cm^{-3} was used.

Evapotranspiration

At the end of the rainy season the model results show a fast dehydration. This is rather predictable, a constant extraction of moisture in the form of evapotranspiration takes place, while there is an absence of moisture supplementation. However, this fast dehydration is not taking place, because other processes start playing a role in the drying process.

There are two major phases, with their specific processes, within the evaporation process:
— energy limited phase;
— soil limited phase.

The first process, where E_a equals E_p is described in the TRIGGER model by Blacks' equation (1969):

$$\Sigma E_a = \alpha t^{\frac{1}{2}} \tag{9}$$

where:

E_a	: actual evaporation	cm d^{-1}
α	: variable characterizing the evaporation process	m $d^{-½}$
t	: time	d

This process is based upon climatological processes and is hardly influenced by soil properties. This is known as the energy limited phase.

The second phase, the soil limited phase, where evaporation mainly consists of vapour pressure, is based upon soil structure and depends on a number of factors. One important factor is the amount of soil cracking that take place during drying. Water vapour diffuses very much faster from the surface or deep cracks into the atmosphere than through the equivalent depth of soil. Furthermore, the greater the average wind speed over the soil surface, the more rapid the transport of water vapour from the sides of the cracks into the atmosphere. A second factor is the magnitude of the temperature gradient in the soil profile and its diurnal variation. This affects the rate and direction of diffusion of water vapour in the profile. This is usually more important in the surface layers of the soil than in the deep subsoil, because the temperature and suction gradients, and the air space are greater at the surface. Under the very strong drying conditions prevailing in the Sahel, downward

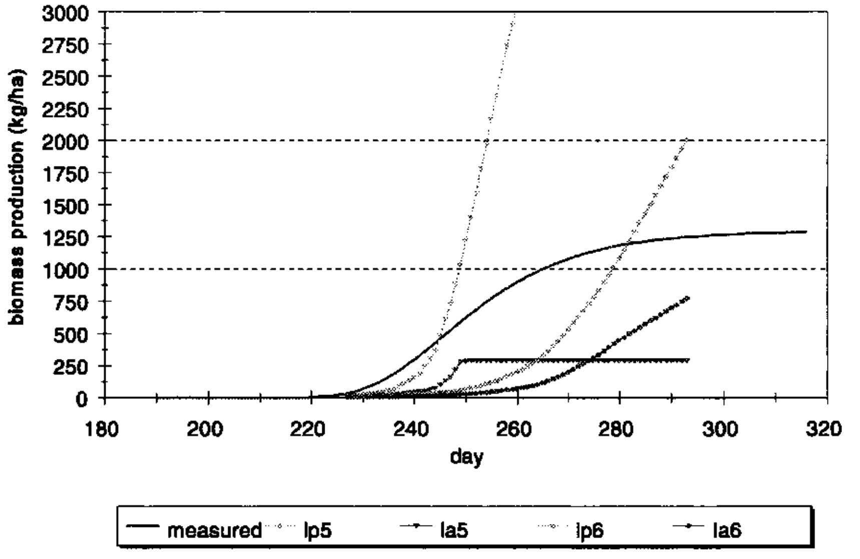


Fig. 15 Calibration of the total plant production, whereby the SSA was minimalised and SPA was brought to zero
lp6: potential production of millet, calibration 6
la6: actual production of millet, calibration 6

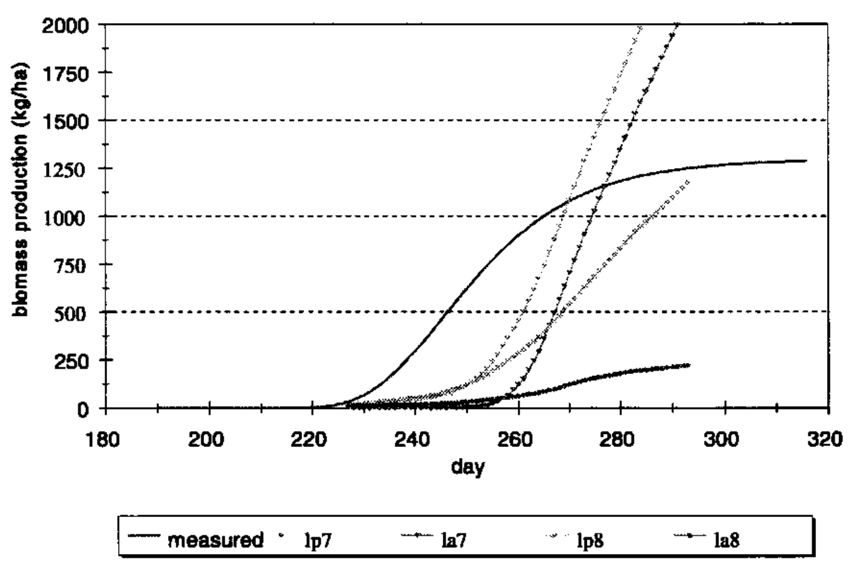


Fig. 16 Calibration of the effects of a decrease of the maximum CO_2 assimilation at the total plant production

flux of water vapour during the day in the surface soil is of the same order of magnitude as the upward flux of liquid water once the soil suction exceeded 300 cm

(Wild, 1988). A pressure head of 300 cm (pF = 2.4) corresponds with a soil moisture content of 0.09 cm^3 cm^{-3} (see Annex H). This corresponds with a soil moisture content of 2.7 cm for the top layer of the HAPEX-Sahel profile (see Fig. 10). Herefore a luvic xerosol out of the reference profiles for Mali of the ISRIC institute was used as reference. At the start of the drying out the measured soil profile contains 2.9 cm of water. Hence, almost from the start of the drying out, evaporation is in the soil limited phase, where evaporation is in balance with downward flux of water vapour. This soil limited phase can not be described by the TRIGGER model. In the TRIGGER model evaporation will still be described according to Black, which continue evaporation until the soil moisture content equals zero.

6.1.3 Results and discussion concerning crop growth calibration

As already stated, the crop growth calibration was not fulfilled, because the soil processes could not be calibrated successfully. Despite, some remarks can be made about the calibration of the crop growth processes. These remarks are principally based on the potential biomass production.

In general the measured millet crop has a quicker initial development than the calibrated crops, while the calibrated crops have a stronger growth onwards the vegetative phase. At the end of the growth season both, the measured and calibrated crop are levelled (see Fig. 15 to 19). The values used during the crop growth calibration are mentioned in tabel 10.

Initial situation
Figures 15 to 19 show a slower initial growth of the calibrated crop growth compared to the measured crop growth curve. As described in Chapter 3 initial crop growth is determined by LAIEM, TDWI and SLATB, if these are underestimated the initial growth, calculated by the model, remains behind. This is not inconceivable, because these parameters are hard to estimate.

Green area
As Fig. 15 shows specific stem area (SSA) and specific pod area (SPA) are very sensitive to slight changes. Unfortunately there is no information about acceptable ranges for these variables.

CO_2 assimilation
The calibration results were strongly influenced by the values used for the assimilation variables. Fig. 16 shows that there is a strong reduction of the biomass production, if the maximum CO_2 assimilation is limited. The period after flowering is most affected by the limitation of the CO_2 assimilation, because during this period millet is most sensitive for water shortages.

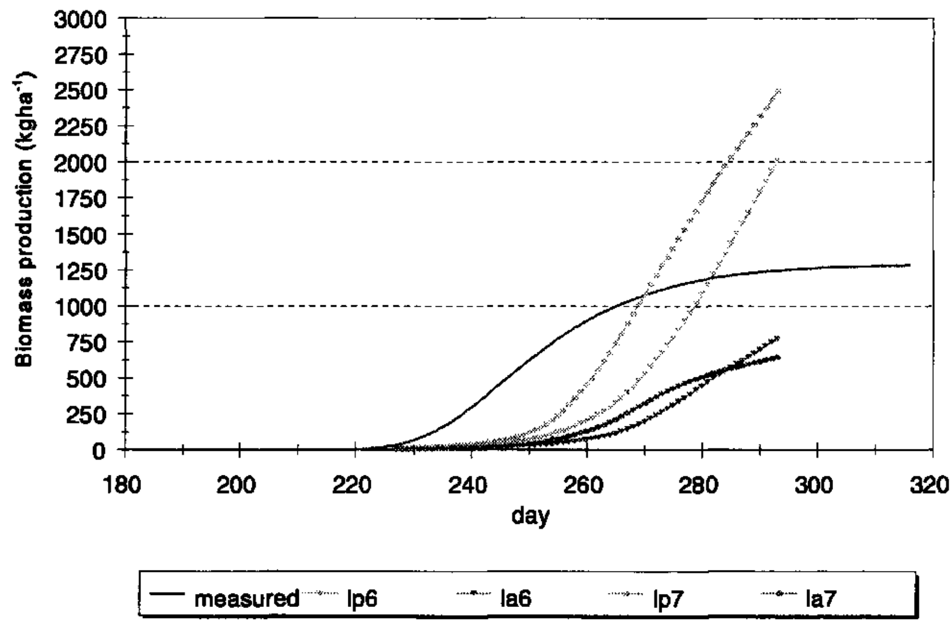


Fig. 17 Effect on the total biomass production while using partitioning factors out of the measurements or using Van Heemst (1988) values

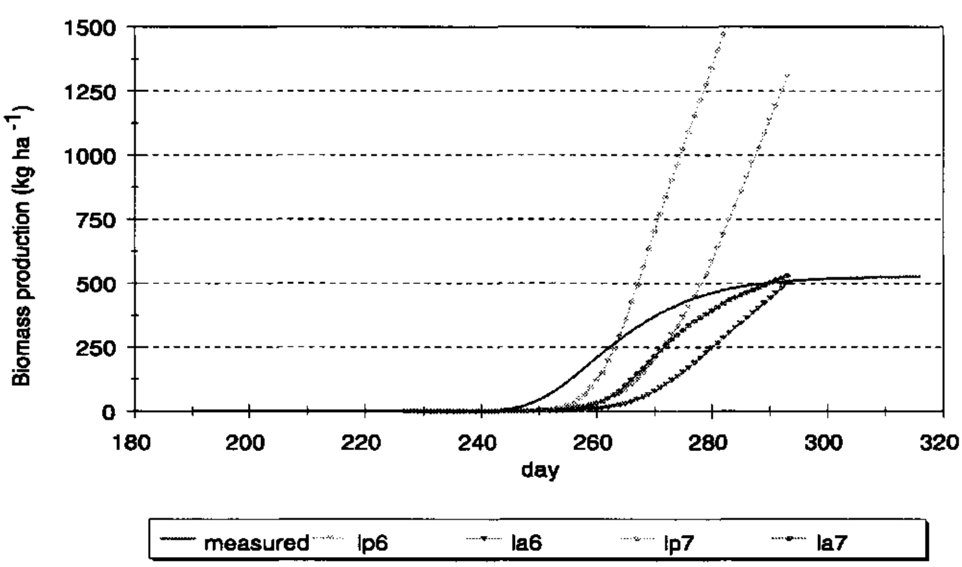


Fig. 18 Effect on the aer production of the switch from partitioning factors extracted out of measurements and towards Van Heemst (1988) values

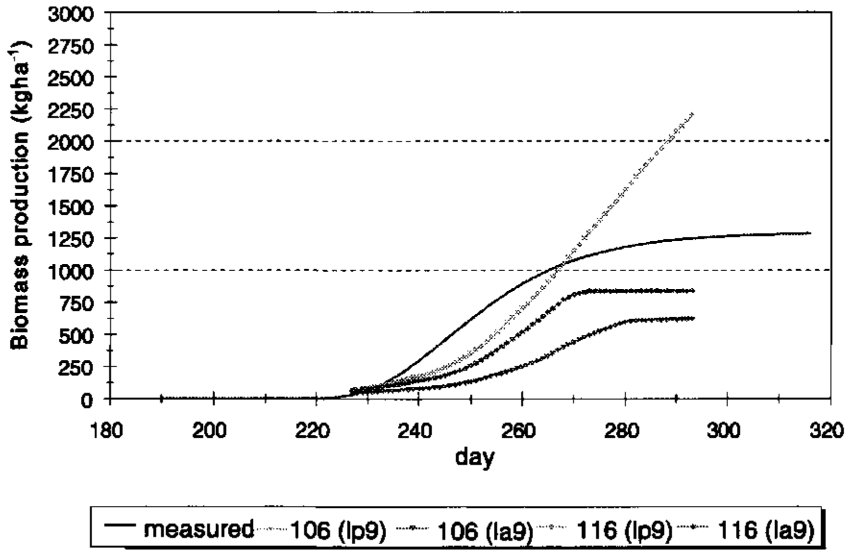


Fig. 19 Effect of a different retention and conductivity curve at the total millet production (see for the curves Annex H)

Partitioning

Figure 17 and 18 show the influence of partitioning. Total crop production increased as well as the spike production. The increase of the total crop production can be explained by the larger amount of biomass partioned to the leaves at the initial situation. The larger amount of leaves gives a higher LAI, as a consequence of which more radiation can be intercepted. This leads to a larger and quicker increase of biomass.

The increase of the spike biomass can be explained by a larger amount of biomass partioned to the storage organs as well as an partitioning to the storage organ in an earlier stage.

Moisture availability

Moisture can be extracted out of the soil by roots. The extraction is e.g. dependent of vertical and lateral root development. The moisture is required for the photosynthesis and will be ejected in the form of transpiration. The influence of moisture availability is shown in Fig. 19.

Rooting

The root growth of millet is characterized by a rapid expansion of the root system. The root penetration at the start of the growth season is 7.1 cm d^{-1}, while the average root penetration is 4.5 cm d^{-1}. Most of the roots are concentrated in the upper twenty centimetres of the soil, while the maximum rooting depth of millet reaches 200 cm (Zaongo, 1994). Root penetration speed is mainly influenced by the wetness of the soil. If soil moisture is restricted the plant requires a more extensive root system in order to extract water. This is one of the methods for a plant living in semi-arid zone to withstand drought. For this reason millet has an extensive rooting system as well.

Review of IOP measurements shows that the average root growth is 1.2 cm d^{-1} (see Annex G). If the rooting development remains behind, extraction of moisture out of the soil leaves behind as well (see Fig. 19). This moisture is of direct importance for biomass production and will thus remain behind as well.

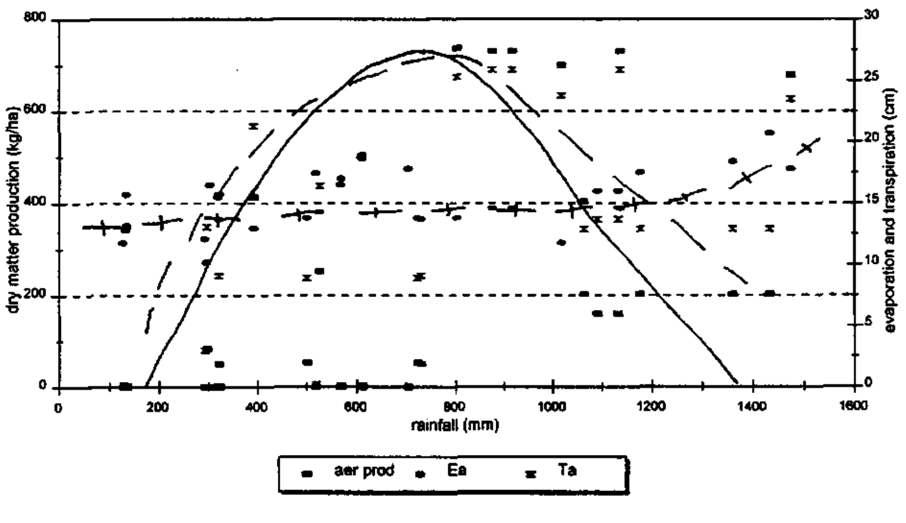


Fig. 20 Comparison of rainfall, dry matter production, evaporation and transpiration with a crop density of 50 cm

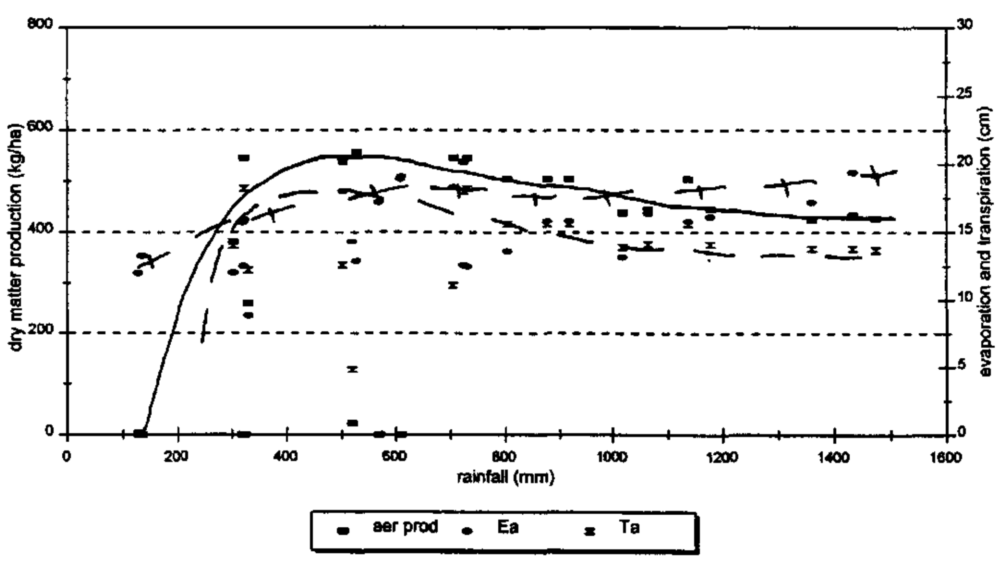


Fig. 21 Comparison of rainfall, dry matter production, evaporation and transpiration with a crop density of 75 cm

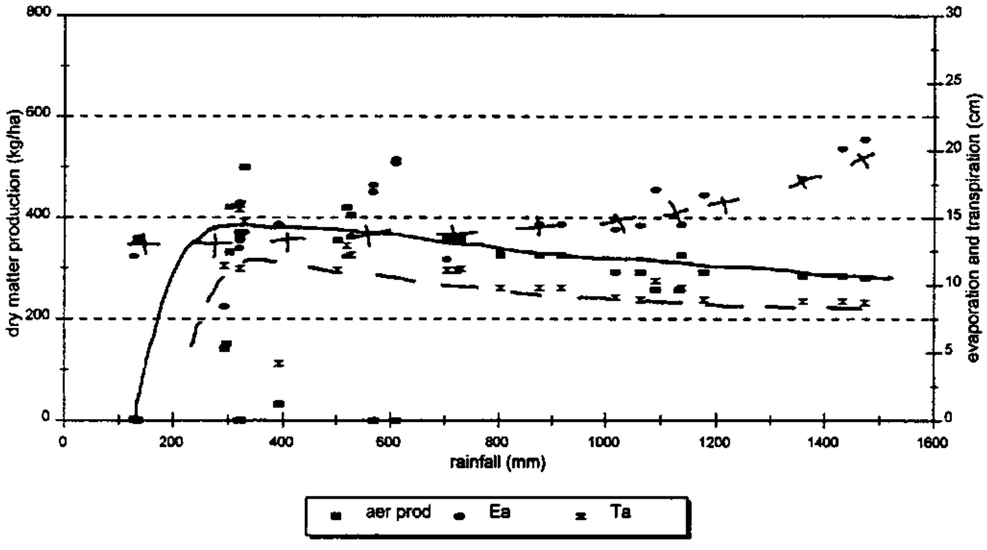


Fig. 22 Comparison of rainfall, dry matter production, evaporation and transpiration with a crop density of 100 cm

On the other hand, the model is based on a maximum uptake of moisture by the roots during the whole growth season. Even at the start of the growth season, the uptake of moisture by the plant is only determined by the sink term and not by the amount of roots. This results in an overestimation of moisture extraction, what influences the growth speed during establishment.

Table 10 Variables, and its values, adjusted during the crop growth calibration

	Phenology		Initial situation			Green area		Assimilation			Partitioning
	TSUMEA	TSUMAM	TDWI	LAIEM	RGLAI	SPA	SSA	KDIF	EFF	AMAXTB (see below)	
lemil5	756	1008	10	0.00486	0.00288	0.005	0.01	0.56	2.00	A	I
lemil6	756	1008	10	0.00486	0.00288	0.0	0.002	0.56	2.00	A	I
lemil7	756	1008	10	0.00486	0.00288	0.0	0.002	0.56	2.00	A	II
lemil8	756	1008	13	0.00749	0.03	0.0	0.0035	0.6	0.45	B	II
lemil9	738	1008	44	0.0104	1.0	0.0	0.0035	0.6	0.45	C	II

I: partitioning according to the measured data (see Annex F)
II: partitioning according to Van Heemst (1988) (see Annex F)
The grey sections indicate the adjustments

DVS	0.00	1.30	1.75	2.00
AMAX A	85	85	-	85
AMAX B	85	70	50	20
AMAX C	85	70	50	40

Transpiration

The calibrated soil moisture lines show a strong decrease of soil moisture at the end of the rainy season (see Fig. ???). This decrease influences crop growth. As described above a certain moisture content is required for the production of biomass. If soil moisture content reaches zero the uptake of moisture by the plant will be minimised. The period with a strongly deceasing moisture apply corresponds with maturation. Hence, the storage organ production will be limited by moisture shortage. This will cause severe damage, because millet is most sensitive for water stress during maturation, while water stress during the late establishment do not give as much damage.

6.1.4 Validation

During the process of calibration it turned out that the model output could not brought into line with the measured data, because of this a validation is useless. Without a validation a simulation can be carried out with restrictions. Only trends can be extracted out of the simulation, but a value judgement can not be given.

Table 11 Relative error (RE) for comparing measured and by SWATRE predicted volumetric soil water contents of a sandy loam soil and a clay soil

Sandy loam soil		Clay soil	
depth (cm)	RE (%)	depth (cm)	RE (%)
0-25	+22	0-15	+16
25-50	-13	15-30	+2
50-100	-4	30-50	+0.8
		50-80	+6
		80-120	-4

6.1.5 Sensitivity analysis

Out of Clemente et al. (1993) can be concluded that SWATRE[11] has a larger deviation in sandy soils compared with clay soil. While the average error in the sandy loam soil ranges between 24-18%, ranges the average error in the clay soil between 5-2% (see Table 11).

SWATRE overestimates the soil moisture content in top soil of the sandy loam, while it underestimates the soil moisture content in the deeper layers. This over-prediction of the soil moisture content can be explained by both the low amount of ET_a calculated by the SWATRE model and the strong drainage of water out of root zone (Clemente et al., 1993). The last decreases evapotranspiration and that results in a higher water content. See for the Figures of the comparison of SWATRE, SWASIM and LEACHW Annex J. Also in the present study it appears that the soil moisture content is overestimated with an average of 30%.

[11]SWAP is the successor of SWATRE. In SWAP various processes were supplemented, for instance hysteresis

6.2 Simulation

The simulations were carried out, despite a doubtful result of the calibrations. A choice was made to carry out the simulation in order to ascertain whether trends, concerning millet production and WUE, are existing. The deviation of the calibration certainly influenced the simulation results, but they were all influenced in the same way. This made it possible to study trends. Because of the deviation in calibration results it was not possible to do a quantitative analysis. The values would not be representive.

The simulations were focused on crop production and water use efficiency (WUE) of the millet crop with different rainfall scenarios and different millet densities. Rainfall ranges between 128 mm and 1474 mm and has different regimes. Crop density ranges between 50 cm x 50 cm and 150 cm x 150 cm. Annex K gives an overview of the simulation results

In the first part of this section the results of the influence of both crop density and rainfall scenarios on millet production are described and discussed, while in the second part the influence of rainfall and crop production on WUE are described and discussed.

Special attention will be paid to spike production of millet, because this is of major importance to food supply. Hence, the Figures show the spike production however, total production give a similar trend.

6.2.1 Results concerning millet production

Figure 20 shows that the crop density of 50 cm x 50 cm requires around 900 mm rainfall to have a maximum crop production. However, the average rainfall in this area of Niger is around 600 mm (Casenave and Valentin, 1989), so this density will not be taken into account during the discussion.

Figures 21 and 22 show that spike production with a crop density of 75 cm x 75 cm is approximately 200 kg ha^{-1} more than with a density of 100 cm x 100 cm. However, the maximum rainfall of the 75 cm x 75 cm crop density simulation is around 100 mm more. Both Figures show a rather strong increase of dry matter towards its maximum, whereafter only a slow decrease will take place if rainfall quantity increases.

Figures 22 and 23 show that maximum production at a crop density of 100 cm x 100 cm and 125 cm x 125 cm are almost similar, though millet in a 125 cm x 125 cm pattern will reach this maximum with 300 mm of rainfall, while the 100 cm x 100 cm pattern requires 400 mm of rainfall to reach maximum production. The 125 cm x 125 cm shows a quicker decrease of production after its maximum.

Figures 23 and 24 show that the maximum production of the 150 cm x 150 cm pattern

aer production
E_a (cm d^{-1})
T_a (cm d^{-1})

is only half of the maximum production of the 125 cm × 125 cm, but both spaces reach their maximum with the same rainfall quantity. This is remarkable. The production decrease of the 125 cm × 125 cm pattern is stronger than the decrease of the 150 cm × 150 cm pattern. The increase of dry matter of the 150 cm × 150 cm towards its maximum is also more gradual.

6.2.2 Discussion concerning millet production

From the results it can be concluded that the optimum crop density depends on the rainfall quantity. If rainfall increases, crop density can increase as well, without hazarding yield failures. If the crop density increases, the maximum yield increases as well. Hence, if the natural situation improves, yield security will also increase.

From these simulations an optimum crop density of 75 cm × 75 cm and 100 cm × 100 cm can be extracted. With this space pattern a yield of a reasonable extent can be achieved, even in a dry year. It is expected that the average rainfall is approximately 600 mm with a coefficient of variation (CV) of between 25-30%[12]. This means that rainfall ranges between 420-780 mm.

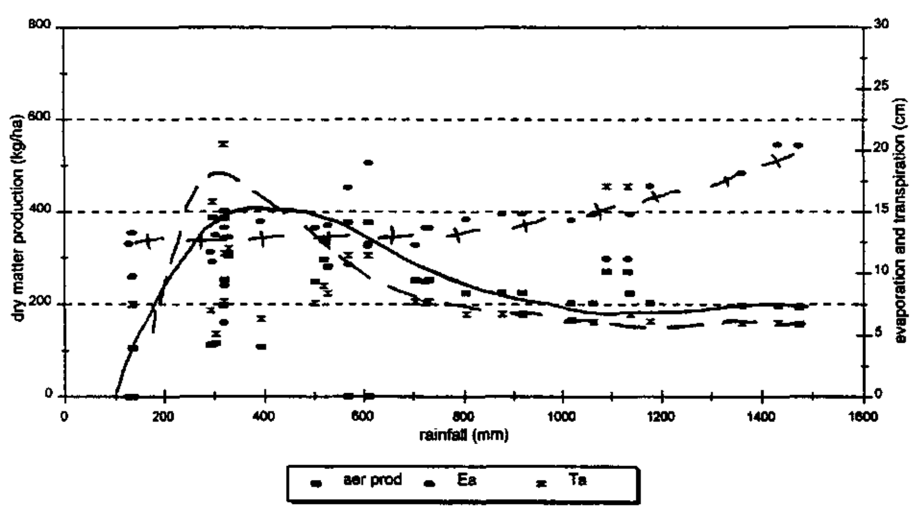


Fig. 23 Comparison of rainfall, dry matter production, evaporation and transpiration with a crop density of 125 cm

[12]CV ranges between 25-30% in areas with similar latitudes which are situated in Burkina Faso (Sivakumar and Gnoumou, 1987)

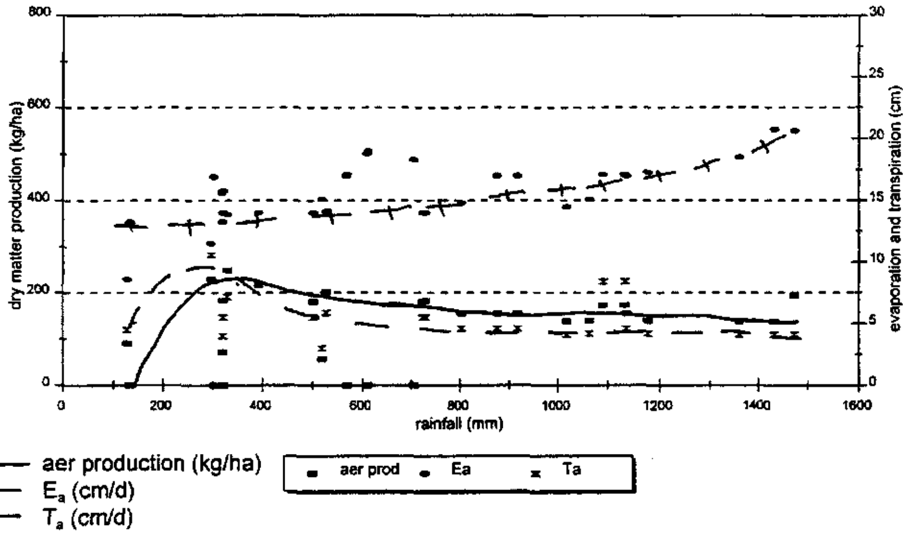


Fig. 24 Comparison of rainfall, dry matter production, evaporation and transpiration with a crop density of 150 cm

From the simulation no relationship was found between rainfall patterns and crop production. This was probably caused by the fact that during the simulation only rainfall patterns were changed, but not the sowing strategy. In general farmers sow their crops directly after the first rains, in order to make optimal use of the rainy season and to make use of the nutrients which are released with the first rains. During the simulations a standard sowing date was taken, 12 June. Other researches (for instance the study of Mellaart (1988)) showed that the sowing date can strongly influence the crop production.

For some reasons the results should be taken with reservations:

- Only general remarks can be given, because during the calibration the fits were not satisfying.
- In several simulations the soil moisture content could not be calculated by the model and was set at Θ_s. As a consequence evapotranspiration could no longer take place and for this reason the plant growth was slowed down or even stopped.

6.2.3 Results concerning WUE

Three types of comparisons were carried out in order to interpretate the influence of rainfall and crop production on evapotranspiration and WUE (see Table 12).

Transpiration and evaporation

Figures 25 and 26 show a linear relationship between actual transpiration and total dry matter production. In addition Fig. 20 until 24 show that both the shape of the production curve and the transpiration curve are rather similar. The latter Figures also show that evaporation is not dependent on crop density, but does slightly increase if the rainfall increases.

Table 12 Comparisons used to interpretate the influence of rainfall and crop production on ET_a and WUE

Rainfall	Dry matter production	ET_a
Dry matter production	WUE	T_a
Rainfall	WUE	

WUE

The WUE of ET_a as well as the WUE of T_a shows a rather horizontal development (see Fig. 25 and 26), though there are some fluctuations. In general, fluctuations of the WUE correspond with fluctuations of the actual transpiration. The patterns of both WEUs are rather similar, only below a biomass production of 200 kg ha^{-1} they show different trends. While the WUE of ET_a shows a slight increase, the WUE of T_a reaches a peak of more than 80,000 kg ha^{-1} m^{-1}. Figures 27 and 28 show that the WUE is relatively independent of rainfall.

6.2.4 Discussion concerning WUE

The discussion concerning WUE is focused on relationships and trends between WUE and crop production. The relationship between transpiration and evaporation with crop production and rainfall increase is also discussed. In first instance transpiration and evaporation will be discussed, thereafter the discussion will be focused on WUE.

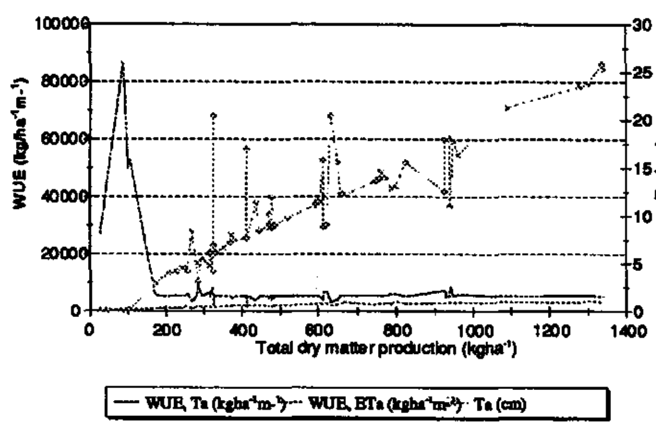


Fig. 25 Water use efficiency compared with the total dry matter production

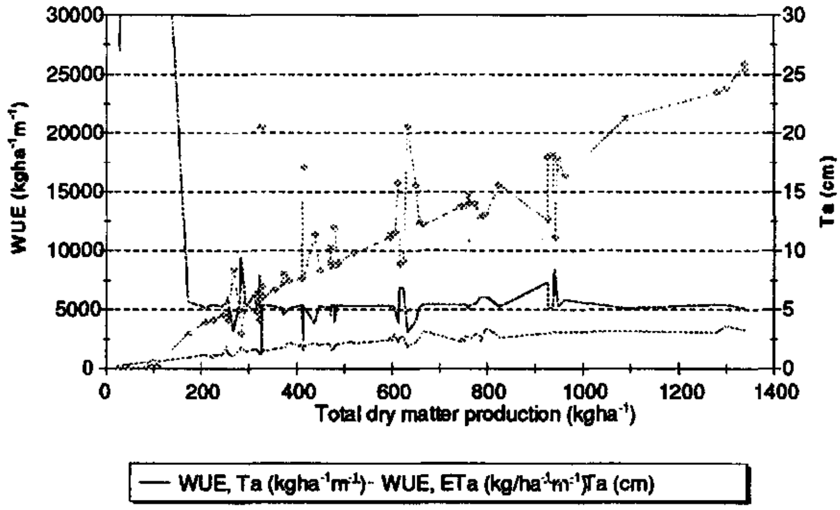


Fig. 26 Enlargement of Figure 25

Transpiration and evaporation

The actual transpiration development over an increase in dry matter production was expected, though, in general the actual transpiration rate is a bit too high.

For instance in a study by Fechter (1993), 85 mm of moisture is required to produce 645 kg ha^{-1}, with a LAI of 0.21 m^3 m^{-3}. In the present study, approximately 125 mm of moisture was required to produce the same amount of total biomass. This means an overestimation of 32%. The overestimation can be considered in combination with a low calculated WUE[13]. If WUE is low, water is inefficiently used during photosynthesis, hence noticeably large amount of water will be transpired by the plant.

The above described may partly explain the problems with the soil moisture content during the simulation (see Section 6.2.2). When extraction of soil moisture by the plant is great the soil, which already has a marginal soil moisture content, will dehydrate too fast. At a certain moment the model cannot withstand this situation any longer and sets the soil moisture content to Θ_r and stops the actual transpiration.

Less expected was the similar actual evaporation development for the different crop densities. It was expected that evaporation decreases with an increase in plant density. Because of the higher crop density, the soil is more shaded by leaves and as a consequence evaporation decreases. The non occurrence of this phenomenon can be explained by the fact that the model always considers a crop which fully covers the soil at a certain development stage (personal remarks Van Diepen). For this reason the evaporation will have a similar pattern, regardless of crop density.

[13]For instance Kanemasu et al. (1984) give a total WUE between 32.0 and 68.0 t ha^{-1} m^{-1}, while during this study a WUE of 5,000 kg ha^{-1} m^{-1} was calculated.

More expected was the actual evaporation increase with an increasing rainfall (see Fig.s 20 to 24). If rainfall increases the moisture availability increases as well and for this reason actual evaporation can approach potential evaporation.

WUE

The WUE is influenced by both environmental and crop factors, some of which can be influenced by the farmer. In semi-arid conditions environmental factors such as rainfall, and soil moisture content play a major role in the WUE. The WUE can be influenced by management practices, such as water harvesting, and soil structure improvement. In humid zones the growth of a crop is primarily determined by crop factors. The major crop factor which determine crop growth is the development of the leaf canopy, expressed by LAI. This can be influenced by an optimalisation of the uptake of radiation and nutrients (Gibbon and Pain, 1985).

WUE together with the leaf canopy temperature tells something about the drought resistance of a plant (Kanemasu et al., 1984). However, it is beyond the scope of the subject of this study to explain the methods used by a plant to arm itself against drought.

As described in the results the WUE has a rather linear development. This means that photosynthesis take place under a regular efficiency independent of the crop production. However, it was expected that the WUE would be somewhat sensitive to rainfall. If rainfall decreases the plant suffers more stress. It is expected that this will be expressed in a more efficient use of moisture hence the WUE will slightly increase[14].

[14]The exact processes which influence photosynthesis efficiency has not been sufficiently researched, but there is evidence that the WUE is influenced by plant stress.

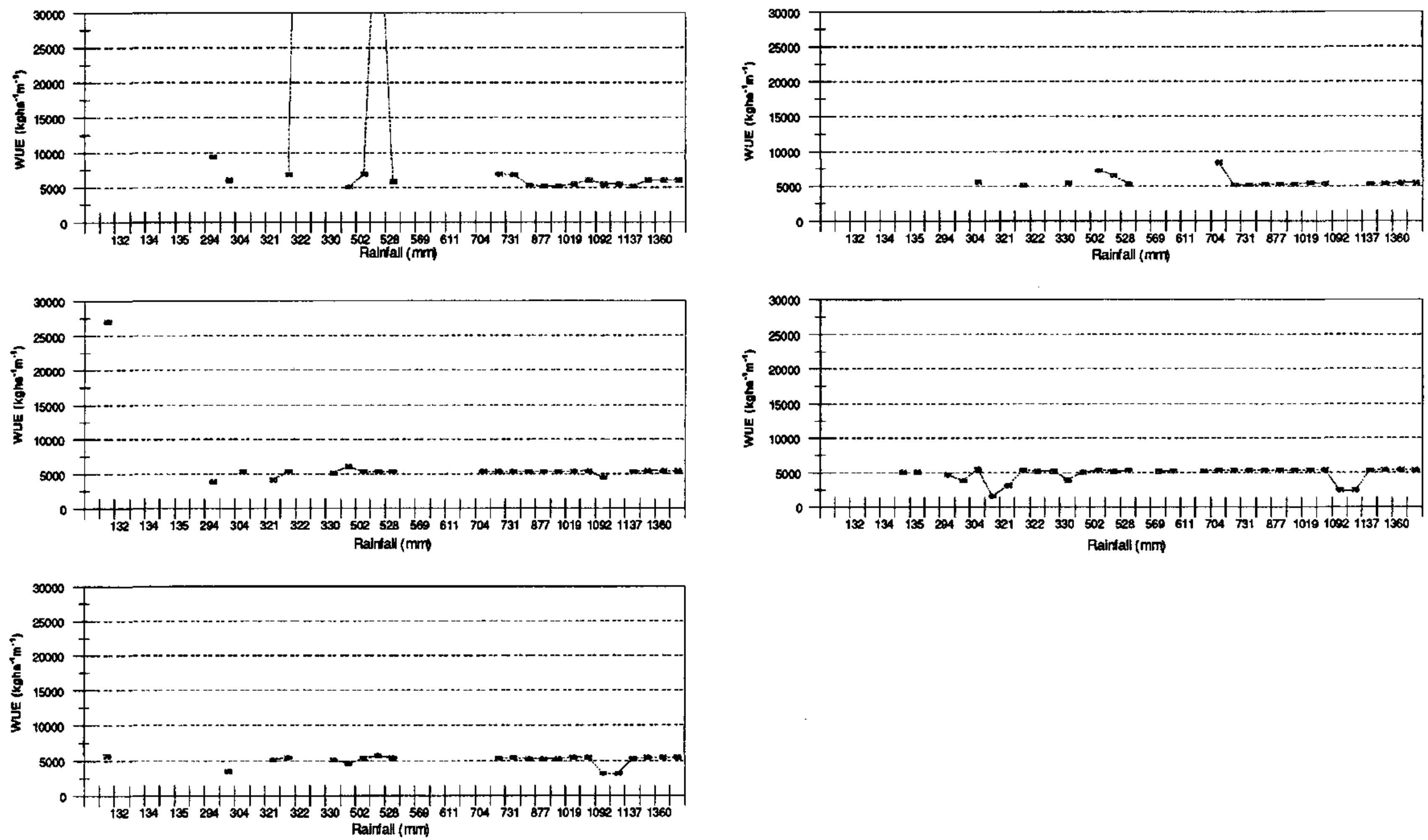


Fig. 27 WUE of the T_a compared with rainfall quantity by different crop densities. The Figure shows a nearly constant water use of the plant, independent of rainfall amount and crop density

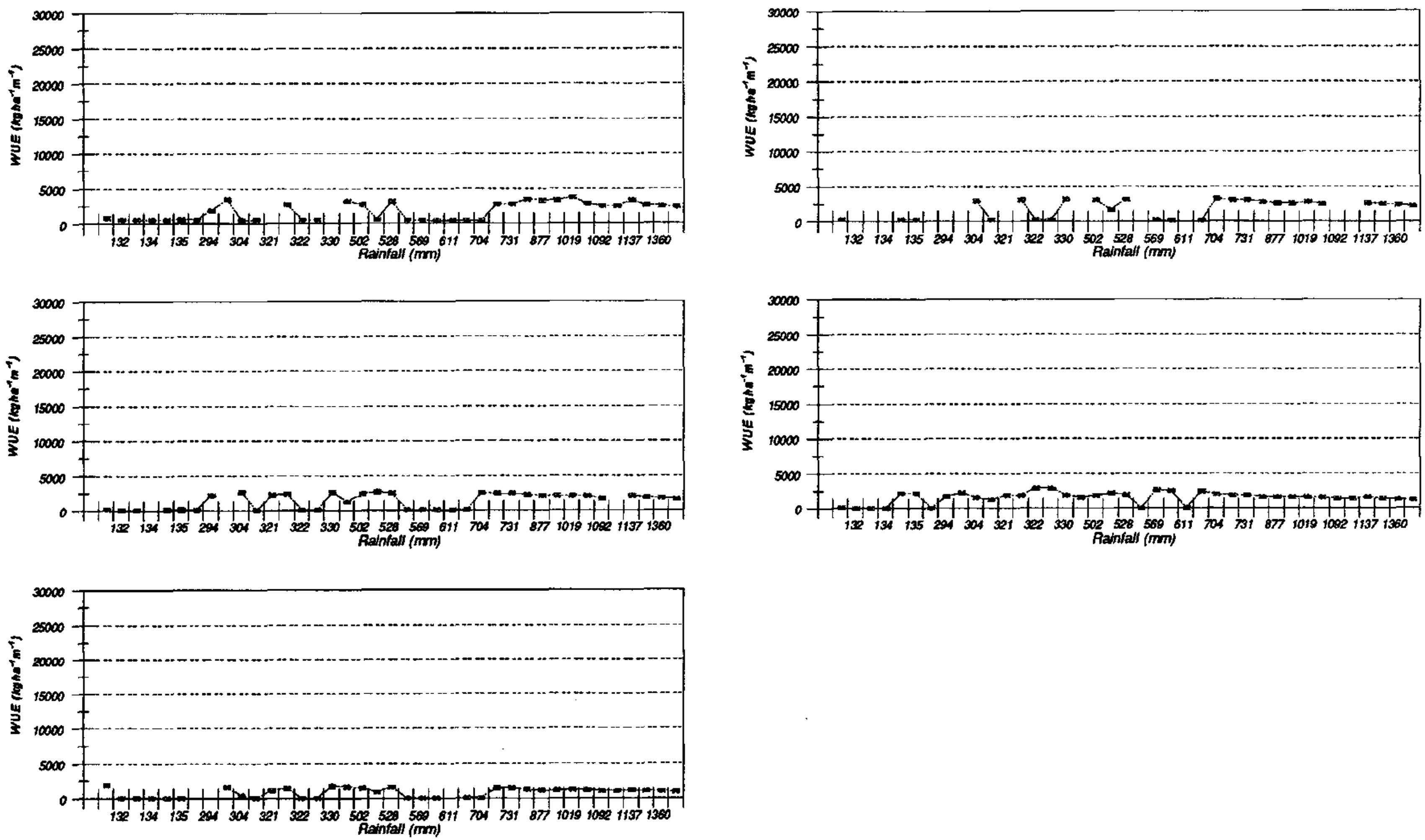


Fig. 28 WUE of ET_a compared with rainfall quantity by different crop densities. The Figure shows a nearly constant water use efficiency, independent of rainfall amount and crop density.

6.3 Discussion concerning methodology

Model versus field research

For the present study there was chosen to use a model to simulate crop production in the Sahel with different climatological circumstances and with different crop densities. Another possibility was to do field research in order to determine the influence of rainfall and crop densities on the growth of millet and water use. What are the characteristics of both methods? and in what way both methods can contribute to the research concerning sustainable farming system development?

The most important characteristics will be enumerated, whereafter both methods will be discussed.

Field research:

- Factual picture. In general the research is carried out within the project area, so all environmental circumstances are taken into account.
- Data set. In general series of test plots are required to test all the possibilities to develop a reliable data set.
- Time. In general field research is time consuming before results can be analysed, because for instance plant growth takes a year and in general more growth seasons are required to see trends. To get a reliable view the whole growth season should be monitored as well.

Model research:

- Factual picture. To give a reliable view of the reality all possible processes which can influence the research object are worked out in detail in the model. If these processes are described it is relatively easy to predict.
- Data set. A detailed data set is required to be able to describe to involving processes. Data should be taken from field measurements, while the variables can be taken from literature.
- Time. The development of a model is a time consuming process, just as field measurements and processing of the data set in the model.

From the above can be concluded that field research gives in general a more reliable view of reality. All, mostly human and environmental factors, are taken into account during this research, while during modelling in general is chosen to model only the most important (most relevant) environmental factors. Because, if all environmental factors are taken into account the model becomes far too complex. Mostly human factors are not taken into account during modelling. While field research gives a rather reliable view of reality, modelling is stronger in predictions. If the model is calibrated satisfactory, predictions can be carried out quite accurate. Though there are always restrictions, because not all influencing factors are taken into account. To predict during field research is far more difficult, because a number of environmental factors can not easily be changed, for instance weather. In general glasshouses are used to carry out predictive field research.

The overall conclusions will be: field research can give a more detailed view of the real situation, while a model can more easily predict trends.

For the farming system development research a combination of both can be used. A model can be used to study trends, while field research is required to transform these trends into information useful for the farmer. This field research requirements evolved out of the fact that spatial variability of for instance soils is of major importance for production in the Sahel.

Spatial variability
On these poor soils, small absolute differences in for example clay content and associated parameters, or in Pb ray content, give rise to large relative differences in availability of nutrients and thus to large differences in plant growth.Differences in soil parameters are thought to be caused by differential wind and water erosion and deposition, growth of trees and shrubs before clearing for cultivation, trees left standing such as *Faidherbia (Acacia) albida*, termite activity, differential leaching, and/or human activities (including uneven application of manure, location of village sites and refuse heaps, and burning of cleared vegetation) (Brouwer et al., 1993).Farmers anticipate at this micro-variability by the use of different millet varieties for soil variability and micro topography. In general farmers possess more fields with different soil properties and topography. The different fields give good yields with different climatological circumstances. This reduces the risk of yield failures for a farmer.

The importance of micro-variability is effaced by the generality of the model. For both the use of several crop varieties and the use of soil variability a general value is used. Hence the model can give general trends for the development of yield improvements, but the very specific circumstances of the Sahel and the adjustments of the farmers to this situation is not taken into account.

7 Conclusions and recommendations

7.1 Conclusions

7.1.1 Calibration

From the calibration it can be concluded that the model overestimates the soil-moisture content within a range between 16% and 44%. The calibration results dehydrate noticeable quicker than the measured points. The following explanation can be given: as a consequence of crust formation, a large part of the rainfall runs off towards the valley and so will not infiltrate into the test field. This causes two problems:
— The soil properties of the top layer changes during calibration. However, the TRIGGER model is based upon a retention and conductivity curve, which does not change during the calibration-time interval.
— Processes such as evapotranspiration in the vapour phase, play a role which cannot be described within the TRIGGER model.
Besides the TRIGGER model is based upon a time interval of one day. Rainfall is divided over a day, while in reality rainstorms pass in two or three hours.

The calibration of the crop growth processes requirements also casts some doubt, because some crop growth variables of the TRIGGER model which are very sensitive, such as the partioning factors and SSA and SPA, are hardly documented. This results in an estimation of these variables and makes the model less reliable. The calibration results showed that the model is mostly sensitive to the initial situation, phenology, green area, assimilation and partitioning.

7.1.2 Simulation

Plant growth and moisture availability
The simulation results show a linear relationship between actual transpiration and both biomass production and rainfall quantity. Also WUE shows a linear relationship with biomass production and rainfall quantity. This means that the photosynthesis is independent of rainfall quantity or crop production, but has a standard conversion coefficient.

In the semi-arid zone WUE is mainly influenced by environmental factors, such as rainfall regimes and soil moisture content. In the humid zone it is principally influenced by crop factors, especially the development of the crop canopy.

Crop density and biomass production
From the simulation it can be concluded that the optimum crop density is between 75 cm x 75 cm and 100 cm x 100 cm. These densities give a reasonable yield, even in a dry year. Whereby it is assumed that rainfall quantity ranges between 420-780 mm. If the crop density increases, the yield increases as well however, a maximum yield requires more rainfall. If the crop density decreases, both rainfall quantity required to reach the maximum production and maximum production decreases.

Rainfall scenarios and climate influences
As described above rainfall does influence crop production. Crop production decreases with a decreasing rainfall and vice versa. This can be explained by the fact that millet requires a certain amount of moisture to produce biomass. If there is only a marginal amount of soil moisture available, like in the Sahel, the plant does not have much water to use for photosynthesis, and thus the plant production also remains low.

It has been proved that rainfall in the Sahel has declined in the last two or three decades. It has also been shown that, in general, there are four good years, four average years and two bad years during one decade. Less research has been carried out on the rainfall patterns within the rainy season. While, it can be concluded from research that the number of showers to determine the total quantity of rainfall does not change over the years.

Rainfall especially influences actual evaporation. If rainfall amounts increase, actual evaporation approaches potential evaporation. Actual transpiration is mainly determined by dry matter production, though this is amongst others dependent on the soilmoisture content, while this is again partly dependent on rainfall quantity. Thus, indirectly transpiration is influenced by rainfall quantity.

Rainfall variability (RV) and the length of the rainy season can be used to determine different rainfall scenarios. For extremely wet circumstances, 10% RV should be used, for general circumstances 50% RV should be used and for extremely dry circumstances 90% RV should be used. The length of the rainy season can also be determined by rainfall variability.

7.2 Recommendations

This report discusses the influence of soil moisture availability at crop growth. It contributes to solutions and support choices which should be taken to develop a sustainable and self-sufficient agriculture in the Sahel. The change of crop density can be one of the solutions. This solution is part of a package of measures required to develop the agriculture in the Sahel. Research is required to achieve a sustainable agricultural system. Probably a permanent agricultural system, with the use of HYV and chemical fertilizers will be required to achieve the aim of food self-sufficiency. However, is a permanent agricultural system realistic in a marginal zone as the Sahel, and can this system recover the cost on the required investments? The above described change of the farming system will be a long term objective. To achieve this objective small-scale developments are required for the short-term. A little density increase can be one of these options.

7.2.1 Farming system

Intercropping

The report showed that crop density influences crop growth. It can be concluded from the simulations that the optimum crop density for crop growth is a bit more dense than there is usually sown. Hence improvement of crop density might be a solution for the improvement of crop growth. However, as only the production of millet has been taken into account, further research is required on the influence of millet density on intercrops, such as cowpea. These crops are also important to the variety of the menu and the economic situation of the farmer. If the crop density of millet increases, intercrops have less chance to develop.

Besides, having a positive effect on the farmers' nutrition and economic situation, intercrops have a positive effect on fertility as well. Cowpea is a nitrogen fixing crop. This is of great importance to the fertility of the fields, because use of manure and chemical fertilizers is marginal and is another very serious constraint. Further research will be required on the effect of fertility of the millet crop if intercrops can no longer be used, because of the higher density of the millet crop.

Use of HYV

If millet is planted as a monocrop, research is required to establish whether HYV, which requires a reasonable extent of (chemical) fertilizer, will benefit. This research should be based upon a number of questions:

- If HYV are used with optimum fertilizer use will water availability become a constraint and will the production be limited by soil moisture content?
- Can a level of production be achieved that benefits the farmer to use HYV and chemical fertilizer? Several consideration should be taken into account:
  - Millet is firstly used for farmers' own consumption and only surpluses are sold on the market. This means that the crop has a low economic value.
  - If surpluses increase, the prices decrease, because the potential market is small. Principally the whole population is self-sufficient and surpluses are used only in very dry years. Only a small surplus is required to feed the population living in non productive areas such as the Sahara zone and the capital Niamey.
  - If the farming system is intensifying other investments are required for machinery etc. Hence, benefits from yields should further increase.

7.2.2 Model

It was concluded that the model did not use the right processes for the simulation of crop growth in the Sahelian situation. This is despite the fact that the model was developed for universal use. To make the model universal useful, further research is required so that a model with a main routine and more sub-routines can be developed. In the main routine the climatological processes should be worked out, while in the sub-routines the crop growth and soil moisture content can be described for different situations, e.g. saturated soil profile, actual evaporation in the soil limited phase, unsaturated soil profile, growth of closed crops, growth of crops which will not close. Depending on the situation the user of the model can switch to the required sub-routines. Though the model will be reasonable expanded, the calculation speed will not be affected, because the user calculates only with a small number of the available subb-routines.

Rooting

The uptake of moisture by the crop is also determined by root volume and growth speed. The model considers a maximum uptake of moisture by the roots, while in reality the uptake of moisture increases with the increase of root volume. If root volume increases can be simulated by the model, would this give a better reproduction of the reality, especially if the crop density is low and the crop do not totally cover the soil during the growth season.

A study will be required to determine the lateral and vertical growth density of roots, the moment competition between roots of different plants start, and the differences in root growth and competition between plant species.

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Terminology

albedo	:	reflection of radiation by the earth surface
anthesis	:	the stage of development in a plant when the anthers rupture and the pollen is shed (Gibbon and Pain, 1985)
assimilation	:	the photosynthesis process
available water	:	that part of the soil water which is held between field capacity and permanent wilting point (Gibbon and Pain, 1985)
C3/C4 plant	:	both plant types have a different photosynthesis pathway
canopy	:	the arrangement and distribution of leaves produced by a crop (Gibbon and Pain, 1985)
conversion coefficient	:	the weight of dry matter produced per unit of solar energy intercepted (Squire et al., 1987)
data set	:	a combination of data and variables, whereby data is measured and variables are (literature) values
emergence	:	come up of a crop
evaporation	:	vaporization of the bare soil
evapotranspiration	:	vaporization of both plant and bare soil
field capacity	:	the amount of water held by the soil after excess water has drained through (Gibbon and Pain, 1985)
inflorescence	:	a group of flowers or individual shoot (Gibbon and Pain,1985)
leaf area index	:	the quantity of leaves per hectare maturity: grain filling period
panicle	:	an open and branched inflorescence, typical of the grass family, with pediceled flowers (Gibbon and Pain, 1985)
partitioning	:	division of dry matter over the different plant organs
pedicel	:	in an inflorescence, a branch that bears or supports a single flower or floret (Gibbon and Pain, 1985)
permanent wilting point	:	the level of soil moisture content at which the plant wilts permanently due to lack of water (Gibbon and Pain, 1985)
phenology	:	crop growth
photosynthesis	:	the process of converting water and carbon dioxide into sugars using light energy; the

		reaction is accom-panied by the production of oxygen (Gibbon and Pain, 1985)
respiration	:	breathing of a plant
tiller	:	side shoot of a grass or cereal plant arising at ground level (Gibbon and Pain, 1985)
transpiration	:	vaporization of the plant
transpiration coefficient	:	kg water transpired per unit dry matter produced (Van Keulen and Wolf, 1986)
water use efficiency	:	dry matter production per unit of moisture applied (Van Keulen and Wolf, 1986)

List of symbols

α	:	variable characterizing the evaporation process	cm $d^{-½}$
α	:	determined shape curve, inverse of pressure head by inflection point, where $d\Theta/dh$ is at its maximum	cm^{-1}
$\alpha(h)l$	:	layered wise reduction factor in the root zone	-
γ	:	psychometric constant	kPa $°C^{-1}$
Δ	:	slope vapour pressure curve	kPa $°C^{-1}$
ΔW	:	water storage change over a given time period	cm d^{-1}
$\Theta_{pF\ 4.2}$	:	soil moisture content at pF = 4.2	$cm^3\ cm^{-3}$
Θ_{crit}	:	critical soil moisture content	$cm^3\ cm^{-3}$
$\Theta_{pF\ 2.3}$	:	soil moisture content at pF = 2.3	$cm^3\ cm^{-3}$
Θ_r	:	residual soil moisture content	$cm^3\ cm^{-3}$
Θ_s	:	saturated soil moisture content	$cm^3\ cm^{-3}$
λ	:	latent heat of vaporization	MJ kg^{-1}
λET_0	:	latent heat flux of evaporation	kJ $m^{-2}\ s^{-1}$
Bm_t	:	biomass at time t	kg ha^{-1}
Bm_{t-1}	:	biomass at time t-1	kg ha^{-1}
$Bm_{t=1}$	:	biomass increase during specific time period	kg ha^{-1}
Bm_{pp}	:	biomass increase of a specific plant part	kg ha^{-1}
BM_T	:	total biomass increase	kg ha^{-1}
$C(h)=d\Theta/dh$	:	differential soil moisture capacity	cm^{-1}
c_p	:	specific heat moist air	kJ $kg^{-1}\ °C^{-1}$
CR	:	rate of capillary rise	cm d^{-1}
$CWDM$	:	cumulative actual weight of above ground biomass	kg ha^{-1}
e_a-e_d	:	vapour pressure deficit	kPa
E_a	:	actual evaporation rate of a soil	cm d^{-1}
E_p	:	potential evaporation rate of a soil	cm d^{-1}
ET_0	:	reference evapotranspiration of standard crop canopy	cm d^{-1}
Et_a	:	actual evapotranspiration	cm d^{-1}
Et_{aero}	:	aerodynamic term	cm d^{-1}
Et_p	:	potential evapotranspiration	cm d^{-1}
Et_{rad}	:	radiation term	cm d^{-1}
FTB	:	partioning factor for a specific plant part	
G	:	atmospheric density	kg m^{-3}
h	:	pressure head	cm
h	:	pressure head	kPa
h_1	:	pressure head at near-saturation below which oxygen persists	
h_2	:	pressure head at near-saturation at which air enters the soil without any flow resistance	
h_3^h	:	pressure head at which stomata starts to close prevent the crop from cell moisture depletion the evaporative demand of the atmosphere is extremely high (10 mm d^{-1})	

h_3^l	:	pressure head at which stomata starts to close since the amount of easily available moisture is consumed; the evaporative demand of the atmosphere is relative low (1 mm d^{-1})	
h_4	:	pressure head at which stomata are completely closed and transpiration is entirely ruled out (wilting point, 0 mm d^{-1})	
I	:	infiltration	cm d^{-1}
IC	:	interception	cm d^{-1}
K	:	hydraulic conductivity	cm d^{-1}
$k(h)$	:	hydraulic conductivity-pressure head relationship	cm d^{-1}
$S(h,z)$	:	sink term for water uptake by roots	cm d^{-1}
l	:	determines the shape of K-h relation	-
n	:	total number of depth intervals	-
n	:	determined rigidity of water retention characteristic	-
p	:	fraction of available soil water	-
P	:	precipitation rate	cm d^{-1}
$Perc$	:	percolation rate	cm d^{-1}
Q	:	net upward flow through the bottom of the profile	cm d^{-1}
r_a	:	aerodynamic resistance	s m^{-1}
r_c	:	crop canopy resistance	s m^{-1}
Rn	:	net radiation flux at surface	kJ m^{-2} s^{-1}
$Smax$	:	maximum possible extraction rate per unit depth of soil	d^{-1}
SR	:	rate of surface run-off	cm d^{-1}
SS	:	surface storage	cm d^{-1}
t	:	time	d
T_a	:	actual transpiration rate of a crop	cm d^{-1}
T_p	:	potential transpiration rate of a plant	cm d^{-1}
WUE	:	water use efficiency	kg ha^{-1} m^{-1}
z	:	depth below the soil surface	cm
z_i	:	layer thickness	cm

Annexes

Annex A Equations

Evapotranspiration

$$\lambda ET_0 = \frac{\Delta(R_n - G) + \rho C_p(e_a - e_d)\frac{1}{r_a}}{\Delta + \gamma(1 + \frac{r_c}{r_a})} \tag{10}$$

where:

λET_0	:	latent heat flux of evaporation	kJ m^{-2} s^{-1}
R_n	:	net radiation flux at surface	kJ m^{-2} s^{-1}
G	:	atmospheric density	kg m^{-3}
c_p	:	specific heat moist air	kJ kg^{-1} $°C^{-1}$
$(e_a$-$e_d)$	:	vapour pressure deficit	kPa
r_c	:	crop canopy resistance	s m^{-1}
r_a	:	aerodynamic resistance	s m^{-1}
Δ	:	slope vapor pressure curve	kPa $°C^{-1}$
γ	:	psychometric constant	kPa $°C^{-1}$
λ	:	latent heat of vaporization	MJ kg^{-1}

To facilitate the analysis of the combination equation the aerodynamic and radiation term are defined as:

$$ET_0 = ET_{rad} + ET_{aero} \tag{11}$$

where:

ET_0	:	reference evapotranspiration of standard crop canopy	cm d^{-1}
ET_{rad}	:	radiation term	cm d^{-1}
ET_{aero}	:	aerodynamic term	cm d^{-1}

Retention and conductivity curve

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^{1 - \frac{1}{n}}} \tag{12}$$

The permeability characteristic is described by the following formula:

$$K(h) = K_s \frac{((1 + |\alpha h|^n)^{1 - \frac{1}{n}} - |\alpha h|^{n - 1})^2}{(1 + |\alpha h|^n)^{(1 - \frac{1}{n})(l + 2)}} \tag{13}$$

where:

Θ_r	:	residual soil moisture content	$cm^3\ cm^{-3}$
Θ_s	:	saturated soil moisture content	$cm^3\ cm^{-3}$
α	:	determined shape curve, inverse of pressure head by inflection point, where $d\Theta/dh$ is at its maximum	cm^{-1}
n	:	determined rigidity of water retention characteristic	-
K	:	hydraulic conductivity	$cm\ d^{-1}$
l	:	determines the shape of K-h relation	-
h	:	pressure head	cm

(Wösten, 1994)

Sink term

Fig. 8 relates these pressure heads h_1 to h_4 to the $\alpha(h)$ reduction factor, where $\alpha(h)$ describes the relative transpiration:

$$\alpha(h) = \frac{T_{act}}{T_{pot}} \tag{14}$$

Where:

T_a	actual transpiration rate	$cm\ d^{-1}$
T_p	potential transpiration rate	$cm\ d^{-1}$

Since $\alpha(h)$ is scaled between 0 and 1, T_{act} cannot exceed T_{pot}.
The total actual transpiration is a cumulative contribution of the stretched uptake patterns:

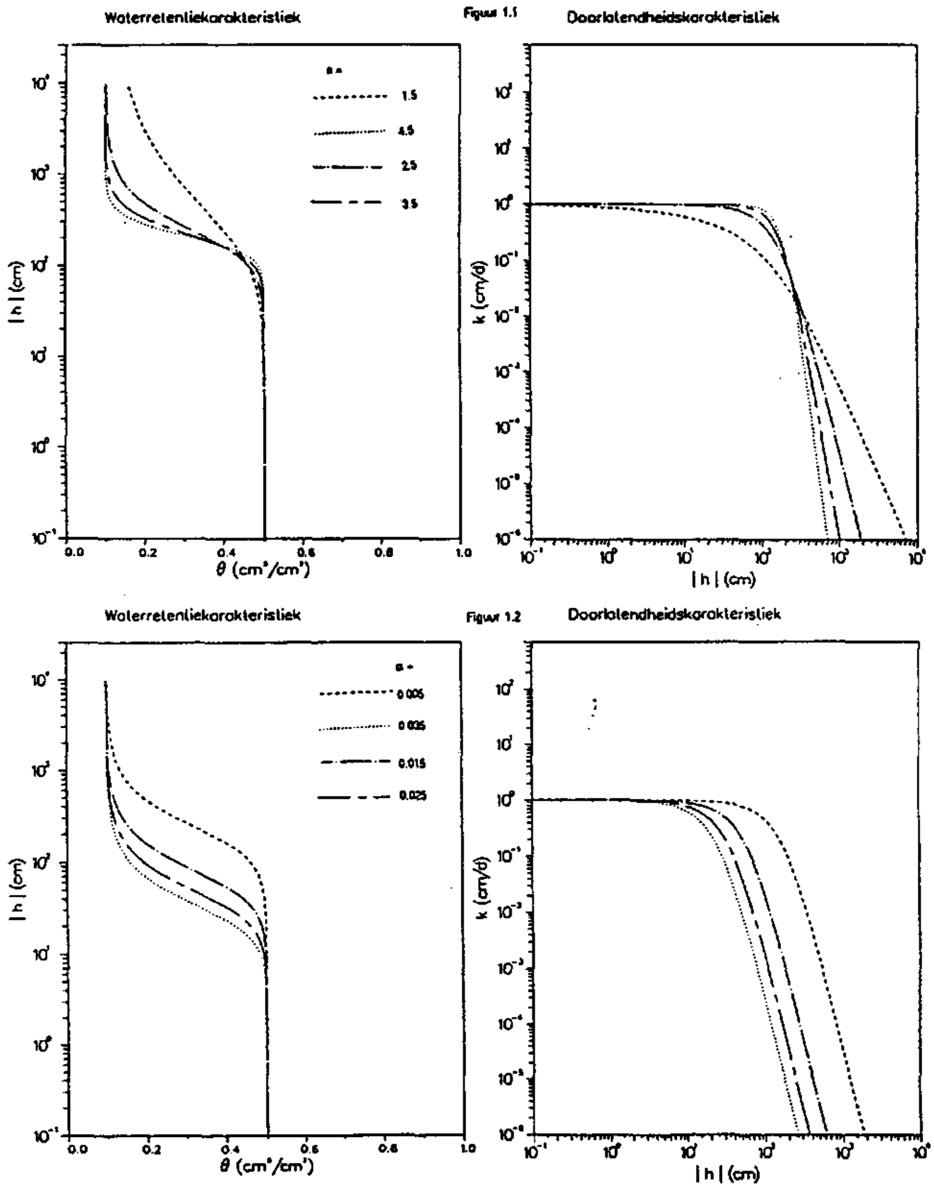
$$T_{act} = \sum_{i=1,n} \alpha(h)_i\ z_i\ S_{\max} \tag{15}$$

Where:

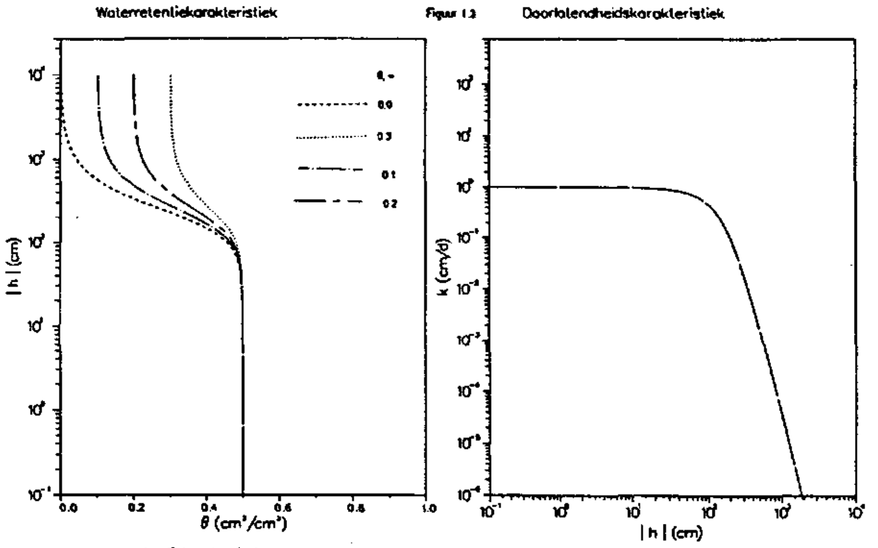
$\alpha(h)_i$	:	layered wise reduction factor in the root zone	-
z_i	:	layer thickness	cm
n	:	total number of depth intervals	-
S_{max}	:	maximum possible extraction rate per unit depth of soil	d^{-1}
T_a	:	actual transpiration	$cm\ d^{-1}$

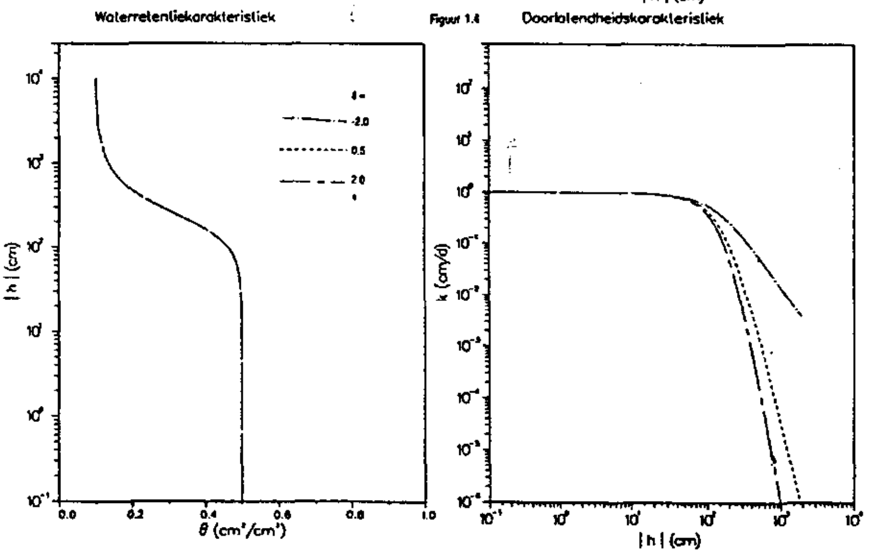
(Bastiaansen, 1994)

Annex B The influence of Van Genuchten variables at the retention and conductivity curve



Figuur 1.1 en 1.2 Effect van de parameters n en α op de curves.





Figuur 1.3 en 1.4 Effect van de parameters θ_r en ℓ op de curves.

Figuur	θ_s	θ_r	α	n	ℓ
1.1	0.5	0.1	0.005	1.5,2.5,3.5,4.5	0.5
1.2	0.5	0.1	0.005,0.015,0.025,0.035	2.5	0.5
1.3	0.5	0,0.1,0.2,0.3	0.005	2.5	0.5
1.4	0.5	0.1	0.005	2.5	0.5,-2.0,2.0

Annex C Division of rainfall data over a decade

decade	rainfall amount (mm)		number of showers		largeness of shower (mm)										contribution towards total rainfall (%)									
	5254	*6653*	*5254*	*6653*	*5254*					*6653*					*5254*					*6653*				
13		0.6		1						0.6										1.00				
14		2.6		1						2.6										1.00				
15		26.2		3						6.2	16	4								0.24	0.61	0.15		
16		0.7		1						0.7										1.00				
17	4.6	4.1	2	2	0.9	3.7				1.1	3				0.20	0.80				0.27	0.70			
18	22	23	2	3	21.5	0.5				4.6	18	0.4			0.98	0.02				0.20	0.75	0.02		
19	54.8	38.4	3	4	9.1	1.4	44			0.4	8.1	3.4	26.5		0.17	0.03	0.81			0.01	0.21	0.09	0.67	
20	58	43.5	2	4	43.4	14.6				0.5	5.7	33	4.7		0.75	0.25				0.01	0.13	0.73	0.11	
21	62.2	27	2	2	61.7	0.5				1.4	25.6				0.99	0.01				0.05	0.91			
22	63.4	33.2	5	5	43.8	2.7	11	1.4	4.1	8.2	2.9	5.8	3.5	12.8	0.69	0.04	0.18	0.02	0.06	0.25	0.09	0.17	0.10	0.37
23	73.4	80.3	5	4	56.4	0.9	9.2	6	0.9	53.8	11.5	6	9		0.77	0.01	0.13	0.08	0.01	0.67	0.14	0.07	0.11	
24	109.1	97.3	4	4	32.3	25.3	28	24		1	37.9	17	41.4		0.30	0.23	0.25	0.22		0.01	0.39	0.17	0.42	
25	27	68.9	3	4	10.9	13.5	2.6			14.3	30.1	17	7.5		0.40	0.50	0.10			0.21	0.43	0.24	0.11	
26	0.8		2		0.4	0.4									0.50	0.50								
27		0.5		1						0.5										1.00				

5524: place situated at 13°55' N.L. and 2°24' W.Long.
6653: place situated at 13°66' N.L. and 2°53' W.Long.

Annex D Calculation of input data *TDWI*

The initial crop weight of one seed is 2.5 g. Total amount of plants per hectare is 10,000 m^2 (a hectare) divided by the square plant density. For the calibration a plant density of 125 cm was taken, makes 6400 plant/hectare. In general two plants are growing per planting hole, thus there are 12800 plants ha^{-1}, this is corresponding with 32 kg TDWI.

LAIEM

fraction initially partitioned to the aboveground parts: 1-FRTB = 1-0.6 = 0.4
initial aboveground biomass: 32 × 0.4 = 12.8 kg ha^{-1}
fraction initially partitioned to the leaves (FLTB): 0.8
initial leave biomass: 12.8 × 0.8 = 10.24 kg ha^{-1}
initial LAI: initial leave biomass × specific leave area (SLATB) = 10.24 × 0.0018 = 0.0184

The values for TDWI and LAIEM used during the simulation are given in the shown Table. These values are calculated corresponding the above mentioned method.

Table D1: simulated TDWI and LAIEM

Plant density (cm)	TDWI	LAIEM
50	200	0.1152
75	89	0.050
100	50	0.0288
125	32	0.0184
150	22	0.0128

Table D2: Increase in biomass and total biomass production

DVS	Aboveground biomass		Roots		Total biomass		Leaves[1]		Stems[1]		Storage organs[1]		Total aboveground biomass	
	increase	total	increase	total	increase	total	increase	total	increase	total	increase	total	increase	total
0	-	-	0	0	0		-	-	-	-	-	-	-	-
0.25	-	-	0.034	0.034	0.034	0.034	-	-	-	-	-	-	-	-
0.29	0.1	0.1	0.064	0.098	0.164	0.2	0.1	0.1	-	-	-	-	0.1	0.1
0.5	4.6	4.7	3.1	3.2	7.7	7.9	4.6	4.7	-	-	-	-	4.6	4.7
0.56	6.6	11.2	4.0	7.1	10.5	18.4	6.5	11.1	0.1	0.1	-	-	6.6	11.2
1.0	231.2	242.4	107.9	115.0	339.1	357.4	116.7	127.8	114.4	114.5	0.1	0.1	231.2	242.4
1.25	333.0	575.4	142.2	257.2	475.2	832.6	80.5	208.4	208.3	322.9	44.1	44.2	333.0	575.4
1.5	390.8	966.2	126.4	383.6	517.1	1349.8	41.0	249.3	112.6	435.4	237.2	281.4	390.8	966.2
1.75	217.7	1183.9	74.9	458.5	292.7	1642.4	15	264.3	34.2	469.6	168.6	450.0	217.7	1183.6
2.0	73.4	1257.3	39.8	498.3	113.2	1755.6	5.0	269.6	9.3	478.9	58.8	508.8	73.4	1257.3

Calculation method for measured partitioning factors

Of every plant part the increase in biomass over a specific time span is calculated (see values in the Table above).

$$BM_t - BM_{t-1} = BM_{t=1} \tag{16}$$

Whereafter the contribution of every plant part to the total biomass is calculated by dividing biomass increase of a certain plant by total biomass (see the values in the Table above).

$$\frac{BM_{pp}}{BM_T} = FTB \tag{17}$$

BM_t: biomass at time t kg ha^{-1}
Bm_{t-1}: biomass at time t-1 kg ha^{-1}
$Bm_{t=1}$: biomass increase during specific time period kg ha^{-1}
Bm_{pp}: biomass increase of a specific plant part kg ha^{-1}
BM_T: total biomass increase kg ha^{-1}
FTB: partioning factor for a specific plant part

Table D3: Partitioning factors calculated and according to Van Heemst

DVS	Aboveground		Root		Leaves		Stem[1]		Storage Organs[1]	
	M	VH	M	VH	M	VH	M	VH	M	VH
0	0	0.4	1	0.6	-	0.8	-	0.2	-	0
0.2	0		1							
0.25	0.3		0.7		-	0.8	-	0.2	-	0
0.29	0.61		0.39		1		-		-	
0.5	0.6		0.4		1		-		-	
0.56	0.62		0.38		0.98		0.02		-	
1	0.68	0.86	0.32	0.14	0.5		0.49		0	
1.13						0.12		0.88		0
1.25	0.7		0.3		0.24		0.63		0.13	
1.3		1		0		0		0.64		0.36
1.5	0.76		0.24		0.1		0.29		0.61	
1.6						0		0		1
1.75	0.74		0.26		0.07		0.16		0.77	
2	0.65	1	0.35	0	0.07	0	0.13	0	0.8	1

M: measured
VH: Van Heemst

Annex E Output files

Crop output

```
*DATE         ID DVS   LAI   CH   RD   CRT0 CRT1 CPWDM CWDM  CPWSO CWSO *
*dd/mm/yyyy                  cm   cm             kg/ha kg/ha kg/ha kg/ha*
<=============><===><===><===><==><==><===><===><====><====><====><====>
 30/ 6/1992  19   .46   .19    3   31   .41 1.00   159   106     0     0
 14/ 7/1992  33   .79   .15   41   48   .18 1.00   314   106     0     0
 17/ 7/1992  36   .87   .15   51   52   .15 1.00   379   106     0     0
.
.
.
  6/ 9/1992  87 1.78   .08 138   79   .04   .00  2740   106  1315     0
  8/ 9/1992  89 1.81   .08 139   79   .04   .00  2860   106  1435     0
 10/ 9/1992  91 1.85   .08 140   79   .04   .00  2983   106  1558     0
```

Soil output

**.bal*

```
*DATE       RAIN IRR   RUO   EVP   TRA [cm]  EVS [cm]  FLUX [cm] GWL *
*dd/mm/yyyy cm   cm    cm    cm    pot..act  pot..act  lat..bot  cm  *
<=========><===><===><===><===><===><===><===><===><===><===><===><===>
 18/ 5/1992   .0    .0    .0    .0    .0    .0    .3    .0    .0    .0  999
 24/ 5/1992   .1    .0    .0    .0    .0    .0   1.8    .1    .0    .0  999
  1/ 6/1992   .8    .0    .0    .0    .0    .0   4.0    .7    .0    .0  999
.
.
.
  7/10/1992 47.8    .0    .0    .0   5.0    .2  36.3  16.6    .0  17.8  999
  9/10/1992 47.8    .0    .0    .0   5.0    .2  36.9  16.7    .0  17.9  999
 31/10/1992 47.8    .0    .0    .0   5.0    .2  43.5  17.4    .0  18.5  999
```

**.sal*

date : 18/ 5/1992

depth	theta	pres. hd	sol.conc	sol.comp
cm	cm3/cm3	cm	mg/cm3	mg
-.5	.012	-59.683	.000	.000
-1.5	.020	-51.301	.000	.000
-2.5	.020	-51.301	.000	.000
-3.5	.020	-51.301	.000	.000
-4.5	.020	-51.301	.000	.000
-6.3	.022	-49.706	.000	.000
-8.8	.022	-49.706	.000	.000
-12.5	.024	-48.266	.000	.000
-17.5	.024	-48.267	.000	.000
-22.5	.024	-119.009	.000	.000
-27.5	.033	-97.250	.000	.000
-32.5	.033	-97.249	.000	.000
-40.0	.041	-86.002	.000	.000
-50.0	.045	-81.770	.000	.000
-60.0	.048	-79.004	.000	.000
-70.0	.048	-79.003	.000	.000
-80.0	.047	-79.891	.000	.000
-90.0	.047	-79.891	.000	.000
-100.0	.048	-79.004	.000	.000
-110.0	.048	-79.003	.000	.000
-120.0	.046	-80.812	.000	.000
-130.0	.046	-80.813	.000	.000
-140.0	.050	-77.320	.000	.000
-150.0	.050	-77.319	.000	.000
-160.0	.047	-79.891	.000	.000
-170.0	.047	-79.891	.000	.000

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.
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date : 31/10/1992

depth	theta	pres. hd	sol.conc	sol.comp
cm	cm3/cm3	cm	mg/cm3	mg
-.5	.100	**********	.000	.000
-1.5	.100	**********	.000	.000
-2.5	.100	**********	.000	.000
-3.5	.100	**********	.000	.000
-4.5	.100	**********	.000	.000
-6.3	.100	**********	.000	.000
-8.8	.100	**********	.000	.000
-12.5	.100	**********	.000	.000
-17.5	.100	**********	.000	.000
-22.5	.350	**********	.000	.000
-27.5	.350	**********	.000	.000
-32.5	.350	**********	.000	.000
-40.0	.350	**********	.000	.000
-50.0	.350	**********	.000	.000
-60.0	.350	**********	.000	.000
-70.0	.350	**********	.000	.000
-80.0	.350	**********	.000	.000
-90.0	.350	**********	.000	.000
-100.0	.350	**********	.000	.000
-110.0	.350	**********	.000	.000
-120.0	.350	**********	.000	.000
-130.0	.350	**********	.000	.000
-140.0	.350	**********	.000	.000
-150.0	.350	**********	.000	.000
-160.0	.350	**********	.000	.000
-170.0	.350	**********	.000	.000

Annex F Required input, its description, values and references

The input and output is divided in several types, they are mentioned below:

GI
general input
SI
soil input
SSI
simple soil input
DSI
detailed soil input
SO
soil output
SSO
simple soil output
DSO
detailed soil output
CI
crop input
SCI
simple crop input
DCI
detailed crop input
CO
crop output
SCO
simple crop output
DCO
detailed crop output

Key file

CODE	TYPE	DESCRIPTION	UNIT	VALUE	REFERENCE	REMARKS
PATH	GI	path from the root directory to subdirectory TRIGGER	-			
ICRMOD	GI	type of crop model to trigger	-	2		
ISOMOD	GI	type of soil model to trigger	-	2		
Time variables						
Start date simulation period			-			
End date simulation period			-			
Start irrigation scheduling period			-			
FMAY	GI	number of the first month of the agricultural year	-			
Parameters concerning the numerical scheme (detailed soil model)						
DTMIN	GI	minimum value of time step allowed	d	1.0×10^{-5}		
DTMAX	GI	maximum value of time step allowed	d	0.1		
SWNUM	GI	switch for setting the iteration precision of the numerical calculation scheme this scheme is used for the solution of the Richards' equation: 1 = implicit scheme with 1 (one) iteration, 2 = implicit scheme with iteration till convergence is reached				
RELTOL	GI	relative tolerance to calculate maximum pressure head change per timestep	-	2×10^{-3}		
ABSTOL	GI	absolute tolerance to calculate maximum pressure head change per timestep	-	1.0		
Input variables METEO submodel						
METFIL	GI	name of the meteo station (implicit name of weather data files)	-			
LAT	GI	latitude of the station in degrees and decimal degrees, positive for the Northern hemisphere	°	13.3	Goutorbe *et al.*	
ALT	GI	altitude of the station above or below mean sea level	m	300	estimated	
SWETR	GI	switch indicating if values for reference evapotranspiration must be used in stead of calculated ones				measured, specified in the meteo data files
Ponding						

PONDMX	GI	maximum thickness of ponding water layer on the soil surface before runoff starts	cm	1.0	estimated	
Soil evaporation						
RSIGNI	GI	significance threshold daily rainfall	cm	0.2	estimated	if rainfall (or irrigation) exceeds the threshold value, the extinction function, used in the Black model to calculate soil evaporation, is reset
Soil physical parameters						
SOLFIL	GI	name of the file or files with Van Genuchten parameters	-			
Soil profile data						
NUMLAY	SDI	number of soil layers	-	2		
NUMNOD	SDI	number of soil compartments	-	26		
BOTCOM	SDI	array with numbers of compartment at the bottom of each soil layer	-	9, 26		
DZ	SDI	array with thickness of each soil compartment	cm	serie	measured	
Sink term parameters						
HLIM1	GI	pressure head below which roots start to extract water from the soil	cm	-10	estimated	
HLIM2U	GI	pressure head below which roots start to extract water optimally from the upper soil layer	cm	-50	estimated	
HLIM2L	GI	the same for all lower soil layers	cm	-50	estimated	
HLIM3H	GI	pressure head below which roots cannot extract water optimally any more, in case of high atmospheric demand	cm	-500	Bastiaanssen	the threshold values defining high and low atmospheric demand are crop specific and as such must be specified in the crop data set
HLIM3L	GI	the same, in case of low atmospheric demand	cm	-2000	Bastiaansen	
HLIM4	GI	pressure head below which no water uptake by roots is possible	cm	-16000	Bastiaansen	
Rooting depth limitation						
RDS	GI	maximum rooting depth allowed by the soil	cm	200	estimated	for instance because of an impermeable layer rooting depth may be limited
Drainage						
SWDRAI	GI	switch for simulation of drainage	-			
Salt						
SWSOLU	SDI	switch for simulation of solute transport				
CMLI	SDI	array with initial salt concentrations in the soil compartments				
OSMOTA	SDI	first regression coefficient				
OSMOTB	SDI	second regression coefficient in equation for the calculation of osmotic head				
Initial soil moisture conditions						
AWINIT	SSI	initial available water in rootable zone (fraction of saturation)	fraction	0.025	derived	
GWLI	SSI	initial groundwater level (groundwater case only)	cm	1000	estimated	will be taken into account, because of the free draining profile
Initial soil moisture conditions						
SWINCO	SDI	choice of initial soil moisture condition	-	0		
THETAI	SDI	initial moisture content of the soil compartments	-	serie	measured	
HI	SDI	initial pressure head at nodal points				
GWLI	SDI	initial groundwater level				
Run specific information						
IRGNAM	GI	generic name of the irrigation input files (IRRIG)	-			
TIMFIL	GI	name of the input file with output dates (TIMER)	-			
CRPFIL	GI	name of the input file with crop parameters (CROP)	-			
EMERG.	GI	date of crop emergence (TIMER)	-			
End_crop	GI	forced last day of active crop growth, relevant only in case maturity has not been reached earlier (TIMER)	-			
BBCFIL	GI	name input file with bottom boundary conditions (SOIL)	-			
LBCFIL	GI	name input file with lateral boundary conditions (SOIL)	-			
OUTNAM	GI	generic name of output files	-			

Meteo file

station name	-		
date	-		
solar radiation	kJ/m^2		measured
minimum temperature	°C		measured
maximum temperature	°C		measured
mean air humidity	kPa		measured
mean windspeed	ms^{-1}		measured
rainfall	mm		measured
reference evapotranspiration	mm		measured

Crop file

Crop height						
CHTAB	DCI	table specifying crop height as a function of development stage of the crop	m	serie	measured	
Phenology						
IDSL	DCI	indicates if pre-anthesis development is driven by temperature, daylength or both	-	0		
DLO	DCI	optimum daylength for development	h	1		DLO and DLC to be specified only in case IDSL is greater than zero
DLC	DCI	minimum daylength for development (lower threshold)	h	1		
TSUMEA	DCI	temperature sum from emergence to anthesis	°C	738	van Heemst/calculated	
TSUMAM	*DCI*	*temperature sum from anthesis to maturity*	°C	1008	*van Heemst/calculated*	
DTSMTB	DCI	table specifying daily increase in temperature sum as a function of 24h average temperature	°C	serie	Ong/Monteith	
DVSEND	DCI	development stage at harvest	-	2		
Initial						
TDWI	DCI	crop weight at emergence (depends on sowing density)	kg/ha		vanHeemst/ vanDiepen	simulation dependable
LAIEM	DCI	leaf area index at emergence	ha/ha		calculated	if crop weight at emergence is determined, LAI at emergence can be calculated, simulation dependable
RGRLAI	DCI	maximum relative increase in LAI	ha/ha/d	0.0188	WOFOST6.0	
Green area						
SLATB	DCI	table specifying specific leaf area as a function of development stage of the crop	ha/kg	serie	van Heemst	
SPA	DCI	specific pod area	ha/kg	0.0	van Diepen *et al.*	
SSA	DCI	specific stem area	ha/kg	0.0035	van Diepen *et al.*	
SPAN	DCI	life span of leaves under optimum conditions	d	59.0	van Diepen *et al.*	
TBASE	DCI	lower threshold temperature (24h average) for ageing of leaves	°C	10.0	van Heemst	
Assimilation						
KDIF	DCI	extinction coefficient for diffuse light	-	0.6	van Heemst	
EFF	DCI	initial light use efficiency	$kg/ha/hr/Jm^2s$	0.45	van Heemst/WOFOST6.0	
AMAXTB	DCI	table specifying assimilation rate at light saturation as a function of development stage of the crop	kg/ha/hr	serie	van Heemst	
TMPFTB	*DCI*	*table specifying reduction factor of AMAX as a function of 24h average temperature*	°C	*serie*	van Heemst	
TMNFTB	DCI	table specifying reduction factor of AMAX as a function of low (7 day running) minimum temperature	°C	serie	van Heemst	
Conversion of assimilates into biomass						
CVL	DCI	efficiency of conversion of primary assimilates into leaves	kg/kg	0.72	van Diepen *et al.*	
CVO	DCI	idem into storage organs	kg/kg	0.74	van Diepen *et al.*	
CVR	DCI	idem into roots	kg/kg	0.72	van Diepen *et al.*	
CVS	DCI	idem into stems	kg/kg	0.69	van Diepen *et al.*	

Maintenance respiration						
Q10	DCI	factor accounting for increase in maintenance respiration with a 10 degrees rise in (24h average) temperature	-	2.0	van Diepen *et al.*	
RML	DCI	relative maintenance respiration rate of leaves	kg CH_2O/kg/d	0.020	van Diepen *et al.*	
RMO	DCI	idem of storage organs	kg CH_2O/kg/d	0.007	van Diepen *et al.*	
RMR	DCI	idem of roots	kg CH_2O/kg/d	0.007	van Diepen *et al.*	
RMS	DCI	idem of stems	kg CH_2O/kg/d	0.010	van Diepen *et al.*	
RFSETB	DCI	table specifying reduction factor for senescence as a function of development stage of the crop	-	0.00		not specified, do not really influence crop growth
Partitioning						
FRTB	DCI	table specifying fraction of total dry matter increase allocated to the roots as a function of development stage	-	serie	van Heemst	
FLTB	DCI	idem to the leaves	-	serie	van Heemst	
FSTB	DCI	idem to the stems	-	serie	van Heemst	
FOTB	DCI	idem to the storage organs	-	serie	van Heemst	
Death rates						
PERDL	DCI	maximum relative death rate of leaves due to water stress	1/d	0.030	van Diepen *et al.*	
RDRRTB	DCI	table specifying relative death rates of roots as a function of development stage of the crop	kg/kg/d	serie		default value
RDRSTB	DCI	idem of stems	kg/kg/d	serie		default value
Water use						
ADCRH	CI	threshold level for high atmospheric demand	cm	0.5		default value
ADCRL	CI	threshold level for low atmospheric demand	cm	0.1		default value
OSMOTP	CI	salt tolerance factor				if OSMOTP = 1, the osmotic potential contributes fully to the total potential, if OSMOTP = 0, the total potential is only determined by the hydraulic potential
Rooting						
RDI	DCI	rooting depth at emergence	cm	10.0	measured	
RRI	DCI	maximum daily increase in rooting depth	cm/d	1.2	derived	
RDC	DCI	maximum rooting depth of the crop/cultivar	cm	220.0	van Heemst	
Crop output (OUTNAM.CRP)						
DATE	CO	date label of the output record	-			
ID	CO	daynumber since start of active crop growth	-			
DVS	DCO	development stage of the crop (0 = emergence, 1 = flowering, 2 = maturity)	-			
LAI	DCO	leaf area index	ha/ha			
CH	DCO	crop height	cm			
RD	CO	rooting depth	cm			
CRT0	CO	cumulative relative transpiration since emergence (= cum. transpiration / cum. potential transpiration)	fraction			
CRT1	DCO	cumulative relative transpiration since flowering	fraction			
CPWDM	DCO	cumulative potential weight of above ground biomass	kg/ha			
CWDM	DCO	cumulative actual weight of above ground biomass	kg/ha			
CPWSO	DCO	cumulative potential weight of storage organs	kg/ha			
CWSO	DCO	cumulative actual weight of storage organs	kg/ha			
KC	SCO	crop coefficient	-			
RELY	SCO	cumulative relative crop yield	fraction			

Soil file

Van Genuchten parameters						
COFGEN 1	SI	residual moisture content	cm^3/cm^3		measured	measured with aid of neutron probe method
COFGEN 2	SI	saturated moisture content	cm^3/cm^3		measured	measured with aid of neutron probe method
COFGEN 3	SI	saturated hydraulic conductivity	cm/d		measured	measured with aid of a disc permeameter
COFGEN 4	SI	alpha	cm^{-1}		determined	determined with aid of soil samples and RETC model
COFGEN 5	SI	L	-		determined	determined with aid of soil samples and RETC model
COFGEN 6	SI	n	-		determined	determined with aid of soil samples and RETC model
BASEGW	SI	depth of semi-impermeable layer, base of the aquifer	m (-)			
L	SI	spacing between drains	m			
ZBOTDR	SI	depth of bottom of drains	cm (-)			
WETPER	SI	wet perimeter of the drain tube, calculated as width of drain trench plus two times the outer radius of the pipe drain	cm			

Bottom boundary conditions					
GWLTAB	SI	table specifying groundwater level as a function of time[1]	cm		one of three options should be chosen
QBOTAB	SI	table specifying flux from the saturated zone as a function of time[1]	cm/d		
free drainage	SI		-	choice	
CGRTAB	SDI	table specifying salt concentration as a function of time[1]	mg/cm^3		in case of condition 1 or condition 2 and if salt transport should be simulated (**SWSOLU** in **TRIGGER.KEY** set to 1) the salinity of the groundwater must be specified
Soil output (OUTNAM.BAL AND OUTNAM.SAL)					
DATE	SO	date label of the output record	-		
RAIN	SO	cumulative rainfall	cm		
IRR	SO	cumulative irrigation depth	cm		
RUO	DSO	cumulative runoff	cm		
EVP	SO	cumulative evaporation from ponding layer	cm		
TRA	SO	cumulative potential and actual transpiration	cm		
EVA	SO	cumulative potential and actual soil evaporation	cm		
FLUX	SO	cumulative flux through the lateral of the profile (drainage flux)	cm		
		cumulative flux through the bottom of the profile	cm		
GWL	SO	groundwater level, not relevant in case of free drainage	cm		
Z	DSO	depth of the centre of the compartment	cm		one record for each soil compartment
THETA	DSO	soil moisture content	cm^3/cm^3		one record for each soil compartment
H	DSO	pressure head	cm		one record for each soil compartment
SA	DSO	salt concentration of soil moisture	mg/cm^3		one record for each soil compartment
SACOMP	DSO	salt content of the compartment	mg		one record for each soil compartment
FRAW	SSO	available water in the rooted zone: fraction of the amount between field capacity and wilting point	fraction		
TSR	SSO	cumulative surface runoff	cm		

notes:

- In addition to the required data a timer file is required. Established dates will be written as output.
- During this simulation irrigation, solute transport and lateral boundary layers are not taken into account.
- More detailed information about the TRIGGER programme can be found in SC-DLO, 1994.

Annex G Input files

Key file

```
<== m100s120.key ======================================================>
<==                                                                  ==>
<==            HYDRA MODEL TRIGGER -  general input data             ==>
<==                                                                  ==>
<======================================================================>
<==                                                                  ==>
<== Demo run TRIGGER, version November  1994                         ==>
<==                                                                  ==>
<========1=========2=========3=========4=========5=========6=========7=>

##Path to TRIGGER
- PATH   path from root to subdir TRIGGER.......<c:\margo\            > C

##TRIGGER configuration
- ICRMOD type of crop model to trigger [simple = 1, detailed = 2]..<2> I
- ISOMOD type of soil model to trigger [simple = 1, detailed = 2]..<2> I

##Time variables
- Start  of the simulation run.............[dd/mm/yyyy]..<18/05/1992> D
- End    of the simulation run.............[dd/mm/yyyy]..<31/10/1992> D
- Start  of the irrig. scheduling period....[dd/mm/yyyy]..<01/01/2000> D
  dd=99: start coincides with crop emergence
- FMAY   first month of the agricultural year [January = 1].......<01> I

##Additional time variables (detailed soil model)
- DTMIN  min. value of timestep allowed [d:1.E-8,0.1]......<   1.0E-5> R
- DTMAX  max. value of timestep allowed [d: 0.01-0.5]......<     0.1 > R
- SWNUM  type of implicit scheme used [1 or 2].....................<1> I
- RELTOL relative tolerance...............................<   2.0E-3> R
- ABSTOL absolute tolerance...............................<      1.0> R

##Meteo
- METFIL name of the meteo station.........................<scen120 > C
- LAT    latitude of the station [degr., N=+]..............<     13.3> R
- ALT    altitude of the station [m]........................<    300.0> R
- SWETR  use ETRef values, if specified................[Y=1, N=0]..<1> I

<== top (of soil) boundary =============================================>

##Ponding
- PONDMX max. thickness of ponding water layer [cm]........<   1.0    > R

##Soil evaporation
- RSIGNI significance threshold daily rainfall [cm]........<   0.2    > R

<== soil ===============================================================>

##Soil physical parameters (simple soil model)
- SOLFIL file with data [.SOL].............................<      mhs> C

##Geometry of the soil profile (detailed soil model)
- NUMLAY number of soil layers (max.=5)...........................<2> I
- NUMNOD number of soil compartments (max.=40)...................<26> I
- BOTCOM compartment number at bottom of soil layers:
<==1==><==2==><==3==><==4==><==5==> I
    9     26
<==1==><==2==><==3==><==4==><==5==> I
- DZ     thickness of soil compartments [cm]:
<==1==><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
   1.0     1.0     1.0     1.0     1.0     2.5     2.5     5.0     5.0     5.0
   5.0     5.0    10.0    10.0    10.0    10.0    10.0    10.0    10.0    10.0
  10.0    10.0    10.0    10.0    10.0    10.0
<=====><=====><=====><=====><=====><=====><=====><=====><=====><==40=> R
```

```
##Soil physical parameters (detailed soil model)
- SOLFIL file with data [.SOL, one for each soil layer]:
<======> C
 up10
 down6
<======> C

##Sink term parameters (detailed soil model)
- HLIM1  pressure head [cm] below which roots start to ex-
         tract water from the soil (starting point)........<     -10.0> R
- HLIM2U pr. head value [cm] below which roots start to ex-
         tract water optimally from the Upper soil layer...<     -50.0> R
- HLIM2L as above, but for all Lower soil layers...........<     -50.0> R
- HLIM3H pr. head [cm] below which roots cannot extract
         water optimally anymore, if high atm. demand......<   -2000.0> R
- HLIM3L pr. head [cm] below which roots cannot extract
         water optimally anymore, if low atm. demand.......<    -500.0> R
- HLIM4  pr. head [cm] below which no water uptake by roots
         is possible (wilting point).......................< -16000.0> R

##Rooting depth limitation
- RDS    maximum rooting depth allowed by the soil [cm]....<     200.0> R

##Drainage
- SWDRAI simulation of lateral drainage................[Y=1, N=0]..<0> I

##Salt (detailed soil model)
- SWSOLU simulation of solute transport................[N=0, Y=1]..<0> I
         If SWSOLU = 1:
- CMLI   initial solute conc. in compartments [mg/cm3]
<==1==><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
<=====><=====><=====><=====><=====><=====><=====><=====><=====><==40=> R
- OSMOTA coeff. A in eqn calc. osmotic head [cm]...........<     0.0  > R
- OSMOTB coeff. B in eqn calc. osmotic head [cm4/mg].......<     0.0  > R

##Initial soil moisture conditions (simple soil model)
- AWINIT available water in rootzone [fraction] ...........<     0.025> R
- GWLI   initial groundwater level [cm]....................<    1000.0> R

##Initial soil moisture conditions (detailed soil model)
- SWINCO selects type of initial conditions........................<0> I
         = 0: volumetric moisture content [cm**3/cm**3] at each
              nodal point is input,
         = 1: pressure head at each nodal point is input [ cm,
              unsaturated = negative value],
         = 2: pressure head at each nodal point is calculated as
              equilibrium with the initial groundwater Table,

++       If SWINCO = 0:
- THETAI initial moisture content of compartments:
<==1==><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
 0.020  0.020  0.020  0.020  0.020  0.022  0.022  0.024  0.024  0.024
 0.033  0.033  0.041  0.045  0.048  0.048  0.047  0.047  0.048  0.048
 0.046  0.046  0.050  0.050  0.047  0.047
<=====><=====><=====><=====><=====><=====><=====><=====><=====><==40=> R

++       If SWINCO = 1:
- HI     initial pressure head at nodal points: pressure heads in the
         unsaturated zone are negative, in the saturated zone posi-
         tive and equal to depth below groundwater level
<=====1=====><===========><===========><===========><===========> R
<===========><===========><===========><===========><=====40=====> R

++       If SWINCO = 2:
- GWLI   initial groundwater level [cm], may be skipped if
         groundwater level is input........................<          > R
```

```
## Run specific information - maximum 30 runs =========================>

IRGNAM  TIMFIL  CRPFIL    EMERGENCE  END_crop   BBCFIL  LBCFIL  OUTNAM
        .DAT    .CRP      dd/mm/yyyy dd/mm/yyyy .BBC    .LBC
<======><======><======> <=========> <=========> <======><======><======>
        sim92   mil100    12/06/1992 10/09/1992  bound1          m100s120
<======><======><======> <=========> <=========> <======><======><======>
  TEST41 YR2000 WHEATD    22/04/2000 25/09/2000  BOTBC2  LATBC1 OUT21241
  TEST41 YR2000 SORGHUMS  22/04/2000 25/09/2000  BOTBC2  LATBC1 OUT12241
  TEST41 YR2000 WHEATD    22/04/2000 25/09/2000  BOTBC2  LATBC1 OUT22241
```

Meteo file

```
* MSTAT  DATE        RAD    TMN    TMX    HUM    WIN    RAI    ETRef*
*        dd/mm/y     kJ/m2  C      C      kPa    m/s    mm     mm    *
<======> <========><====><====><====><====><====><====><====>
 ce6653  1/ 1/1992  1941. 15.8  27.5  .005   3.3    .0   5.3
 ce6653  2/ 1/1992  1791. 16.2  26.9  .005   3.0    .0   5.0
 ce6653  3/ 1/1992  1304. 16.1  25.6  .005   2.8    .0   3.9
 ce6653  4/ 1/1992  1691. 15.0  24.9  .005   2.9    .0   4.6
 ce6653  5/ 1/1992  1758. 15.0  25.2  .004   3.1    .0   4.7
 ce6653  6/ 1/1992  1697. 14.8  26.2  .005   2.7    .0   4.6
 ce6653  7/ 1/1992  2090. 14.0  28.4  .006   2.5    .0   5.3
 ce6653  8/ 1/1992  2057. 11.1  29.6  .005   2.5    .0   5.4
 ce6653  9/ 1/1992  1989. 15.1  27.2  .006   2.9    .0   5.2
.
.
.
 ce6653 21/12/1992  2154. 15.3  35.3  .008   2.3    .0   6.2
 ce6653 22/12/1992  2031. 15.3  35.2  .008   2.4    .0   6.2
 ce6653 23/12/1992  1774. 15.3  35.2  .008   2.3    .0   6.2
 ce6653 24/12/1992  2090. 15.2  35.1  .007   2.4    .0   6.2
 ce6653 25/12/1992  2105. 15.2  35.0  .008   2.3    .0   6.2
 ce6653 26/12/1992  2065. 15.2  35.0  .007   1.9    .0   6.2
 ce6653 27/12/1992  2068. 15.2  34.9  .010   1.9    .0   6.2
 ce6653 28/12/1992  1932. 15.2  34.8  .010   1.4    .0   6.1
 ce6653 29/12/1992  2096. 15.1  34.7  .010   1.5    .0   6.1
 ce6653 30/12/1992  1971. 10.0  36.0  .009   1.6    .0   6.9
 ce6653 31/12/1992  1825. 14.6  35.7  .009   1.9    .0   7.5
```

Crop file

```
<== lemil9.crp =========================================================>
<==                                                                   ==>
<==               HYDRA - crop data /detailed crop routine            ==>
<==                                                                   ==>
<=======================================================================>
<==                                                                   ==>
<== Run millet measured during IOP HAPEX-Sahel 1992                   ==>
<==                                                                   ==>
<========1=========2=========3=========4=========5=========6=========7=>

##CROP HEIGHT
- CHTAB  AFGEN-table (max. 15 data pairs): crop height        X:-
         as a function of development stage of the crop       Y:m
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
   0.00   0.00   0.25   0.00   0.50   0.04   1.00   0.68   1.25   1.09
   1.50   1.32   2.00   1.44   0.00   0.00   0.00   0.00   0.00   0.00
   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
```

```
##PHENOLOGY
- IDSL   indicates whether pre-anthesis development depends........<0> I
         on temp. (=0), daylength (=1), or both (=2)
- DLO    optimum daylength for development    [h]..........<   1.0    > R
- DLC    critical daylength (lower threshold) [h]..........<   1.0    > R
- TSUMEA temp. sum from emergence to anthesis [C]..........< 738.0    > R
- TSUMAM temp. sum from anthesis to maturity  [C]..........< 1008.0   > R
- DTSMTB AFGEN-table (max. 15 data pairs): daily increase      X:C
         in temperature sum as function of AVerage Temp.       Y:C
<=AVT=><=====><=AVT=><=====><=AVT=><=====><=AVT=><=====><=AVT=><=====> R
  0.00   0.00  10.00   0.00  19.00   9.00  25.00  15.00  28.00  18.00
 34.00  18.00  45.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- DVSEND development stage at harvest.....................<  2.00    > R

##INITIAL
- TDWI   initial total crop dry weight [kg/ha].............<  50.0    > R
- LAIEM  leaf area index at emergence [ha/ha]..............< 0.0288   > R
- RGRLAI maximum relative increase in LAI [ha/ha/d]........< 0.03     > R

##GREEN AREA
- SLATB  AFGEN-table (max.15 data pairs): specific leaf        X:-
         area as a function of dev. stage of the crop          Y:ha/kg
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00 0.0018   0.15 0.0020   0.40 0.0027   0.85 0.0018   2.00 0.0018
  0.00  0.00    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00  0.00    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- SPA    specific pod area  [ha/kg]........................< 0.0      > R
- SSA    specific stem area [ha/kg]........................< 0.0035   > R
- SPAN   life span of leaves under optimum.................< 59.0     > R
         temperature and daylength conditions [d]
- TBASE  lower threshold temp. for ageing of leaves [C]....< 10.0     > R

##ASSIMILATION
- KDIF   extinction coeff. for diffuse visible light.......< 0.6      > R
- EFF    light use effic. single leaf [kg/ha/hr/Jm**2s]....< 0.45     > R
- AMAXTB AFGEN-table ( max. 15 data  pairs) : maximum        X:-
         CO2 assimilation rate as a function of              Y:kg/ha/hr
         development stage of the crop
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00  85.00   1.30  70.00   1.75  50.00   2.00  40.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- TMPFTB AFGEN-table (max. 15 data pairs ) : reduction         X:C
         factor of AMAX as function of AV. day Temperature     Y:-
<=AVT=><=====><=AVT=><=====><=AVT=><=====><=AVT=><=====><=AVT=><=====> R
  0.00   0.00   4.00   0.00  15.00   0.37  25.00   0.72  35.00   1.00
 40.00   1.00  50.00   0.58  64.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- TMNFTB AFGEN-table (max. 15 data pairs ) : reduction factor   X:C
         of gross assim. rate as function of low MiN. Temp.     Y:-
<=MNT=><=====><=MNT=><=====><=MNT=><=====><=MNT=><=====><=MNT=><=====> R
  5.00   0.00  12.00   1.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====>

##CONVERSION OF ASSIMILATES INTO BIOMASS
- CVL    efficiency of conversion into leaves [kg/kg]......<  0.72    > R
- CVO    idem into storage organ dry matter   [kg/kg]......<  0.74    > R
- CVR    idem into root dry matter            [kg/kg]......<  0.72    > R
- CVS    idem into stem dry matter            [kg/kg]......<  0.69    > R

##MAINTENANCE RESPIRATION
- Q10    rel. incr. in resp. rate per 10 d. temp. incr.....<  2.0     > R
- RML    rel. mainten. resp. rate leaves [kgCH2O/kg/d].....<  0.020   > R
- RMO    idem of storage organs          [kgCH2O/kg/d].....<  0.007   > R
- RMR    idem of roots                   [kgCH2O/kg/d].....<  0.007   > R
- RMS    idem of stems                   [kgCH2O/kg/d].....<  0.010   > R
- RFSETB AFGEN-table (max. 15 data pairs): reduction           X:-
         factor for senescence as function of DVS              Y:-
```

```
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R

##PARTITIONING
- FRTB   AFGEN-table (max. 15 data pairs): the fraction         X:-
         of total dry  matter  increase  partitioned to         Y:-
         the roots as a function of development stage
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00   0.6    1.00   0.14   1.13   0.08   1.30   0.00   2.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- FLTB   AFGEN-table (max. 15 data pairs): the fraction         X:-
         of total above ground dry matter increase par-         Y:-
         titioned to the leaves as a  function of deve-
         lopment stage
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00   0.8    0.20   0.80   1.13   0.12   1.30   0.00   1.60   0.00
  2.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- FSTB   AFGEN-table (max. 15 data pairs): the fraction         X:-
         of total above ground dry matter increase par-         Y:-
         titioned to the  stems as a  function of deve-
         lopment stage
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00   0.20   0.20   0.20   1.13   0.88   1.30   0.64   1.60   0.00
  2.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- FOTB   AFGEN-table (max. 15 data pairs): the fraction         X:-
         of total above ground dry matter increase par-         Y:-
         titioned to the  storage organs as a  function
         of development stage
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00   0.00   0.20   0.00   1.13   0.00   1.30   0.36   1.60   1.00
  2.00   1.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R

##DEATH RATES
- PERDL  maximum relative death rate of leaves due to......<  0.030  > R
         water stress [/d]
- RDRRTB AFGEN-table (max. 15 data pairs): relative death      X:-
         rate of roots as a function of DVS                    Y:kg/kg/d
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00   0.00   1.00   0.00   1.13  0.018   2.00  0.018   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R
- RDRSTB AFGEN-table (max. 15 data pairs): relative death      X:-
         rate of stems as a function of DVS                    Y:kg/kg/d
<=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====><=DVS=><=====> R
  0.00   0.00   1.30   0.00   1.6   0.0075  2.00 0.0075   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
  0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
<=====><=====><=====><=====><=====><=====><=====><=====><=====><=====> R

##WATER USE
- ADCRH  threshold level high atmospheric demand [cm]......<    0.5  > R
- ADCRL  threshold level low atmospheric demand  [cm]......<    0.1  > R
- OSMOTP salt tolerance factor.............................<     1.0 > R

##ROOTING
- RDI    initial rooting depth [cm]........................<    10.0 > R
- RRI    maximum daily increase in rooting depth [cm/d]....<     1.2 > R
- RDC    maximum rooting depth crop/cultivar [cm]..........<   220.0 > R
```

Soil file

```
<== top10.SOL =========================================================>
<==                                                                   ==>
<==                  TRIGGER - soil physical data                     ==>
<==                                                                   ==>
<======================================================================>
<==                                                                   ==>
<==  verslempte bovenlaag                                             ==>
<==                                                                   ==>
<========1=========2=========3=========4=========5=========6=========7=>

## Van Genuchten parameters
- COFGEN 1 residual moisture content [cm3/cm3]............<   0.0001> R
- COFGEN 2 saturated moisture content [cm3/cm3]...........<   0.10   > R
- COFGEN 3 saturated hydraulic conductivity [cm/d].........<  240     > R
- COFGEN 4 alpha [1/cm]...................................<   0.03   > R
- COFGEN 5 L [-]..........................................< 11.      > R
- COFGEN 6 n [-]..........................................< 4.5      > R

<== deep6.SOL =========================================================>
<==                                                                   ==>
<==                  TRIGGER - soil physical data                     ==>
<==                                                                   ==>
<======================================================================>
<==                                                                   ==>
<==  verslempte bovenlaag                                             ==>
<==                                                                   ==>
<========1=========2=========3=========4=========5=========6=========7=>

## Van Genuchten parameters
- COFGEN 1 residual moisture content [cm3/cm3]............<   0.01   > R
- COFGEN 2 saturated moisture content [cm3/cm3]...........<   0.35   > R
- COFGEN 3 saturated hydraulic conductivity [cm/d].........<  100.    > R
- COFGEN 4 alpha [1/cm]...................................<   0.03   > R
- COFGEN 5 L [-]..........................................< 4.       > R
- COFGEN 6 n [-]..........................................< 3.5      > R

<== BOund1.BBC ========================================================>
<==                                                                   ==>
<==                TRIGGER - Bottom Boundary Condition                ==>
<==                                                                   ==>
<======================================================================>
<==                                                                   ==>
<== Demo run TRIGGER, agricultural year 2000                          ==>
<==                                                                   ==>
<========1=========2=========3=========4=========5=========6=========7=>

Choose one of three options:

##Condition 1
- Given groundwater level.............................[Y=1, N=0]..<0> I
  Specify date and GroundWate≥ leve∞ [cm¼ positivσ o≥ negative]:

DATE       GW level
dd/mm/yyyy cm
<========><========>R
<========><========>R

##Condition 2
- Flux from saturated zone is given...................[Y=1, N=0]..<0> I
  Specify date and flux froφ thσ saturateΣ zonσ [cm/d¼ ½ ╝ upwards]:

DATE       QBOTOM
dd/mm/yyyy cm/day
<========><========>R
01/01/2000   0.0
31/12/2000   0.0
<========><========>R

##Condition 3
- Free drainage at the bottom of the profile..........[Y=1, N=0]..<1> I
```

```
==========================================================================

##Solute concentration in groundwater.
  Give datapair values, with date [dd/mm/yyyy] and corresponding salt
  concentration in groundwater [mg/cm3]:

DATE        CGRO
dd/mm/yyyy mg/cm3
<=========><=========> R
01/01/2000  20.0
31/12/2000  20.0
<=========><=========> R
```

Annex H Overview of the used retention and conductivity curves and retention curves determined by ISRIC

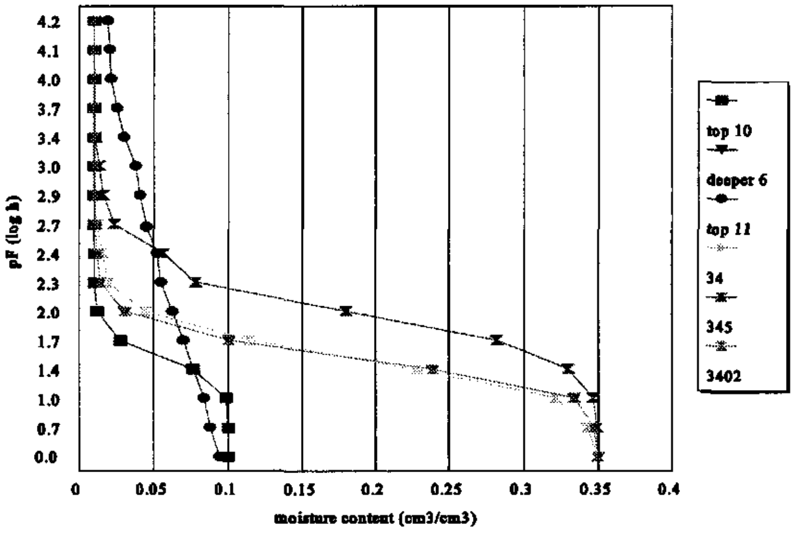


Fig. H1 pF curves which gave the best calibration results

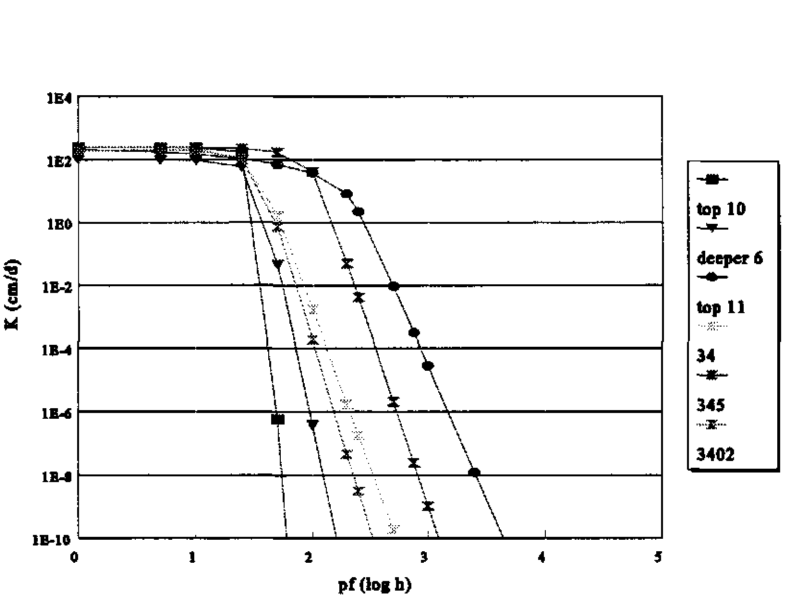


Fig. H2 K-h relations which gave the best calibration results

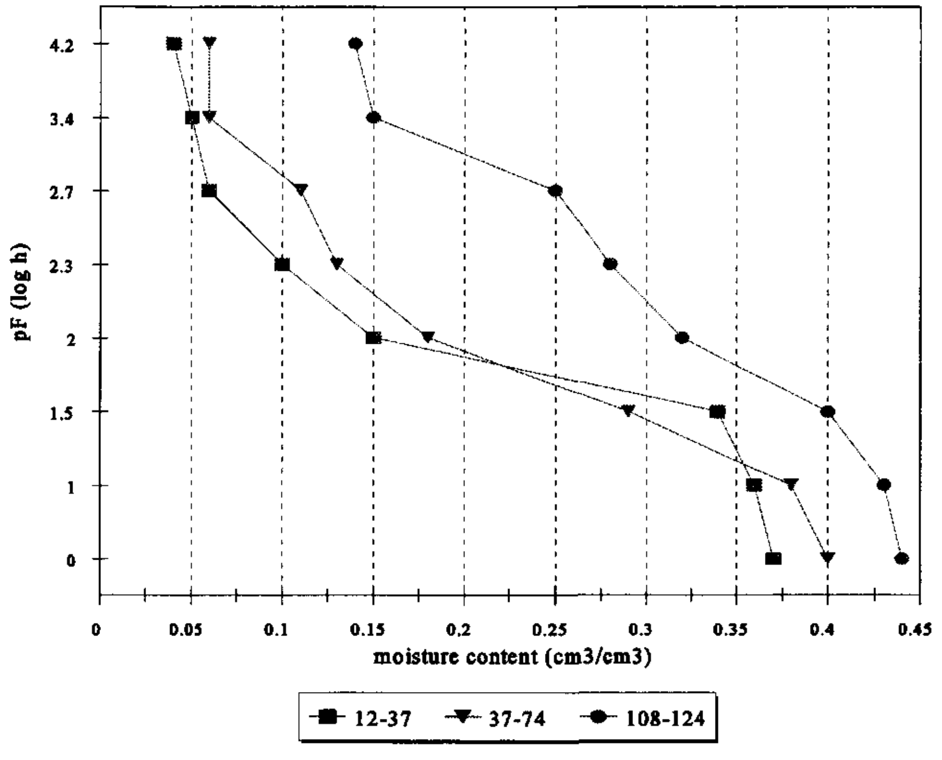


Fig. H3 Retention curves determined by ISRIC

Annex I Estimation of the waterbalance

t (day)	Θ_{up} (cm)	Θ_{down} (cm)	$\Delta\Theta_{up}$ (cm)	$\Delta\Theta_{down}$ (cm)	$\Delta\Theta_{total}$ (cm)	P (cm)	Int+SR (cm)	Int+SR>0 (cm)	Int+SR (excl. Ta) (cm)	Int+Ru > 0 (excl. Ta) (cm)	Ta (cm)	E_a (cm)	ET_a (cm)	CR and Perc (cm)
227	1.19	16.85				0.00					0.20	0.10	0.30	0.00
228	1.68	17.32	0.49	0.48	0.97	1.28	-0.19		0.01	0.01	0.20	0.30	0.50	0.00
229	1.17	17.68	-0.51	0.36	-0.15	0.00	-0.25		-0.05		0.20	0.20	0.40	0.00
230	1.23	15.78	0.06	-1.90	-1.84	0.00	1.59	1.59	1.74	1.74	0.15	0.10	0.25	0.00
231	1.05	15.87	-0.18	0.09	-0.09	0.00	-0.16		-0.01		0.15	0.10	0.25	0.00
232	1.25	15.05	0.20	-0.82	-0.62	0.00	0.42	0.42	0.52	0.52	0.10	0.10	0.20	0.00
233	1.08	15.16	-0.18	0.11	-0.07	0.00	-0.13		-0.03		0.10	0.10	0.20	0.00
234	1.88	18.92	0.81	3.77	4.57	5.38	0.26	0.26	0.41	0.41	0.15	0.40	0.55	0.00
235	1.67	20.13	-0.21	1.20	0.99	1.15	-0.19		-0.04		0.15	0.20	0.35	0.00
236	1.20	19.09	-0.47	-1.04	-1.50	0.00	1.03	1.03	1.1	1.1	0.07	0.10	0.17	-0.30
237	1.44	19.17	0.24	0.07	0.31	0.60	-0.08		-0.01		0.07	0.30	0.37	0.00
238	1.64	19.62	0.20	0.46	0.66	0.90	-0.13		-0.06		0.07	0.20	0.27	-0.10
239	1.19	17.73	-0.45	-1.89	-2.35	0.00	1.25	1.25	1.65	1.65	0.40	0.10	0.50	-0.60
240	1.27	16.98	0.08	-0.75	-0.67	0.10	0.17	0.17	0.27	0.27	0.10	0.10	0.20	-0.40
241	1.85	20.45	0.59	3.47	4.05	3.79	-0.56		-0.46		0.10	0.10	0.20	-0.10
242	1.72	19.26	-0.14	-1.20	-1.33	1.70	2.08	2.08	2.13	2.13	0.05	0.20	0.25	-0.70
243	1.87	23.12	0.15	3.87	4.02	4.14	-0.03		0.02	0.02	0.05	0.10	0.15	0.00
244	1.21	21.79	-0.66	-1.33	-1.99	0.00	2.02	2.02	2.09	2.09	0.07	0.10	0.17	0.20
245	1.07	21.82	-0.14	0.03	-0.11	0.00	-0.16		-0.09		0.07	0.10	0.17	-0.10
246	1.00	21.79	-0.07	-0.03	-0.10	0.00	0.03	0.03	0.10	0.1	0.07	0.00	0.07	0.00
247	1.18	17.57	0.18	-4.22	-4.05	0.00	3.70	3.70	3.95	3.95	0.25	0.10	0.35	0.00
248	1.05	17.60	-0.13	0.03	-0.10	0.00	-0.25		0.00		0.25	0.10	0.35	0.00
249	1.21	16.19	0.16	-1.41	-1.25	0.00	0.88	0.88	1.05	1.05	0.17	0.10	0.27	-0.10
250	1.69	16.81	0.48	0.62	1.10	1.43	-0.54		-0.37		0.17	0.30	0.47	-0.40
251	1.21	17.19	-0.48	0.39	-0.10	0.00	-0.17		0.00		0.17	0.10	0.27	0.00
252	1.19	15.94	-0.02	-1.25	-1.27	0.00	0.57	0.57	1.07	1.07	0.50	0.10	0.60	-0.10
253	1.04	16.01	-0.15	0.06	-0.09	0.00	-0.51		-0.01		0.50	0.10	0.60	0.00
254	1.20	15.72	0.17	-0.29	-0.12	0.00	-1.13		-0.58		0.55	0.10	0.65	-0.60
255	1.81	17.80	0.61	2.08	2.69	3.01	-0.53		0.02	0.02	0.55	0.30	0.85	0.00
256	1.20	15.77	-0.61	-2.03	-2.63	0.00	1.83	1.83	2.33	2.33	0.50	0.10	0.60	-0.20

257	1.04	15.84	-0.17	0.07	-0.10	0.00	-0.50		0.00		0.50	0.10	0.60	0.00
258	1.69	16.64	0.65	0.80	1.46	1.70	-0.66		-0.15		0.50	0.40	0.90	0.00
259	1.58	17.25	-0.10	0.61	0.50	0.75	-0.75		-0.25		0.50	0.30	0.80	-0.20
260	1.16	17.50	-0.42	0.25	-0.17	0.00	-0.43		0.07	0.07	0.50	0.10	0.60	0.00
261	1.18	16.06	0.02	-1.45	-1.43	0.00	0.33	0.33	1.23	1.23	0.90	0.10	1.00	-0.10
262	1.03	16.14	-0.15	0.09	-0.06	0.00	-0.94		-0.04		0.90	0.10	1.00	0.00
263	0.98	16.15	-0.05	0.01	-0.04	0.00	-0.86		0.04	0.04	0.90	0.00	0.90	0.00
264	1.22	15.53	0.24	-0.62	-0.38	0.00	-0.82		0.28	0.28	1.10	0.10	1.20	0.00
265	1.07	15.62	-0.15	0.09	-0.06	0.00	-1.15		-0.04		1.10	0.10	1.20	0.00
266	1.21	14.87	0.14	-0.75	-0.62	0.00	-0.38		0.52	0.52	0.90	0.10	1.00	0.00
267	1.05	14.96	-0.16	0.10	-0.06	0.00	-0.94		-0.04		0.90	0.10	1.00	0.00
268	1.28	14.41	0.23	-0.55	-0.32	0.00	-0.78		0.22	0.22	1.00	0.10	1.10	0.00
269	1.10	14.53	-0.18	0.12	-0.06	0.00	-1.04		-0.04		1.00	0.10	1.10	0.00
270	1.26	13.81	0.16	-0.72	-0.56	0.00	-0.27		0.46	0.46	0.73	0.10	0.83	0.00
271	1.13	13.93	-0.13	0.12	-0.00	0.00	-0.73		0.00		0.73	0.00	0.73	0.00
272	1.06	13.99	-0.07	0.06	-0.01	0.00	-0.72		0.01	0.01	0.73	0.00	0.73	0.00
273	1.21	13.22	0.15	-0.77	-0.62	0.00	-1.03		0.52	0.52	1.55	0.10	1.65	0.00
274	1.16	13.27	-0.05	0.05	-0.00	0.00	-1.55		0.00		1.55	0.00	1.55	0.00
275	1.15	12.89	-0.01	-0.38	-0.39	0.00	-0.17		0.39	0.39	0.55	0.00	0.55	0.00
276	1.11	12.93	-0.03	0.04	0.00	0.00	-0.55		0.00		0.55	0.00	0.55	0.00
277	1.12	12.44	0.00	-0.49	-0.49	0.05	-0.01		0.44	0.44	0.45	0.10	0.55	0.00
278	1.09	12.47	-0.02	0.03	0.00	0.00	-0.45		0.00		0.45	0.00	0.45	0.00
279	1.06	12.28	-0.04	-0.19	-0.22	0.00	-0.08		0.22	0.22	0.30	0.00	0.30	0.00
280	1.04	12.30	-0.02	0.02	-0.00	0.00	-0.30		0.00		0.30	0.00	0.30	0.00
281	0.94	11.94	-0.10	-0.36	-0.46	0.00	0.41	0.41	0.46	0.46	0.05	0.00	0.05	0.00
282	0.92	11.95	-0.02	0.01	-0.01	0.00	-0.04		0.01	0.01	0.05	0.00	0.05	0.00
total			-0.27	-4.90	-5.17	25.98	-3.56	16.57	21.05	23.25	24.80	6.40	31.20	-3.80

Annex J Sensitivity analysis

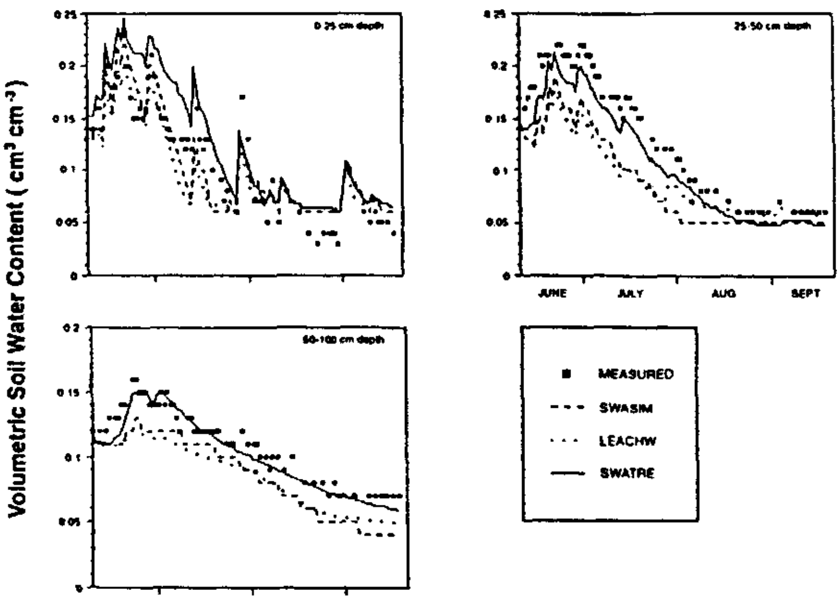
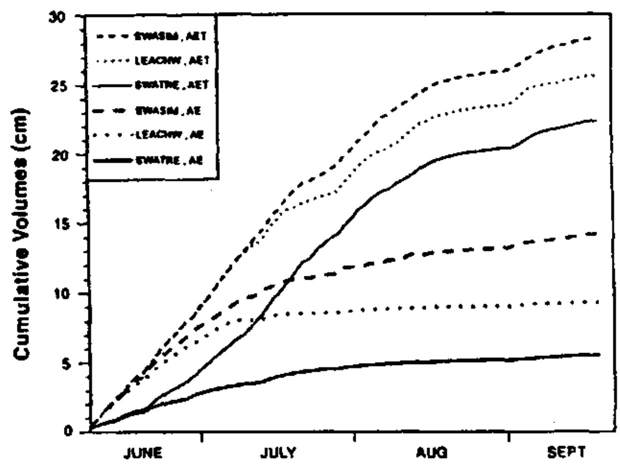
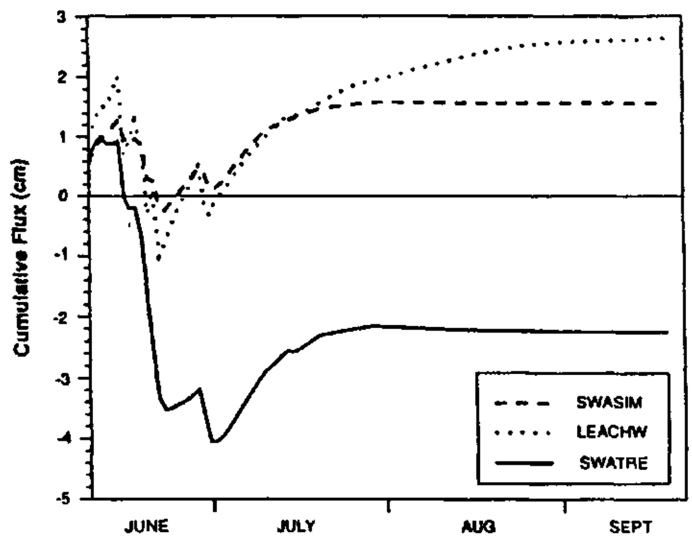


Fig. 4.



Predicted cumulative actual evaporation (AE) and actual evapotranspiration (AET) at the Simcoe site.



Predicted cumulative water flux at the bottom of the root zone at the Simcoe site (positive flux indicates upward flow).

Annex K Simulation results

Millet density 50 cm

No.	Scenario			Rainfall (mm)	CWDM (kg ha^{-1})	CWSO (kg ha^{-1})	Ea (cm)	Ta (cm)	ETa (cm)	WUE (Ta) (kg ha^{-1} m^{-1})	WUE (ETa) (kg ha^{-1} m^{-1})
s163	lds	dms	ede	128	100	0	11.8	0.2	12	50000.00	833.33
s166	lds	dms	mde	132	80	0	12.8	0	12.8	ERR	625.00
s169	lds	dms	lde	133	80	0	12.8	0	12.8	ERR	625.00
s4	eds	dms	mde	134	80	0	12.9	0	12.9	ERR	620.16
s 85	mds	dms	mde	134	87	0	15.7	0.1	15.8	87000.00	550.63
s 7	eds	dms	lde	135	87	0	13.2	0.1	13.3	87000.00	654.14
s88	mds	dms	lde	135	80	0	13	0	13	ERR	615.38
s94	mds	ams	mde	294	283	0	12.1	3	15.1	9433.33	1874.17
s199	las	ams	ede	298	798	84	10.2	13.1	23.3	6091.60	3424.89
s 205	las	ams	lde	304	82	0	16.5	0	16.5	ERR	496.97
s 167	lds	dms	mae	320	87	0	15.5	0.1	15.6	87000.00	557.69
s121	mas	ams	mde	321							
s 124	mas	ams	lde	322	623	50	13.7	9.1	22.8	6846.15	2732.46
s 86	mds	dms	mae	322	87	0	15.7	0.1	15.8	87000.00	550.63
s 5	eds	dms	mae	323	87	0	15.7	0.1	15.8	87000.00	550.63
s 43	eas	ams	lde	330							
s148	mws	ams	mde	393	1090	413	13	21.3	34.3	5117.37	3177.84
s 203	las	ams	mae	502	615	53	13.8	8.9	22.7	6910.11	2709.25
s 122	mas	ams	mae	520	106	0	17.4	0.2	17.6	53000.00	602.27
s 41	eas	ams	mae	528	962	252	14.3	16.4	30.7	5865.85	3133.55
s168	lds	dms	mwe	568	80	0	16.5	0	16.5	ERR	484.85
s 87	mds	dms	mwe	569	87	0	17	0.1	17.1	87000.00	508.77
s 171	lds	dms	lwe	609	87	0	18.7	0.1	18.8	87000.00	462.77
s90	mds	dms	lwe	611	80	0	18.6	0	18.6	ERR	430.11
s 9	eds	dms	lwe	611	87	0	18.9	0.1	19	87000.00	457.89
s 201	las	ams	ewe	704	82	0	17.8	0	17.8	ERR	460.67
s 120	mas	ams	ewe	723	615	53	13.8	8.9	22.7	6910.11	2709.25
s 39	eas	ams	ewe	731	623	50	13.7	9.1	22.8	6846.15	2732.46
s 235	lws	wms	ede	804	1339	737	13.8	25.3	39.1	5292.49	3424.55
s 154	mws	wms	ede	877	1337	731	14.6	25.9	40.5	5162.16	3301.23
s 73	ews	wms	ede	918	1337	731	14.6	25.9	40.5	5162.16	3301.23
s 237	lws	wms	ewe	102	1300	700	11.8	23.8	35.6	5462.18	3651.69
s 239	lws	wms	mae	106	786	202	15.2	12.9	28.1	6093.02	2797.15
s156	mws	wms	ewe	109	746	160	16	13.7	29.7	5445.26	2511.78
s75	ews	wms	ewe	113	746	160	16	13.7	29.7	5445.26	2511.78
s 158	mws	wms	mae	114	1337	731	14.6	25.9	40.5	5162.16	3301.23
s 77	ews	wms	mae	118	786	202	17.5	12.9	30.4	6093.02	2585.53
s 243	lws	wms	lwe	136	786	202	18.4	12.9	31.3	6093.02	2511.18
s 162	mws	wms	lwe	143	786	202	20.7	12.9	33.6	6093.02	2339.29
s 81	ews	wms	lwe	147	1279	679	17.8	23.5	41.3	5442.55	3096.85

Millet density 75 cm

No.	Scenario			Rainfall (mm)	CWDM ($kg\ ha^{-1}$)	CWSO ($kg\ ha^{-1}$)	Ea (cm)	Ta (cm)	ETa (cm)	WUE (Ta) ($kg\ ha^{-1}\ m^{-1}$)	WUE(ETa) ($kg\ ha^{-1}\ m^{-1}$)
s163	lds	dms	ede	128	47	0	12	0.1	12.1	47000.00	388.43
s166	lds	dms	mde	132							
s169	lds	dms	lde	133							
s4	eds	dms	mde	134							
s 85	mds	dms	mde	134	40	0	13.3	0	13.3	ERR	300.75
s 7	eds	dms	lde	135	40	0	13.3	0	13.3	ERR	300.75
s88	mds	dms	lde	135							
s94	mds	ams	mde	294							
s199	las	ams	ede	298							
s 205	las	ams	lde	304	775	381	12	14	26	5535.71	2980.77
s 167	lds	dms	mae	320	40	0	15.7	0	15.7	ERR	254.78
s121	mas	ams	mde	321							
s 124	mas	ams	lde	322	937	545	12.5	18.2	30.7	5148.35	3052.12
s 86	mds	dms	mae	322	40	0	15.9	0	15.9	ERR	251.57
s 5	eds	dms	mae	323	40	0	15.9	0	15.9	ERR	251.57
s 43	eas	ams	lde	330	668	259	8.8	12.2	21	5475.41	3180.95
s148	mws	ams	mde	393							
s 203	las	ams	mae	502	927	539	18	12.6	30.6	7357.14	3029.41
s 122	mas	ams	mae	520	315	22	14.3	4.8	19.1	6562.50	1649.21
s 41	eas	ams	mae	528	948	557	12.9	17.8	30.7	5325.84	3087.95
s168	lds	dms	mwe	568							
s 87	mds	dms	mwe	569	40	0	17.2	0	17.2	ERR	232.56
s 171	lds	dms	lwe	609	40	0	18.9	0	18.9	ERR	211.64
s90	mds	dms	lwe	611							
s 9	eds	dms	lwe	611	40	0	19.1	0	19.1	ERR	209.42
s 201	las	ams	ewe	704	941	546	18.3	11.1	29.4	8477.48	3200.68
s 120	mas	ams	ewe	723	927	539	12.6	18	30.6	5150.00	3029.41
s 39	eas	ams	ewe	731	937	545	12.5	18.2	30.7	5148.35	3052.12
s 235	lws	wms	ede	804	825	504	13.6	15.6	29.2	5288.46	2825.34
s 154	mws	wms	ede	877	825	504	15.8	15.6	31.4	5288.46	2627.39
s 73	ews	wms	ede	918	825	504	15.8	15.6	31.4	5288.46	2627.39
s 237	lws	wms	ewe	1019	756	438	13.2	13.9	27.1	5438.85	2789.67
s 239	lws	wms	mae	1064	764	445	16.4	14.1	30.5	5418.44	2504.92
s156	mws	wms	ewe	1092							
s75	ews	wms	ewe	1133							
s 158	mws	wms	mae	1137	825	504	15.8	15.6	31.4	5288.46	2627.39
s 77	ews	wms	mae	1178	764	445	16.1	14.1	30.2	5418.44	2529.80
s 243	lws	wms	lwe	1360	752	424	17.2	13.8	31	5449.28	2425.81
s 162	mws	wms	lwe	1433	752	433	19.4	13.8	33.2	5449.28	2265.06
s 81	ews	wms	lwe	1474	745	427	19.2	13.7	32.9	5437.96	2264.44

Millet density 100 cm

No.	Scenario			Rainfall (mm)	CWDM (kg ha^{-1})	CWSO (kg ha^{-1})	Ea (cm)	Ta (cm)	ETa (cm)	WUE (Ta) (kg ha^{-1} m^{-1})	WUE (ETa) (kg ha^{-1} m^{-1})
s163	lds	dms	ede	128	27	0	12.1	0.1	12.2	27000.00	221.31
s166	lds	dms	mde	132	20	0	13.1	0	13.1	ERR	152.67
s169	lds	dms	lde	133	20	0	13.1	0	13.1	ERR	152.67
s4	eds	dms	mde	134	20	0					
s 85	mds	dms	mde	134	22	0	13.5	0	13.5	ERR	162.96
s 7	eds	dms	lde	135	22	0	13.5	0	13.5	ERR	162.96
s88	mds	dms	lde	135	20	0	13.3	0	13.3	ERR	150.38
s94	mds	ams	mde	294	437	141	8.4	11.4	19.8	3833.33	2207.07
s199	las	ams	ede	298	460	151					
s 205	las	ams	lde	304	657	421	12.4	12.4	24.8	5298.39	2649.19
s 167	lds	dms	mae	320	22	0	15.9	0	15.9	ERR	138.36
s121	mas	ams	mde	321	651	370	12.7	15.6	28.3	4173.08	2300.35
s 124	mas	ams	lde	322	598	358	13.3	11.2	24.5	5339.29	2440.82
s 86	mds	dms	mae	322	22	0	16.1	0	16.1	ERR	136.65
s 5	eds	dms	mae	323	22	0	16.1	0	16.1	ERR	136.65
s 43	eas	ams	lde	330	761	498	13.9	14.7	28.6	5176.87	2660.84
s148	mws	ams	mde	393	256	31	14.5	4.2	18.7	6095.24	1368.98
s 203	las	ams	mae	502	592	355	13.3	11.1	24.4	5333.33	2426.23
s 122	mas	ams	mae	520	678	419	12.1	12.9	25	5255.81	2712.00
s 41	eas	ams	mae	528	650	403	13.6	12.2	25.8	5327.87	2519.38
s168	lds	dms	mwe	568	20	0	16.9	0	16.9	ERR	118.34
s 87	mds	dms	mwe	569	22	0	17.4	0	17.4	ERR	126.44
s 171	lds	dms	lwe	609	22	0	19.1	0	19.1	ERR	115.18
s90	mds	dms	lwe	611	20	0	19	0	19	ERR	105.26
s 9	eds	dms	lwe	611	22	0	19.3	0	19.3	ERR	113.99
s 201	las	ams	ewe	704	595	357	11.9	11.1	23	5360.36	2586.96
s 120	mas	ams	ewe	723	592	355	13.3	11.1	24.4	5333.33	2426.23
s 39	eas	ams	ewe	731	598	358	13.3	11.2	24.5	5339.29	2440.82
s 235	lws	wms	ede	804	520	325	12.6	9.8	22.4	5306.12	2321.43
s 154	mws	wms	ede	877	520	325	14.5	9.8	24.3	5306.12	2139.92
s 73	ews	wms	ede	918	520	325	14.5	9.8	24.3	5306.12	2139.92
s 237	lws	wms	ewe	1019	486	292	14.1	9.1	23.2	5340.66	2094.83
s 239	lws	wms	mae	1064	485	291	14.4	8.9	23.3	5449.44	2081.55
s156	mws	wms	ewe	1092	470	257	17.1	10.3	27.4	4563.11	1715.33
s75	ews	wms	ewe	1133	470	257					
s 158	mws	wms	mae	1137	520	325	14.5	9.8	24.3	5306.12	2139.92
s 77	ews	wms	mae	1178	485	291	16.7	8.9	25.6	5449.44	1894.53
s 243	lws	wms	lwe	1360	478	284	17.9	8.8	26.7	5431.82	1790.26
s 162	mws	wms	lwe	1433	477	284	20.1	8.8	28.9	5420.45	1650.52
s 81	ews	wms	lwe	1474	474	280	20.8	8.7	29.5	5448.28	1606.78

Millet density 125 cm

No.	Scenario			Rainfall (mm)	CWDM (kg ha^{-1})	CWSO (kg ha^{-1})	Ea (cm)	Ta (cm)	ETa (cm)	WUE (Ta) (kg ha^{-1} m^{-1})	WUE (kg ha^{-1} m^{-1})
s163	lds	dms	ede	128	17	0	12.4	0	12.4	ERR	137.10
s166	lds	dms	mde	132	12	0	13.3	0	13.3	ERR	90.23
s169	lds	dms	lde	133	12	0	13.3	0	13.3	ERR	90.23
s4	eds	dms	mde	134	12	0	13.3	0	13.3	ERR	90.23
s 85	mds	dms	mde	134	384	106	9.7	7.5	17.2	5120.00	2232.56
s 7	eds	dms	lde	135	383	106	9.8	7.5	17.3	5106.67	2213.87
s88	mds	dms	lde	135	12	0	13.3	0	13.3	ERR	90.23
s94	mds	ams	mde	294	326	112	11.7	7	18.7	4657.14	1743.32
s199	las	ams	ede	298	613	387	10.9	15.8	26.7	3879.75	2295.88
s 205	las	ams	lde	304	281	116	13.1	5.1	18.2	5509.80	1543.96
s 167	lds	dms	mae	320	326	197	6	20.5	26.5	1590.24	1230.19
s121	mas	ams	mde	321	632	401	12.8	20.5	33.3	3082.93	1897.90
s 124	mas	ams	lde	322	413	252	13.7	7.7	21.4	5363.64	1929.91
s 86	mds	dms	mae	322	605	386	9	11.6	20.6	5215.52	2936.89
s 5	eds	dms	mae	323	605	386	9	11.6	20.6	5215.52	2936.89
s 43	eas	ams	lde	330	478	305	12.9	12	24.9	3983.33	1919.68
s148	mws	ams	mde	393	316	108	14.2	6.3	20.5	5015.87	1541.46
s 203	las	ams	mae	502	408	249	13.7	7.6	21.3	5368.42	1915.49
s 122	mas	ams	mae	520	469	296	12.6	9	21.6	5211.11	2171.30
s 41	eas	ams	mae	528	446	281	13.9	8.4	22.3	5309.52	2000.00
s168	lds	dms	mwe	568	12	0	17	0	17	ERR	70.59
s 87	mds	dms	mwe	569	595	376	10.7	11.4	22.1	5219.30	2692.31
s 171	lds	dms	lwe	609	595	376	12.2	11.4	23.6	5219.30	2521.19
s90	mds	dms	lwe	611	12	0	19	0	19	ERR	63.16
s 9	eds	dms	lwe	611	595	376	12.4	11.4	23.8	5219.30	2500.00
s 201	las	ams	ewe	704	410	250	12.3	7.7	20	5324.68	2050.00
s 120	mas	ams	ewe	723	408	249	13.7	7.6	21.3	5368.42	1915.49
s 39	eas	ams	ewe	731	413	252	13.7	7.7	21.4	5363.64	1929.91
s 235	lws	wms	ede	804	354	224	14.4	6.7	21.1	5283.58	1677.73
s 154	mws	wms	ede	877	354	224	14.8	6.7	21.5	5283.58	1646.51
s 73	ews	wms	ede	918	354	224	14.8	6.7	21.5	5283.58	1646.51
s 237	lws	wms	ewe	1019	331	202	14.3	6.2	20.5	5338.71	1614.63
s 239	lws	wms	mae	1064	331	202	14.8	6.1	20.9	5426.23	1583.73
s156	mws	wms	ewe	1092	413	270	11.2	17.1	28.3	2415.20	1459.36
s75	ews	wms	ewe	1133	413	270	11.2	17.1	28.3	2415.20	1459.36
s 158	mws	wms	mae	1137	354	224	14.8	6.7	21.5	5283.58	1646.51
s 77	ews	wms	mae	1178	331	202	17.1	6.1	23.2	5426.23	1426.72
s 243	lws	wms	lwe	1360	326	197	18.2	6	24.2	5433.33	1347.11
s 162	mws	wms	lwe	1433	326	197	20.5	6	26.5	5433.33	1230.19
s 81	ews	wms	lwe	1474	323	194	20.4	5.9	26.3	5474.58	1228.14

Millet density 150 cm

No.	Scenario			Rainfall (mm)	CWDM (kg ha^{-1})	CWSO (kg ha^{-1})	Ea (cm)	Ta (cm)	ETa (cm)	WUE (Ta) (kg ha^{-1} m^{-1})	WUE (kg ha^{-1} m^{-1})
s163	lds	dms	ede	128	254	90	8.6	4.5	13.1	5644.44	1938.93
s166	lds	dms	mde	132	8	0	13.1	0	13.1	ERR	61.07
s169	lds	dms	lde	133	8	0	13.2	0	13.2	ERR	60.61
s4	eds	dms	mde	134	8	0	13.3	0	13.3	ERR	60.15
s 85	mds	dms	mde	134	11	0	13.2	0	13.2	ERR	83.33
s 7	eds	dms	lde	135	11	0	13.2	0	13.2	ERR	83.33
s88	mds	dms	lde	135							
s94	mds	ams	mde	294							
s199	las	ams	ede	298	364	229	11.5	10.6	22.1	3433.96	1647.06
s 205	las	ams	lde	304	69	0	16.9	0	16.9	ERR	408.28
s 167	lds	dms	mae	320	11	0	15.6	0	15.6	ERR	70.51
s121	mas	ams	mde	321	208	71	13.3	4	17.3	5200.00	1202.31
s 124	mas	ams	lde	322	296	183	14	5.5	19.5	5381.82	1517.95
s 86	mds	dms	mae	322	11	0	15.8	0	15.8	ERR	69.62
s 5	eds	dms	mae	323	11	0	15.8	0	15.8	ERR	69.62
s 43	eas	ams	lde	330	370	249	13.9	7.2	21.1	5138.89	1753.55
s148	mws	ams	mde	393	372	216	14	8.1	22.1	4592.59	1683.26
s 203	las	ams	mae	502	294	181	14	5.5	19.5	5345.45	1507.69
s 122	mas	ams	mae	520	172	57	15.1	3	18.1	5733.33	950.28
s 41	eas	ams	mae	528	317	201	14.1	5.9	20	5372.88	1585.00
s168	lds	dms	mwe	568	8	0	17	0	17	ERR	47.06
s 87	mds	dms	mwe	569	11	0	17.1	0	17.1	ERR	64.33
s 171	lds	dms	lwe	609	11	0	18.8	0	18.8	ERR	58.51
s90	mds	dms	lwe	611							
s 9	eds	dms	lwe	611	11	0	19	0	19	ERR	57.89
s 201	las	ams	ewe	704	9	0	18.3	0	18.3	ERR	49.18
s 120	mas	ams	ewe	723	294	181	14	5.5	19.5	5345.45	1507.69
s 39	eas	ams	ewe	731	296	183	14	5.5	19.5	5381.82	1517.95
s 235	lws	wms	ede	804	243	155	14.8	4.6	19.4	5282.61	1252.58
s 154	mws	wms	ede	877	243	155	17	4.6	21.6	5282.61	1125.00
s 73	ews	wms	ede	918	243	155	17	4.6	21.6	5282.61	1125.00
s 237	lws	wms	ewe	1019	226	139	14.5	4.1	18.6	5512.20	1215.05
s 239	lws	wms	mae	1064	228	140	15.1	4.2	19.3	5428.57	1181.35
s156	mws	wms	ewe	1092	268	173	17.1	8.4	25.5	3190.48	1050.98
s75	ews	wms	ewe	1133	268	173	17.1	8.4	25.5	3190.48	1050.98
s 158	mws	wms	mae	1137	243	155	17	4.6	21.6	5282.61	1125.00
s 77	ews	wms	mae	1178	228	140	17.3	4.2	21.5	5428.57	1060.47
s 243	lws	wms	lwe	1360	224	137	18.5	4.1	22.6	5463.41	991.15
s 162	mws	wms	lwe	1433	225	137	20.7	4.1	24.8	5487.80	907.26
s 81	ews	wms	lwe	1474	323	194	20.6	4.1	24.7	7878.05	1307.69