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The use of crop growth models in agro-ecological zonation of rice

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Preface

This volume of the SARP Research Proceedings presents a framework for the use of crop growth models in agro-ecological characterisation and zonation of rice, as developed in the research theme 'Agro-ecosystems' of SARP III. The simulation model used in this volume is ORYZA_W (version 2.0) for rice growth and development in irrigated and rainfed lowland and rainfed upland production environments. This version of ORYZA_W is a follow-up of the version (1.0) as presented at the Agro-ecosystems workshop in Hangzhou, China, April 1993. ORYZA_W is not described in this volume and will be presented in a separate SARP Research Proceedings by Wopereis et al. (in prep.). Though the framework for the use of crop growth models in zonation studies is illustrated using ORYZA_W for rice, the principles, and the tools developed, are applicable using other models (e.g. ORYZA1), and for other crops as well.

All models and computer programs presented here are written in FORTRAN77 under the FORTRAN Simulation Environment (FSE) as developed by van Kraalingen (1991a). Complete listings of the models and computer programs including input and output files are given in the Appendices. The models can be run on a 'stand alone' basis or under the SARP-Shell. In this report, it is explained how to run the models 'stand alone'. In a separate manual by Riethoven (1994), it is explained how to operate the models and programs under the SARP-Shell.

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Preface

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1 Introduction

This volume presents a framework for the use of crop growth modelling in agro-ecological characterisation and zonation of rice, as developed in the research theme 'Agro-ecosystems' of the project Simulation and Systems Analysis for Rice Production (SARP). Agro-ecological zonation generally refers to the stratification of a geographical area into homogeneous land-units. This stratification is usually based on properties that are physical-environmental (e.g. climate, landscape, soil) and agronomic (e.g. land use, production system characteristics), but can also include socio-economic factors (e.g. labour, subsistence/cash-cropping). The purposes of agro-ecological zonation vary. Often, it is used to create so-called recommendation domains for the transfer of agro-technological knowledge that has been developed at particular sites such as agricultural research stations. Examples in the SARP network have been reported by Bhuiyan & Ahmed (1993) and Garcia (1993). Another purpose of zonation is the exploration of water-limited and irrigated crop production levels (e.g. Wan Sulaiman & Surjit Singh, 1993; Makarim & Las, 1993; Thiyagarajan et al., 1993). In such zonation studies, a quantitative description of the relationship between the physical environment and potential cropping systems and production levels is of main importance. In this respect, crop growth simulation modelling is a useful tool. Recent results of the use of simulation modelling in agro-ecological zonation of rice in the SARP network have been presented at the 'International Workshop on Agro-Ecological Zonation of Rice', held at the Zhejiang Agricultural University, Hangzhou, P.R. of China, 14-17 April 1993 (Bouman et al., 1993).

For zonation studies, crop growth models need to be adapted to the specific characteristics of the agro-ecological environment under consideration. Two characteristic environments in Asia for rice are lowlands and uplands (IRRI, 1984). In lowland environments, soils are puddled in the beginning of the growing season. Rice is mostly transplanted from seed-bed or, to a lesser extent, direct-seeded. Bunds along the field allow for ponded water. The crop can be either irrigated or fully dependent on rainfall. In upland environments, soils are not puddled, and rice is direct-seeded and completely dependent on natural rainfall. Fields are generally not bunded and part of the rainfall can be lost as run-off. Thus, important differences between lowlands and uplands are soil tillage practices and, as a result, the crop-soil water balance. In the SARP project, a simple soil water balance model was developed for lowlands LOWBAL (LOwland Water BALance; Bouman, 1993a), and the existing model SAHEL (Soils in semi-Arid Habitats that Easily Leach; van Keulen, 1975) was selected for uplands. These water balance modules were combined with the above-ground growth module ORYZAW in the agro-ecological rice-growth model ORYZA_W (2.0) for zonation studies.

The regional scale that is used in zonation affects the level of detail with which crop growth and water balance processes can be described. For instance, a detailed description of the water balance of soils, such as in SAWAH (Simulation Algorithm for Water flow in Aquic Habitats; ten Berge et al., 1992) or PADDY (Wopereis, 1993), requires detailed information on soil physical properties, e.g. soil water retention characteristics (pF curve), conductivity curves, and ground water table depth. Such detailed information is generally not available on a regional scale, and soil-physical information often has to be derived from general descriptions on soil maps and/or from sparse measurements. Therefore, simulation models for zonation need to describe physical processes with a level of detail that matches that of the input data available. In ORYZA_W 2.0, the relatively simple soil water balance models LOWBAL and SAHEL were especially developed and selected for application on regional scales. The price that has to be paid for a more general description of physical processes in a simulation model is twofold. First, the results (simulated output) may be less accurate than when a more detailed model (with correspondingly more detailed input data) is used. Secondly, the validity domain - and thus the application domain - may be more restricted. For example, SAWAH can be used in more various and hydrological complex situations than LOWBAL (Bouman et al., 1994).

Two more aspects related to input data need to be taken into account when crop growth models are used on a regional scale: uncertainty and spatial variation. Usually in zonation, a set of model input parameters is supposed to be representative for each of the (homogeneous) land-units under consideration. Using these sets, the simulation model is run and 'representative' model output (e.g. yield) is obtained. However, this approach ignores the uncertainty that is present in the, generally estimated, input parameter values of the land-units. A method is needed that relates the accuracy or uncertainty in simulated output to the accuracy or uncertainty in input parameter values. Second, input parameter values from a geographically extended land-unit are often characterised by spatial variation. The effect of spatial variation in input parameter values on simulated output also needs to be taken into account. The program RIGAUS (Random Input Generator for the Analysis of Uncertainty in Simulation) was developed to quantify the effects of uncertainty and spatial variation in input parameter values on simulated output. The method is based on Monte Carlo simulation. Monte Carlo simulation is also the basis for a method to 'translate' probabilities of input parameter values into probabilities of model output and to perform risk analysis.

In this volume, a framework is presented for the use of crop growth models in agro-ecological zonation of rice. The framework is illustrated using the model ORYZA_W, version 2.0, for irrigated and water-limited production situations. However, the framework can also be used using other crop growth models (e.g. ORYZA1 for potential production) and for other crops. In Chapter 2, ORYZA_W 2.0 is briefly introduced. ORYZA_W can simulate the growth and development of rice in irrigated and rainfed lowland and in rainfed upland environments. The above-ground growth module ORYZAW and the water balance module LOWBAL were developed from field experiments at IRRI (International Rice

Research Institute, Philippines). The module SAHEL, originally developed by van Keulen (1975), was taken and adapted from the MACROS series (Modules of an Annual CROp Simulator; Penning de Vries et al., 1989). In Chapter 3, a framework is presented for the application of ORYZA_W on a regional scale in agro-ecological zonation. The geographic unit of simulation is the land-unit as derived by 'conventional' methods of zonation (stratification by physical-environmental and agronomic characteristics). It is shown how ORYZA_W can be used to characterise (single) rice cropping systems by e.g. level and variation of yield, irrigation water needs and crop growth duration. The framework presents a method to relate simulated model output (e.g. yield) to input parameter accuracy, which is useful in designing and optimising sampling strategies, and to deal with uncertainty and spatial variation in model input parameters. The last step of the framework presents a method for risk analysis including variation in weather and probability distributions of soil and management parameters. Chapter 4 describes the program RIGAUS that is used to generate probability distributions of parameter values for Monte Carlo simulation. Chapter 5 illustrates the presented methodology for a case-study on rainfed lowland rice in the Philippines.

The model ORYZA_W and the program RIGAUS are written in FORTRAN77 and can be executed on a 'stand-alone' basis. However, ORYZA_W and RIGAUS may also be accessed using the user-friendly SARP-Shell that allows easy running of ORYZA_W with large input data sets (Riethoven, 1994). The Appendices contain complete listings of ORYZA_W (version 2.0) and RIGAUS (version 1.1) including all input and output files.

2 The ORYZA_W (2.0) rice growth model

ORYZA_W (2.0) simulates growth and development of rice in irrigated and rainfed lowland and in rainfed upland environments, and is especially designed for zonation studies. In irrigated lowlands, ORYZA_W simulates timing and total amounts of irrigation water needs as well. Currently, a new version of ORYZA_W, 3.0, is under development, that will also be suitable for other purposes, e.g. field and experiment studies. ORYZA_W is described in detail in a SARP Research Proceeding by Wopereis et al., 1995. In the rest of the text in this volume, ORYZA_W always refers to version 2.0 (as listed in appendix 1). ORYZA_W is programmed under the FORTRAN Simulation Environment (FSE, version 2.0) as developed by van Kraalingen (1991a). A complete listing of the model with input and output files is given in Appendix 1. The FSE system consists of a main program, weather data and utilities for specific tasks. One of the main features of FSE is the distinction of four main tasks that control the order of the calculations in the crop growth program (above-ground growth module and below-ground water balance modules): ITASK = 1 for initialisation; ITASK = 2 for rate calculations; ITASK = 3 for state calculations/updates; and ITASK = 4 to mark the end of the program. For an understanding of the tasks of initialisation and rate and state calculations, the reader is referred to text books on crop growth simulation modelling (e.g. Penning de Vries & van Laar, 1982; van Keulen & Wolf, 1986). FSE also facilitates in- and output data handling. The WEATHER system (van Kraalingen et al., 1990) is used to read weather data. Utilities from the library TTUTIL (Rappoldt & van Kraalingen, 1990) are extensively used for specific tasks such as reading input data, writing output data, and integration of state variables.

The structure of ORYZA_W under the FSE system is schematically presented in Figure 2.1. The ITASK succession, the reading of weather data, and the handling of input and output files takes place in the subroutine FSE. This information is passed on to the subroutine MODELS. This subroutine calls the subroutine ORYZAW, which is the actual above-ground growth module, and the subroutines LOWBAL for the water balance of lowland soils, and SAHEL for the water balance of upland soils. A switch in the program is used to select the production environment and to combine ORYZAW with either LOWBAL or SAHEL: SWIWLP = 0 for irrigated lowland (LOWBAL); SWIWLP = 1 for rainfed lowland (LOWBAL); SWIWLP = 2 for rainfed upland (SAHEL). The switch SWIWLP is set in an input file (see Paragraph 2.2.1). The modules ORYZAW, LOWBAL and SAHEL are the core of the actual growth model ORYZA_W, and have been described by several authors: van Keulen, 1975, and Penning de Vries et al., 1989 (SAHEL), Kropff et al., 1993 (the ORYZA1 version as basis for ORYZAW), Bouman, 1993a (LOWBAL) and Wopereis et al., 1995 (ORYZA_W, version 3.0). A complete listing of ORYZA_W with input and output files, and a variable name list is given in Appendix 1 (all referring to version 2.0 as used in this volume).

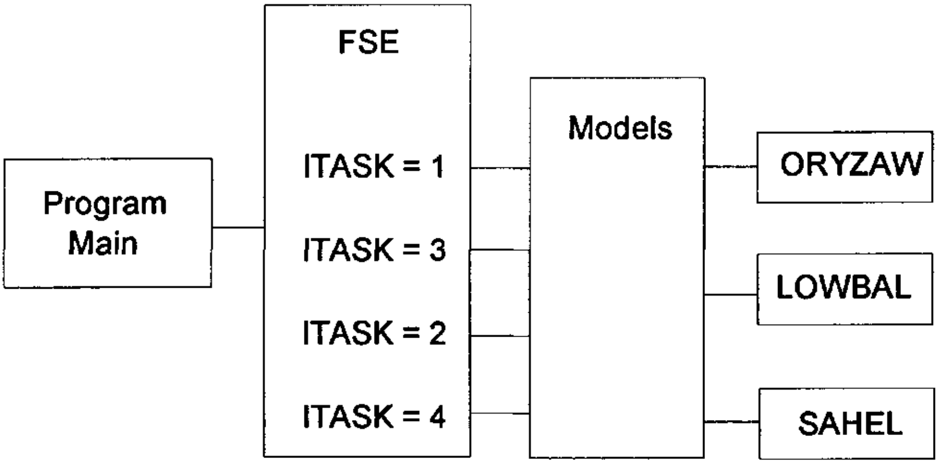


Figure 2.1. Main components of the rice growth model ORYZA_W under the FORTRAN Simulation Environment.

2.1 Model validity domain

The application of ORYZA_W in zonation studies generally means that the model is extrapolated from the environment where it was designed, tested and validated to other agro-ecological environments. Therefore, it is important to know the characteristics of the environment in which the model was developed and to indicate its general validity domain. Here, the validity domain of ORYZA_W, version 2.0, is briefly described.

For potential production in irrigated lowland situations, the ORYZA1 model (version 1.0), which is the basis of ORYZAW, has been well-tested with field experiments at IRRI, the Philippines: "Yield potential in a given environment (planting date, latitude, radiation, temperature, variety as input) can be simulated based on the leaf N content of the highest yielding experiments. The recent IRRI experiments could be used as starting point. [However], a restriction for photoperiod insensitive varieties holds" From: Kropff et al. (1993). ORYZA1 (1.0) simulates potential rice yield with no sink limitations: effects of low and/or high temperatures on spikelet sterility are not included. [The new version of

ORYZA_W, 3.0, is based on an updated version of ORYZA1, 1.3, that includes the effects of photoperiod sensitivity and sink limitations; Kropff et al., 1994].

The effects of drought stress on crop growth and development were derived from pot experiments, and validated with field experiments at IRRI (Wopereis, 1993). These experiments were held in the dry season, in puddled lowland conditions with ample supply of nutrients. The yield levels were 5-8.4 t ha^{-1} (Wopereis, 1993; p.128). The maximum number of continuous drought stress days in these experiments was 25; therefore, simulations with ORYZA_W are aborted when more than 25 days of drought stress are recorded. In ORYZAW, the same effects of drought stress are assumed to be applicable for rainfed upland conditions. This hypothesis has not been tested, however, and more research on growth and development of rainfed upland rice is still needed.

ORYZAW simulates potential and water-limited growth and development of rice. It is assumed that the nutrient supply of the crop is optimal and that the crop is free from pests, diseases and weeds.

The model LOWBAL was validated for irrigated lowland conditions on field experiments at IRRI (Bouman, 1993a), and with model simulations using the detailed soil water balance model SAWAH (Bouman et al., 1994). The model performs accurately if a combined seepage & percolation rate, SPSOIL, has been measured, and does not change in time. Field average SPSOIL rate can easily be measured using sloping gauges placed in the field. Percolation rates may change when the poorly permeable layer at the interface of puddled topsoil and non-puddled subsoil is disturbed (e.g. as occurred in an IRRI field experiment by a large numbers of weeders (Wopereis, 1993; pp. 108-109). Seepage losses may be enhanced if neighbouring fields are drained at the end of the growing season, by inducing water flow through and underneath bunds. Seepage may also change if water levels in neighbouring ditches, creeks or drains vary. Such changes depend on texture, compaction and state of maintenance of the bunds, and on the ratio of bund length over the surface area of the field (Tuong et al., 1994).

In LOWBAL, it is assumed that roots do not penetrate through the poorly permeable layer in the lower zone of the puddled topsoil and, therefore, water extraction from the unpuddled subsoil is not taken into account.

The SAHEL water balance can be used for non-puddled, freely draining, sandy and loamy upland soils with a deep ground water table (> 1 m below the root zone) (Penning de Vries et al., 1989). This type of soil has high hydraulic conductivity when wet, permitting fast downward water transport, so that saturation of soil layers does not occur. The model can also be used for clayey soils with deeper ground water tables (> 2 m below the root zone), but the simulations are then more crude. SAHEL is not suitable for (heavy) clay soils with impeded drainage.

2.2 Running and editing ORYZA_W

2.2.1 Input and output file control

Under the SARP-Shell, control over input and output files is facilitated with a menu-system (Riethoven, 1994). If the FORTRAN program ORYZA_W is run without this Shell, the input and output files are controlled in the file CONTROL.DAT (an example is given in Appendix 1.2a). The contents of this file are:

FILEI1 = name of file that contains the crop data, e.g. 'RICE_W.DAT'
FILEI2 = name of file that contains the soil data, e.g. 'LOAM.DAT'
FILEIT = name of file that contains timer variables, e.g. 'TIMER.DAT'
FILEIR = name of file that contains data for reruns, 'RERUNS.DAT'
FILEON = name of output file, 'RESULTS.OUT'
FILEOL = name of the log file 'RESULTS.LOG'

Crop data

Specific crop parameter are needed for the above-ground growth module ORYZAW. An example is given in Appendix 1.2b for IR72. These data were derived from field experiments at IRRI (Kropff et al., 1993). Crop parameters should preferably be derived for the local rice variety under consideration, from field experiments under potential growth conditions.

Soil data

Specific soil physical parameters are needed for the soil-water balance modules LOWBAL and SAHEL. If ORYZA_W is used for irrigated or rainfed lowland environments, a file containing soil data for LOWBAL should be supplied for FILEI2; if ORYZA_W is used for rainfed upland conditions, a file containing soil data for SAHEL should be selected. If the wrong file is supplied, ORYZA_W is aborted and gives an error message. Examples of soil files are given in Appendix 1.2c. For the SAHEL water balance module, 18 example files are available that contain soil-physical data derived from measurements on Dutch soils (Wösten et al., 1987).

Timer data

Timer data control the model environment, the selection of weather data and the start and end of the growing season. An example is given in Appendix 1.2d. Important parameters in this file are:

- *Production environment*

SWIWLP = switch to control the production environment: 0 = irrigated lowland;
1 = rainfed lowland; 2 = rainfed upland

- *Weather data*

The selection of files containing weather data is controlled by the following parameters:

WTRDIR = directory name where the weather files are stored
CNTR = country name of the weather station, e.g. 'PHIL' for the Philippines
ISTN = station number of weather data, e.g. 1.

If sunshine hours are available in the weather data instead of radiation values, these are automatically converted using the Angstrom parameters:

ANGA = Angstrom parameter A:
dry tropical, A=0.25
humid tropical, A=0.29
cold and temperate A=0.18.
ANGB = Angstrom parameter B:
dry tropical, B=0.45
humid tropical, B=0.42
cold and temperate, B=0.55.

Radiation values in the weather file should be given in KJ or MJ; a parameter MULTIP is used to convert these in to J values:

MULTIP = multiplication factor for radiation:
if radiation data are in KJ: MULTIP = 1,
if radiation data in MJ: MULTIP = 1000.

Weather data itself are stored in files according to the specifications of the WEATHER system (van Kraalingen et al., 1990). The name of a weather file consists of a country-code, CNTR, with an extension designating the number of the weather station, ISTN (E.g. PHIL1 for weather station 1 in the Philippines). The weather file should contain daily values of radiation, minimum temperature, maximum temperature, vapour pressure, wind speed and rainfall. The format of the data is very strict. An example of a weather data file in the WEATHER format is given in Appendix 1.2e.

- *Time variables*

YEAR = year of weather data (= simulation year), e.g. 1991.
STTIME = start day of simulation (sowing day), e.g. 150.
FINTIM = finish time of simulation; a high value should be supplied here to guarantee the continuation of the simulation until the crop has reached maturity, e.g. 1000.
DTRP = days between sowing and transplanting. DTRP = 0. for direct-seeding.
DELT = time step of integration, 1.

- *Output options*

These parameters are pre-set and normally do not need changing.
IFLAG = indicates where weather error and warnings go, e.g. 1100 means errors and warnings go only to a log file, see WEATHER manual, van Kraalingen et al., 1990.
COPINF = switch variable denoting what should be done with input files:
'Y' = copy input files into output file
'N' = do not copy input files into output file
PRDEL = time in days between consecutive outputs to file, e.g. 5.
IPFORM = format of the output tables: 0 = no output table, 4 = normal table, 5 = tab-delimited (for Excel), 6=TTPLOT format.
DELTMP = switch variable what should be done with the temporary output file: 0 = do not delete; 1 = delete

Rerun data

The FSE systems provides a facility for model reruns using changed model parameter and/or initial state variable values (van Kraalingen, 1991a). A 'reruns file' with a name defined in CONTROL.DAT, e.g. RERUNS.DAT, should contain parameter and/or initial state variable names and values for a model rerun. When ORYZA_W is executed, it will automatically search for the presence of a reruns file. If such a file is not found, the model will be executed only once, using the data from the standard data files. If a reruns file is present, the model will automatically be rerun with the (set of) new parameter values. The total number of runs made by the model is always equal to the number of rerun sets plus one (the 'default' run). Names of parameters/variables originating from different data files can be redefined in the same rerun file, e.g. crop, soil and timer parameters. The format of the rerun file is identical to that of the other data files, except that the name of parameters may appear in the file more than once, indicating different rerun sets. Arrays can also be redefined in a rerun file. The order and number of the variables should be the same in each set. A new set starts as soon as the first variable is repeated. An example of a reruns file is given in Appendix 1.2f.

The maximum number of parameter values for reruns with ORYZA_W is 10000. This can be either 10000 values of one single parameter, or, for instance, 1000 values of ten parameters each. When many reruns are made, the time step between consecutive output that is written to file, PRDEL, in the Timer file (see above) should be set a high value, e.g. 1000, so that only initial and end values of output variables are printed. Otherwise, the output file defined in the file CONTROL.DAT, e.g. RESULTS.OUT, will become extremely large.

Output files

Two output files are created by ORYZA_W. The file OP.DAT contains 'end-of-season' values of selected variables. E.g. the weight of rough rice, WRR, in OP.DAT is the final weight at the end of the simulation run. Variable names and values are written to OP.DAT in the model via a call to the subroutine OPSTOR of the TTUTIL library: CALL OPSTOR(<variable name>, <variable value>).

The second file name is defined in the file CONTROL.DAT, e.g. RESULTS.OUT. In this file, values of selected variables are written during execution of the model with a 'print time step' as defined by PRDEL in the timer file (see above). Variable names and values are written to RESULTS.OUT by a call to the subroutine OUTDAT of the TTUTIL library: CALL OUTDAT(<variable name>, <variable value>).

Examples of OP.DAT and RESULTS.OUT are given in Appendix 1.3a and 1.3b respectively.

Log files

Two log files are created. WEATHER.LOG contains the headers of the weather files used, and any error and/or warning messages created by the WEATHER system. The second file name is defined in the file CONTROL.DAT, e.g. RESULTS.LOG, and contains information on the execution of the model and any error and/or warning messages generated by ORYZA_W.

2.2.2 Editing ORYZA_W

ORYZA_W is written in the programming language FORTRAN-77 on an IBM compatible 486 PC. If the source code of the model is edited, ORYZA_W should be re-compiled and linked before execution. After compilation, the object file ORYZA_W.OBJ should be linked with an object file OPSYS.OBJ (containing some specialised subroutines) and with the libraries TTUTIL and WEATHER (in this sequence).

3 ORYZA_W in agro-ecological zonation

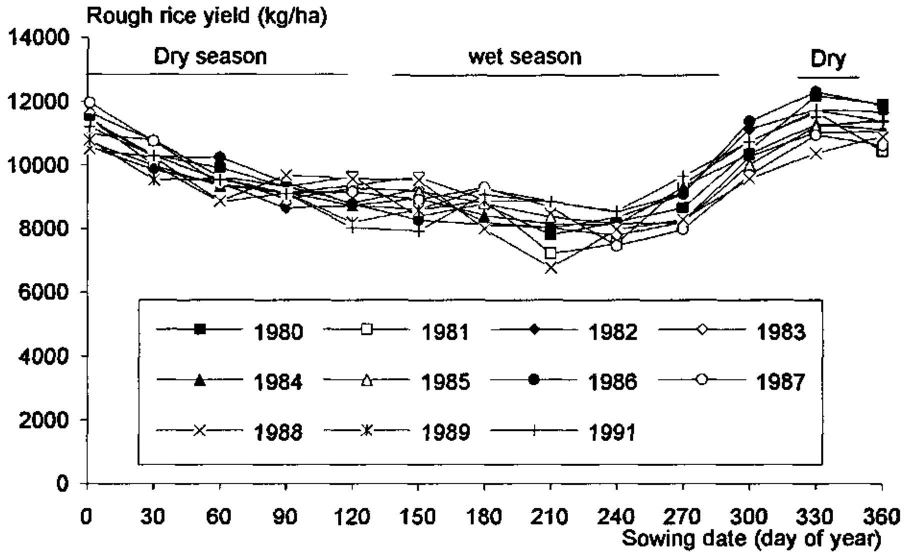
3.1 Simulation on a regional scale

ORYZA_W can be used in agro-ecological zonation to quantify characteristics of rice cultivation in upland or lowland environments, e.g. potential and water-limited rice yields, irrigation requirements, optimum sowing/transplanting dates and crop durations. Based on soil and climatic maps and data, a regional area under study can be divided into land units that are more or less homogeneous in soil and climatic characteristics (e.g. Aggarwal, 1993; Garcia, 1993; Pannangpetch, 1993; Wopereis et al., 1993). For each land-unit, input data for ORYZA_W have to be derived with respect to crop, soil, weather and management characteristics. Crop data should preferably be obtained from field experiments under optimal conditions, using regional-specific rice varieties. If this is not possible, crop data form other locations and experiments can serve as a starting point (Kropff et al., 1993). Weather data are obtained from meteorological stations in the area that are assigned to the land-units by spatial interpolation (e.g. Beek, 1991a/b). Soil parameters needed for simulation are generally difficult to obtain and costly and time-consuming to measure (Wopereis et al., 1993). If no measurements can be carried out, as often will be the case in zonation studies, such soil data may be estimated from soil maps using so-called pedotransfer functions (Driessen, 1986a, 1986b; Bouma and van Lanen, 1987; Ritchie and Crum, 1989; van Genuchten et al., 1989; Reinds et al., 1991). For instance, soil moisture characteristics are often estimated from texture descriptions. Management parameters, such as sowing date or bund height, may be derived from expert knowledge or from local field enquiries. Thus, for each identified land unit of the zonation study, a set of crop, weather (preferably a number of years), soil and management parameters is identified that is considered to be representative for the whole land unit. Using these sets, ORYZA_W can compute rice yield (and other variables of interest) for lowland and upland production situations.

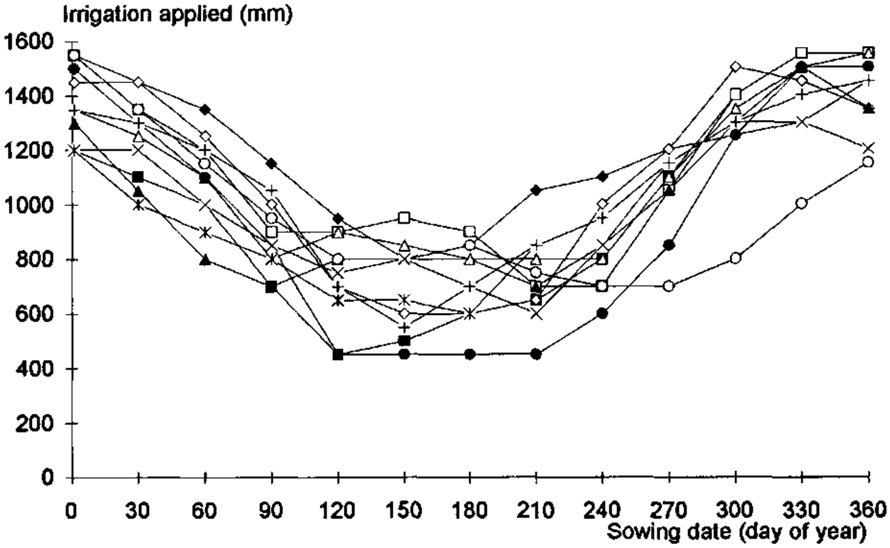
An example for irrigated lowland rice in the Philippines is given in Figure 3.1. ORYZA_W was used to quantify rough rice yield, irrigation water needs and crop duration as a function of sowing date for 1981-1991. Weather data were taken from the IRRI wetland station. Crop data were derived from field experiments conducted at IRRI using rice variety IR72 (Kropff et al., 1993; Wopereis, 1993). Soil and management data were obtained from expert knowledge and literature (Wickham & Singh, 1978; Wopereis, 1993). Highest potential yields occurred if sowing was done at the beginning of the dry season, (i.e. days 330-360), and are explained by high levels of radiation and long crop durations. The high potential yields in the dry season were associated with the highest irrigation water needs. The simulated crop duration is an important variable in the planning of crop rotations (e.g. Sattar, 1993; Yang Jingping & Zhang Xigu, 1993).

The procedure described above is commonly used when crop growth models are applied at a regional scale (Buringh et al., 1979; van Lanen, 1991; van Diepen et al., 1991; Hammer & Muchow, 1991; Netherlands Scientific Council for Government Policy, 1992). Though this procedure is a valid, practical approach in itself, it does not account for the 'regional' nature of the simulations. A land-unit is considered fully homogeneous with respect to model input parameters and only one set of, mostly estimated, input data values per land-unit is used in the simulation. The effect of uncertainty or spatial variation in the input parameter values of a land-unit on simulated output is not accounted for. Also, the relationships between quality, or accuracy, of input data and simulated output are not quantified. Such relationships are important in the phase of input data collection, especially for the design of measurement programs. Moreover, these relationships can indicate relevant management practices to optimize rice cropping, e.g. high yields associated with low water losses.

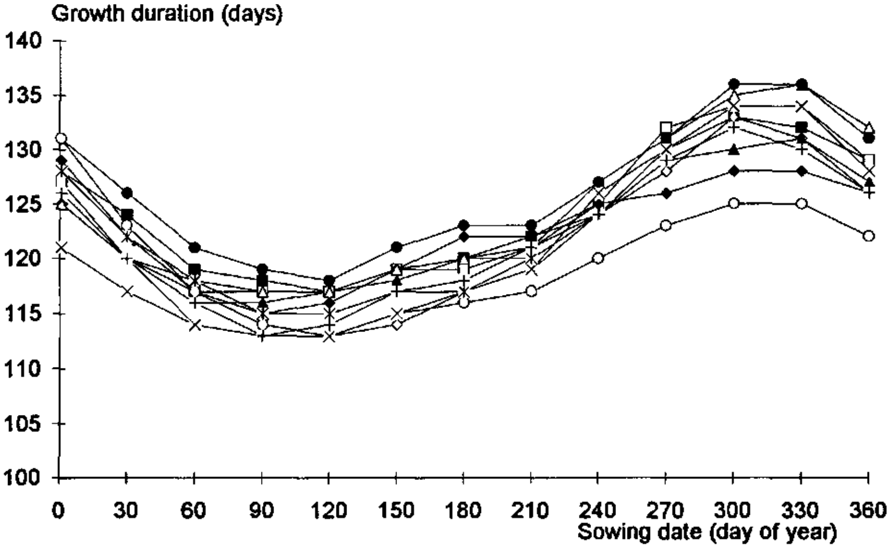
This Chapter provides a framework to quantify the relationship between model input and output accuracy for input data collection (Paragraph 3.2) and to deal with uncertainty and spatial variation in input data on a regional scale (Paragraph 3.3). Uncertainty and variation in input parameter values are 'translated' in risk analysis (Paragraph 3.4). The focus is on soil and management parameters because these data have to be collected on a regional scale. Some comments on the derivation and handling of crop and weather data are given in Paragraph 3.6. The framework presented here is illustrated in detail for a case-study on rainfed lowland rice in the Philippines in Chapter 5. Here, it is briefly illustrated with an example for irrigated lowland rice.



(3.1a)



(3.1b)



(3.1c)

Figure 3.1. Simulated potential rough rice yield (a), amount irrigation water needs (b) and crop duration (c) of irrigated lowland rice at Los Baños, the Philippines, 1980-1991.

3.2 Data collection

The use of ORYZA_W for zonation studies requires knowledge of management procedures and data on crop characteristics, soil properties and weather variation in the region under study. Crop characteristics are generally derived from literature and well-controlled field experiments (Kropff et al., 1993). In principle, these parameter values are only crop (variety) specific and do not change with environment (at least if the environment falls within the validity domain of the model; see Paragraph 2.1). Therefore, once a set of crop parameters has been determined at a certain location, such a set can be used for extrapolation to other land-units of the zonation study. Procedures for the derivation of crop parameters, and the uncertainty and variation therein, fall outside the scope of this volume. Some comments are given in Paragraph 3.6. Weather data are measured at meteorological stations and, as mere data-users, crop modellers can not influence the accuracy of these measurements. The quality of weather data should be thoroughly checked, and preferably quantified, before embarking on model simulations. Some comments on dealing with uncertainty or inaccuracy in weather data are given in Paragraph 3.6. A good overview of techniques for spatial interpolation of weather data from meteorological stations to land-units of interest is given by Beek (1991a/b).

Soil and management data need to be collected for each land unit within the zonation study area. A land unit is defined here as a geographic area with a unique combination of weather, soil and management characteristics. The collection of these data on a regional scale is generally expensive and time-consuming. Therefore, the design of cost-effective measurement and data collection strategies deserves ample attention. In this respect, sensitivity analysis (SA) with the model to be used, i.e. ORYZA_W, is a helpful tool. It reveals the type of data that need to be collected with a relatively high accuracy, and the type of data for which a rough estimate or general inventory will do. SA relates the accuracy with which input parameters need to be quantified to the desired accuracy of the simulated output (e.g. yield or amount of irrigation water). In SA, the value of input parameters are gradually changed and the effect on the simulated output is quantified. If a number of years with weather data are available, it is best to repeat the analyses for a number of 'good', 'bad' and 'average' years. Good, bad and average are defined here in relation to the observed simulated output, e.g. a good year has a relatively high simulated yield and a bad year a relatively low simulated yield. The results of the SA for various years can be compared by standardising the simulated outputs for each year to the output for that year using standard (representative) input parameter values (Bouman, 1994).

Three points have to be considered in setting up a sensitivity analysis:

1. Which parameters need to be included ?
2. What is the range in parameter values ?
3. What is the correlation between parameters ?

Ad 1. When no prior knowledge about the relative importance of the parameters is available, all parameters should be included in SA. If information is available, only the relevant parameters are selected. For ORYZA_W, the following soil and management parameters may be included if simulated yield, irrigation water and crop duration are of interest:

Irrigated lowland

- Soil parameters: seepage & percolation rate, SPSOIL.
- Management parameters: Bund height, WL0MXI; critical depth of ponded water, WL0MIN; irrigation requirements for land preparation, RIPUD; development stage at which irrigation is stopped, DVSIE; sowing date, STTIME; duration of the seed-bed, DTRP; number of plants in seed-bed, NPLSB; number of hills, NH; number of plants per hill, NPLH; number of plants direct-seeded, NPLDS (only if direct-seeded).

Rainfed lowland

- Soil parameters: seepage & percolation rate, SPSOIL; water content of puddled layer at saturation, WCSTP, at field capacity, WCFCP, and at wilting point, WCWPP (and for cracking soil types: linear shrink factor, SHRINK; water content at which cracks penetrate the compacted layer, WCCRAC; drainage rate of the subsoil, DDR).
- Management parameters: bund height, WL0MXI; thickness puddled layer, TKLPI; sowing date, STTIME; duration of the seed-bed, DTRP; number of plants in seed-bed, NPLSB; number of hills, NH; number of plants per hill, NPLH; number of plants direct-seeded, NPLDS (only if direct-seeded).

Rainfed upland

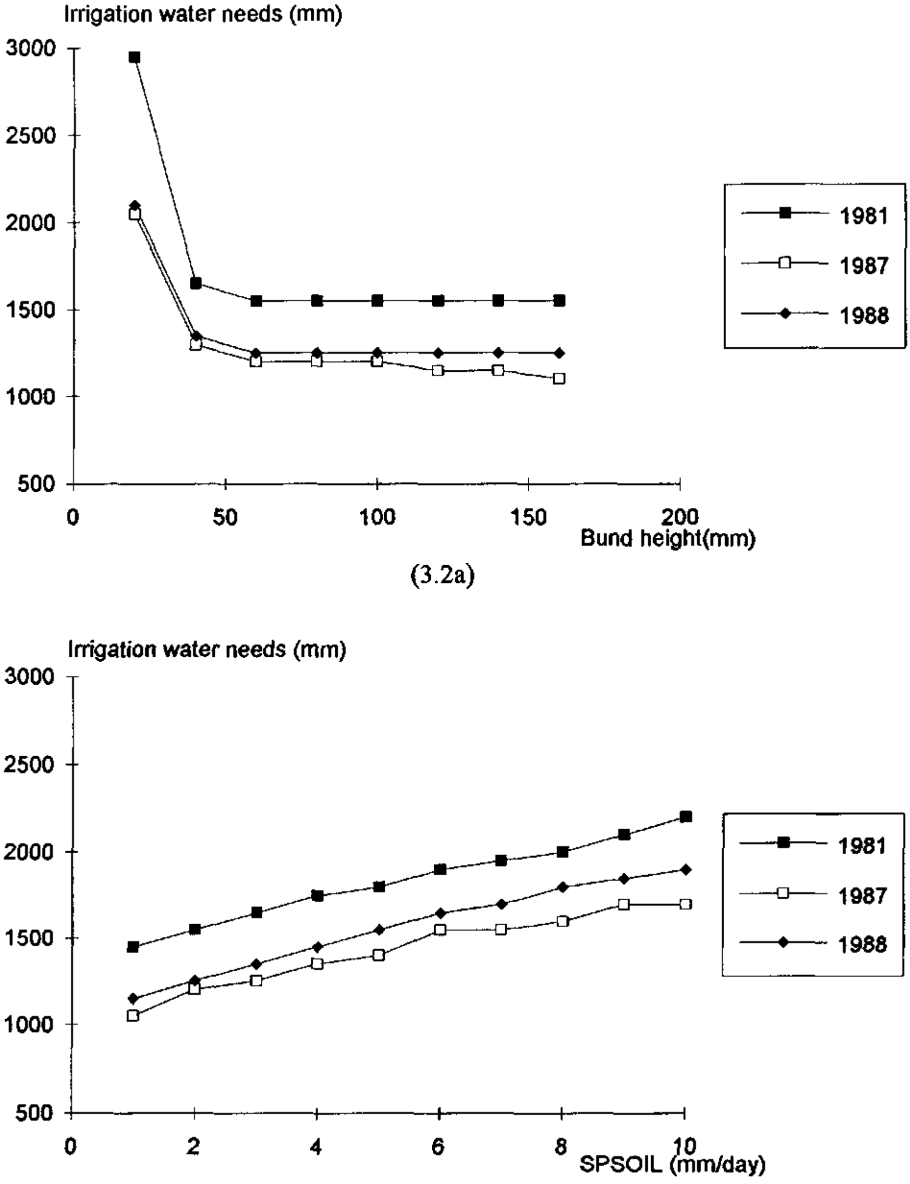
- Soil parameters: water content at saturation, WCST, at field capacity, WCFC, and at wilting point, WCWP; fraction initial water content, FWCLI; fraction runoff, FRNOF; rooting depth of soil profile, ZRTMS.
- Management parameters: sowing date, STTIME; number of plants direct-seeded, NPLDS.

Ad 2. The ranges of the parameter values should be taken as broad as possible to make sure that the actual values in the land-unit under study are covered. The boundary values can be taken from initial survey data, from expert knowledge, from literature, or from any reasonable guess, as long as the values are not beyond the validity domain of ORYZA_W.

Ad 3. Input parameter values can not always be varied without considering the values of (some of) the other input parameters (i.e. 'ceteris paribus' condition). Correlation between parameters may exist and should be taken into account. In the water balance module for upland conditions, SAHEL, for instance, the water contents at saturation, WCST, at field capacity, WCFC, and at wilting point, WCWP, are correlated parameters. This means that when, for instance, the value of WCST is varied between certain ranges, the values of WCFC and WCWP should be adapted too, so that a realistic set of moisture characteristics is obtained. The correlation between soil moisture characteristics for the SAHEL water balance module is taken into account in the program RIGAUS (Paragraph 4.3).

An example of SA is given for the case-study of Figure 3.1. In Figure 3.2, the sensitivity of the simulated irrigation water needs to seepage & percolation rate (SPSOIL) and to bund height is given. The simulations were carried out for the dry season (sowing date was day 345) for three years. In this environment, bund heights larger than 40 mm hardly affected the amount of irrigation water, whereas the SPSOIL rate was a major irrigation-determining factor. A first, rough estimate for bund height of 100 mm, from expert-knowledge, needs no further refinement by field observations. On the other hand, the actual value of SPSOIL rates needs relatively accurate measurements. An inaccuracy of 1 mm d^{-1} in the quantification of SPSOIL lead to an inaccuracy in simulated irrigation water of 100 mm (which is about 6% on an average amount of 1600 mm). The accuracy with which SPSOIL data actually need to be collected in a zonation study depends on the desired accuracy of needed irrigation water (e.g. for irrigation system design).

The reruns option of the FSE system provides an easy way for SA with ORYZA_W. Parameter values can be changed in the file RERUNS.DAT (Paragraph 2.2.1), which is automatically read and executed by ORYZA_W. A special option for SA is available under the SARP-Shell (Riethoven, 1994).



(3.2a)

(3.2b)

Figure 3.2. Simulated irrigation water needs in the dry season as a function of bund height (a) and seepage & percolation rate SPSOIL (b) in 1981, 1987 and 1988.

3.3 Uncertainty and spatial variation in soil and management parameters

Soil and management parameter values for individual land-units can be estimated (e.g. from expert knowledge, soil maps) or measured. Especially when data are estimated, there is always a degree of uncertainty. Usually, a representative value for the whole land-unit under consideration is estimated and this value is used in ORYZA_W. In this approach, the effect of uncertainty in input parameter values on the simulated output remains unquantified. If a number of actual measurements has been performed in a land-unit, the parameter value is mostly characterised by spatial variation. Again, ORYZA_W can be run with average values only, but the effect of spatial variation on simulated output can and should be quantified. Similarly, the effect of measurement errors on simulation output should be quantified. In the following, however, measurement errors are not addressed specifically, but assumed to be part of uncertainty.

Monte Carlo (MC) simulation is a useful technique to quantify uncertainty or spatial variation in input parameter values on simulated output (Hazelhof et al., 1990; Kros et al., 1990; Rossing et al., 1993; Bouman, 1994). In applying this technique, a simulation model is run a large number of times using random values for specified input parameters. These random values are drawn from probability distributions or from measurement series (frequency distributions). The resulting distribution of simulated output values represents a probability distribution as a function of input uncertainty (probability), or a frequency distribution as a function of spatial variation of input data (including any measurement errors). A probability distribution for input parameter values can be derived from expert knowledge, literature data and some actual measurements. E.g. the moisture characteristics of a soil can be estimated from the texture description on the legend of a soil map. For a 'loamy soil', we can construct a probability distribution for the water content at field capacity, WCFC, from literature data: uniform distribution between 0.27 and 0.40 cm^3 cm^{-3} (Wösten et al., 1987). For a 'clayey loam', we could narrow the probability distribution down to 0.35-0.40 cm^3 cm^{-3}, and for 'sandy loam' to 027-0.34 cm^3 cm^{-3}. If a large number of measured values of a parameter are available, a frequency distribution can be drawn that represents the actual spatial variation. The sensitivity analysis described in the previous Paragraph can be used to select the soil and management parameters that have a relatively large effect on simulated output for MC analysis. Again, correlation between input parameters has to be taken into account. The program RIGAUS (Random Input Generator for Uncertainty Analysis in Simulation; see Chapter 4) was especially developed to generate an FSE reruns file with random parameter values from probability and/or frequency distributions for MC analysis with ORYZA_W.

A simple example of MC simulation is given for the case-study of Figures 3.1 and 3.2. First, the effect of uncertainty is illustrated in Figure 3.3. From SA, it was concluded that SPSOIL rate had a large effect on simulated irrigation water of irrigated lowland rice in the Philippines (Figure 3.2.b). Three probability distributions for SPSOIL rate were constructed: a uniform distribution when expert-knowledge suggests that any value between certain boundary values is a reasonable guess; a normal-type of distribution, when expert-knowledge suggests that a certain average value has the highest probability of occurrence; and a skewed beta distribution, when expert-knowledge suggests that a lower or upper boundary value has highest probability of occurrence (Figure 3.3.a). Five hundred random values of SPSOIL rate were generated by RIGAUS from each probability distribution and subsequently used to simulate irrigation water needs in the dry season using ORYZA_W. The resulting simulated values of irrigation water needs (Figure 3.3.b) are probability distributions that quantify the effect of uncertainty in, and expert-knowledge on, SPSOIL rate. Here, the probability distribution was only calculated for one year (the 'average' year 1981). The calculations can be repeated for more years ('good', 'bad' and 'average') to study the variation between years.

For the example of spatial variation, SPSOIL data were taken from literature. Wickham & Singh (1978) presented measured SPSOIL rates for 10 field sites in Nueva Ecija, Bulacan and Laguna Provinces, the Philippines, in the 1969-70 growing season. Table 3.1 lists the SPSOIL rates as measured in the dry season. Using these data, ORYZA_W was used to calculate the amount of irrigation water needed in the dry seasons of 1980-1991. The resulting simulated values are a frequency distribution of amounts of irrigation water as function of spatial variation in SPSOIL rates (Figure 3.4).

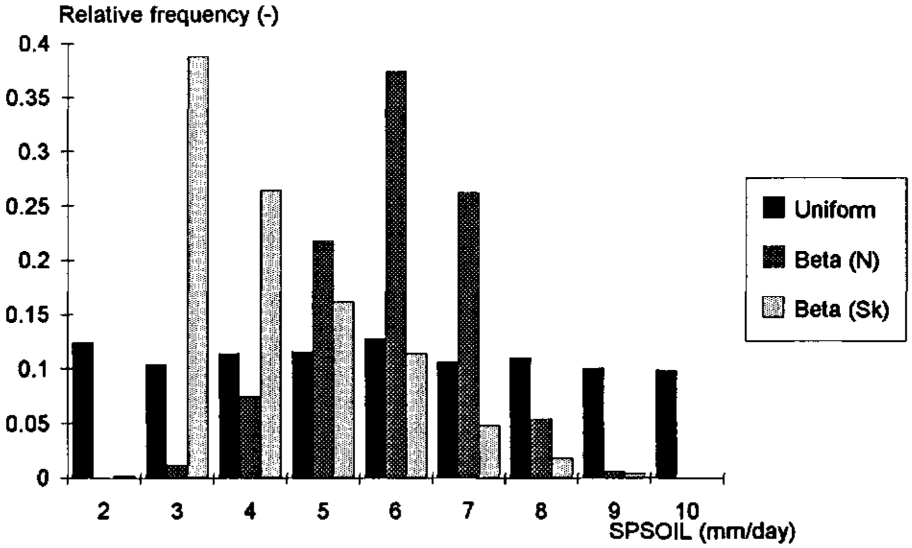


Figure 3.3a. Frequency distribution of 500 randomly generated values of SPSOIL from a uniform distribution and from a beta distribution using A= 10 and B=10 ('normal' distribution, N) and A=1 and B=4 (skewed distribution, Sk).

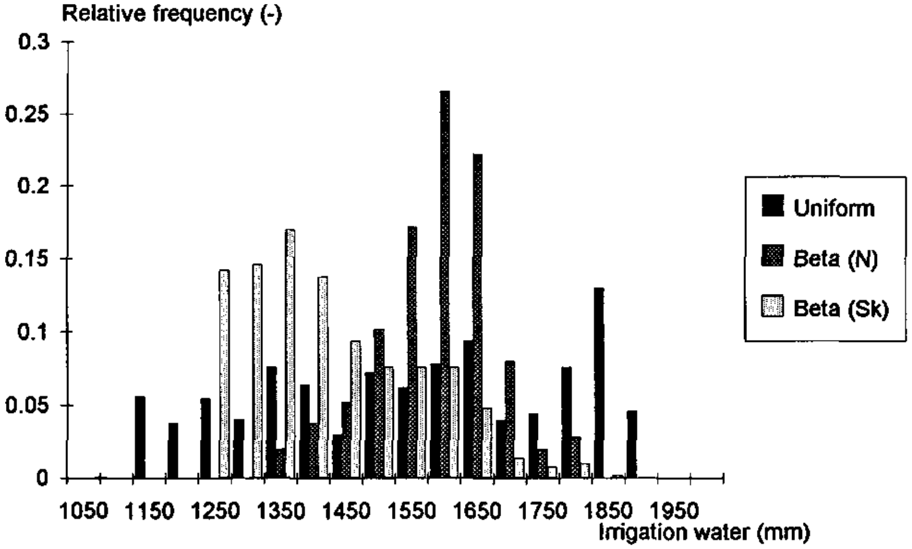


Figure 3.3b. Frequency distribution of irrigation water needs in the dry season of 1981, using ORYZA_W with the SPSOIL values from Figure 3.3a as input .

In this simple example, only the effect of uncertainty and spatial variation in one parameter value was illustrated. In practice, a number of parameters will have a relatively large effect on simulated output, and MC analysis has to include all these parameters. A detailed example is given for rainfed lowland rice in Chapter 5.

Table 3.1. Measured values of SPSOIL rate (mm d^{-1}) in the dry season of 1969-70 for 10 field sites in Nueva Ecija (NE), Bulacan (Bu) and Laguna Provinces (Lag), Philippines. Data taken from: Wickham & Singh, 1978. Note: negative values mean upwelling water, and can be handled by ORYZA_W.

Field	NE1	NE2	NE3	NE4	Bul1	Bul2	Bul4	Lag1	Lag2	Lag3
SPS	16.5	9.0	0.2	1.3	-0.2	0	3.7	1.0	21.2	25.8

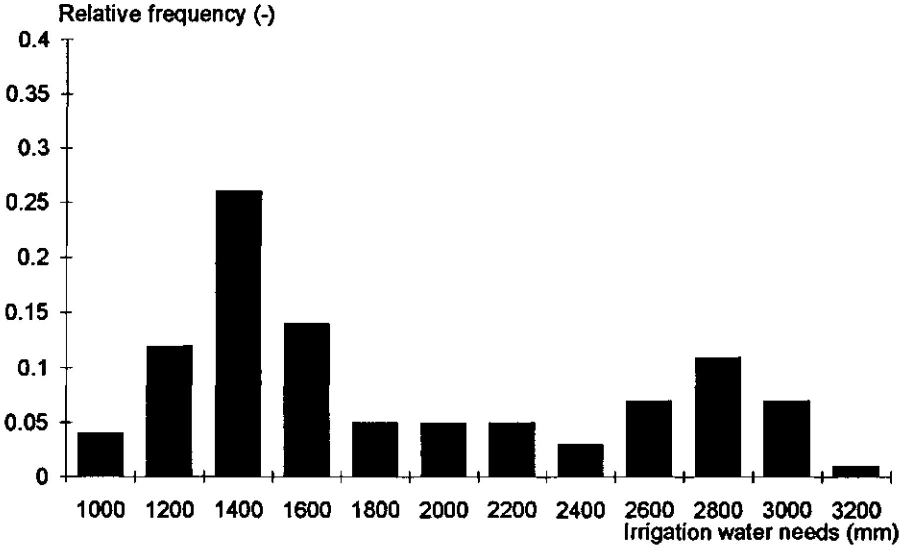


Figure 3.4. Frequency distribution of simulated irrigation water needs in the dry seasons of 1980-1991, using ORYZA_W with the SPSOIL values from Table 3.1 as input (MC simulation).

3.4 Risk analysis

Crop growth models are suitable to quantify and evaluate risk of a certain production system (e.g. irrigated lowland, rainfed lowland) in land-units of a zonation study. A crop growth model can be used to 'translate' the variation, or probability of occurrence, in input parameters into a probability of occurrence of simulated output, such as yield or irrigation water needs, as a function of environmental properties. The technique to do this is again Monte Carlo simulation. First the probability of occurrence of (soil and management) model input parameters has to be determined for the land-units under consideration (Paragraph 3.3). Using RIGAUS, a large number of input sets is generated that combine randomly chosen parameter values from their respective probability distribution functions and/or measured frequency distributions. ORYZA_W is then run using this set of input parameters for all years that weather data are available. To quantify the variation in simulated model output, as caused by variation in weather, preferable some 10-20 years of weather data should be used. Weather generators are helpful when the number of years with weather data is too small. The resulting set of simulated model outputs is used to compute cumulative frequency distributions that express the probability of exceedance of certain threshold values.

An example of risk analysis for the case of irrigated lowland rice is given in Figures 3.5 and 3.6. Again, the example focuses on the seepage & percolation rate of the soil, SPSOIL, as the only variable model input parameter. Two soil types (land-units) were considered: a relatively permeable puddled topsoil, and a relatively poorly permeable puddled topsoil. For the poorly permeable soil, a uniform probability distribution was assumed for SPSOIL between 0-5 mm d^{-1}, and for the permeable soil, between 5-10 mm d^{-1}. ORYZA_W was run to simulate dry season rice yield (sowing on day 345) and total irrigation water requirements using all weather data between 1980-1991. Figure 3.5 gives the exceedance probability of simulated rice yield for both soil types. The (potential) rice yield was fairly stable with about 100% probability of having very high yields between 10.6 and 12.2 t ha^{-1}, due to favourable temperature and solar radiation input. [Note: with the newer version of ORYZA_W, 3.0, simulated yield levels at Los Baños are about 1 t ha^{-1} lower, though relative differences within and between years are the same]. The small difference between the two soil types was caused by the difference in the rate of drying of the puddled layer after irrigation was stopped (at DVS = 1.85 in this example). On the permeable soil type, water drained relatively fast from the puddled layer and some (slight) drought stress occurred at the end of the growing season. On the poorly permeable soil type, the puddled layer dried out relatively slowly and there was no effect of drought stress at the end of the growing season. Simulated yields were therefore a bit higher on the poorly permeable soil type than on the permeable soil type: the probability of yields higher than 11 t ha^{-1} was 78% on the poorly permeable soil type, and 70% on the permeable soil type.

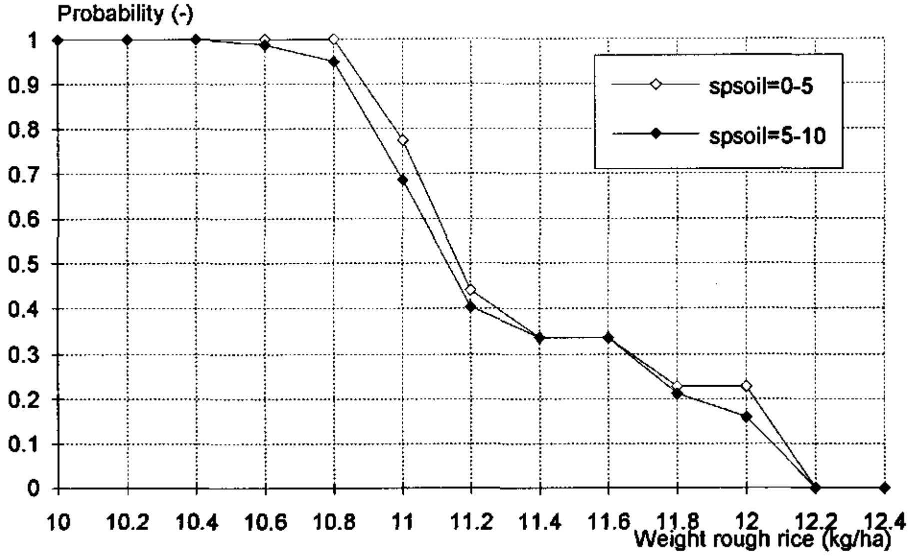


Figure 3.5. Exceedance probability of simulated rice yield (t ha^{-1}) in irrigated lowland on relatively poorly permeable soil (white diamonds) and on permeable soil (black diamonds). The legend gives the SPSOIL rates of the soils in cm d^{-1}.

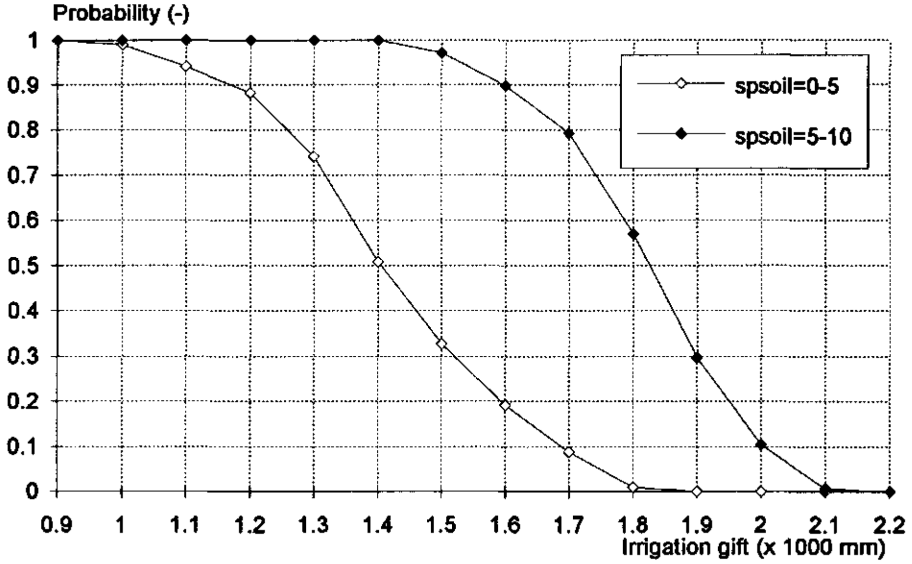


Figure 3.6. Exceedance probability of total irrigation water requirements (10^3 mm) in irrigated lowland on relatively poorly permeable soil (white diamonds) and on permeable soil (black diamonds). The legend gives the SPSOIL rates of the soils in cm d^{-1}.

Figure 3.6 gives the exceedance probabilities of the total irrigation water needs for both soil types. The difference between soil types was relatively large. On the permeable soil type, the probability was 100% that irrigation water needs exceeded 1400 mm, whereas on the poorly permeable soil type this was only 50%. These probability curves are important information in irrigation system design. The combination of Figure 3.5 and 3.6 learns that the yield level of irrigated rice (in this environment) was stable, but that associated irrigation water requirements were variable and dependent on the seepage & percolation rate of the puddled layer (land unit characteristic).

In this simple example, only the probability distribution of one parameter, SPSOIL, was illustrated. In practice, the risk analysis has to take into account the probability distribution of all relevant input parameters (as determined from SA). A detailed example is given for rainfed lowland rice in Chapter 5.

3.5 A practical framework for zonation

Because SA and MC simulation takes a lot of computing time, the following practical framework is suggested for the use of crop growth modelling in zonation studies.

1 For <u>all</u> land-units distinguished in the study area, representative soil and management input parameter values are derived from expert-knowledge, maps or measurements. Weather data are taken from nearby, representative weather stations, and crop data are derived from field-experiments and taken from literature. The environment for rice growth zonation with ORYZA_W is determined: irrigated or rainfed lowland, or rainfed upland. Next, ORYZA_W is run for all land-units, using all available weather data and the set of representative soil and management input parameter values for each land-unit. Long-term averages and standard deviations of simulated outputs (e.g. yield, amount of irrigation water, growth duration) are calculated. Maps of the long-term averages can be produced manually or using Geographic Information Systems, GIS, (e.g. Garcia, 1993; Pannangpetch, 1993; Wopereis et al., 1993).

2 For <u>selected</u> land-units that are considered representative for different agro-ecological environments, sensitivity analysis on soil and management parameters is carried out. If the data permit, the sensitivity analysis should be repeated for some 'good', 'average' and 'bad' years. The input parameters that have a relatively large effect on simulated output are determined, and the relationship between parameter input accuracy and model output accuracy is quantified.

3 For the same selected land units as under point 2, probability distributions are estimated for each parameter that was found to have a relatively large effect on simulated output. Monte Carlo simulation is used to 'translate' the uncertainty in soil and management input parameter values into uncertainty (a probability distribution) of the simulated model output. If the data permit, the MC simulation should be repeated for some 'good', 'average' and 'bad' years. If the resulting accuracy in simulated output is too low to meet the requirements of the study, the sensitivity analysis of point 2 has indicated the accuracy with which input parameter values need to be measured in the field. If a number of actual field measurements are available, Monte Carlo simulation can be used to calculate the frequency distribution of simulated model output as function of spatial variation in input parameter values. If the calculated frequency distribution of the model output for the land-unit under consideration is found to be too broad, the land-unit can be sub-stratified into smaller land-units that are more homogeneous in input parameter values. The collection of new data and/or substratification implies that step 1 should be repeated.

4 For the selected land-units, risk analysis is carried out by Monte Carlo simulation using the probability input data sets from point 3 and 10-20 years of weather data (if need be obtained with a weather generator). Exceedance probabilities are calculated.

3.6 Crop and weather data

Most crop parameters needed to run ORYZA_W are taken from measurements reported in literature and from experiments conducted at IRRI (Kropff et al., 1993). Some of these parameters have been measured often and world-wide, e.g. extinction coefficient of leaves, KDF, or CO_2 assimilation rate of leaves, whereas others have only been observed or estimated sparsely, e.g. growth rate of roots, GZRT, transplanting shock for leaf area development, TSHCKL, critical soil water contents, LLDL .... ULRT (see Appendix 1.4 for explanation variable names). Only a relatively small number of parameters needs to be determined for a (new) rice variety of interest from well-controlled field experiments: development rate at the vegetative and generative growth stage, DVRV and DVRR respectively, relative growth rate, RGRL, assimilate partitioning tables, FLVTB, FSTTB and FSOTB, and nitrogen content of the leaves, NFLV. All crop parameters, whether taken from literature or derived from field experiments have a certain degree of uncertainty or variation. The determination and quantification of these uncertainties and variations is difficult, involving complicated statistical procedures, and falls beyond the scope of this Chapter. However, two simple approaches are mentioned here to deal with uncertainty and variation in crop parameters.

1. The same approach can be followed as presented for soil and management parameters: SA and MC analysis. SA can be used to find the crop parameters that have a relatively large effect on simulated output in the specific environment under consideration.

This does not mean, however, that all these parameters actually need to be measured in an experiment. For instance, the assimilation rate of leaves, AMAX, may be found to have a large effect on simulated yield, but its value may be derived from literature with sufficient precision. On the other hand, if for a given soil type the growth rate of roots, GZRT, has a large effect on simulated rainfed rice yield, its value will probably not be easily derived from literature for that specific soil type, thus indicating the need for measurements. MC analysis can be used to quantify the effect of uncertainty and variation in crop parameters on simulated output. However, probability distributions for the crop parameters are difficult to estimate or to measure. In the case that parameter values have been directly measured, e.g. AMAX or GZRT, a number of measurements will yield a frequency distribution. When parameter values have been indirectly derived from field experiments using statistical packages, e.g. GENSTAT (1988) or FSEOPT (Stol et al., 1992), errors of estimate can usually be calculated. In both cases, however, the spread in parameter values not only expresses the uncertainty or variation in the model parameter itself, but also includes the effects of error and/or inaccuracy in the measured variables (from which the parameter value was derived), possible errors and/or inaccuracies in the mathematical description of the crop growth processes involved, and, in the case of indirect derivation, errors and/or uncertainties in other model parameter values. Finally, the correlation between model parameters and the interdependence of various process descriptions in the model often complicate a straightforward SA and MC analysis.

2. A more pragmatic approach is to use the calibration result of a field experiment, i.e. the difference between simulated output of the, calibrated, model and the observed values. In a calibration experiment, the conditions for a precise simulation are generally (or should be) as optimal as possible: important crop parameters are directly measured or inferred from observations, soil properties are often known, weather data are taken from a nearby meteorological station and management activities are exactly known. Still, there is mostly some deviation between simulated variables and observed variables (e.g. yield). This difference is the integrated result of any errors, inaccuracies and uncertainties in crop parameters, mathematical process descriptions and measurements, and can be considered as a 'minimum inaccuracy' of the model. If a crop growth model is used for extrapolation, as in zonation, this minimum inaccuracy should be added to the simulated output. A way to do this is to add to the simulated model outputs a randomly drawn inaccuracy value from a uniform or normal distribution with boundaries and σ respectively derived from the calibration experiments. Typical minimum inaccuracies for well-calibrated crop growth models are 5-15%.

Measured weather data also have some degree of inaccuracy and, sometimes, error. If measurement inaccuracies are random, and their magnitude is known, MC analysis can again be used to 'translate' these inaccuracies into probabilities of simulated output. Each time a weather variable is read from data file by ORYZA_W, a random inaccuracy value can be added to that variable. Measurement errors can be treated the same way, provided that they are random. Errors that show a specific trend, e.g. consequently plus or minus a certain value, should preferably be corrected in the weather data files.

4 The program RIGAUS for Monte Carlo simulation

The description of RIGAUS (Random Input Generator for the Analysis of Uncertainty in Simulation) in this Chapter is largely taken from Bouman & Jansen (1993). RIGAUS allows the user to draw random values from uniform, beta and normal statistical distributions, and from measured data sets for a number of variables at the same time. The version of RIGAUS presented here is especially adapted to generate parameter values (rerun sets) for ORYZA_W. With one exception (see below), values for different parameters/variables are drawn independently, i.e. without taking into account correlation between parameters/variables. RIGAUS has special provisions for drawing random input data for the soil water balance module SAHEL for rainfed upland environments. The correlation between the soil moisture characteristics water content at saturation, WCST, at field capacity, WCFC, and at wilting point, WCWP, can optionally be taken into account. Relationships between these variables have been derived from empirical data and are used in RIGAUS to generate values for WCST and WCWP from randomly drawn values of WCFC. The generated values of WCST, WCFC and WCWP are automatically assigned to all three soil layers distinguished in SAHEL. Also, the initial water content, expressed as fraction of WCFC, FWCLI, is automatically assigned to all three soil layers.

For the lowland water balance module LOWBAL, the correlation between the soil moisture characteristics of the shrunken puddled layer (WCSTP, WCFCP and WCWPP) is not taken into account by RIGAUS. Lack of data prohibited the derivation of these correlations.

4.1 Statistical distributions

In RIGAUS, values can be generated randomly from uniform, beta or normal statistical distributions. In the current version, a maximum of 25 variables for a uniform distribution, 25 for a beta distribution and for a 25 normal distribution can be selected simultaneously (hence in total 75 variables/parameters). In principle there is no limit to the number of draws that can be made for each variable. However, there is a limit to the number of reruns that can be made with ORYZA_W in the FSE system. Therefore, the maximum number of draws for reruns is set to 999 (see also Paragraph 4.4)

4.1.1 Uniform distribution

Random values for a uniform distribution are generated using the function RUNI. The algorithm in RUNI originates from L'Ecuyer (1986) as implemented in Bratley et al. (1983) and Press et al. (1992). The values generated by RUNI are restricted between 0 and 1, but are rescaled in RIGAUS between upper and lower boundaries as specified by the user. An example of the frequency distribution of randomly generated values from a uniform distribution is given in Figure 4.1.

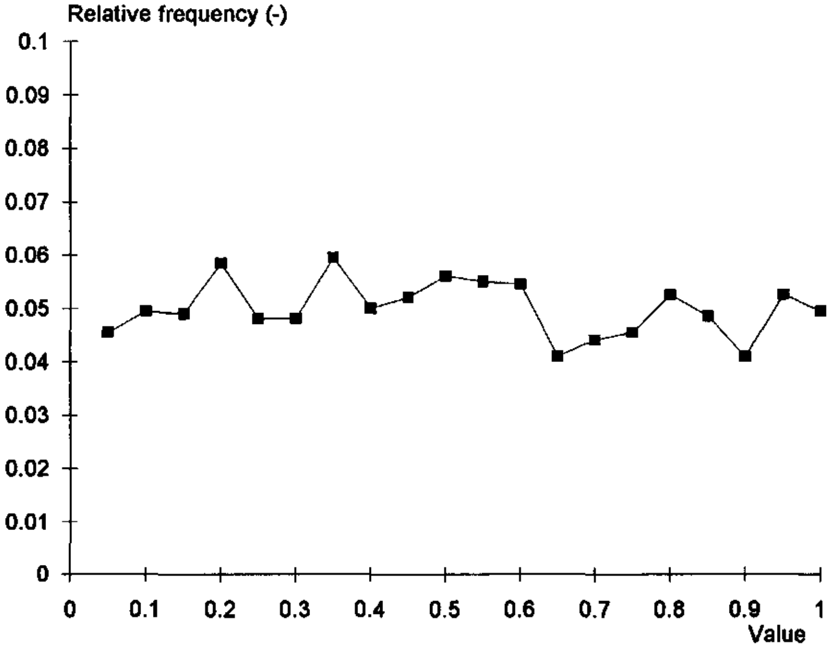


Figure 4.1. Relative frequency distribution (fraction) of randomly drawn values from a uniform distribution between 0 and 1, using RIGAUS. N=2000.

The input that has to be supplied by the user for drawing from a uniform distribution is (per parameter/variable):

- Name of variable(s) for which random values have to be chosen (VUNI)
- Upper limit (UNIUP)
- Lower limit (UNILO)

4.1.2 Beta distribution

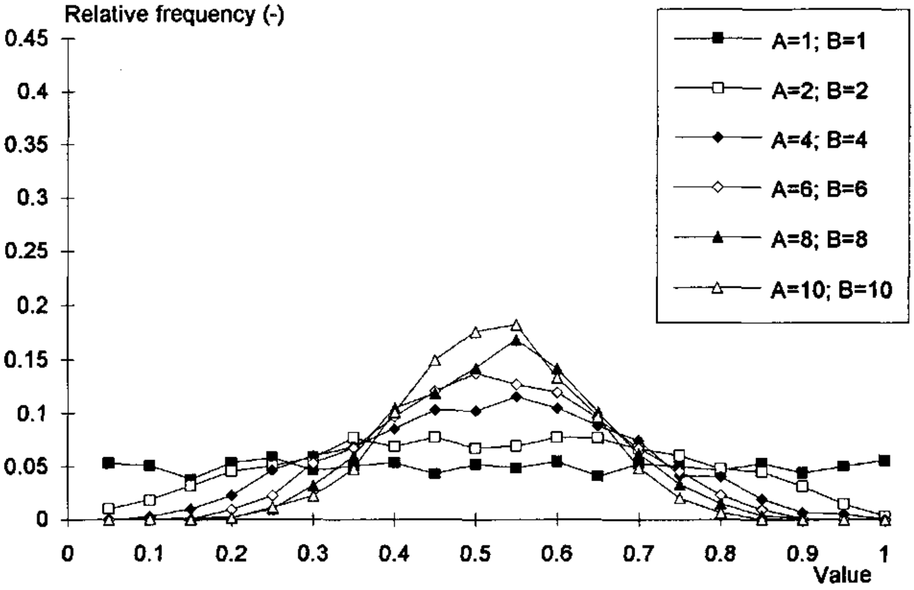
Random values for a beta distribution are generated using the function RBET. This random generator is fully based on the function BETACH (Bratley et al., 1983). A beta distribution is characterised by two 'shape' parameters, A and B, that define the shape of the distribution, e.g. 'bell' shaped, 'triangular' or 'skewed'. The examples given in Figure 4.2 are distributions of randomly generated values using RIGAUS with different A and B values. The mean of the distribution is A/(A+B) and the variance is AB/[(A+B+1)(A+B)(A+B)], as illustrated in Table 4.1. As with the uniform distribution, the values generated by RBET are restricted between 0 and 1, but are rescaled in RIGAUS between upper and lower boundaries as specified by the user.

Table 4.1. Mean μ (upper number, bold) and variance σ^2 (lower number) of the beta distribution between 0-1 as function of the shape parameters A and B.

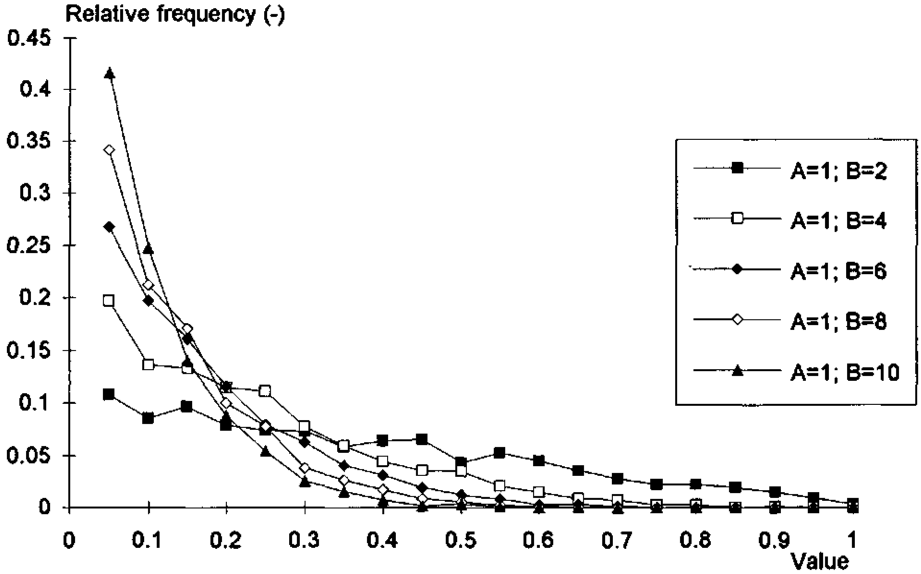
A \ B	1	2	4	6	8	10
1	**0.500** 0.083	**0.333** 0.056	**0.200** 0.027	**0.143** 0.015	**0.111** 0.010	**0.091** 0.007
2	**0.667** 0.056	**0.500** 0.050	**0.333** 0.032	**0.250** 0.021	**0.200** 0.015	**0.167** 0.011
4	**0.800** 0.027	**0.667** 0.032	**0.500** 0.028	**0.400** 0.022	**0.333** 0.017	**0.286** 0.014
6	**0.857** 0.015	**0.750** 0.021	**0.600** 0.022	**0.500** 0.019	**0.429** 0.016	**0.375** 0.014
8	**0.889** 0.010	**0.800** 0.015	**0.667** 0.017	**0.571** 0.016	**0.500** 0.015	**0.444** 0.013
10	**0.909** 0.007	**0.833** 0.011	**0.714** 0.014	**0.625** 0.014	**0.556** 0.013	**0.500** 0.012

The input that has to be supplied by the user for drawing from a beta distribution is (per parameter/variable):

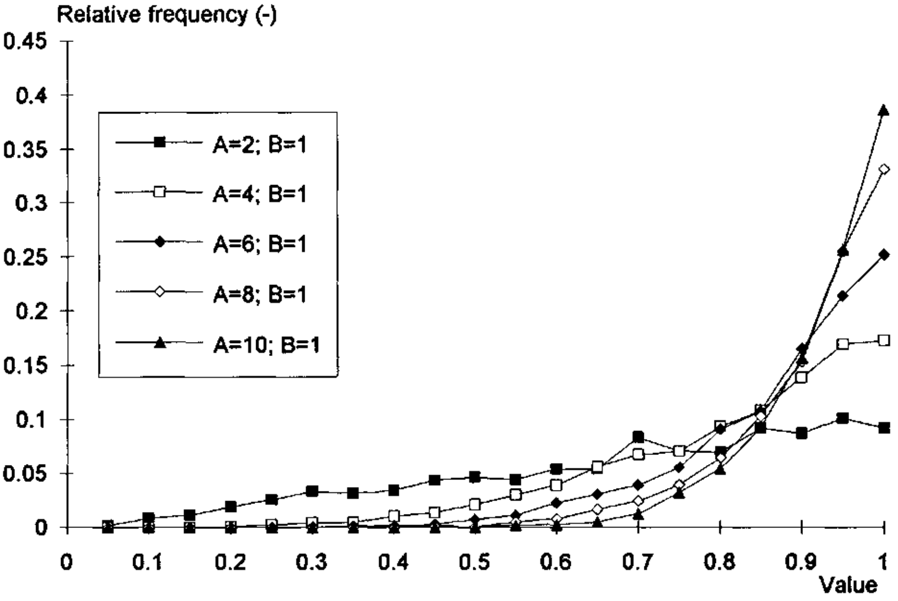
- Name of variable(s) for which random values have to be chosen (VBETA)
- Shape parameter A (ABETA)
- Shape parameter B (BBETA)
- Upper limit (BETAUP)
- Lower limit (BETALO)


Relative frequency (-)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Value
A=1; B=1
A=2; B=2
A=4; B=4
A=6; B=6
A=8; B=8
A=10; B=10

(4.2a)


Relative frequency (-)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Value
A=1; B=2
A=1; B=4
A=1; B=6
A=1; B=8
A=1; B=10

(4.2b)



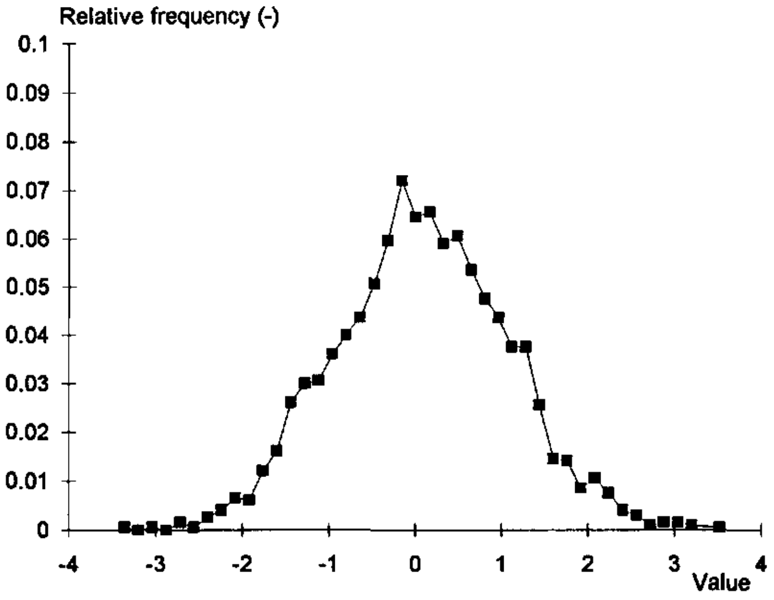
(4.2c)

Figure 4.2. Relative frequency distribution (fraction) of randomly drawn values from a beta distribution between 0 and 1, using RIGAUS. N=2000. Different combinations of the A and B parameters are used in Figs. 4.2a, 4.2b and 4.2c, see legends.

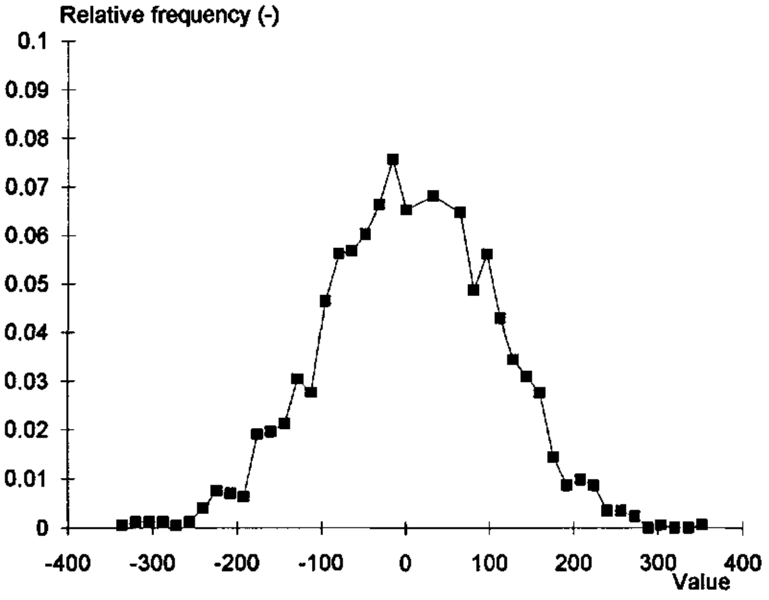
4.1.3 Normal distribution

Random values for a normal distribution are generated using the function RGAU. This random generator is based on the Box-Muller method (Box & Muller, 1958). The normal distribution generated by RGAU has a mean of 0 and a variance of 1, but in RIGAUS, the mean and variance of the distribution can be set by the user. Examples of normal distributions with different means μ and variances σ^2 , as generated by RIGAUS, are given in Figure 4.3. Note, that on average, 95% of the values of a normal distribution lie between μ- $2\sigma^2$ and μ+ $2\sigma^2$.

Warning: a normal distribution is not bound by pre-set minimum and maximum values. If values from a normal-type distribution have to be contained between fixed boundaries (as is often the case for model parameter values), a beta distribution with equal A and B values can be used (see Paragraph 4.1.2).



(4.3a)



(4.3b)

Figure 4.3. Relative frequency distribution (fraction) of randomly drawn values from a normal distribution, using RIGAUS. N=2000. In Fig. 4.3a, the variance (VARU) of the distribution was 1, in Figure 4.3b, it was 100. The mean of the distribution (MEANU) was 0.

The input that has to be supplied by the user for drawing from a normal distribution is (per parameter/variable):

- Name of variable(s) for which random values have to be chosen (VNORM)
- Mean μ of the distribution (MEANU)
- Variance σ^2 of the distribution (VARU)

4.1.4 Seed

The seed of a random generator controls the starting point of the generator and determines the reproducibility of the generated values. In RIGAUS, the seed is called ISEED and is used by the function RUNI for uniform distributions. Because RUNI is also called by the functions RGAU and RBET, the same ISEED 'controls' the generation of normal and beta distributions respectively.

The value for ISEED is read from the input file RIGAUS.IN (see Paragraph 4.4.1). When the supplied ISEED is 0, an integer function TSEED is called in RUNI to generate a seed value. TSEED produces a seed in the range 1-86412 based on the system (computer) time in seconds from midnight. This generated seed value is written to the output file RERUNS.DAT (see Paragraph 4.4.2). Each time RIGAUS is run with ISEED = 0 in the input file, a new seed is generated and subsequent runs of RIGAUS produce different output. If the results of RIGAUS should be reproducible, any value not equal to 0 can be given for ISEED in the input file RIGAUS.IN. Each run with RIGAUS that uses the same ISEED value produces the same results.

4.2 Measured data

Random variables are uniformly drawn from a series of measured data using the RUNI function. Random values can be drawn simultaneously and independently from five measurement series (five parameters/variables). Measured values can be randomly drawn simultaneously and independently with draws from the statistical distributions.

The input that has to be supplied by the user for drawing from measured data is (per parameter/variable):

- Name of measured variable(s) for which random values have to be chosen (NMVAR)
- Measured data

The total number of measured values for each parameter/variable may not be greater than 500 (see Paragraph 4.4.1)

4.3 Special provisions for SAHEL

RIGAUS has the following three special provisions for the water balance module SAHEL for rainfed uplands:

1. Important input data for this model are three characteristic points on the water retention curve: water contents at saturation, WCST, at field capacity, WCFC, and at wilting point, WCWP. In sensitivity and MC analyses, these three parameter values may be varied to study the effect on crop growth. However, these three parameter are correlated, and these correlations should be taken into account when drawing random values. In RIGAUS, empirical relations between WCST-WCFC-WCWP are included and can optionally be used.

2. The soil water content at the start of simulation (WCLI in SAHEL) also depends on the soil moisture characteristic of the soil. With variable values for e.g. WCFC, WCLI can not be a fixed value as is currently done in SAHEL. Therefore, it is suggested to calculate WCLI in SAHEL as a fraction FWCLI of WCFC (the same way as it was defined from WCWP in the 'original' version of SAHEL, van Keulen, 1975)

   WCLI = FWCLI * WCFC

   This way, values for WCST, WCFC and WCWP can be varied without running into problems with a fixed value for WCLI. The variable name FWCLI is automatically recognised in RIGAUS (optionally).

3. Three soil layers are distinguished in SAHEL, and for each layer the variable names WCST, WCFC, WCWP and WCLI have a suffix to identify the layer number (from top to bottom), i.e. WCST1, WCFC1, WCWP1, WCLI1, WCST2,.... WCLI3. In RIGAUS, random values for these variables can optionally be assigned to all three layers. The generated random values are, per variable, the same for all three layers.

The above three options can be implemented when drawing random variable values for SAHEL by setting the control switch ISWI in the input file: ISWI = 1: implement empirical relations; ISWI = 0: ignore empirical relations.

4.3.1 Empirical relations

Measured values of WCST, WCFC and WCWP were used to investigate the correlations among these parameters (Figure 4.4). The measurements refer to Dutch soils ranging from coarse sands to heavy clays and peat (Wösten et al., 1987). There was a close relationship between WCWP and WCFC, and between WCST and WCFC, regardless of soil type (except for peat in the WCWP-WCFC relationship). The following quadratic expressions were fitted through the data set:

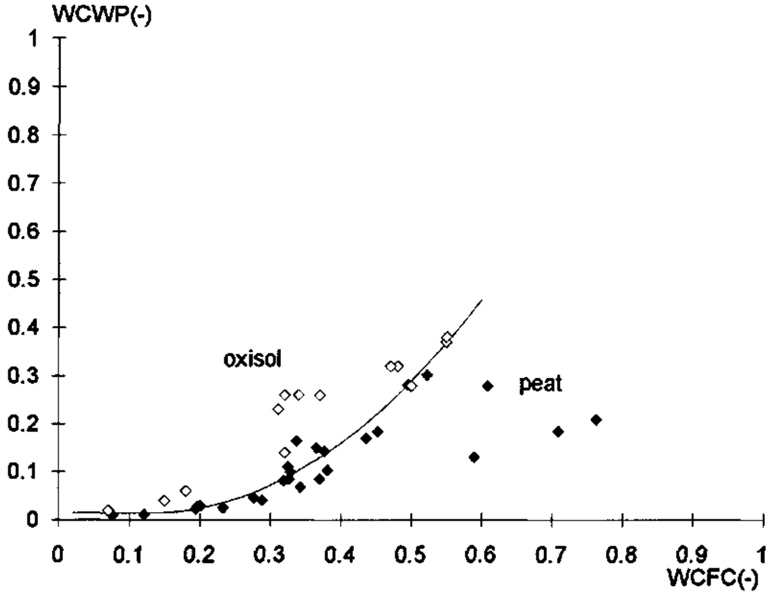
WCWP = 0.050 - 0.535*WCFC + 2.027*WCFC^2 (cm^3 cm^{-3}) [4.1]
(with WCWP minimum = 0.015; see Figure 4.4a)

WCST = 0.347 - 0.164*WCFC + 1.217*WCFC^2 (cm^3 cm^{-3}) [4.2]

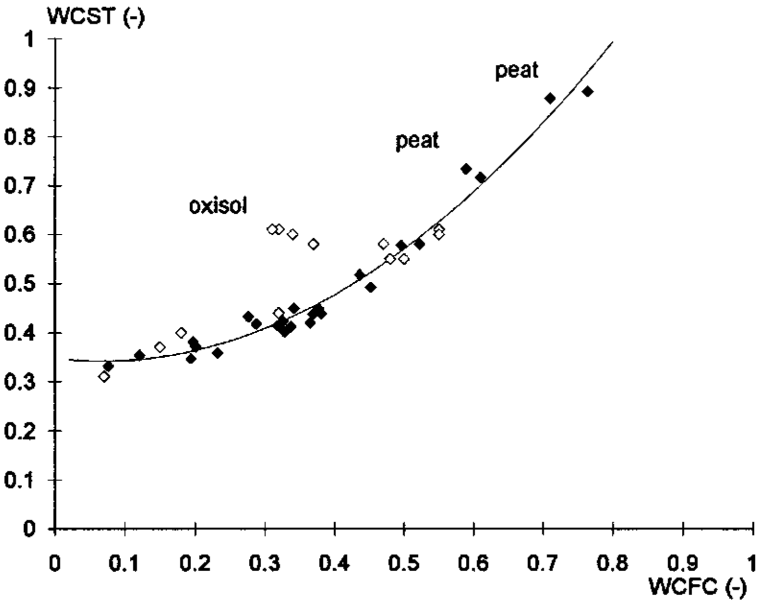
Some statistical information on the regression lines is given in Table 4.2.

A validation set of various soils in the tropics supported the above relationships, except for deeply weathered oxisols (Figure 4.4). For all soil types, the water content at air-dryness, pF 7 (WCAD), was close to 0 and no relationship with the other water contents could be established. Currently, soil data are being collected in the SARP network to further validate the derived regressions for South-east Asian soils. If users have own soil data on water retention characteristics, they should check whether the above regressions are applicable.

The derived regression equations are only valid between the limits of 0.05 and 0.60 for WCFC. When the user specifies boundaries of WCFC outside these limits, RIGAUS is terminated and produces an error message (Paragraph 4.4.3).



(4.4a)



(4.4b)

Figure 4.4. Measured values of WCWP versus WCFC (4.4a) and of WCST versus WCFC (4.4b). The black diamonds are data from Dutch soils, the white diamonds are data from tropical soils. The drawn lines are the fitted regressions.

Table 4.2. Statistical information on the regression lines (equations 4.1 and 4.2) derived between WCWP and WCFC and between WCST and WCFC (in cm^3 cm^{-3}).

1. $WCWP = A + B*WCFC + C*WCFC^2$

	A	B	C
Value	0.050	-0.535	2.027
Sigma	0.0286	0.1910	0.2930
T-value	1.87	-2.80	6.91

Number of data (N) = 30 (without data peat soils)
Variance accounted for = 93%
Mean square residual s^2 = 0.000993
Validity limits: $0.05 < WCFC < 0.60$ (cm^3 cm^{-3})

2. $WCST = A + B*WCFC + C*WCFC^2$

	A	B	C
Value	0.347	-0.164	1.217
Sigma	0.0182	0.0982	0.1210
T-value	19.07	-1.66	10.04

Number of data (N) = 34
Variance accounted for = 97%
Mean square residual s^2 = 0.000647
Validity limits: $0.05 < WCFC < 0.60$ (cm^3 cm^{-3})

4.3.2 Random drawing of WCST, WCFC and WCWP

If the switch ISWI is set to 0, the above relations are ignored in RIGAUS and random values for WCST, WCFC and WCWP can independently be drawn from any of the statistical distributions or from measured data series. Because three soil layers are distinguished in SAHEL, values have to be generated for each of the three layers separately, i.e. WCST1, WCST2, WCST3, WCFC1, WCFC2,...., WCWP3.

If the switch ISWI is set to 1, the WCST-WCFC and WCWP-WCFC relations are included. The user has to specify a statistical distribution for the parameter WCFC, either uniform, beta or normal (Warning: random drawing from measured data is not possible in this situation). RIGAUS automatically recognises the variable name WCFC and uses equations 4.1 and 4.2 to calculate a corresponding value for WCST and WCWP from each randomly drawn value for WCFC. Variation around these regression lines (Figure 4.4) is accounted for by adding a randomly drawn value from a normal distribution with the root mean square residual of the regression lines as standard deviation: in equation 4.1, σ = 0.032, in equation 4.2, σ = 0.025. An example of 500 generated values of WCST, WCFC and WCWP is given in Figure 4.5 where WCFC was drawn from a uniform distribution between 0.05 and 0.60 cm^3 cm^{-3}. The random data accurately reproduced the variation around the regression lines.

The random values generated for WCST, WCFC and WCWP are assigned to all three soil layers distinguished in SAHEL: WCST1 = WCST2 = WCST3, WCFC1 = WCFC2 = WCFC3 and WCWP1 = WCWP2 = WCWP3. In the output file RERUNS.DAT, the generated random values are defined with the above suffixes; in the output file COLUMN.DAT, suffixes are omitted (see Paragraph 4.4.2).

4.3.3 Random drawing of FWCLI

With the switch ISWI set to 0, FWCLI is not recognised by RIGAUS as a special variable and is treated as any other variable. Values can be generated from any of the three statistical distributions or from measured values. Because three soil layers are distinguished in SAHEL, values have to be generated for each of the three layers separately, i.e. FWCLI1, FWCLI2 and FWCLI3.

With the switch ISWI set to 1, FWCLI is automatically recognised by RIGAUS, and randomly generated values from any of the three statistical distribution types are assigned to all three soil layers: FWCLI1 = FWCLI2 = FWCLI3. In the output file RERUNS.DAT, the generated random values are defined with the above suffixes; in the output file COLUMN.DAT, they are omitted (i.e. FWCLI) (see Paragraph 4.4.2).

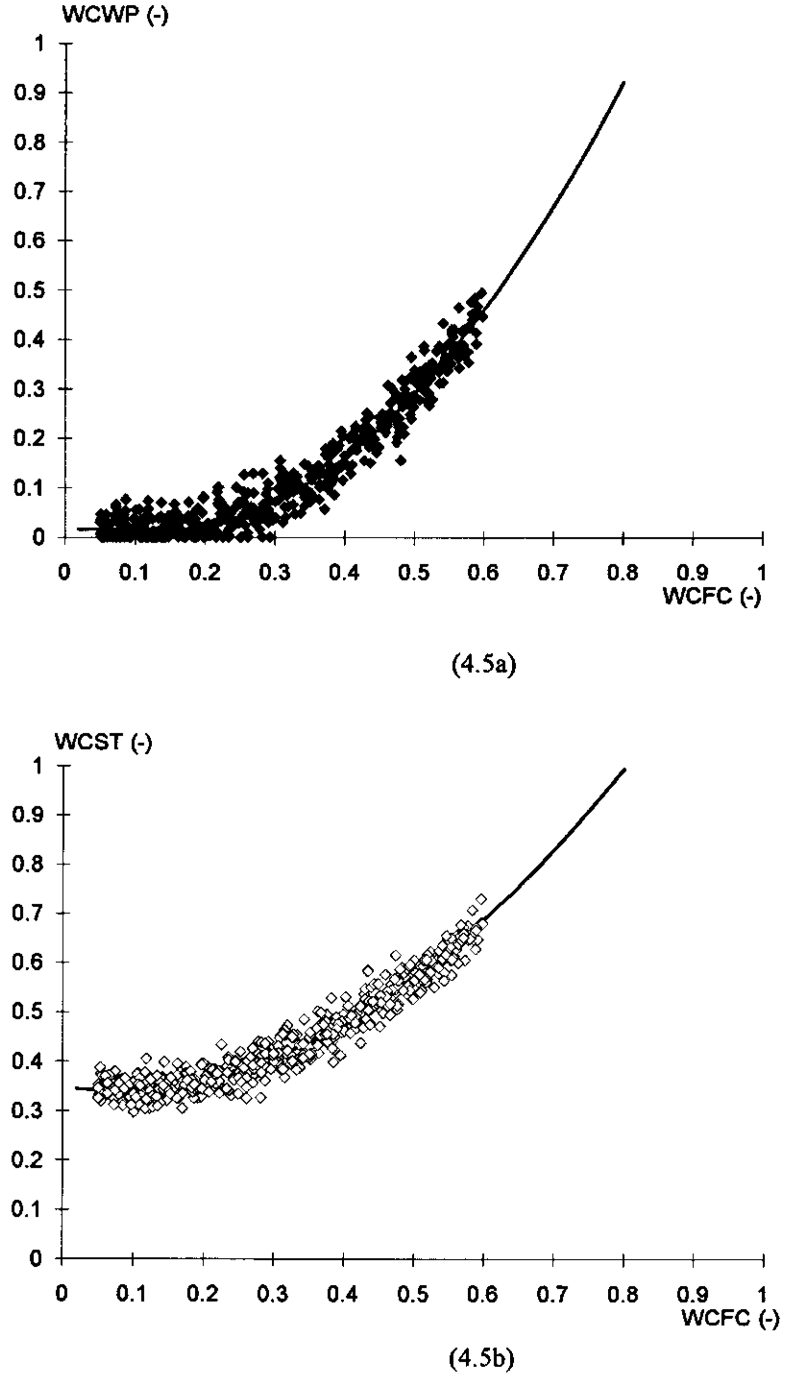


Figure 4.5. 500 randomly drawn variables for WCFC (uniform distribution) and WCWP (4.5a) and WCST (4.5b), using RIGAUS. The drawn lines are the regression lines, i.e. equations 4.1 and 4.2.

4.4 Running RIGAUS

Under the SARP-Shell, the running of RIGAUS is facilitated with a menu-system (Riethoven, 1994). If RIGAUS is run without this Shell, or if RIGAUS is to be adapted, this Paragraph provides some useful information. RIGAUS (developed on an 486 IBM compatible PC) is written in the programming language FORTRAN77. A full listing of the source code is given in Appendix 2.1. Subroutines and functions are called from the CABO/TPE library TTUTIL (Rappoldt & van Kraalingen, 1990), which should be linked when the user changes the source code. The function TSEED uses compiler-specific subroutines; the current RIGAUS program uses a Microsoft compiler subroutine, but a provision for the use of a VAX compiler subroutine is included in the source code.

The maximum number of draws per variable, of total drawn values (draws per variable times number of variables), of variables that can be selected from each statistical distribution type, and of measured data per variable are set in RIGAUS:

NDRAW = maximum number of draws (=999)

ILPREP = maximum number of total drawn values (=10000)

IMNP = maximum number of variables per statistical distribution type (=25)

KMNP = maximum number of measured data per variable (=500)

The maximum number of total drawn, ILPREP, is determined by the total number of parameter values that can be used in reruns of ORYZA_W. For example: there may be 10000 draws for one single parameter, or 500 draws for 20 parameters each. Note that both the values of NDRAW and ILPREP are determined by ORYZA_W (in fact, by the set of subroutines OPSYS that is to be linked with ORYZA_W).

One input file is needed, RIGAUS.IN, and two output files are generated, RERUNS.DAT and COLUMN.DAT. Examples of these files are given in Appendices 2.2 and 2.3.

4.4.1 Program input

The number of random draws, the type of statistical distributions and the measured data series to choose from are specified in the input file RIGAUS.IN. The format of the required input is 'real' (R), i.e. with decimal point, 'integer' (I), i.e. without decimal point, and 'character' (C). The following data have to be supplied.

General

First the switch defining the mode of the program, i.e. whether to include or ignore the special provisions for the water balance model SAHEL, should be set (Paragraph 4.3).
ISWI = 0: special provisions are ignored **(I)**
ISWI = 1: special provisions are included **(I)**

The number of random draws should be set.
TND = ... **(I)**

The seed should be supplied.
ISEED = 0: a seed between 1-86412 will be generated RIGAUS itself **(I)**
= 'any integer value': the supplied value is used as seed.

UNIFORM distributions

NDU = ... Number of variables (maximum = 25) **(I)**
VUNI = '........', '.........', ... List of variable names (max. = 25) **(C)**
UNILO = ... , ... , ... , Lower boundary of variable values, in the order of the variables specified above (max. = 25) **(R)**
UNIUP = ... , ... , ... , Upper boundary of variable values, in the order of the variables specified above (max. = 25) **(R)**

BETA distributions

NDB = ... Number of variables (maximum = 25) **(I)**
VBETA = '........', '.........', ... List of variable names (max. = 25) **(C)**
ABETA = ... , ... , ... , A-value for beta distribution, in the order of the variables specified above (max. = 25) **(R)**
BBETA = ... , ... , ... , B-value for beta distribution, in the order of the variables specified above (max. = 25) **(R)**
BETALO = ... , ... , ... , Lower boundary of variable values, in the order of the variables specified above (max. = 25) **(R)**
BETAUP = ... , ... , ... , Upper boundary of variable values, in the order of the variables specified above (max. = 25) **(R)**

NORMAL distributions

NDN = ... Number of variables (maximum = 25) **(I)**
VNORM = '........', '.........', ... List of variable names (max. = 25) **(C)**
MEANU = ... , ... , ... Mean of the normal distribution, in the order of the variables specified above (max. = 25) **(R)**
VARU = ... , ... , ... Variance of the normal distribution, in the order of the variables specified above (max. = 25) **(R)**

MEASURED data

NDN = ... Number of variables (maximum = 5) **(I)**
VNORM = '........', '.........', ... List of variable names (max. = 5) **(C)**
MDATA1-5 = ... ' ...... ' ....' Measured data first to fifth variable (max. = 500) **(R)**

4.4.2 Program output

Two output files are generated by RIGAUS: RERUNS.DAT and COLUMN.DAT. A third file, ERROR.LOG, is only created when a fatal error has occurred and contains messages on the nature of the error (see Paragraph 4.4.3).

RERUNS.DAT

This file has the right format to serve as a reruns file in the FSE system. Appendix 2.3a illustrates the output generated using the input file RIGAUS.IN given in Appendix 2.2. If the special provisions for the soil water balance model SAHEL are included in the random drawing (ISWI = 1), values for WCST, WCFC, WCWP and FWCLI are generated for all three soil layers (as distinguished in SAHEL) each time the variable names 'WCFC' and 'FWCLI' are encountered in RIGAUS.IN. All variable values drawn simultaneously, that should serve as one rerun set for the model are separated with the comment line '* This is rerun set x'. The seed value, ISEED, is given in the first line of the file for reproducibility of the generated distributions.

All output data (random values) are declared REAL, and formatted in exponential notation E10.3.

COLUMN.DAT

In this file, the randomly drawn values are listed in columns per parameter/variable, as illustrated in Appendix 2.3b that was generated using the input file RIGAUS.IN given in Appendix 2.2. This file can be used in programs such as GENSTAT or EXCEL for checking and evaluating the data, e.g. to check the generated distributions or the boundary values. If RIGAUS is operated under the SARP-Shell, a plotting facility is available to check the generated distributions. If the special provisions for the soil water balance SAHEL have been included in the random drawing (ISWI = 1), values for WCST, WCFC, WCWP and FWCLI are given without suffixes each time the variable names 'WCFC' and 'FWCLI' are encountered in RIGAUS.IN to avoid redundancy (COLUMN.DAT only serves to check and evaluate the generated results).

All output data (random values) are declared REAL, and formatted in exponential notation E10.3.

4.4.3 Error and warning messages

A number of consistency checks on the input data are incorporated in RIGAUS. If inconsistencies are detected, either fatal error messages are given and the program is aborted, or warning messages are given. In the latter case, the program is still completed successfully. All error and warning messages are sent to the screen during program execution, whereas fatal error messages are also sent to a special output file, ERROR.LOG. If no fatal error messages occurred, ERROR.LOG will not be created (and previous ERROR.LOG files will be deleted).

What does RIGAUS check automatically?

Input data are checked on the maximum numbers allowed and on consistency. RIGAUS is aborted and fatal error messages are given if:

- The number of drawings TND exceeds 999 (NDRAW)
- The number of total drawn values, TND * (NDU+NDB+NDN+NMV) exceeds 10000 (ILPREP)
- The number of variables for uniform (NDU), beta (NDB) or normal (NDN) distributions exceeds 25
- The number of data for the statistical distributions is inconsistent (e.g. the number of UNIUP values is not the same as that of UNILO values)
- The number of data or the number of variable names for the statistical distributions exceeds 25 (e.g. the number of UNIUP values or VUNI names exceeds 25)

- The number of data or the number of variable names for the statistical distributions is smaller than the number of variables given for random drawing (e.g. the number of UNIUP values is smaller than NDU)
- Supplied values of upper boundaries are lower than supplied values of lower boundaries (e.g. UNIUP < UNILO)
- The number of measured variables (NMV) exceeds 5
- The number of variable names for drawing from measured data is smaller than the given number of measured variables (NMV)
- The number of measured data exceeds 500

Error and warning messages can also be generated by the TTUTIL subroutines that are used in RIGAUS (Rappoldt & van Kraalingen, 1990). E.g. the program is aborted and an error message is given by the 'read' routines if:

- Format of supplied input does not match the defined format (e.g. 'integer' is given when 'real' should be given, or vice versa).

Informative warnings are also given if some inconsistencies are detected but when RIGAUS can still be successfully completed:

- The number of data or the number of variable names for the statistical distributions exceeds the number of variables given for random drawing (e.g. the number of UNIUP values exceeds NDU)

If the special provisions for the soil water balance SAHEL are included in the random drawing (ISWI = 1), checks are carried out on the boundary values of WCST, WCFC, WCWP and FWCLI, and on consistencies among the generated values for these variables. RIGAUS is aborted and fatal error messages are given if:

- Boundary values supplied for WCFC are outside the validity range of the derived relationships with WCST and WCWP, i.e. smaller than 0.05 or larger than 0.60 in all statistical distributions (e.g. UNIUP > 0.60)
- Randomly generated values of WCFC are outside the validity range of the derived relationships with WCST and WCWP, i.e. WCFC smaller than 0.05 or larger than 0.60, in the normal distribution.
- Randomly generated values of FWCLI are smaller than 0 or larger than 1 in the normal distribution.

In RIGAUS, all randomly drawn values for WCST, WCFC and FWCLI are restricted between 0.001 and 0.999.

If the special provisions for the soil water balance SAHEL are ignored (ISWI=0), no consistency checks on the values of WCST, WCFC, WCWP and FWCLI are carried out. Also, no consistency checks are carried out for variables randomly drawn from measured values.

What does the user have to check ?

- The format in which the input data are given should match the required format.

- The user has to check carefully the (input) boundary values for drawing from the uniform and beta statistical distributions. The same applies to the measured input data. If random draws are made from a normal distribution, there are in principle no limits to the range of possible values. Therefore, the results (randomly drawn values) have to be carefully checked for unrealistic values.

- It is advisable to check the generated distributions (shape and minimum and maximum values) of the randomly drawn parameter/variable values before actually using these data for Monte Carlo simulation. Checks can simply be made by plotting the generated values (option available under the SARP-Shell; Riethoven, 1994)

- The standard format of the randomly generated parameter/variable values is REAL with exponential notation (E10.3). This format is compatible with almost all variables and input parameters used in ORYZA_W. However, if this format proves not compatible (i.e. INTEGER data are needed), either the output format in RIGAUS may be adapted, or the format in the simulation model should be converted (e.g. INT and NINT functions to convert REAL data into INTEGER data).

5 Case study: rainfed lowland rice

An example of the framework described in the previous Chapters for the use of crop modelling in agro-ecological characterisation and zonation of rice is given for transplanted, rainfed lowland rice in the wet season at IRRI, Philippines. Crop data derived for IR72 were used (Kropff et al., 1993; Appendix 1.2b); weather data were taken from the IRRI lowland weather station (11 years of complete data between 1979-1991); soil data were for a (fictive) non-cracking, puddled topsoil overlying a permeable subsoil (topsoil moisture characteristics from measurements in Tarlac, Wopereis, pers. com.); and management parameters were taken from practices at IRRI. Input data for soil and management parameters are given in Table 5.1, and are supposed to be representative for a land-unit of a (fictive) zonation study.

Table 5.1. Soil and management parameters for a case-study of rainfed lowland rice at IRRI.

Seepage & percolation rate, SPSOIL = 5 mm d^{-1}
Drainage rate subsoil, DDR = 2000 mm d^{-1}
Initial depth water layer, WL0I = 50 mm
Minimum depth of water layer, WL0MIN = 0 (not relevant)
Shrinkage factor, SHRINK = 0.7
Water content at cracking, WCCRAC = 0 cm^3 cm^{-3}
Water content saturation, WCSTP = 0.52 cm^3 cm^{-3}
Water content wilting point, WCWPP = 0.01 cm^3 cm^{-3}
Water content field capacity, WCFCP = 0.01 cm^3 cm^{-3} (actually not used in LOWBAL)
Water content air-dry, WCADP = 0.01 cm^3 cm^{-3}
Irrigation gift, RIGIFT = 0 (not relevant)
Initial amount of irrigation, RIPUD = 0 (not relevant)
Development stage to stop irrigation, DVSIE = 0 (not relevant)

Bund height, WL0MXI = 100 mm
Thickness puddled layer, TKLPI = 200 mm
Days in seed-bed, DTRP = 12 days
Number of hills, NH = 25
Number of plants per hill, NPLH = 3
Number of plants in seed-bed, NPLSB = 1000
Sowing date, STTIME = June-July

5.1 Sensitivity analysis

First, rainfed rice yield (WRR, weight of rough rice) was simulated using all weather data with sowing dates between day 165 (half June) and day 212 (end of July). Results are presented in Figure 5.1. Day of sowing had a large effect on simulated rice yield: in all but one year, rice yield declined with later sowing. It may be expected that simulated yields are even higher when sowing is done before day 165 (see Paragraph 5.2). In 9 out of 11 years, yields were below 4 t ha^{-1}, no or hardly any yield was simulated when sowing dates fell before day 185. Low yields were mostly caused by early termination of the model run because the period of drought stress exceeded the validity domain of the model (more than 25 days; see Paragraph 2.1), or because the soil water content dropped below the lower limit for dying of the leaves. It can be concluded that optimum sowing dates for this case-study are earlier than the range of dates in Figure 5.1 (i.e. before day 165).

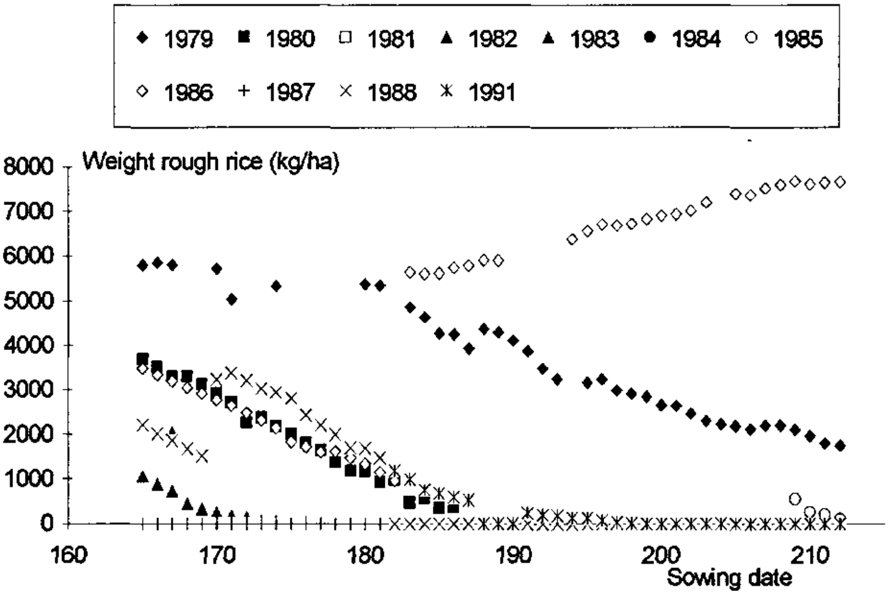
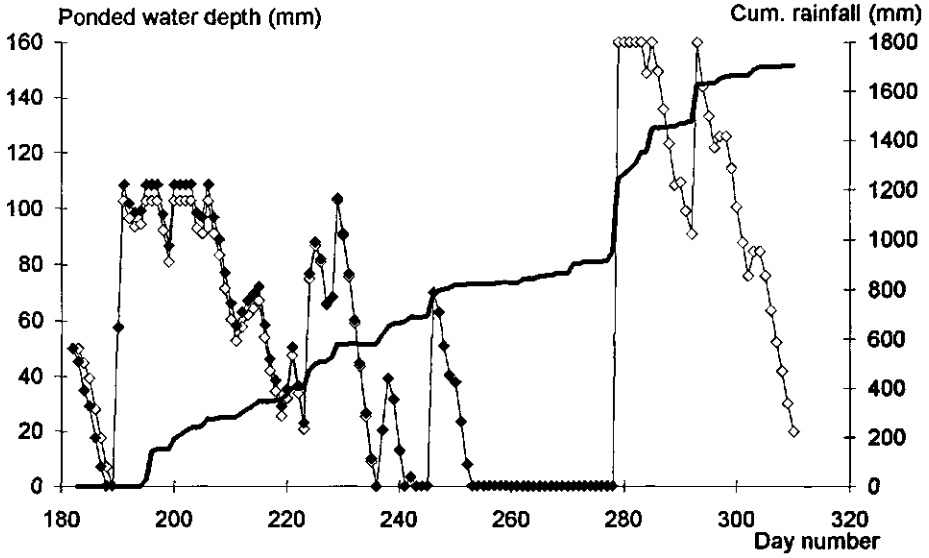


Figure 5.1. Simulated rainfed, lowland rough rice yield versus sowing date for 11 years between 1979-1991

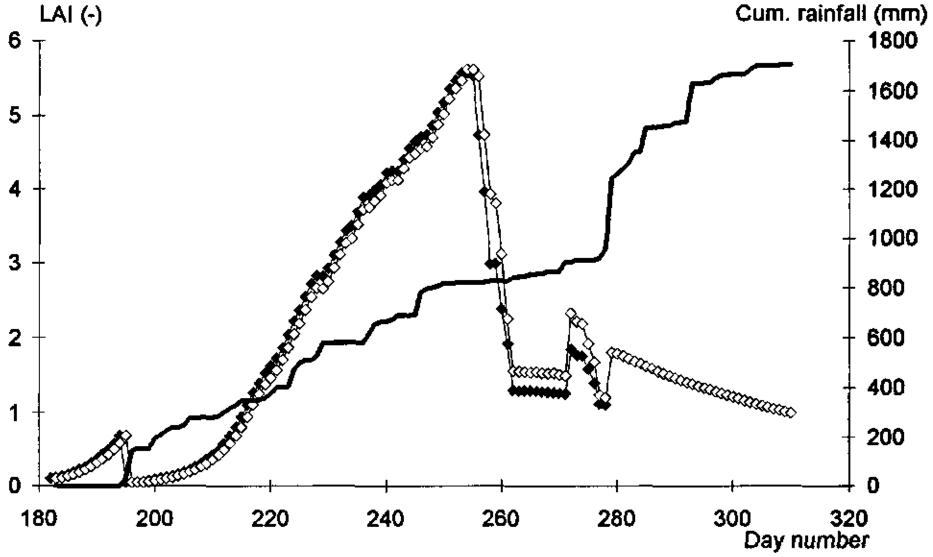
In Figure 5.1, some abrupt changes occur in the trend of yield versus sowing date. E.g. in 1986, simulated yields gradually declined from about 3.5 to 1 t ha^{-1} with sowing dates going from day 165 to 182, then suddenly jumped to about 6 t ha^{-1} at sowing date 183, after which they gradually increased to about 8 t ha^{-1} at sowing date 212. Also in 1986, zero yield was simulated with sowing between days 190-193, whereas yields with earlier or later sowing dates were about 6 t ha^{-1}. These abrupt changes in simulated yield are explained by two factors. First, there are sharp boundaries in the model that govern the simulation of crop death and the termination of the model run. For instance, soil moisture contents just below or above the lower limit for dying of leaves or the number of drought stress days make the difference between acute abortion (e.g. already in the vegetative phase) or the continuation of a simulation run. The timely rainfall on a specific day can determine whether such a boundary condition is passed or not. Under such conditions, only one day difference in sowing can make the difference between 0 or, for instance, 6 t ha^{-1} simulated yield, as in 1986. Secondly, it is implicitly assumed that the crop and soil are fully homogeneous with no variation in properties. In reality, there is always some variation in both crop and soil. This means that whereas at certain spots in a field, the passing of boundary conditions during simulation may results in zero yield, at other spots these boundary conditions may not be passed and some yield may still be obtained. The result in practice is an averaging of yield on a field basis, which is not simulated in ORYZA_W.

An example of abrupt changes in simulated yield is further elaborated for 1986 in Figure 5.2. In Figure 5.2a, the depth of ponded water, WL0, and the cumulative rainfall are plotted versus time for simulations with sowing day 182 and 183. Gradually declining amounts of rainfall during the first half of crop growth (days 180-250) resulted in decreasing depths of ponded water. Fluctuations in ponded water depth matched rainfall (note: rainfall is only plotted for the main field, i.e. after transplanting!). A long drought spell occurred between days 253-278. With sowing on day 182, this drought stress lasted 25 days, after which the simulation was aborted with about 1 t ha^{-1} grain weight. With sowing one day later, the soil moisture content was slightly higher, and only 24 days of drought stress were recorded. The rainfall on day 279 relieved the drought stress just in time, and subsequent rainfall secured sufficient amounts of water to attain a yield of about 6 t ha^{-1}. The dynamics of simulated LAI in time is plotted in Figure 5.2b. Somewhere halfway the drought spell of days 253-278, LAI decreased dramatically with both sowing dates. The slight amount of rainfall on day 271 resulted in a small, temporary, increase in LAI. With sowing on day 183, the rains after day 179 were sufficient to maintain LAI levels of 1-1.5 until crop maturity.

[The observations made here for simulated rainfed rice yield using ORYZA_W agree with simulation results for rainfed rice using the MACROS modules (Bouman, 1994)].



5.2a



5.2b

Figure 5.2. Simulated depth of ponded water (5.2a) and LAI (5.2b) in 1986 with sowing on day 182 (black diamonds) and 183 (white diamonds). The thick line indicates the cumulative amount of rainfall.

Based on the results of Figure 5.1, it was decided to perform further sensitivity analysis (SA) in three years with different yield levels: 1979 with sowing day 195 (yield = 3.1 t ha^{-1}), 1980 with sowing day 177 (yield = 1.6 t ha^{-1}), and 1986 with sowing day 200 (yield = 6.9 t ha^{-1}). All relevant management and soil parameters were included in the SA, Table 5.2.

Table 5.2. Ranges of management and soil parameter values used in sensitivity analysis.

Parameter	Range
WL0MXI	100, 120, ..., 300 mm
TKLPI	150, 170, ..., 350 mm
DTRP	10, 12, ..., 30 days
NPLSB	750, 800, ..., 1250 plants
NH	15, 17, ..., 30 hills
NPLH	1,2,..., 5 plants hill^{-1}
SPSOIL	0, 1, ..., 20 mm d^{-1}
SHRINK	0.1, 0.2, ..., 1.0
WCSTP	0.30, 0.35, ..., 0.80 cm^3 cm^{-3}
WCFCP	0.05, 0.10, ..., 0.50 cm^3 cm^{-3}
WCWPP	0.05, 0.10, ..., 0.50 cm^3 cm^{-3}
WCADP	0, 0.01, ..., 0.10 cm^3 cm^{-3}
WCCRAC	0, 0.02, ..., 0.20 cm^3 cm^{-3}

Note: drainage rate of the subsoil, DDR, was not included in SA because the soil type under consideration was non-cracking.

5.1.1 Management parameters

The results of SA analysis on management parameters are graphically illustrated in Figure 5.3. Results are also quantitatively expressed by the mean slope between simulated yield and management parameter value, Table 5.3.

The thickness of the puddled layer, TKLPI, had relatively the largest effect on simulated rice yield. Increasing thickness lead to increasing yield because more water could be stored that was available for crop growth. Bund heights, WL0MXI, larger than 12 cm had no effect on rice yield; there was no benefit from a potentially larger capacity of water storage. Simulated yields only decreased when bunds were lower than 12 cm.

Increasing duration of the seed-bed, DTRP, decreased yield substantially. At the high yield level, year 1986, yields only declined significantly if the seed-bed duration exceeded 18 days.

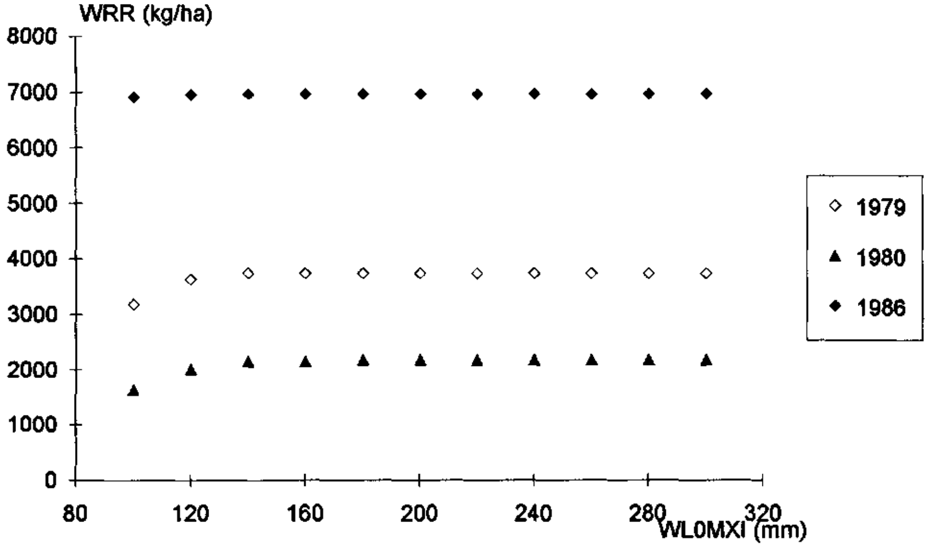
The parameters that control the crop density, i.e. number of plants in seed-bed, NPLSB, number of hills, NH, and number of plants per hill, NPLH, had no or little effect on simulated yield.

In setting up a management data collection strategy for this case-study, attention should focus on the thickness of the puddled layer and on the duration of the seed-bed (and on sowing date, see above). The values in Table 5.3 can be used as rough indicators of the accuracy (range) with which the management input data need to be determined to arrive at certain accuracies (ranges) in simulated yield.

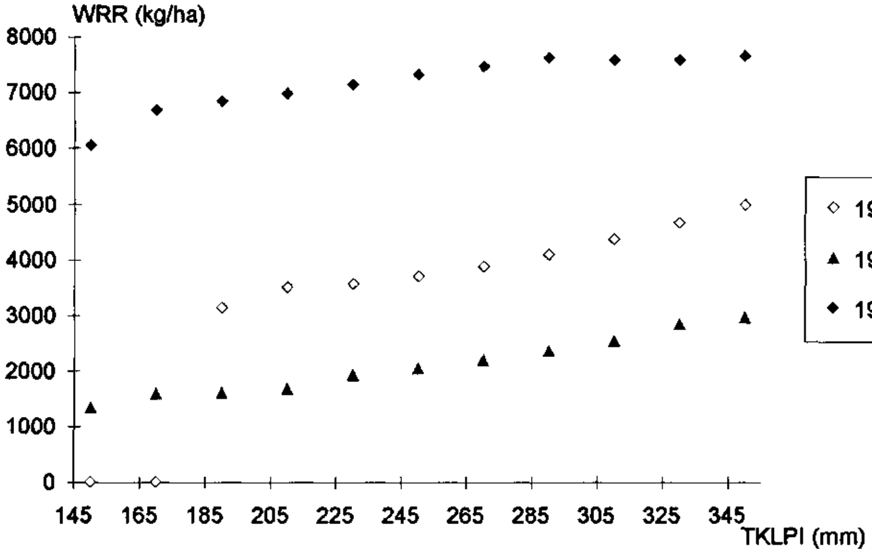
Also, conclusions can be drawn with respect to optimising crop management to maximum rice yield. Simulations with ORYZA_W indicated that, in this environment, deep puddling and short duration of the seed-bed favour high yields. Bund heights should be around 12 cm or higher. Crop densities in the seed-bed and in the main field had no to little effect on rice yield. These simulation results can be used to focus experimental field research.

Table 5.3. Mean slope between simulated rice yield and management and soil parameters. The slope is expressed in kg ha^{-1} rough rice yield per (increase in) unit of the management/soil parameter in 1979, 1980 and 1983. The mean slopes only apply to data ranges of the management/soil parameters with yield > 0, specifically: SPSOIL < 8 mm d^{-1}; WCSTP > 0.40 cm^3 cm^{-3}; WCWPP < 0.15 cm^3 cm^{-3}; WCCRAC < 0.1 cm^3 cm^{-3}. Note: DTRP (1) = DTRP < 20 days, DTRP (2) = DTRP > 20 days.

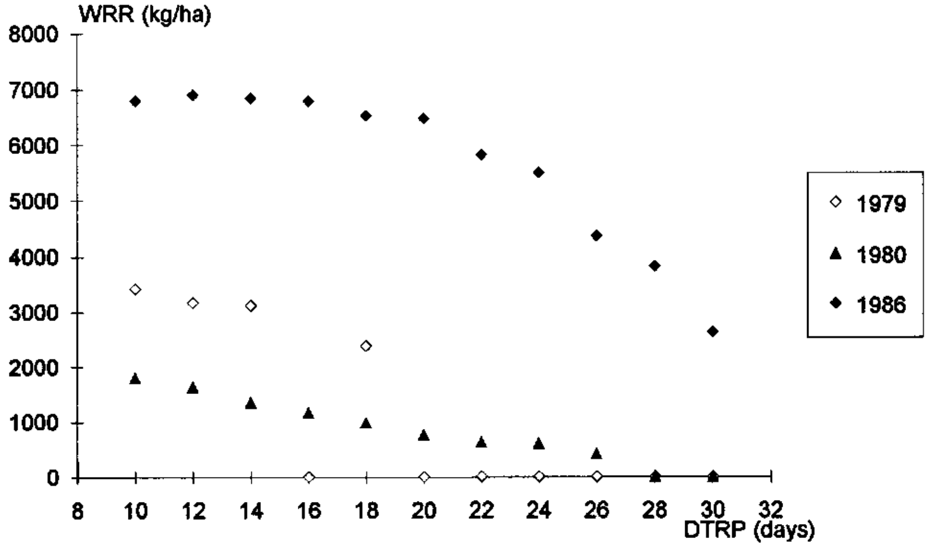
Parameter	Unit	1979	1980	1986
WL0MXI	1 cm	15	16	1
TKLPI	1 cm	108	80	70
DTRP (1)	1 day	-127	-104	-32
DTRP (2)	1 day	-	-85	-377
NH	1 hill	-4	-2	19
NPLH	1 plant $hill^{-1}$	-45	-25	134
NPLSB	100 plants	-47	-2	-14
SPSOIL	1 mm d^{-1}	-1184	-525	-198
SHRINK	0.01 (-)	-26	-48	17
WCSTP	0.01 cm^3 cm^{-3}	17	-2	18
WCFCP	0.01 cm^3 cm^{-3}	0	0	0
WCWPP	0.01 cm^3 cm^{-3}	-8	15	-40
WCADP	0.01 cm^3 cm^{-3}	0	0	0
WCCRAC	0.01 cm^3 cm^{-3}	0	0	0


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
80
120
160
200
240
280
320
WL0MXI (mm)
1979
1980
1986

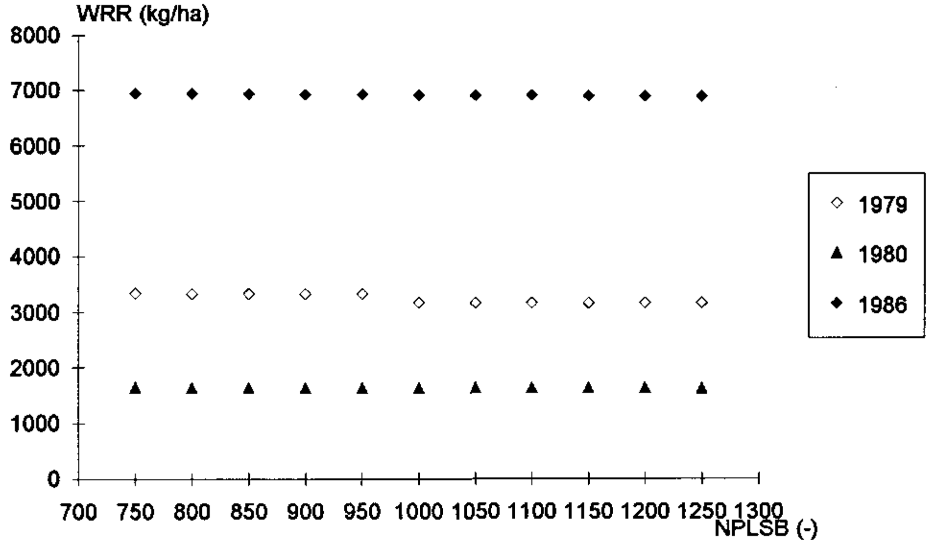
5.3a


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
145
165
185
205
225
245
265
285
305
325
345
TKLPI (mm)
1979
1980
1986

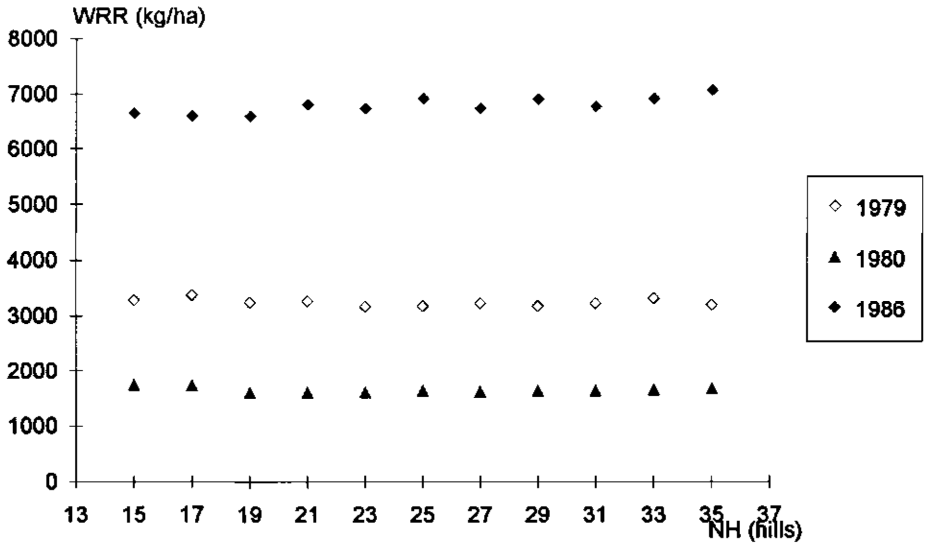
5.3b


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
8
10
12
14
16
18
20
22
24
26
28
30
32
DTRP (days)
◇ 1979
▲ 1980
◆ 1986

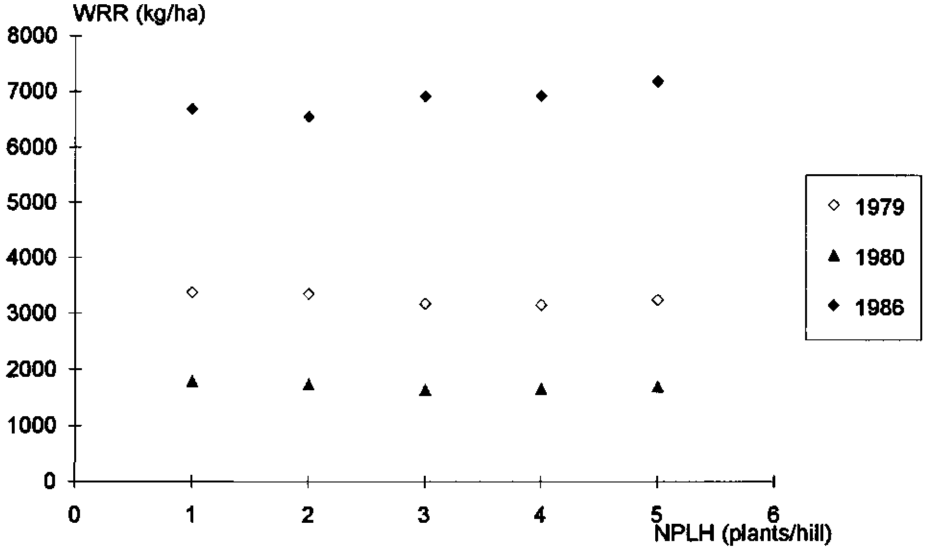
5.3c


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
NPLSB (-)
◇ 1979
▲ 1980
◆ 1986

5.3d



5.3e



5.3f

Figure 5.3. Simulated rough rice yield, WRR, versus WL0MXI (5.3a), TKLPI (5.3b), DTRP (5.3c), NPLSB (5.3d), NH (5.3e) and NPLH (5.3f), in 1979, 1980 and 1986.

5.1.2 Soil parameters

Results of the SA on soil parameters are given in Figure 5.4 and Table 5.3.

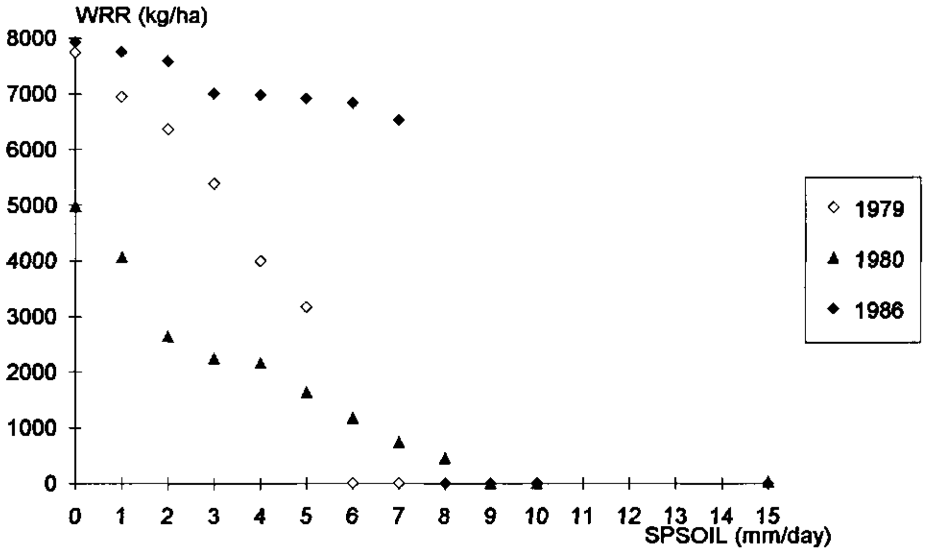
Seepage & percolation rate, SPSOIL, had relatively the largest effect on simulated rice yield; increasing SPSOIL lead to decreasing rice yields. Abrupt changes in the curves of simulated yield versus SPSOIL, e.g. when SPSOIL > 8 mm d^{-1} in 1986, Figure 5.4a, again point to sharp boundaries between process descriptions in the model (see above). In these situations, ORYZA_W should be carefully studied to find out what is actually happening during simulation (c.f. Figure 5.2). With SPSOIL rates > 8 mm d^{-1}, simulated yield was 0 in all three years.

The shrinkage factor of the puddled layer, SHRINK, also had a considerable, though non-consistent, effect on simulated yield.

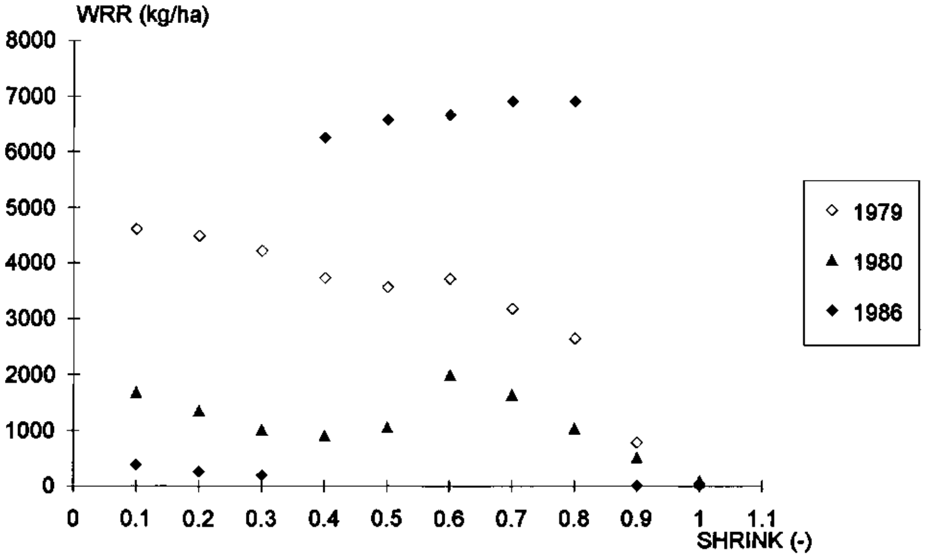
The effects of the soil moisture characteristics of the puddled layer on simulated yield were generally relatively small, though sharp transitions occurred. Decreasing water content at saturation, WCSTP, lead to gently decreasing yields. However, yields suddenly dropped to about 0 when WCSTP decreased below 0.40 cm^3 cm^{-3}. Water content at field capacity, WCFCP, and at air-dryness, WCADP, had no effect on simulated yield. The effect of water content at wilting point, WCWPP, was generally small for values between 0 and 0.15 cm^3 cm^{-3}. Simulated yields dropped to around 0 when WCWPP was larger than 0.15 cm^3 cm^{-3}.

The water content at which cracks penetrate the compacted layer, WCCRAC, did not affect simulated rice yield when its value was below 0.10 cm^3 cm^{-3}. After 0.10 cm^3 cm^{-3}, simulated rice yield declined (except for the high yield level in 1986) until 0 yield was obtained at values of WCCRAC larger than 0.14 cm^3 cm^{-3}.

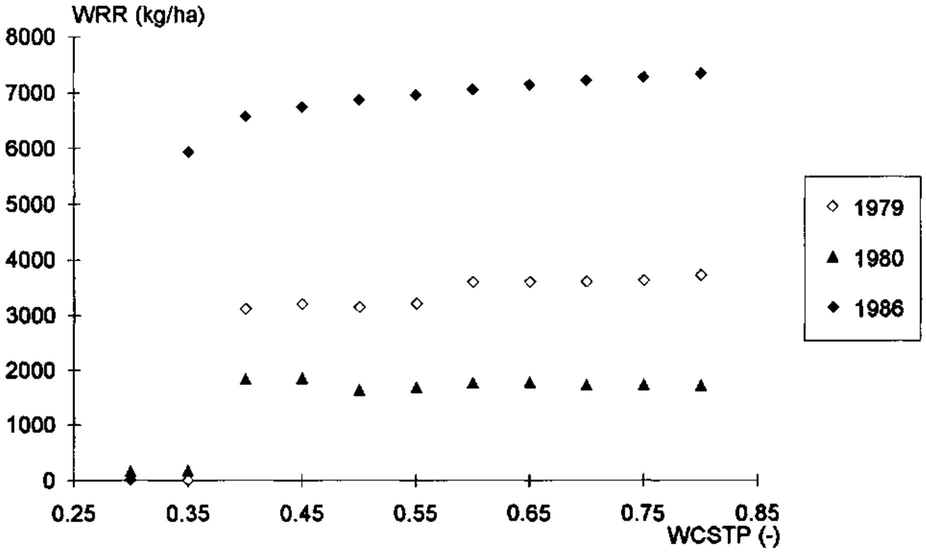
In soil data acquisition, much attention has first to be paid to seepage & percolation rate, and secondly to the shrinkage factor of the soil. Soil moisture characteristics can be collected with relatively less detail, provided the values of WCSTP and WCWPP are within certain ranges, 0.40-0.85 and 0-0.15 cm^3 cm^{-3} respectively. If the soils are non-cracking, as in this case-study, a margin is allowed for WCCRAC of 0-0.10 cm^3 cm^{-3} at which there is no effect on simulated yield. When WCCRAC is found to be higher than 0.10 cm^3 cm^{-3}, the soils can no longer be considered as non-cracking, and the SA should be repeated for cracking soil types (including the parameter DDR). The values in Table 5.3 can be used as rough indicators of the accuracy (range) with which the soil input data need to be determined to arrive at certain accuracies (ranges) in simulated yield.


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
SPSOIL (mm/day)
◇ 1979
▲ 1980
◆ 1986

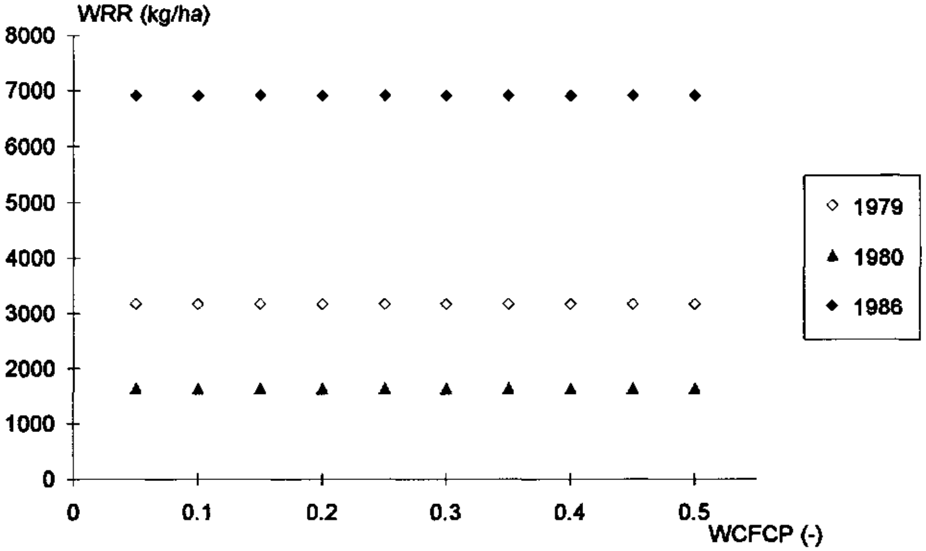
5.4a


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
SHRINK (-)
◇ 1979
▲ 1980
◆ 1986

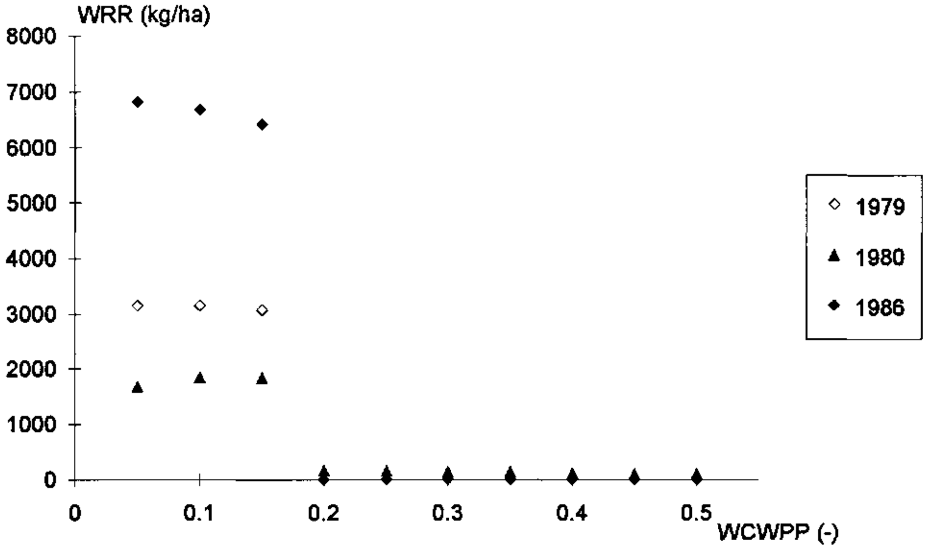
5.4b


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
0.25
0.35
0.45
0.55
0.65
0.75
0.85
WCSTP (-)
◇ 1979
▲ 1980
◆ 1986

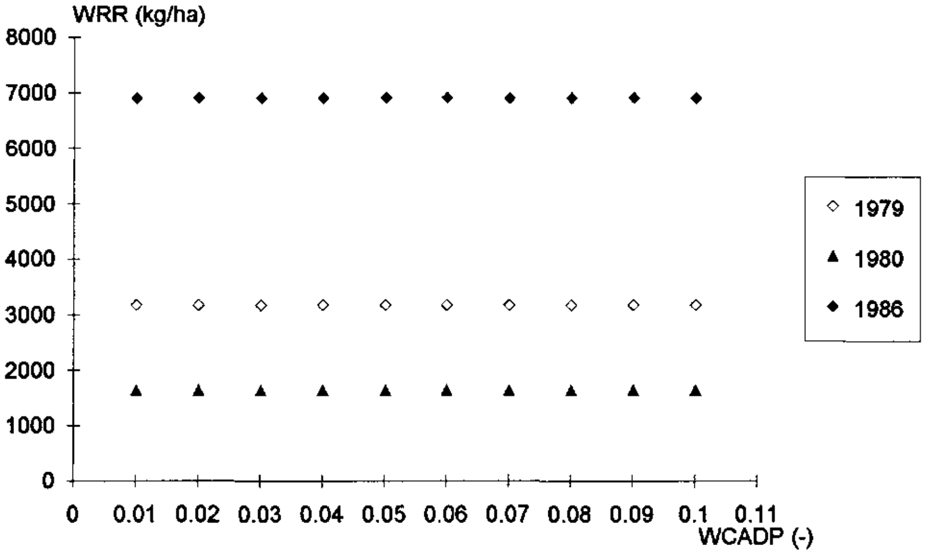
5.4c


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
WCFCP (-)
◇ 1979
▲ 1980
◆ 1986

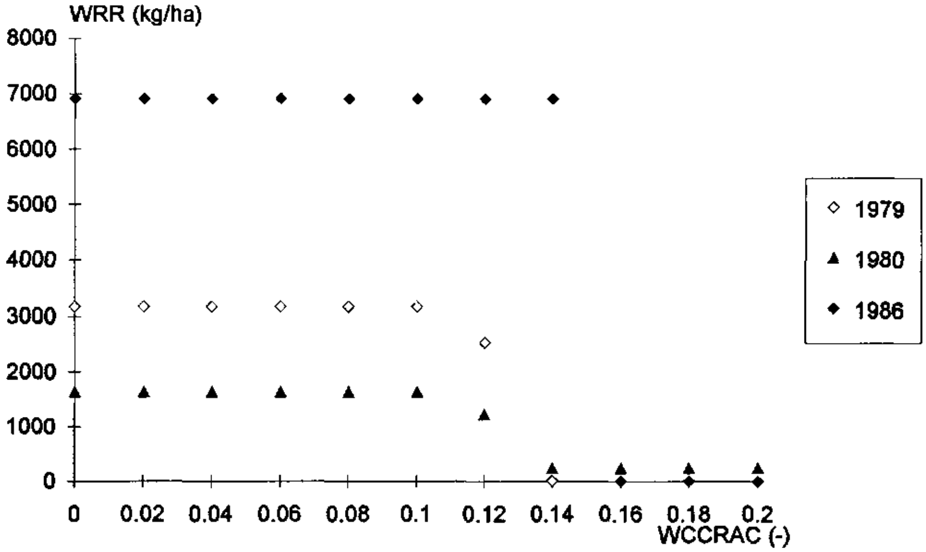
5.4d


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
WCWPP (-)
◇ 1979
▲ 1980
◆ 1986

5.4e


WRR (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
WCADP (-)
◇ 1979
▲ 1980
◆ 1986

5.4f



5.4g

Figure 5.4. Simulated rough rice yield, WRR, versus SPSOIL (5.4a), SHRINK (5.4b), WCSTP (5.4c), WCFCP (5.4d), WCWPP (5.4e), WCADP (5.4f) and WCCRAC (5.4g), in 1979, 1980 and 1986.

5.2 Uncertainty and variation analysis

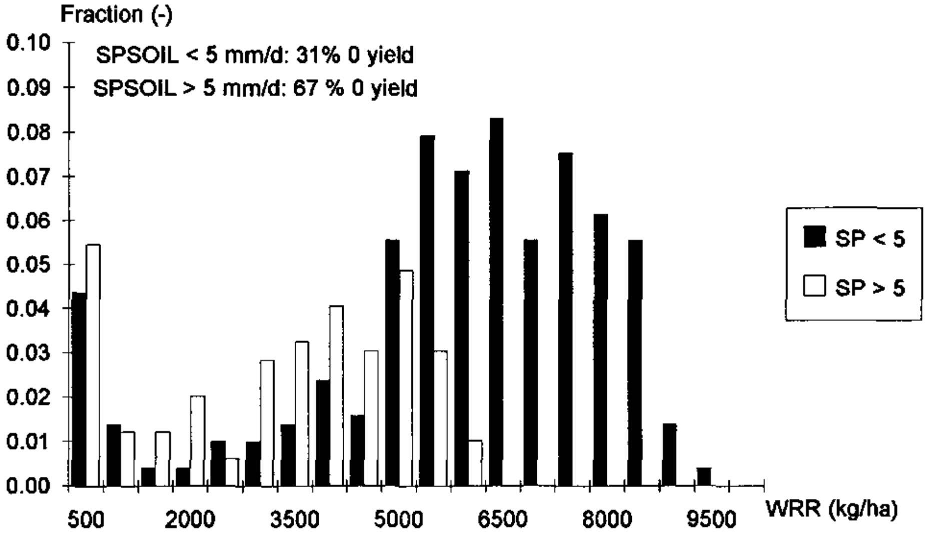
From the sensitivity analysis, the following parameters were found to have a relatively large effect on simulated yield: sowing date, STTIME, thickness puddled layer, TKLPI, days in seed-bed, DTRP, seepage & percolation rate, SPSOIL, and shrinkage factor, SHRINK. Ranges of parameter values were estimated for a land-unit of a zonation study where parameter values are typically quite uncertain or variable, Table 5.4 (see also Wopereis et al., 1993). Based on the results of the SA, Figure 5.1, sowing dates earlier than day 165 were included: the range of sowing dates spanned the whole month of June. Two soil types were used, one characterised by SPSOIL rates of 0-5 mm d^{-1}, and one by SPSOIL rates of 5-10 mm d^{-1} (other soil parameters were the same). Using the program RIGAUS, 999 random parameter sets were generated from uniform probability distributions for each parameter from Table 5.4. ORYZA_W was run with the 999 parameter sets using weather data for three years, 1979, 1980 and 1983, that characterise different yield levels (a different year was used in comparison with the SA study because the STTIME's were somewhat earlier). Frequency distributions of the simulated rice yields (excluding 0 yields) are given in Figure 5.5, and some statistics of the yield distribution are given in Table 5.5. The yield statistics were only calculated for 'harvestable' yields, that was set arbitrarily to yields exceeding 100 kg ha^{-1}. In each year, ORYZA_W was also run using the average value of each parameter from Table 5.4, resulting in the *average* simulated yield, Table 5.5.

Table 5.4. Ranges of parameter values used in Monte Carlo simulation.

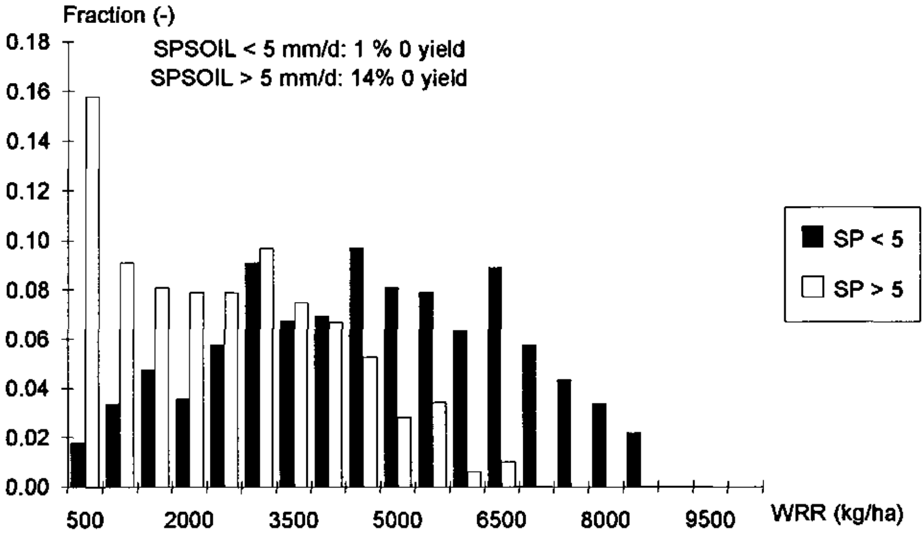
Parameter	Range
STTIME	150-180 d
TKLPI	150-250 mm
DTRP	10-21 d
SPSOIL	0-5, 5-10 mm d^{-1}
SHRINK	0.65-0.9 (-)

Table 5.5. Statistical parameters of yield distribution from the Monte Carlo simulations: % 0 yield, 1st and 3td quartile and mean yield. The quartile values and the mean yield are calculated for yields > 100 kg ha^{-1}. The *average* yield results from a single simulation run using average input parameter values (see text). SD = sowing date (day of year), SP = seepage & percolation rate (mm d^{-1}).

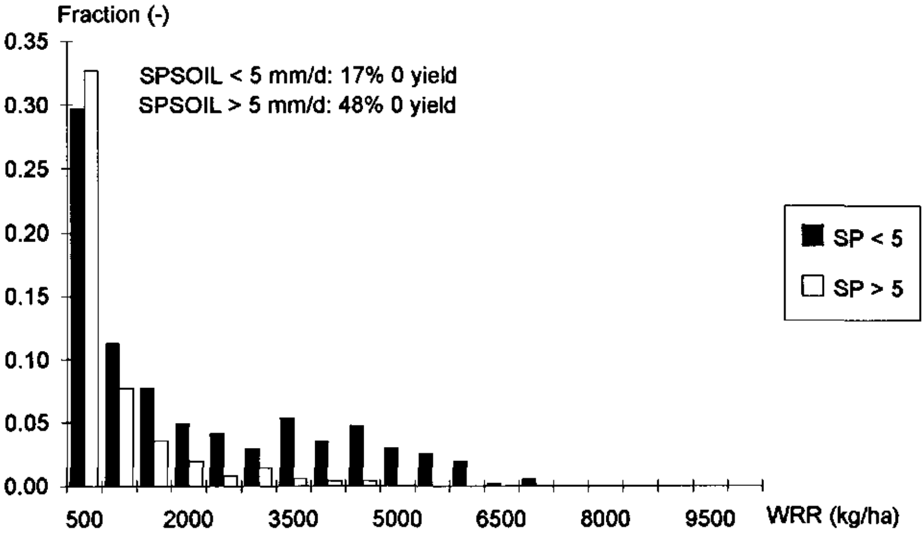
Year	Yield	SD:150-180		SP: 0-5	
	statistic	SP: 0-5	SP: 5-10	SD:150-160	SD:170-180
1979	% 0 yield	31	76	35	26
	1st quartile	4.98	2.68	5.17	4.54
	3td quartile	7.23	4.65	7.03	7.61
	mean	5.84	3.47	5.64	5.90
	average	5.87	4.24	5.74	6.76
1980	% 0 yield	1	14	0	4
	1st quartile	2.81	1.00	5.15	1.42
	3td quartile	5.97	3.44	7.00	3.18
	mean	4.36	2.35	6.12	2.51
	average	4.22	2.75	5.95	2.38
1983	% 0 yield	17	48	7	38
	1st quartile	0.48	0.28	1.69	0.19
	3td quartile	3.37	1.04	4.54	0.70
	mean	2.02	0.86	3.26	0.55
	average	0.94	0.17	3.83	0.27


Fraction (-)
SPSOIL < 5 mm/d: 31% 0 yield
SPSOIL > 5 mm/d: 67 % 0 yield
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
500
2000
3500
5000
6500
8000
9500
WRR (kg/ha)
SP < 5
SP > 5

5.5a


Fraction (-)
SPSOIL < 5 mm/d: 1 % 0 yield
SPSOIL > 5 mm/d: 14% 0 yield
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
500
2000
3500
5000
6500
8000
9500
WRR (kg/ha)
SP < 5
SP > 5

5.5b



5.5c

Figure 5.5. Frequency distribution of simulated rough rice yield, WRR, in 1979 (5.5a), 1980 (5.5b) and 1983 (5.5c), on soils with SPSOIL (SP in legends) rates of 0-5 mm d^{-1} (black bars) and on soils with SPSOIL rates of 5-10 mm d^{-1} (white bars).

From Figure 5.5 and Table 5.5, the following conclusions were drawn:

- Simulated yields of 0 kg ha^{-1} indicate that the simulation was stopped in the vegetative phase either because of crop death or because the duration of the drought stress lasted longer than 25 days (in which case it can be assumed that the crop died too). Zero yield may therefore be seen as indicator for complete crop failure. A high percentage of 0 yield was simulated in 1979 and in 1983, ranging from 76% on relatively permeable soils (SPSOIL 5-10 mm d^{-1}) to 17% on relatively poorly permeable soils (SPSOIL 0-5 mm d^{-1}). On average, 46% complete crop failure was simulated on permeable soils, and 16% on poorly permeable soils.
- The relatively broad range in input parameter values resulted in a large variation in simulated yield, though there were differences between the years. The distribution of yields (that are larger than 0 kg ha^{-1}) was broadest in 1980 and least broad in 1983. A good indicator of the broadness, or uncertainty, in simulated yields are the first and third quartile values, i.e. the yield levels that are obtained by 25% and 75% of the data. For instance, on relatively poorly permeable soils in 1979, 50% of the simulated yields were between 5 (first quartile) and 7.2 t ha^{-1} (third quartile). On average, the difference between the first and third quartile values was 2.8 and 1.7 t ha^{-1} on relatively poorly permeable and permeable soils respectively. The quartile values are also useful

to translate the results of the MC analysis in terms of risk. E.g. on relatively poorly permeable soils in 1979, there was 75% probability of obtaining rice yields larger than 5 t ha^{-1}, and 25% probability of obtaining rice yields larger than 7.2 t ha^{-1}.

- Beside the broadness of the simulated yield distributions, the shape of the distributions also differed among the years. E.g. in 1979, the percentage of extremely low yields (100-500 kg ha^{-1}) was relatively low, whereas it was very high in 1983.
- Despite the large variation in simulated yields, there is a clear trend that simulated yields were larger on relatively poorly permeable soils than on permeable soils. Quartile and mean yields were much higher on soils with 0-5 mm d^{-1} seepage & percolation rate than on soils with 5-10 mm d^{-1} seepage & percolation rate.
- In 1979 and 1980, the mean yield of the simulated yield distribution was quite comparable with the simulated yield using the average input parameter values, Table 5.5 (mean and *average* values respectively). On both soil types, the difference was only 0.34 t ha^{-1} on the average. However, in 1983, the average difference was 0.89 t ha^{-1}. In general, whether the mean of the simulated yield distribution will resemble the simulated yield with average input parameter values depends on the shape of the distribution of the input parameter values (in this case: uniform distribution).

The effect of a higher degree of certainty in input parameter data on simulated rice yield is illustrated for sowing date, STTIME. The original 999 parameter sets with a monthly-range of STTIME were divided into three subsets sets with decade-ranges of STTIME values: days 150-160, 160-170 and 170-180. The distribution of the simulated rice yields using the parameter sets with the first (day 150-160) and the last (day 170-180) decade of June as sowing date, and on the permeable soil type, is summarised in Table 5.5. A frequency distribution is given for 1980 in Figure 5.6.

In 1980 and 1983, there was a clear distinction between the rice yields with sowing dates 150-160 and with sowing dates 170-180. Early sowing in June resulted in higher yields than late sowing in June. In 1979, the differences were relatively small, and late sowing resulted in slightly higher yields than early sowing. Note that with late sowing, days 170-180, in 1979, there was a relatively large difference between the mean of the simulated yield distribution and the simulated yield using average input parameter values, Table 5.5. Overall, decreasing the uncertainty in sowing date from a month-range to a decade-range decreased the broadness in simulated yield distribution: the average difference between the first and the third yield quartile decreased from 2.8 t ha^{-1} to 2 kg ha $^{-1}$ (on poorly permeable soils).

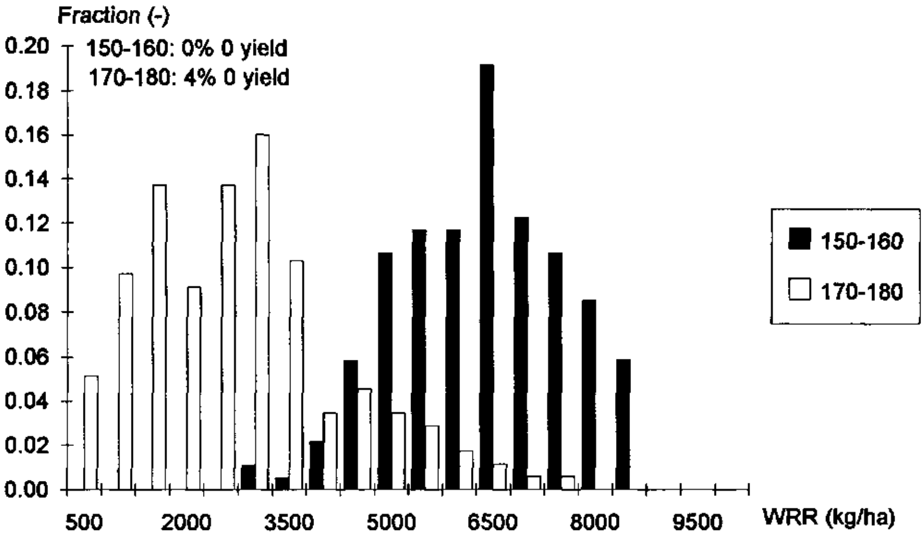


Figure 5.6. Frequency distribution of simulated rough rice yield, WRR, on relatively poorly permeable soil in 1980. Black bars are simulations with sowing dates 150-160, white bars with sowing dates between 170-180.

5.3 Risk analysis

In the previous Paragraph, the effect of uncertainty and spatial variation in management and soil parameters in a (fictive) land-unit on the uncertainty/variation in simulated rice yield was investigated in selected years. In this Paragraph, the study was extended to risk analysis including the variation in weather data. Two hundred random parameter sets were generated using RIGAUS with the same uniform probability distribution of selected parameters as in Table 5.4. ORYZA_W was run for all 11 years of available weather data using each year the 200 randomly generated parameter sets. Exceedance probability distributions were calculated from the total of 2200 simulated rough rice yields (Figures 5.7-5.9).

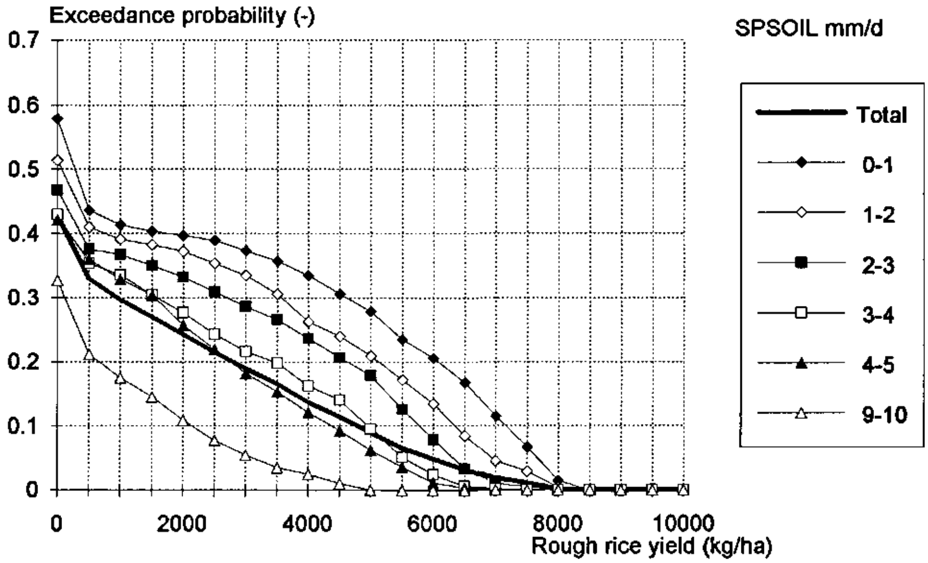


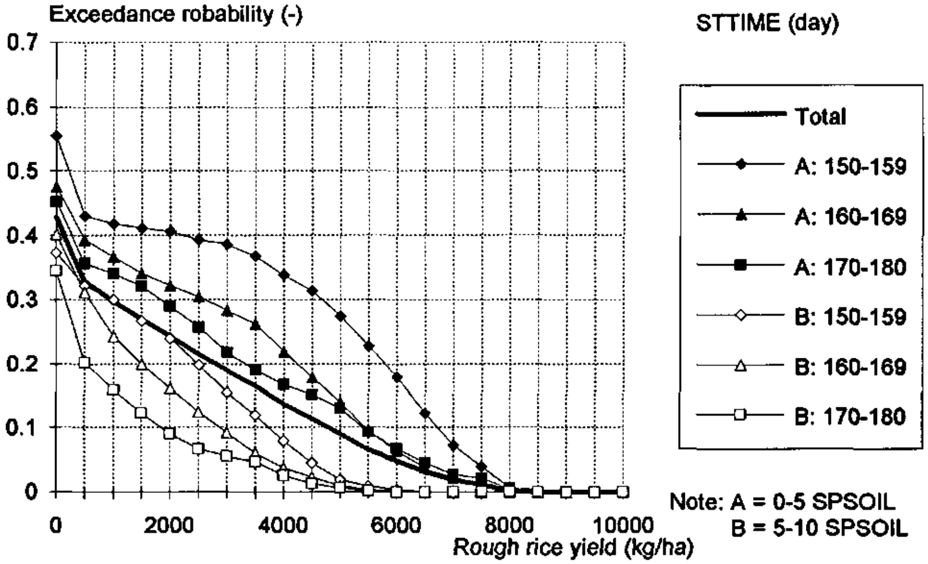
Figure 5.7. Exceedance probability of rough rice yield, WRR (kg ha^{-1}) as average for the whole land-unit (thick line) and separated to soil classes of different seepage & percolation rates (see legend; in mm d^{-1}).

Given the uncertainty, or spatial variation, in management and soil parameters of Table 5.4, and the variation in weather data between 1979-1991, simulated rice yields were highly variable, see Figure 5.7 (thick line). Growing rainfed rice without irrigation is, therefore, risky. The probability of 0 yield was about 58%, and the probability of obtaining more than 1 t ha^{-1} rough rice yield was only 30%.

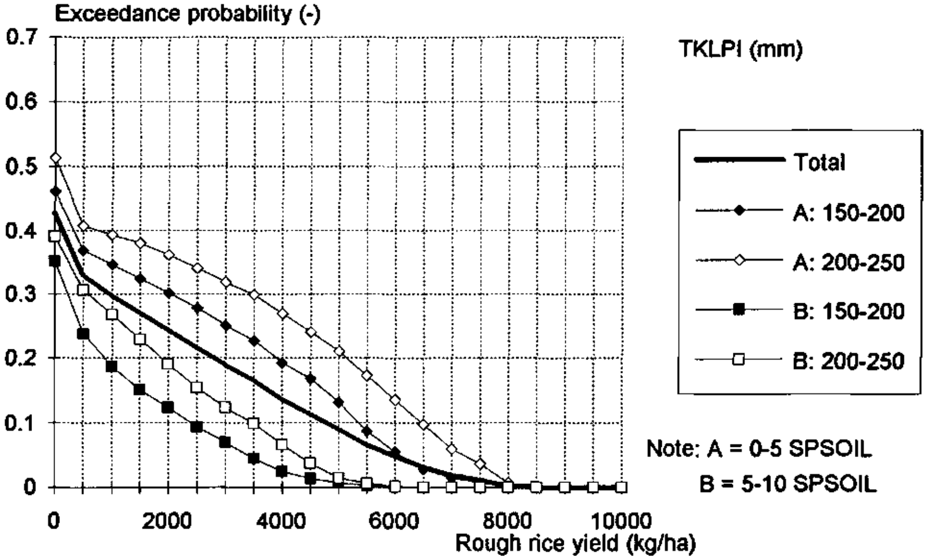
The soil property seepage & percolation rate, SPSOIL, had a large effect on simulated rice yields, Figure 5.7. With only 0-1 mm d^{-1} SPSOIL, the exceedance probabilities were much higher than the average: the probability of 0 yield was some 42% and the probability of yield higher than 1 t ha^{-1} was 41%. With 9-10 mm d^{-1} SPSOIL, the probability of 0 yield was 67% and the probability of yield higher than 1 t ha^{-1} was only 18%. Thus, substratification of the area with respect to seepage & percolation rate will result in higher accuracies of predicted yield level and variation. If a land-unit can not be further stratified into 'mappable' units, e.g. because SPSOIL values are evenly or randomly distributed throughout the land-unit, the thick line of Figure 5.7 represents the average variation in rice yield of the land-unit. Individual farmers that have knowledge of the SPSOIL rate of their own fields can use the separate curves in Figure 5.7 to get a more accurate estimate of yield variation for their particular conditions.

Management parameters also affected simulated yield variation. In Figures 5.8a/c, the soil type was divided into a relatively poorly permeable soil (SPSOIL 0-5 mm d^{-1}) and a relatively permeable soil (SPSOIL 5-10 mm d^{-1}). The date of sowing had relatively the largest effect on yield variation. On both soil types, sowing in the first decade of June (day 150-159) resulted in much higher yields than sowing in the last decade of June (day 170-180), Figure 5.8a. Next, thickness of the puddled layer affected simulated rice yields: deep puddling (200-250 mm) resulted in higher yield levels than shallow puddling (150-200 mm) on both soil types, Figure 5.8b. The effect of duration of the seed-bed on simulated rice yields was relatively small: short durations (10-15 days) resulted in slightly higher yields than relatively long durations (16-21 days), Figure 5.8c.

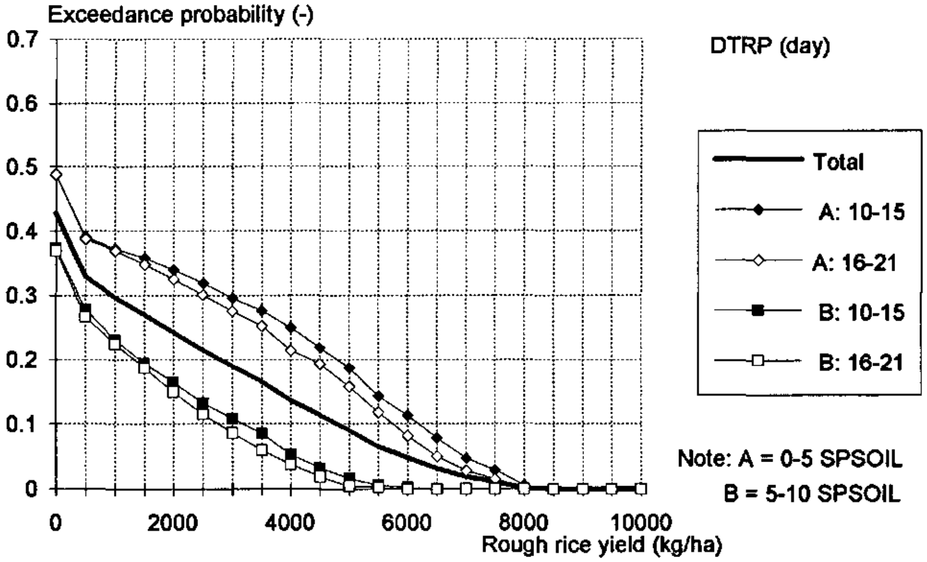
The extreme situations that can be encountered in the land-unit under consideration are illustrated in Figure 5.9. The worst situation in terms of yield levels occurred with late sowing (day 170-180) on a very permeable soil (9-10 mm d^{-1} SPSOIL): 71% probability of 0 yield and only 10% probability of obtaining more than 1 t ha^{-1}. The best situation occurred with early sowing (day 150-160) on a very poorly permeable soil (0-1 mm d^{-1} SPSOIL): only 32% probability of 0 yield and 45% probability of obtaining more than 1 t ha^{-1}.


Exceedance robability (-)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
Rough rice yield (kg/ha)
STTIME (day)
Total
A: 150-159
A: 160-169
A: 170-180
B: 150-159
B: 160-169
B: 170-180
Note: A = 0-5 SPSOIL
B = 5-10 SPSOIL

5.8a


Exceedance probability (-)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
Rough rice yield (kg/ha)
TKLPI (mm)
Total
A: 150-200
A: 200-250
B: 150-200
B: 200-250
Note: A = 0-5 SPSOIL
B = 5-10 SPSOIL

5.8b



5.8c

Figure 5.8. Exceedance probability of rough rice yield, WRR (kg ha^{-1}) as average for the whole land-unit (thick line) and separated to classes of sowing date, STTIME, (5.8a), thickness of puddled layer, TKLPI, (5.8b) and days in seed-bed, DTRP, (5.8c) (see legends), on poorly permeable soil (A in legend) and permeable soil (B in legend) (SPSOIL in mm d^{-1}).

5.4 Comments

The results of the sensitivity and Monte Carlo analyses found in this Chapter apply to the specific crop and environmental conditions of this case-study. The analyses may give different results in other climates (weather, cropping season), with other soil types (e.g. with cracking soils, the drainage rate of the subsoil, DDR, will affect simulated yield) and with other crop characteristics (e.g. short-long duration cultivars). Therefore, for each case-study, the sensitivity and Monte Carlo analyses should be applied again until sufficient insight is gained in the behaviour of the model in various agro-ecological environments. For the particular case-study presented here, the results agree with those of a zonation study carried out for Tarlac Province, the Philippines, as reported by Wopereis et al., 1993. Using a version of ORYZA_W with another, more detailed soil-water balance, they too found a large variation in simulated rainfed (lowland) rice yields and concluded that growing rice under rainfed conditions is risky.

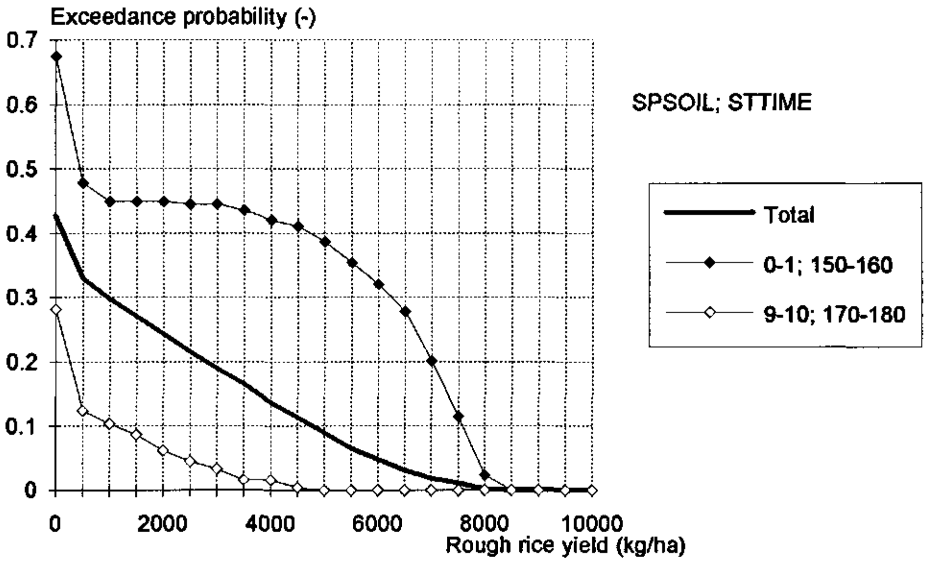


Figure 5.9. Exceedance probability of rough rice yield, WRR (kg ha^{-1}) as average for the whole land-unit (thick line) and for the worst (white diamonds) and best (black diamonds) situation (see text). The first class in the legend indicates SPOIL rate (mm d^{-1}) and the second STTIME (sowing date, d).

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Appendix 1. Listing of ORYZA_W with input and output files

1.1 ORYZA_W

```
*-----------------------------------------------------------------------*
*                             ORYZA_W 2.0                               *
*                                                                       *
* Agro-ecological growth model for rice in three ecosystems             *
* (environments): irrigated lowland, rainfed lowland, rainfed upland.   *
*                                                                       *
* Authors: B.A.M. Bouman, M.C.S. Wopereis, M.J. Kropff, J.J. Riethoven *
*         : & SARP Staff 1993                                           *
* Version: 2.0                                                          *
* Date   : February 1994                                                *
*                                                                       *
* Reference: Bouman, B.A.M., M.S.C. Wopereis & J.J. Riethoven, 1994.   *
*         Crop growth modelling in agro-ecological zonation of rice,    *
*         SARP Research Proceedings, AB-DLO, Wageningen,                *
*         The Netherlands.                                              *
* Info:   B.A.M. Bouman,  DLO Research Institute for Agrobiology and    *
*         Soil Fertility, PO Box 14, 6700 AA, Wageningen,               *
*         The Netherlands. e-mail: bouman@cabo.agro.nl.                 *
*-----------------------------------------------------------------------*

*-----------------------------------------------------------------------*
*                             MAIN PROGRAM                              *
*                 FORTRAN Simulation Environment (FSE 2.0)              *
*                             July, 1993                                *
*                                                                       *
*     FSE 2.0 is a simulation environment suited for simulation of     *
*     biological processes in time, such as crop and vegetation growth,*
*     insect population development etc.                                *
*                                                                       *
*     The MAIN program, subroutine FSE and subroutine MODELS are        *
*     programmed by D.W.G. van Kraalingen, DLO Centre for              *
*     Agrobiological Research, PO Box 14, 6700 AA, Wageningen, The      *
*     Netherlands (e-mail: d.w.g.van.kraalingen@cabo.agro.nl).          *
*                                                                       *
*     A manual of FSE 2.0 is in preparation.                            *
*                                                                       *
*     Version 1.0 of FSE is described in:                               *
*     Kraalingen, D.W.G. van 1991. The FSE system for crop simulation, *
*     Simulation Report CABO-TT No.23, Centre for Agrobiological        *
*     Research, Dept. of Theoretical Production Ecology, 77 pp.         *
*                                                                       *
*     Data files needed for FSE 2.0:                                    *
*           (excluding data files used by models called from MODELS):  *
*        - CONTROL.DAT (contains file names to be used),                *
*        - timer file whose name is specified in CONTROL.DAT,           *
*        - optionally, a rerun file whose name is specified in          *
*          CONTROL.DAT,                                                 *
*        - weather data files as specified in timer file                *
*     Object libraries needed for FSE 2.0:                              *
*        - TTUTIL (at least version 3.2)                                *
*        - WEATHER (at least version from 17-Jan-1990)                  *
*-----------------------------------------------------------------------*

      PROGRAM MAIN

      CALL FSE

      END

*-----------------------------------------------------------------------*
*      SUBROUTINE FSE (2.0)                                             *
*-----------------------------------------------------------------------*
      SUBROUTINE FSE

      IMPLICIT REAL (A-Z)

*-----Standard declarations for simulation and output control
      INTEGER   ITASK   , INSETS, ISET  , IPFORM, IL, ILEN
      INTEGER   INPRS, IPRS, IMNPRS
      LOGICAL   OUTPUT  , TERMNL, RDINQR
      CHARACTER COPINF*1, DELTMP*1
      PARAMETER (IMNPRS=100)
      CHARACTER PRSEL(IMNPRS)*11

*-----Declarations for time control
      INTEGER   IDOY, IYEAR

*-----Declarations for weather system
      INTEGER   IFLAG   , ISTAT1, ISTAT2 , ISTN
      LOGICAL   WTRMES  , WTRTER
      CHARACTER WTRDIR*80, CNTR*7, WSTAT*7, DUMMY*1

*-----Declarations for file names and units
      INTEGER   IUNITR  , IUNITD  , IUNITO   , IUNITL   , IUNITC
      CHARACTER FILEON*80, FILEOL*80
      CHARACTER FILEIC*80, FILEIR*80, FILEIT*80
      CHARACTER FILEI1*80, FILEI2*80, FILEI3*80, FILEI4*80, FILEI5*80

*-----Declarations for observation data facility
      INTEGER   INOD , IOD
      INTEGER   IMNOD
      PARAMETER (IMNOD=100)
      INTEGER   IOBSD(IMNOD)

*-----Unit numbers for control file (C), data files (D),
*     output file (O), log file (L) and rerun file (R). File name for
*     control file and empty strings for input files 1-5.
*     WTRMES flags any messages from the weather system
```

```
      DATA IUNITC /10/, IUNITD /20/, IUNITO /30/
      DATA IUNITL /40/, IUNITR /50/
      DATA FILEIC /'CONTROL.DAT'/
      DATA FILEI1 /' '/, FILEI2 /' '/, FILEI3 /' '/
      DATA FILEI4 /' '/, FILEI5 /' '/
      DATA WTRMES /.FALSE./

*-----Open control file and read names of normal output file, log file
*     and rerun file (these files cannot be used in reruns)
      CALL RDINIT (IUNITC,0, FILEIC)
      CALL RDSCHA ('FILEON', FILEON)
      CALL RDSCHA ('FILEOL', FILEOL)
      CALL RDSCHA ('FILEIR', FILEIR)
      CLOSE (IUNITC)

*-----Open output file and possibly a log file
      CALL FOPENS  (IUNITO, FILEON, 'NEW', 'DEL')
      IF (FILEOL.NE.FILEON) THEN
         CALL FOPENS  (IUNITL, FILEOL, 'NEW', 'DEL')
      ELSE
         IUNITL = IUNITO
      END IF

*-----See if rerun file is present, and if so read the number of rerun
*     sets from rerun file
      CALL RDSETS (IUNITR, IUNITL, FILEIR, INSETS)

*-----Initialise logfile for end-of-year state values
      CALL OPINIT

*======================================================================*
*                     Main loop and reruns begin here                  *
*======================================================================*
      DO 10 ISET=0,INSETS
      WRITE (*,'(A)') ' Initialize model...'
*-----Select data set
      CALL RDFROM (ISET, .TRUE.)

*======================================================================*
*                        Initialization section                        *
*======================================================================*
      ITASK  = 1
      TERMNL = .FALSE.
      WTRTER = .FALSE.

*-----Read names of timer file and input files 1-5 from control
*     file (these files can be used in reruns)
      CALL RDINIT (IUNITC,IUNITL,FILEIC)
      CALL RDSCHA ('FILEIT', FILEIT)
      IF (RDINQR ('FILEI1')) CALL RDSCHA ('FILEI1', FILEI1)
      IF (RDINQR ('FILEI2')) CALL RDSCHA ('FILEI2', FILEI2)
      IF (RDINQR ('FILEI3')) CALL RDSCHA ('FILEI3', FILEI3)
      IF (RDINQR ('FILEI4')) CALL RDSCHA ('FILEI4', FILEI4)
      IF (RDINQR ('FILEI5')) CALL RDSCHA ('FILEI5', FILEI5)
      CLOSE (IUNITC)

*-----Read time, control and weather variables from timer file
      CALL RDINIT (IUNITD  , IUNITL, FILEIT)
      CALL RDSREA ('STTIME', STTIME)
      STTIME = ANINT(STTIME)
      CALL RDSREA ('FINTIM', FINTIM)
      CALL RDSREA ('PRDEL' , PRDEL )
      CALL RDSREA ('DELT'  , DELT  )
      CALL RDSREA ('YEAR' , YEAR )
      CALL RDSINT ('ISTN'  , ISTN  )
      CALL RDSREA ('MULTIP', MULTIP)
      CALL RDSINT ('IPFORM', IPFORM)
      CALL RDSCHA ('COPINF', COPINF)
      CALL RDSCHA ('DELTMP', DELTMP )
      CALL RDSCHA ('WTRDIR', WTRDIR)
      CALL RDSCHA ('CNTR'  , CNTR)
      CALL RDSINT ('IFLAG' , IFLAG)

*-----For sensitivity analysis
      IYEAR = INT(YEAR)

*-----See if observation data variable exists, if so read it
      IF (RDINQR('IOBSD')) THEN
         CALL RDAINT ('IOBSD' , IOBSD, IMNOD, INOD)
      ELSE
         INOD = 0
      END IF

*-----See if variable with print selection exists, if so read it
      IF (RDINQR('PRSEL')) THEN
         CALL RDACHA ('PRSEL',PRSEL,IMNPRS,INPRS)
      ELSE
         INPRS = 0
      END IF
      CLOSE (IUNITD)

*-----Initialize TIMER and OUTDAT routines
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &             IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      CALL OUTDAT (ITASK, IUNITO, 'TIME', TIME)

*-----Open weather file and read station information and return
*     weather data for start day of simulation.
*     Check status of weather system, WTRMES flags if warnings or errors
*     have occurred during the whole simulation. WTRTER flags if the run
*     should be terminated because of missing weather

      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY  , ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      IF (ISTAT1.GE.0) THEN
         WRITE (WSTAT,'(I7)') ISTAT2
      ELSE
         WSTAT  = '-444444'
         WTRTER = .TRUE.
         TERMNL = .TRUE.
      END IF

*-----Conversion of total daily radiation from kJ(mJ)/m2/d to J/m2/d
```

```
      RDD = RDD*1000.*MULTIP

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  , LAT,
     &             WSTAT , WTRTER, ISTAT1, ISTAT2, WTRMES,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*======================================================================*
*                      Dynamic simulation section                      *
*======================================================================*

      WRITE (*,'(A,/)') ' Dynamic loop...'

20    IF (.NOT.TERMNL) THEN

*----------------------------------------------------------------------*
*                     Integration of rates section                     *
*----------------------------------------------------------------------*
      IF (ITASK.EQ.2) THEN

*--------Carry out integration only when previous task was rate
*        calculation
         ITASK = 3

*--------Call routine that handles the different models
         CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                FILEIT, OUTPUT, TERMNL,
     &                DOY   , IDOY  , YEAR  , IYEAR ,
     &                TIME  , STTIME, FINTIM, DELT  , LAT,
     &                WSTAT , WTRTER, ISTAT1, ISTAT2, WTRMES,
     &                RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

      END IF

*----------------------------------------------------------------------*
*                Calculation of driving variables section              *
*----------------------------------------------------------------------*
      ITASK = 2

*-----Turn on output when TERMNL logical is set to .TRUE.
      IF (TERMNL) OUTPUT = .TRUE.

*-----Write time of output to screen and file
      IF (OUTPUT) THEN
         IF (ISET.EQ.0) THEN
            WRITE (*,'(A,I5,A,F7.2)')
     &         ' Default set, Year:', IYEAR, ', Day:', DOY
         ELSE
            WRITE (*,'(A,I3,A,I5,A,F7.2)')
     &         ' Rerun set:', ISET, ', Year:', IYEAR, ', Day:', DOY
         END IF
         CALL OUTDAT (ITASK, 0, 'TIME', TIME)
         CALL OUTDAT (ITASK, 0, 'DOY' , DOY)
```

```
      END IF

*-----Get weather data for new day and flag messages
      CALL STINFO (IFLAG , WTRDIR, ' ', CNTR, ISTN, IYEAR,
     &             ISTAT1, LONG  , LAT, ELEV, ANGA, ANGB)
      CALL WEATHR (IDOY, ISTAT2, RDD, TMMN, TMMX, VP, WN, RAIN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      IF (ISTAT1.GE.0) THEN
         WRITE (WSTAT,'(I7)') ISTAT2
      ELSE
         WSTAT  = '-444444'
         WTRTER = .TRUE.
         TERMNL = .TRUE.
      END IF

*-----Conversion of total daily radiation from kJ(mJ)/m2/d to J/m2/d
      RDD = RDD*1000.*MULTIP

*----------------------------------------------------------------------*
*                Calculation of rates and output section               *
*----------------------------------------------------------------------*
*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  , LAT,
     &             WSTAT , WTRTER, ISTAT1, ISTAT2, WTRMES,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*----------------------------------------------------------------------*
*                             Time update                              *
*----------------------------------------------------------------------*

*-----Check for FINTIM, OUTPUT and observation days
      CALL TIMER2 (ITASK, STTIME, DELT, PRDEL, FINTIM,
     &             IYEAR, TIME  , DOY , IDOY , TERMNL, OUTPUT)
      YEAR = REAL (IYEAR)
      IF (IOBSD(1).NE.0) THEN
         DO 30 IOD=1,INOD,2
            IF (IYEAR.EQ.IOBSD(IOD).AND.IDOY.EQ.IOBSD(IOD+1))
     &          OUTPUT = .TRUE.
30       CONTINUE
      END IF

      GOTO 20
      END IF

*======================================================================*
*                           Terminal section                           *
*======================================================================*
      ITASK = 4

      WRITE (*,'(/,A)') ' Terminate model...'

      IF (WTRTER) THEN
         WRITE (*,'(/,A,/)')
     &      ' The run was terminated due to missing weather'
```

```
         WRITE (IUNITO,'(A)')
     &     ' The run was terminated due to missing weather'
      END IF

*-----Call routine that handles the different models
      CALL MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &             FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &             FILEIT, OUTPUT, TERMNL,
     &             DOY   , IDOY  , YEAR  , IYEAR ,
     &             TIME  , STTIME, FINTIM, DELT  , LAT,
     &             WSTAT , WTRTER, ISTAT1, ISTAT2, WTRMES,
     &             RDD   , TMMN  , TMMX  , VP    , WN, RAIN)

*-----Generate output file dependent on option from timer file
      IF (IPFORM.GE.4) THEN
         IF (INPRS.EQ.0) THEN
            CALL OUTDAT (IPFORM, 0, 'Simulation results',0.)
         ELSE
*           Selection of output variables was in timer file
            DO 40 IPRS=1,INPRS
               IF (PRSEL(IPRS).NE.'<TABLE>') THEN
                  CALL OUTDAT (3, 0, PRSEL(IPRS), 0.)
               ELSE
                  CALL OUTDAT (IPFORM, 0, 'Simulation results',0.)
               END IF
40          CONTINUE
*           If last word of print selection was not '<TABLE>' create
*           a table anyway
            IF (PRSEL(INPRS).NE.'<TABLE>') CALL OUTDAT
     &         (IPFORM, 0, 'Simulation results',0.)
         END IF
      END IF

*-----Delete temporary output file dependent on switch from timer file
      IF (DELTMP.EQ.'Y'.OR.DELTMP.EQ.'y') CALL OUTDAT (99, 0, ' ', 0.)

10    CONTINUE

      IF (INSETS.GT.0) CLOSE (IUNITR)

*-----If input files should be copied to the output file,
*     copy rerun file (if present) and timer file and if there, input
*     files 1-5
      IF (COPINF.EQ.'Y'.OR.COPINF.EQ.'y') THEN
         IF (INSETS.GT.0) CALL COPFL2 (IUNITR, FILEIR, IUNITO, .TRUE.)
         CALL COPFL2 (IUNITD, FILEIT, IUNITO, .TRUE.)
         IF (FILEI1.NE.' ') CALL COPFL2 (IUNITD, FILEI1, IUNITO, .TRUE.)
         IF (FILEI2.NE.' ') CALL COPFL2 (IUNITD, FILEI2, IUNITO, .TRUE.)
         IF (FILEI3.NE.' ') CALL COPFL2 (IUNITD, FILEI3, IUNITO, .TRUE.)
         IF (FILEI4.NE.' ') CALL COPFL2 (IUNITD, FILEI4, IUNITO, .TRUE.)
         IF (FILEI5.NE.' ') CALL COPFL2 (IUNITD, FILEI5, IUNITO, .TRUE.)
      END IF

*-----Delete all .TMP files that were created by the RD* routines
*     during simulation
      CALL RDDTMP (IUNITD)

*-----Write to screen which files contain what
      IL = ILEN (FILEON)
      WRITE (*,'(/,3A)') ' File: ',FILEON(1:IL),
     & ' contains simulation results'
      WRITE (*,'(2A)') ' File: WEATHER.LOG',
     & ' contains messages from the weather system'
      IL = ILEN (FILEOL)
      WRITE (*,'(3A,/)') ' File: ',FILEOL(1:IL),
     & ' contains messages from the rest of the model'

*-----Write message to screen and output file if warnings and/or errors
*     have occurred from the weather system, pause and wait for return
*     from user to make sure he has seen this message
      IF (WTRMES) THEN
         WRITE (*,'(/,A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'
         WRITE (IUNITO,'(A,/,A,/,A)') ' WARNING from FSE:',
     &     ' There have been errors and/or warnings from',
     &     ' the weather system, check file WEATHER.LOG'
         WRITE (*,'(A)') ' Press <RETURN>'
         READ  (*,'(A)') DUMMY
      END IF

*-----Close output file and temporary file of OUTDAT
      CLOSE (IUNITO)
      CLOSE (IUNITO+1)

*-----Close log file (if used)
      IF (FILEOL.NE.FILEON) CLOSE (IUNITL)

*-----Close log file of weather system
      CLOSE (91)

*-----Write end-of-year data to output table
      CALL OPWRIT (IUNITO)

      RETURN

      END

*----------------------------------------------------------------------*
* SUBROUTINE MODELS  (FSE 2.0)                                         *
* Authors: Daniel van Kraalingen                                       *
* Date   : 5-Jul-1993                                                  *
* Purpose: This subroutine is the interface routine between the FSE-   *
*          driver and the simulation models. This routine is called    *
*          by the FSE-driver at each new task at each time step. It    *
*          can be used by the user to specify calls to the different   *
*          models that have to be simulated                            *
*                                                                      *
*  In ORYZA_W, MODELS calls the following sub-models:                  *
*  - ORYZAW for the above ground part (crop growth and development)    *
*  - SAHEL for the soil water balance in upland environments           *
*  - LOWBAL for the soil water balance in lowland environments         *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning                                    units  class *
* ----   ---- -------                                    -----  ----- *
```

```
* ITASK   I4  Task that subroutine should perform          -       I  *
* IUNITD  I4  Unit that can be used for input files        -       I  *
* IUNITO  I4  Unit used for output file                    -       I  *
* IUNITL  I4  Unit used for log  file                      -       I  *
* FILEI1  C*  Name of input file no. 1                     -       I  *
* FILEI2  C*  Name of input file no. 2                     -       I  *
* FILEI3  C*  Name of input file no. 3                     -       I  *
* FILEI4  C*  Name of input file no. 4                     -       I  *
* FILEI5  C*  Name of input file no. 5                     -       I  *
* OUTPUT  L4  Flag to indicate if output should be done    -       I  *
* TERMNL  L4  Flag to indicate if simulation is to stop    -     I/O  *
* DOY     R4  Day number within year of simulation (REAL)     d    I  *
* IDOY    I4  Day number within year of simulation (INTEGER) d    I  *
* YEAR    R4  Year of simulation (REAL)                    y       I  *
* IYEAR   I4  Year of simulation (INTEGER)                 y       I  *
* TIME    R4  Time of simulation                           d       I  *
* STTIME  R4  Start time of simulation                     d       I  *
* FINTIM  R4  Finish time of simulation                    d       I  *
* DELT    R4  Time step of integration                     d       I  *
* LAT     R4  Latitude of site                       dec.degr.     I  *
* WSTAT   C7  Status code from weather system              -       I  *
* WTRTER  L4  Flag whether weather can be used by model    -       O  *
* RDD     R4  Daily shortwave radiation               J/m2/d       I  *
* TMMN    R4  Daily minimum temperature             degrees C      I  *
* TMMX    R4  Daily maximum temperature             degrees C      I  *
* VP      R4  Early morning vapour pressure             kPa        I  *
* WN      R4  Average wind speed                        m/s        I  *
* RAIN    R4  Daily amount of rainfall                 mm/d        I  *
*                                                                     *
* Fatal error checks: none                                            *
* Warnings          : none                                            *
* Subprograms called: WEATHER, ORYZAW, LOWBAL, SAHEL                  *
*                     RDINIT, RDSINT, RDSREA (from TTUTIL)            *
* File usage        : none                                            *
*---------------------------------------------------------------------*
      SUBROUTINE MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                   FILEI1, FILEI2, FILEI3, FILEI4, FILEI5,
     &                   FILEIT, OUTPUT, TERMNL,
     &                   DOY   , IDOY  , YEAR  , IYEAR,
     &                   TIME  , STTIME, FINTIM, DELT , LAT,
     &                   WSTAT , WTRTER, ISTAT1, ISTAT2, WTRMES,
     &                   RDD   , TMMN  , TMMX  , VP   , WN, RAIN)
      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER   ITASK, IUNITD, IUNITO, IUNITL, IDOY, IYEAR
      INTEGER   ISTAT1, ISTAT2
      CHARACTER FILEI1*(*), FILEI2*(*), FILEI3*(*)
      CHARACTER FILEI4*(*), FILEI5*(*), FILEIT*(*)
      LOGICAL   OUTPUT, TERMNL, WTRTER, WTRMES
      CHARACTER WSTAT*7

*-----Local variables
      INTEGER IDOYH, ITIM, ISTT, ITRT

*-----Standard local declarations
      INTEGER ITOLD, IMNP, INL, I
      PARAMETER (IMNP=100)
      PARAMETER (INL=3)

*-----Declarations for water limited production
      REAL TKL(INL), WCWP(INL), WCFC(INL), WCST(INL)
      REAL WCLQT(IMNP), TRWL(INL)
      INTEGER NL, SWIWLP

      SAVE

      IF (DELT.LT.1.0) CALL ERROR
     &   ('ORYZAW','DELT too small for ORYZAW')

      IF (ITASK.EQ.2) THEN
         IF (WSTAT(2:2).EQ.'4'.OR.
     &       WSTAT(3:3).EQ.'4'.OR.
     &       WSTAT(4:4).EQ.'4') THEN
            WTRTER = .TRUE.
            TERMNL = .TRUE.
            ITOLD  = ITASK
            RETURN
         END IF
      END IF

      ITIM = NINT(TIME)

*----------------------------------------------------------------------
*        Initialization section
*----------------------------------------------------------------------
      IF (ITASK.EQ.1) THEN

         CALL RDINIT (IUNITD, IUNITL, FILEIT)
         CALL RDSINT ('SWIWLP', SWIWLP)
         CALL RDSREA ('DTRP'  , DTRP)
         CALL RDSREA ('STTIME', STTIME)
         CLOSE (IUNITD)

         STTIME = ANINT (STTIME)
         DTRP   = ANINT (DTRP)
         ISTT   = NINT( STTIME)
         IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
           ITRT = NINT (STTIME + DTRP)
         ELSE IF (SWIWLP.EQ.2) THEN
           ITRT = NINT (STTIME)
         END IF

         EVSC  = 0.
         RAINN = 0.
         DVS   = 0.

*--------Set transpiration rates in all soil compartments to 0
         DO 5 I=1,INL
            TRWL(I) = 0.
5        CONTINUE
      END IF

*-----To run soil water balance; to get rain of next day
      IDOYH = MIN (IDOY+1, 365)
      CALL WEATHR (IDOYH, ISTAT2,
```

```
     &     RDDN, TMMNN, TMMXN, VPN, WNN, RAINN)
      IF (ISTAT1.NE.0.OR.ISTAT2.NE.0) WTRMES = .TRUE.
      IF (ISTAT1.GE.0) THEN
         WRITE (WSTAT,'(I7)') ISTAT2
      ELSE
         WSTAT  = '-444444'
         WTRTER = .TRUE.
         TERMNL = .TRUE.
      END IF

      IF (SWIWLP .EQ. 2) THEN
         CALL SAHEL (ITASK, IUNITD, IUNITO, IUNITL, FILEI2,
     &        OUTPUT, TERMNL, TIME, DELT, SWIWLP, RAIN, RAINN,
     &        EVSC, TRWL, NL, TKL, TKLT, ZRTMS, WCWP, WCFC, WCST,
     &        WCLQT, WL0)
      ELSE
         CALL LOWBAL (ITASK, IUNITD, IUNITO, IUNITL,
     &        FILEI2, OUTPUT, TERMNL, DELT, SWIWLP, ITIM, ITRT,
     &        DVS, TRWL, EVSC, RAIN, RAINN, NL, TKL, TKLT, ZRTMS,
     &        WCWP, WCFC, WCST, WCLQT, WL0)
      END IF

      CALL ORYZAW (ITASK , IUNITD, IUNITO, IUNITL, FILEIT, FILEI1,
     &             WSTAT, OUTPUT, TERMNL, WTRTER,
     &             DOY  , DELT  ,  ITIM, ISTT, ITRT,
     &             LAT   , RDD   , TMMN   , TMMX, VP, WN,
     &             NL, TKL, TKLT, ZRTMS, EVSC, WCWP, WCFC, WCST,
     &             WCLQT, TRWL, SWIWLP, WL0, DVS)

      RETURN
      END

*=============================================================================*
* SUBROUTINE ORYZAW                                                           *
*                                                                             *
* Adapted from ORYZA1: Above-ground module for simulating rice growth         *
* and development under potential production situations; Authors:            *
* M.J. Kropff and H.H. van Laar.                                              *
*                                                                             *
* Changes made to simulate water limited production by M.C.S. Wopereis        *
* and B.A.M. Bouman.                                                          *
* Version: 1.0                                                                *
* Date    : November, 1993                                                    *
*=============================================================================*
      SUBROUTINE ORYZAW (ITASK , IUNITD, IUNITO, IUNITL, FILEIT,
     &                   FILEI1, WSTAT, OUTPUT, TERMNL, WTRTER,
     &                   DOY, DELT, ITIM, ISTT, ITRT, LAT, RDT,
     &                   TMN, TMX, VAPOR, WIND, NL, TKL, TKLT,
     &                   ZRTMS, EVSC, WCWP, WCFC, WCST,
     &                   WCLQT, TRWL, SWIWLP, WL0, DVS)

      IMPLICIT REAL (A-Z)

*-----Formal parameters
      INTEGER   ITASK,  IUNITD, IUNITO, IUNITL, SWIWLP
      LOGICAL   OUTPUT, TERMNL, WTRTER
      CHARACTER FILEIT*(*), FILEI1*(*)
      CHARACTER WSTAT*7

*-----Standard local declarations
      INTEGER ITOLD, IMNP
      INTEGER ITIM, ITRT, ISTT
      PARAMETER (IMNP=40)

      LOGICAL DLEAF,DROUT

*-----Species parameters and rates
      INTEGER ILFSH, ILFLV,ILFST, ILFRT
      INTEGER ILFSO, ILSAI, ILREDF, ILEFF, ILDRLV
      INTEGER ISTD, INSD
      REAL FSHTB(IMNP), FLVTB(IMNP), FSTTB(IMNP)
      REAL FRTTB(IMNP), FSOTB(IMNP), SSGATB(IMNP)
      REAL REDFTT(IMNP), EFFTB(IMNP), DRLVT(IMNP)

      INTEGER  ILKDF
      REAL KDFTB(IMNP)

      INTEGER ILNLV, ILNPRF
      INTEGER ILSLA, INSLA
      REAL NFLVTB(IMNP), NPROFT(IMNP)
      REAL SLATB(IMNP), NSLATB(IMNP)

      INTEGER I, NL, INL, ICNT
      PARAMETER (INL = 3)
      REAL TKL(NL), WCWP(NL), WCFC(NL), WCST(NL)
      REAL WCLQT(NL), TRWL(NL)
      REAL WCREF(INL)
      SAVE

      DATA ITOLD /4/

*     The task that the subroutine should do (ITASK) against the task
*     that was done during the previous call (ITOLD) is checked. Only
*     certain combinations are allowed. These are:
*
*          New task:             Old task:
*          initialization        terminal
*          integration           rate calculation
*          rate calculation      initialization, integration
*          terminal              <any old task>
*     Note: there is one combination that is correct but will not cause
*     calculations to be done i.e. if integration is required immediately
*     after initialization.

      CALL CHKTSK ('ORYZAW', IUNITO, ITOLD, ITASK)

      IF (ITASK.EQ.2) THEN
         IF (WSTAT(2:2).EQ.'4'.OR.
     &        WSTAT(3:3).EQ.'4'.OR.
     &        WSTAT(4:4).EQ.'4') THEN
            WTRTER = .TRUE.
            TERMNL = .TRUE.
            ITOLD  = ITASK
            RETURN
         END IF
      END IF
```

```
*=========================================================================*
*                          Initialization                                 *
*=========================================================================*

      IF (ITASK.EQ.1) THEN

*--------Send title to output file
       IF (SWIWLP.EQ.0) THEN
        CALL OUTCOM ('ORYZA_W: Irrigated lowland rice production')
       ELSE IF (SWIWLP .EQ. 1) THEN
        CALL OUTCOM ('ORYZA_W: Rainfed lowland rice production')
       ELSE
        CALL OUTCOM ('ORYZA_W: Rainfed, upland rice production')
       END IF

*********Initialization section***********************************

         IF (DELT.LT.1.0) CALL ERROR
     &      ('ORYZAW','DELT too small for ORYZAW')

         CALL RDINIT (IUNITD, IUNITL, FILEIT)
         CALL RDSREA ('ANGA', ANGA)
         CALL RDSREA ('ANGB', ANGB)
         CLOSE (IUNITD)

*--------States
         ZRT  = 0.0001
         TRCT = 0.
         TRWCU = 0.
         DVS  = 0.
         LAI  = 0.
         WLVG = 0.
         WLVD = 0.
         WST  = 0.
         WSTR = 0.
         WSTS = 0.
         WRT  = 0.
         WSO  = 0.
         WRR  = 0.
         TNASS= 0.
         TS    = 0.
         TSTR = 0.
         TSLV = 0.
         TSLVTR = 0.
         WLVEXP = 0.
         LAIEXP = 0.
         GRDUR = 0.
         DLDRT = 0.
         WLPOOL = 0.
         LAIEXS = 0.
         WLVEXS = 0.
         ISTD = 0
         INSD = 0

         WAG    = WLVG + WST + WSO  + WLVD

*--------Rates
         DTGA   = 0.
         GCR    = 0.
         CRGCR  = 0.
         LLV    = 0.
         GSTR   = 0.
         LSTR   = 0.
         GMAINT = 0.
         TRC    = 0.
         TRW    = 0.

*--------Other parameters
         CALL RDINIT (IUNITD, IUNITL, FILEI1)
         CALL RDSREA ('NPLH'  , NPLH)
         CALL RDSREA ('NH'  ,   NH)
         CALL RDSREA ('NPLSB' , NPLSB)
         CALL RDSREA ('NPLDS', NPLDS)
         CALL RDSREA ('LAPO',   LAPO)
         CALL RDSREA ('FSTR',   FSTR)
         CALL RDSREA ('RGRL',   RGRL)
         CALL RDAREA ('EFFTB',  EFFTB, IMNP, ILEFF)
         CALL RDSREA ('SCP',    SCP)
         CALL RDAREA ('REDFTT', REDFTT, IMNP, ILREDF)
         CALL RDSREA ('TBD',    TBD)
         CALL RDSREA ('TBLV',   TBLV)
         CALL RDSREA ('MAINLV', MAINLV)
         CALL RDSREA ('MAINST', MAINST)
         CALL RDSREA ('MAINSO', MAINSO)
         CALL RDSREA ('MAINRT', MAINRT)
         CALL RDSREA ('CRGLV',  CRGLV)
         CALL RDSREA ('CRGST',  CRGST)
         CALL RDSREA ('CRGSTR', CRGSTR)
         CALL RDSREA ('CRGSO',  CRGSO)
         CALL RDSREA ('CRGRT',  CRGRT)
         CALL RDSREA ('FCLV',   FCLV)
         CALL RDSREA ('FCST',   FCST)
         CALL RDSREA ('FCSTR',  FCSTR)
         CALL RDSREA ('FSTR',   FSTR)
         CALL RDSREA ('FCRT',   FCRT)
         CALL RDSREA ('FCSO',   FCSO)
         CALL RDSREA ('TCLSTR', TCLSTR)
         CALL RDSREA ('LRSTR', LRSTR)
         CALL RDAREA ('KDFTB', KDFTB, IMNP, ILKDF)
         CALL RDAREA ('FSHTB', FSHTB,  IMNP, ILFSH)
         CALL RDAREA ('FRTTB', FRTTB,  IMNP, ILFRT)
         CALL RDAREA ('FLVTB', FLVTB,  IMNP, ILFLV)
         CALL RDAREA ('FSTTB', FSTTB,  IMNP, ILFST)
         CALL RDAREA ('FSOTB', FSOTB,  IMNP, ILFSO)
         CALL RDAREA ('DRLVT',  DRLVT, IMNP, ILDRLV)
         CALL RDSREA ('DVRV',  DVRV)
         CALL RDSREA ('DVRR',  DVRR)
         CALL RDSREA ('SHCKD', SHCKD)
         CALL RDSREA ('SHCKL', SHCKL)
         CALL RDAREA ('NFLVTB', NFLVTB, IMNP, ILNLV)
         CALL RDAREA ('NPROFT', NPROFT, IMNP, ILNPRF)
         CALL RDAREA ('SSGATB', SSGATB, IMNP, ILSAI)
         CALL RDAREA ('SLATB',  SLATB,  IMNP, ILSLA)
         CALL RDAREA ('NSLATB', NSLATB,  IMNP, INSLA)
```

```
         CALL RDSREA ('ZRTMC', ZRTMC)
         CALL RDSREA ('GZRT', GZRT)
         CALL RDSREA ('ULLGTR', ULLGTR)
         CALL RDSREA ('LLLGTR', LLLGTR)
         CALL RDSREA ('ULLSTR', ULLSTR)
         CALL RDSREA ('LLLSTR', LLLSTR)
         CALL RDSREA ('ULDLTR', ULDLTR)
         CALL RDSREA ('LLDLTR', LLDLTR)
         CALL RDSREA ('ULRTTR', ULRTTR)
         CALL RDSREA ('LLRTTR', LLRTTR)
         CALL RDSREA ('ULLGTF', ULLGTF)
         CALL RDSREA ('LLLGTF', LLLGTF)
         CALL RDSREA ('ULLSTF', ULLSTF)
         CALL RDSREA ('LLLSTF', LLLSTF)
         CALL RDSREA ('ULDLTF', ULDLTF)
         CALL RDSREA ('LLDLTF', LLDLTF)
         CALL RDSREA ('ULRTTF', ULRTTF)
         CALL RDSREA ('LLRTTF', LLRTTF)
         CLOSE (IUNITD, STATUS='DELETE')

*------- Set stress factors to drought at transplanting
         IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
           ULLG = ULLGTR
           LLLG = LLLGTR
           ULLS = ULLSTR
           LLLS = LLLSTR
           ULDL = ULDLTR
           LLDL = LLDLTR
           ULRT = ULRTTR
           LLRT = LLRTTR
         ELSE IF (SWIWLP .EQ. 2) THEN
*--------No stress factors at day of sowing in upland
           ULLG = 0.
           LLLG = 0.
           ULLS = 0.
           LLLS = 0.
           ULDL = 0.
           LLDL = 0.
           ULRT = 0.
           LLRT = 0.
         END IF

*--------For water limited production; upper limit for start
*        scenescence of leaves due to drought
         DLEAF = .FALSE.
         DROUT = .FALSE.
         WCRDR = ULDL
         LSTRS = 1.
         DSTRS = 1.
         PCEW = 1.
         DVEW = 1.
         ICNT = 0

*-------Set refernece water content level at which stress occurs,
*       according to production environment
      IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
           DO 10 I=1,NL
               WCREF(I) = WCST(I)
10         CONTINUE
      ELSE IF (SWIWLP .EQ. 2) THEN
           DO 20 I=1,NL
               WCREF(I) = WCFC(I)
20         CONTINUE
      END IF

*======================================================================*
*                      Rate calculation section                        *
*======================================================================*

      ELSE IF (ITASK.EQ.2) THEN

******* Leaf area development **********************************

         SLA  = LINT (NSLATB, INSLA, DVS)
         SSGA  = LINT (SSGATB, ILSAI, DVS)
         SAI   = SSGA * WST

*-------Calculate transplanting shock
          IF (ITIM.EQ.ITRT) THEN
                 TSLVTR = TSLV
                 TSHCKL = SHCKL * TSLVTR
           END IF

*-------'Unrol' the leaves in case of leaf-rolling before entering the
*          'LAI' calculations
          IF (LSTRS .LT. 1.) THEN
              LAI = (LAI + (LSTRS-1.)*0.5*SAI)/LSTRS
              LAIL = LAI - 0.5*SAI
          END IF

*-------LAI calculation. Note: in the 'main' field, there is no leaf growth
*         with drought stress (ICNT = 1)
*------- 1) leaf area development in seed-bed (or on day of sowing
*          of upland crop)
          IF (ITIM.LE.ITRT) THEN
              IF (LAI.LT.1.) THEN
                 LAPI  = LAP0 * (EXP(RGRL*TSLV))
                 IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
                    LAII  = LAPI * NPLSB
                 ELSE IF (SWIWLP .EQ. 2) THEN
                    LAII  = LAPI * NPLDS
                 END IF
                 LAI   = LAII
                 WLVEXS= WLVG
                 LAIEXS= LAI
              ELSE
                  LAII  = 0.5 * SAI + SLA * (WLVG-WLVEXS) + LAIEXS
                  LAI = LAII
              ENDIF
*-------- 2) leaf area development after transplanting
          ELSE IF (ITIM .GT. ITRT) THEN
            IF (TSLV.LT.(TSLVTR+TSHCKL)) THEN
*             Dilution only at transplanting:
              IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
                 LAI  = LAII * NPLH * NH / NPLSB
              ELSE IF (SWIWLP .EQ. 2) THEN
```

```
                 LAI = LAII
              END IF
            ELSE
              IF (LAI.LT.1.0 .AND. DVS.LT.0.6 .AND. ICNT .EQ. 0) THEN
                  IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
                     LAI = LAII * NH * NPLH / NPLSB *
     &               (EXP (RGRL*(TSLV-TSLVTR-TSHCKL)))
                  ELSE IF (SWIWLP .EQ. 2) THEN
                     LAI = LAII * (EXP (RGRL*(TSLV-TSLVTR-TSHCKL)))
                  END IF
                  WLVEXP= WLVG
                  LAIEXP= LAI
              ELSE
                  LAI  = 0.5 * SAI + SLA * (WLVG-WLVEXP) + LAIEXP
              END IF
            END IF
          END IF

*------Leaf rolling in case of drought
         LAI = LSTRS*(LAI-0.5*SAI) + 0.5*SAI
         LAIL = LAI - 0.5 * SAI
*******************************************************************

*------Set water content level at which stress occurs, and
*      set the stress factors
       CALL STRFAC(SWIWLP, DROUT, DVS, ZRT, WCFC, WCWP, NL,
     &   TKL, ULLGTR, LLLGTR, ULLSTR, LLLSTR, ULDLTR, LLDLTR,
     &   ULRTTR, LLRTTR, ULLGTF, LLLGTF, ULLSTF, LLLSTF,
     &   ULDLTF, LLDLTF, ULRTTF, LLRTTF,
     &   ULLG, LLLG, ULLS, LLLS, ULDL, LLDL, ULRT, LLRT)

*--------Driving variables
         TAV  = 0.5*(TMX + TMN)
         TAVD = 0.5*(TAV + TMX)

********* Calculation of photosynthesis, evapotranspiration *********
********* and reduction factors ************************************

         EFF   = LINT (EFFTB,  ILEFF, TAVD)
         REDFT = LINT (REDFTT, ILREDF,TAVD)
         KDF = LINT (KDFTB, ILKDF, DVS)
         NPROF = LINT (NPROFT, ILNPRF, DVS)
         NFLV = NPROF* LINT (NFLVTB, ILNLV, DVS)
         AMAX  = MIN (60., (-6.5 + 32.4 * NFLV) * REDFT)

*-----Calculation of light absorption and photosynthesis
      CALL TOTASS (DOY,  LAT , RDT, SCP, AMAX, EFF, KDF, LAI,
     &             DAYL, DTGA,  DSO)

*----Calculation of potential transpiration and evaporation
       CALL ETPOT (SWIWLP, ITIM, ITRT, ANGA, ANGB, RDT, DSO,
     &     TAV, VAPOR, WIND, LAI, WCLQT, WCST, WL0, TRC, EVSC)

*---Calculation of actual evapotranspiration and of the effects
*   of water stress on crop growth and development
       CALL DRSTRS (TERMNL, SWIWLP, DELT, DVS, TRC, ZRT, TKL, NL,
     &    WCREF, WCLQT, WCWP, LLRT, ULRT, LLDL, ULLS, ULLG,
     &    LLLS, TRW, TRWL, WCRREL, ICNT, DROUT,
     &     LSTRS, PCEW, DVEW)

*******************************************************************
*          Calculation of growth rates, development rates
*******************************************************************

*------Calculation of effect of drought on growth rate DTGA
       DTGA = DTGA * PCEW

*      Calculation of growth rate (plus effect drought stress)
         IF (ITIM.GE.ISTT) THEN
            HU    = MIN (30.-TBD, (MAX (0., TAV-TBD)))
            HULV  = MIN (26.-TBLV,(MAX (0., TAV-TBLV)))

            IF (DVS.LT.1.) THEN
               DVR = DVRV * HU * DVEW
               IF (ITIM.EQ.ITRT) TSTR = TS
               TSHCKD = SHCKD * TSTR
               IF (ITIM.GT.ITRT .AND. TS.LT.(TSTR+TSHCKD)) DVR = 0.
            ELSE
               DVR = DVRR * HU
            END IF

            Q10  = 2.
            TREF = 25.
            TEFF = Q10**((TAV-TREF)/10.)
            IF ((WLVG+WLVD).GT.0.) THEN
               MNDVS = WLVG/(WLVG+WLVD)
            ELSE
               MNDVS = 1.
            END IF

            RMCR   = (WLVG*MAINLV + WST*MAINST +
     &                WSO *MAINSO + WRT*MAINRT) * TEFF * MNDVS

*--------Partitioning factors
         FSH  = LINT (FSHTB, ILFSH, DVS)
         FRT  = LINT (FRTTB, ILFRT, DVS)
         FLV  = LINT (FLVTB, ILFLV, DVS)
         FST  = LINT (FSTTB, ILFST, DVS)
         FSO  = LINT (FSOTB, ILFSO, DVS)

         CRGCR = FSH*(CRGLV*FLV + CRGST*FST*(1.-FSTR)+
     &           CRGSTR*FSTR*FST+ CRGSO*FSO) + CRGRT*FRT

            LLV = WLVG * LINT(DRLVT, ILDRLV, DVS)
            IF (DVS.LT.1.) THEN
               LSTR = 0.
            ELSE
               LSTR = WSTR / TCLSTR
            END IF

*-----Dead leaves in case of drought stress
            IF (WCRREL.GT.ULDL) THEN
               DLEAF = .FALSE.
               WCRDR = ULDL
               DLDRT = 0.
```

```
            END IF
            IF ((WCRREL.LE.ULDL).AND.(.NOT.DLEAF)) THEN
               WLVGIT = WLVG
               DLEAF = .TRUE.
            END IF
            DLDR = 0
            IF (DLEAF) THEN
               IF (WCRREL.LE.WCRDR) THEN
                 DSTRS = LIMIT(0.,1.,(WCRREL-LLDL)/(ULDL-LLDL))
                 DLDR = WLVGIT*(1.-DSTRS)-DLDRT
                 WCRDR = WCRREL
                 DLDRT = DLDR + DLDRT
               END IF
            END IF
* Check if lower limit dead leaves is reached
         IF (WCRREL.LE.LLDL) THEN
            PRINT *,'SOIL DRYER THEN LOWER LIMIT DEAD LEAVES'
            PRINT *,'=> SIMULATION STOPPED'
            CALL OUTCOM('soil dryer than LLDL - simulation stopped')
            TERMNL = .TRUE.
         END IF

         GCR = ((DTGA*30./44.)-RMCR+(LSTR*LRSTR*FCSTR*30./12.))/
     &         CRGCR
         GCR    = ((DTGA*30./44.)-RMCR+(LSTR*LRSTR*FCSTR*30./12.))/CRGCR
         GRT    = GCR * FRT
         GLV    = GCR * FSH * FLV
         GST    = GCR * FSH * FST * (1.-FSTR)
         GSTR   = GCR * FSH * FST * FSTR
         GSO    = GCR * FSH * FSO

* If drought stress store carbohydrates for leaves in pool
         IF (WCRREL.LE.ULLG .AND. WCLQT(1)
     &               .LT.0.95*WCREF(1)) THEN
            GRPOOL = GLV
            GLV = 0.
         ELSE
* No more drought stress:
* release reserves in pool for leaf growth if DVS has not yet
* reached PI, or release reserves for panicle growth if DVS > 0.7
            IF (DVS.LT.1.0) THEN
               GLV = GLV + WLPOOL
               GRPOOL = 0.
            ELSE
               GSO = GSO + WLPOOL
               GRPOOL = 0.
            END IF
         END IF

         CO2RT  = 44./12. * (CRGRT *12./30. - FCRT)
         CO2LV  = 44./12. * (CRGLV *12./30. - FCLV)
         CO2ST  = 44./12. * (CRGST *12./30. - FCST)
         CO2STR = 44./12. * (CRGSTR*12./30. - FCSTR)
         CO2SO  = 44./12. * (CRGSO *12./30. - FCSO)

         GMAINT = ((DTGA*30./44.)-RMCR)*44./30. -
     &             (GRT*CO2RT  +  GLV*CO2LV +
     &             GST*CO2ST   +  GSO*CO2SO +
```

```
     &              GSTR*CO2STR          +
     &              (1.-LRSTR)*LSTR*FCSTR*44./12.)

         END IF

*--------Output of states and rates only if it is required.
         IF (OUTPUT) THEN
           CALL OUTDAT (2, 0, 'DVS',    DVS)
           CALL OUTDAT (2, 0, 'LAI',    LAI)
           CALL OUTDAT (2, 0, 'WAG',    WAG)
           CALL OUTDAT (2, 0, 'WLVG',   WLVG)
           CALL OUTDAT (2, 0, 'WRR',    WRR)
           CALL OUTDAT (2, 0, 'WCRREL', WCRREL)
           CALL OUTDAT (2, 0, 'TRW',      TRW)
           CALL OUTDAT (2, 0, 'TRC',      TRC)
         END IF

*=========================================================================*
*                        Integration section                              *
*=========================================================================*

      ELSE IF (ITASK.EQ.3) THEN

*-----------Initialization of states on date of emergence
       IF (ITIM.GT.ISTT) THEN
          DVS    = INTGRL (DVS , DVR,          DELT)
          WLPOOL = INTGRL (WLPOOL, GRPOOL, DELT)
          WLVG = INTGRL (WLVG, GLV - LLV - DLDR,    DELT)
          WLVD = INTGRL (WLVD, LLV + DLDR  ,        DELT)
          WSTS = INTGRL (WSTS, GST,            DELT)
          WSTR = INTGRL (WSTR, GSTR - LSTR,    DELT)
          WSO  = INTGRL (WSO,  GSO  ,          DELT)
          WRT  = INTGRL (WRT , GRT  ,          DELT)
          TS   = INTGRL (TS  , HU   ,          DELT)
          TSLV = INTGRL (TSLV, HULV ,          DELT)
          ZRTM = MIN(ZRTMC, ZRTMS, TKLT)
          ZRT = INTGRL (ZRT, GZRT, DELT)
          ZRT = MIN (ZRT, ZRTM)
          WST   = WSTS + WSTR
          WAG   = WLVG + WST  + WSO  + WLVD
          WCR   = WAG + WRT
          WRR   = WSO * 0.90 / 0.86
          GRDUR = 1. * (ITIM - ISTT)
*---------Cumulative values of transpiration only for main field
          IF (ITIM .GE. ITRT) THEN
            TRCT = INTGRL (TRCT, TRC, DELT)
            TRWCU = INTGRL (TRWCU, TRW, DELT)
          END IF

*------Root length can decrease in puddled soil with shrinkage
       IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) ZRT = MIN(ZRT,ZRTM)

*------If biomass is negative: set to 0 and abort simulation
       IF (WSO .LT. 0. .OR. WLVG .LT. 0 .OR. WST .LT.0) THEN
         PRINT *,'NEGATIVE BIOMASS => SIMULATION STOPPED'
         CALL OUTCOM('Negative biomass => simulation stopped')
         TERMNL = .TRUE.
       END IF
```

```
*-----Empty the wlpool again, and reset stress-day counters
*     to 0 if there are more than 3 'no drought stress days'
        IF (WCRREL.GT.ULLG.OR.WCLQT(1).GT.0.95*WCREF(1)) THEN
          WLPOOL = 0.0
          DROUT = .FALSE.
          INSD= INSD + INT(DELT)
          IF (INSD .GT. 3) ISTD = 0
        END IF

*-----Count the drought stress days
        IF (WCRREL.LE.ULLG .AND. WCLQT(1).LT.0.95*WCREF(1)) THEN
          ISTD = ISTD + INT(DELT)
          INSD = 0.
        END IF

*------Stop the simulation when number of stress days exceeds maximum
*       values (from pot experiments Wopereis)
        IF (ISTD .GE. 25) THEN
          PRINT *,'DROUGHT TOO LONG => SIMULATION STOPPED'
          CALL OUTCOM('More than 25 days drought: simulation stopped')
          TERMNL = .TRUE.
        END IF

*------Carbon balance check
        CHCIN  = (WLVG+WLVD)*FCLV + WSTS*FCST +
     &             WSTR*FCSTR +
     &             WRT*FCRT          + WSO*FCSO
        TNASS  = INTGRL (TNASS, GMAINT, DELT)
        CHCFL  = TNASS * (12./44.)

*-----Nothing is done with CHCDIF!!
       IF (CHCIN.LE.0.) CHCDIF = (CHCIN-CHCFL)/(1.+CHCIN)
            IF (CHCIN.GT.0.) CHCDIF = (CHCIN-CHCFL)/CHCIN

          ENDIF

*--------Determine the finish conditions of the simulation
          IF (DVS.GE.2.0) TERMNL = .TRUE.

*======================================================================*
*                          Terminal section                            *
*======================================================================*

       ELSE IF (ITASK.EQ.4) THEN

*-------Define graph for output
*        CALL OUTPLT (1,WAG')
*        CALL OUTPLT (7, 'ORYZAW simulation model')

*-------Store end-of-year data to a special file.
         CALL OPSTOR ('GRDUR', GRDUR)
         CALL OPSTOR ('WAG',WAG)
         CALL OPSTOR ('WRR',WRR)
         CALL OPSTOR ('TRWCU', TRWCU)

       END IF
```

```
      ITOLD = ITASK

      RETURN
      END

*======================================================================*
* SUBROUTINE STRFAC                                                    *
*                                                                      *
* Author: B.A.M. Bouman and M.C.S Wopereis                             *
* Version: 1.0                                                         *
* Date: November 1993                                                  *
* Purpose: Sets drought stress factors for rice growth and development *
*          according to production environment (lowland or upland)    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                     units  class *
*  ----   ---- -------                                     -----  ----- *
*  SWIWLP  I   Switch to select production environment       -       C *
*  DROUT   L   Switch for leaf growth stress                 -       C *
*  DVS     R   Development stage                             -       I *
*  ZRT     R   Rooted depth                                  m       I *
*  WCFC    R   Array water content field capacity/layer   cm3/cm3    I *
*  WCWP    R   Array water content wilting point/layer    cm3/cm3    I *
*  NL      I   Number of soil layers                         -       I *
*  TKL     R   Array soil layer thicknesses                  m       I *
*  ULLGTR  R   Upper limit leaf growth before DVS=0.5        -       I *
*  LLLGTR  R   Lower limit leaf growth before DVS=0.5        -       I *
*  ULLSTR  R   Upper limit leaf rolling before DVS=0.5       -       I *
*  LLLSTR  R   Lower limit leaf rolling before DVS=0.5       -       I *
*  ULDLTR  R   Upper limit dead leaves before DVS=0.5        -       I *
*  LLDLTR  R   Lower limit dead leaves before DVS=0.5        -       I *
*  ULRTTR  R  Upper limit rel. transpiration before DVS=0.5 -       I *
*  LLRTTR  R  Lower limit rel. transpiration before DVS=0.5 -       I *
*  ULLGTF  R   Upper limit leaf growth after DVS=0.5         -       I *
*  LLLGTF  R   Lower limit leaf growth after DVS=0.5         -       I *
*  ULLSTF  R   Upper limit leaf rolling after DVS=0.5        -       I *
*  LLLSTF  R   Lower limit leaf rolling after DVS=0.5        -       I *
*  ULDLTF  R   Upper limit dead leaves after DVS=0.5         -       I *
*  LLDLTF  R   Lower limit dead leaves after DVS=0.5         -       I *
*  ULRTTF  R   Upper limit rel. transpiration after DVS=0.5 -       I *
*  LLRTTF  R   Lower limit rel. transpiration after DVS=0.5 -       I *
*  ULLG    R   Actual upper limit leaf growth                -       O *
*  LLLG    R   Actual lower limit leaf growth                -       O *
*  ULLS    R   Actual upper limit leaf rolling               -       O *
*  LLLS    R   Actual lower limit leaf rolling               -       O *
*  ULDL    R   Actual upper limit dead leaves                -       O *
*  LLDL    R   Actual lower limit dead leaves                -       O *
*  ULRT    R   Actual upper limit rel. transpiration         -       O *
*  LLRT    R   Actual lower limit rel. transpiration         -       O *
*======================================================================*

       SUBROUTINE STRFAC(SWIWLP, DROUT, DVS, ZRT, WCFC, WCWP, NL,
     &   TKL, ULLGTR, LLLGTR, ULLSTR, LLLSTR, ULDLTR, LLDLTR,
     &   ULRTTR, LLRTTR, ULLGTF, LLLGTF, ULLSTF, LLLSTF,
     &   ULDLTF, LLDLTF, ULRTTF, LLRTTF,
     &   ULLG, LLLG, ULLS, LLLS, ULDL, LLDL, ULRT, LLRT)

       IMPLICIT REAL (A-Z)
```

```
       INTEGER I, NL, INL, SWIWLP

       PARAMETER (INL = 3)

       REAL WCFC(INL), WCWP(INL), TKL(INL)
       REAL ULLGT(INL), LLLGT(INL), ULLST(INL), LLLST(INL)
       REAL ULDLT(INL), LLDLT(INL), ULRTT(INL), LLRTT(INL)
       REAL ULLGF(INL), LLLGF(INL), ULLSF(INL), LLLSF(INL)
       REAL ULDLF(INL), LLDLF(INL), ULRTF(INL), LLRTF(INL)

       LOGICAL DROUT

**********************************************************
*   1. Set the stress factors for lowland
**********************************************************
*   Set the stress factors for Lowland with DVS; if there is
*   already drought, the stress factors will not be changed
      IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
       IF (.NOT.DROUT) THEN
           IF (DVS.LT.0.5) THEN
* --- Set stress factors to drought at transplanting
             ULLG = ULLGTR
             LLLG = LLLGTR
             ULLS = ULLSTR
             LLLS = LLLSTR
             ULDL = ULDLTR
             LLDL = LLDLTR
             ULRT = ULRTTR
             LLRT = LLRTTR
           ELSE IF (DVS.GE.0.5) THEN
* --- Set stress factors to drought at mid-tillering,
*     pannicle initiation or flowering
             ULLG = ULLGTF
             LLLG = LLLGTF
             ULLS = ULLSTF
             LLLS = LLLSTF
             ULDL = ULDLTF
             LLDL = LLDLTF
             ULRT = ULRTTF
             LLRT = LLRTTF
           END IF
         END IF

**********************************************************
*   2. Calculate and set the stress factors for upland
**********************************************************
*   Calculate and set the stress factors with DVS for this day;
*   if there is already drought, the stress factors will not
*   be changed

      ELSE IF (SWIWLP .EQ. 2) THEN
        IF (.NOT.DROUT) THEN
* -- Calculate the stress factors for drought before DVS = 0.5,
*    as average over the rooted soil profile
           IF (DVS.LT.0.5) THEN
             UULGTR = 0.
             ULLGTR = 0.
             UULSTR = 0.
```

```
             ULLSTR = 0.
             UUDLTR = 0.
             ULDLTR = 0.
             UURTTR = 0.
             ULRTTR = 0.
             ZLL = 0.
             ZR = ZRT

             DO 30 I=1,NL
              ZRTL = MIN(TKL(I),MAX((ZR-ZLL),0.0))
              ULLGT(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-2.76)
              LLLGT(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-2.76)
              ULLST(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-3.71)
              LLLST(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-4.06)
              ULDLT(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-3.91)
              LLDLT(I) = WCWP(I)
              ULRTT(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-2.95)
              LLRTT(I) = 0.
              UULGTR = UULGTR + (ZRTL/(ZR+1.0E-10))*ULLGT(I)
              ULLGTR = ULLGTR + (ZRTL/(ZR+1.0E-10))*LLLGT(I)
              UULSTR = UULSTR + (ZRTL/(ZR+1.0E-10))*ULLST(I)
              ULLSTR = ULLSTR + (ZRTL/(ZR+1.0E-10))*LLLST(I)
              UUDLTR = UUDLTR + (ZRTL/(ZR+1.0E-10))*ULDLT(I)
              ULDLTR = ULDLTR + (ZRTL/(ZR+1.0E-10))*LLDLT(I)
              UURTTR = UURTTR + (ZRTL/(ZR+1.0E-10))*ULRTT(I)
              ULRTTR = ULRTTR + (ZRTL/(ZR+1.0E-10))*LLRTT(I)
              ZLL = ZLL + TKL(I)
30           CONTINUE

* --- Set stress factors for drought
             ULLG = UULGTR
             LLLG = ULLGTR
             ULLS = UULSTR
             LLLS = ULLSTR
             ULDL = UUDLTR
             LLDL = ULDLTR
             ULRT = UURTTR
             LLRT = ULRTTR

* --- Calculate stress factors to drought at mid-tillering,
*     pannicle initiation or flowering (aftre DVS = 0.5), as
*     average over the rooted soil profile.
           ELSE IF (DVS.GE.0.5) THEN
             UULGTF = 0.
             ULLGTF = 0.
             UULSTF = 0.
             ULLSTF = 0.
             UUDLTF = 0.
             ULDLTF = 0.
             UURTTF = 0.
             ULRTTF = 0.
             ZLL = 0.
             ZR = ZRT

             DO 40 I=1,NL
              ZRTL = MIN(TKL(I),MAX((ZR-ZLL),0.0))
              ULLGF(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-2.80)
              LLLGF(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-2.80)
```

```
                ULLSF(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-2.87)
                LLLSF(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-3.90)
                ULDLF(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-3.80)
                LLDLF(I) = WCWP(I)
                ULRTF(I) = WCWP(I) + ((WCFC(I)-WCWP(I))/2.2)*(4.2-2.87)
                LLRTF(I) = WCWP(I)
                UULGTF = UULGTF + (ZRTL/(ZR+1.0E-10))*ULLGF(I)
                ULLGTF = ULLGTF + (ZRTL/(ZR+1.0E-10))*LLLGF(I)
                UULSTF = UULSTF + (ZRTL/(ZR+1.0E-10))*ULLSF(I)
                ULLSTF = ULLSTF + (ZRTL/(ZR+1.0E-10))*LLLSF(I)
                UUDLTF = UUDLTF + (ZRTL/(ZR+1.0E-10))*ULDLF(I)
                ULDLTF = ULDLTF + (ZRTL/(ZR+1.0E-10))*LLDLF(I)
                UURTTF = UURTTF + (ZRTL/(ZR+1.0E-10))*ULRTF(I)
                ULRTTF = ULRTTF + (ZRTL/(ZR+1.0E-10))*LLRTF(I)
                ZLL = ZLL + TKL(I)
40             CONTINUE

* --- Set stress factors to drought at mid-tillering,
*     pannicle initiation or flowering
               ULLG = UULGTF
               LLLG = ULLGTF
               ULLS = UULSTF
               LLLS = ULLSTF
               ULDL = UUDLTF
               LLDL = ULDLTF
               ULRT = UURTTF
               LLRT = ULRTTF
             END IF
           END IF
         END IF

         RETURN

         END

*=======================================================================*
* SUBROUTINE ETPOT                                                      *
* Author: B.A.M. Bouman                                                 *
* Version: 2.0                                                          *
* Date: November 1993                                                   *
* Purpose: Calculation of Penman reference value for potential evapo-   *
*          transpiration of a reference crop (mostly from formulation   *
*          as given in van Laar et al., 1992).                          *
*          Calculation of potential transpiration of a rice crop (with *
*          a soil or a water layer background), and of potential        *
*          evaporation of soil surfaces and of open water.              *
* Reference: van Laar, HH., J. Goudriaan & H. van Keulen (Eds.), 1992   *
*          Simulation of crop growth for potential and water-limited    *
*          production situations (as applied to sprin wheat),           *
*          CABO-DLO report 27, CABO-DLO, P.O. Box, 14                   *
*          6700 AA Wageningen, The Netherlands.                         *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                   units  class *
*  ----   ---- -------                                   -----  ----- *
*  SWIWLP  I   Switch to select production environment     -        C *
*  ITIM    I   Time of simulation                          d        T *
*  ITRT    I   Time of transplanting                       d        T *
```

```
*  ANGA     R4  Constant A in Angstrom formulae              -         I  *
*  ANGB     R4  Constant B in Angstrom formulae              -         I  *
*  RDT      R4  Daily solar radiation                     J m-2 d-1 I  *
*  DSO      R4  Daily extraterrestrial radiation          J m-2 d-1 I  *
*  TAV      R4  Daily average temperature                   degree I  *
*  VAPOR    R4  Daily actual vapour pressure               mbar    I  *
*  WIND     R4  Daily average wind speed                   m s-1   I  *
*  LAI      R4  Total area index (leaves+stems)             m/m    I  *
*  WCLQT    R4  Array of volumetric soil water content/layer m-3 m-3 I  *
*  WCST     R4  Array of volumetric soil water content                 *
*               at saturation/layer                        m-3 m-3 I  *
*  WLO      R4  Amount of ponded water                      mm     I  *
*  TRC      R4  Potential transpiration rate               mm d-1  O  *
*  EVSC     R4  Potential evaporation rate                 mm d-1  O  *
*                                                                      *
*  FATAL ERROR CHECKS: none                                            *
*  FILE usage : none                                                   *
*======================================================================*

      SUBROUTINE ETPOT (SWIWLP, ITIM, ITRT, ANGA, ANGB, RDT, DSO,
     &         TAV, VAPOR, WIND, LAI, WCLQT, WCST, WLO, TRC, EVSC)

      IMPLICIT REAL(A-Z)
      REAL WCLQT(1), WCST(1)
      INTEGER ITIM, ITRT, SWIWLP

      LHVAP = 2.4E6
      PSYCH = 0.67
      BOLTZM = 5.668E-8
      ALBDS = 0.25
      ALBOW = 0.05
      ALBC = 0.25

      WCUP = WCLQT(1)
      WCSTUP = WCST(1)

*===========================================================*
*------Calculation of Penman terms for evapotranspiration   *
*===========================================================*

      SVP  = 6.11*EXP(17.4*TAV/(TAV+239.))
      SLOPE = 4158.6*SVP/(TAV+239.)**2

      ALBS = ALBDS*(1.-0.5*WCUP/WCSTUP)
      ALB = ALBS*EXP(-0.5*LAI)+ALBC*(1.-EXP(-0.5*LAI))
      ALBWL =ALBOW*EXP(-0.5*LAI)+ALBC*(1.-EXP(-0.5*LAI))

      CLEAR = LIMIT(0., 1., ((RDT/DSO)-ANGA)/ANGB)
      FCLEAR = 0.1+0.9*CLEAR
      FVAP = 0.56-0.079*SQRT(VAPOR)
      BBRAD = BOLTZM*(TAV+273.)**4
      RLWN = BBRAD*FVAP*FCLEAR*86400.
      NRAD = (1.-ALB)*RDT-RLWN
      NRADWL =(1.-ALBWL)*RDT-RLWN
      NRADOW = (1.-ALBOW)*RDT-RLWN

      WDF = 0.263*(1.0+0.54*WIND)
      WDFOW = 0.263*(0.5+0.54*WIND)
```

```
      DRYP = (SVP-VAPOR)*WDF
      DRYPOW = (SVP-VAPOR)*WDFOW

*------Calculation of EVR and EVD
      EVD = DRYP*PSYCH/(SLOPE+PSYCH)
      EVDOW = DRYPOW*PSYCH/(SLOPE+PSYCH)
      EVR = (1./LHVAP)*(SLOPE/(SLOPE+PSYCH))*NRAD
      EVRWL = (1./LHVAP)*(SLOPE/(SLOPE+PSYCH))*NRADWL
      EVROW = (1./LHVAP)*(SLOPE/(SLOPE+PSYCH))*NRADOW

*=========================================================*
*------Calculation of transpiration and evaporation of crop *
*=========================================================*

*------Crop transpiration with water layer
      TRCWL = EVRWL*(1.-EXP(-0.5*LAI))+EVD*(MIN(2.5,LAI))
*------Crop transpiration with soil background
      TRCS = EVR*(1.-EXP(-0.5*LAI))+EVD*(MIN(2.5,LAI))

*------Soil evaporation with water layer
      EVSCWL = EXP(-0.5*LAI)*(EVRWL+EVD)
*------Soil evaporation with soil background
      EVSCS = EXP(-0.5*LAI)*(EVR+EVD)

*------Open water evaporation
      EVSCOW = EVROW+EVDOW

*==============================================================*
*   Set potential transpiration and evaporation according      *
*   to production situation                                    *
*==============================================================*

*-----1. Irrigated and rainfed lowland
      IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
          IF (WLO .LT. 0 .AND. WCLQT(1) .LT. WCST(1)) THEN
              TRC = TRCS
              EVSC = EVSCS
          ELSE
              TRC = TRCWL
              EVSC = EVSCWL
          END IF
*---------In puddled soil before transplanting: evaporation is open
*         water evaporation
          IF (ITIM .LE. ITRT) THEN
            EVSC = EVSCOW
          END IF

*-----2. rainfed upland situation
      ELSE IF (SWIWLP .EQ. 2) THEN
          TRC = TRCS
          EVSC = EVSCS
      END IF

       RETURN
       END

*=====================================================================*
*  SUBROUTINE DRSTRS                                                  *
```

```
*                                                                       *
*  Author: B.A.M. Bouman and M.C.S. Wopereis                            *
*  Version: 2.0                                                         *
*  Date: November 1993                                                  *
*  Purpose: Calculate actual transpiration of a crop, and the  effects *
*           of water stress on growth and development of rice.          *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name    type meaning                                   units  class *
*  ----    ---- -------                                   -----  ----- *
*  SWIWLP  I    Switch te select production environment    -       I   *
*  DELT    R    Time set of integration                    d       T   *
*  DVS     R    Development stage                          -       I   *
*  TRC     R    Potential transpiration rate              mm d-1   I   *
*  ZRT     R    Rooting depth                              m       I   *
*  TKL     R    Array ofthicknesses soil layers            m       I   *
*  NL      I    Number of soil layers                      -       I   *
*  WCREF   R    Array of reference soil water contents/layer cm3/cm3 I *
*  WCLQT   R    Array of actual soil water contents/layer  cm3/cm3 I   *
*  WCWP    R    Array of soil water content at wilting                 *
*               point/layer                               cm3/cm3 I   *
*  LLRT    R    Lower limit relative transpiration rate    -       I   *
*  ULRT    R    Upper limit relative transpiration rate    -       I   *
*  LLDL    R    Lower limit dead leaves                    -       I   *
*  ULLS    R    Upper limit leaf rolling                   -       I   *
*  ULLG    R    Upper limit leaf growth                    -       I   *
*  LLLS    R    lower limit leaf growth                    -       I   *
*  TRW     R    Actual transpiration rate                 mm d-1   O   *
*  TRWL    R    Array of actual transpiration rate/layer  mm d-1   O   *
*  WCRREL  R    Relative water content in rootzone        cm3/cm3  O   *
*  ICNT    I    Counter for leaf growth stress             -       O   *
*  DROUT   L    Switch for leaf growth stress              -      C/O  *
*  LSTRS   R    Stress factor for leaf rolling             -       O   *
*  PCEW    R    Stress factor for CO2 assimilation         -       O   *
*  DVEW    R    Stress factor for development rate         -       O   *
*=======================================================================*
      SUBROUTINE DRSTRS (TERMNL, SWIWLP, DELT, DVS, TRC, ZRT, TKL, NL,
    &    WCREF, WCLQT, WCWP, LLRT, ULRT, LLDL, ULLS, ULLG,
    &    LLLS, TRW, TRWL, WCRREL, ICNT, DROUT,
    &    LSTRS, PCEW, DVEW)

      IMPLICIT REAL(A-Z)

      INTEGER SWIWLP, NL, I, INL, ICNT
      PARAMETER(INL=3)

      LOGICAL TERMNL, DROUT

      REAL TRWL(NL), TKL(NL), WCLQT(NL), WCWP(NL)
      REAL WCREF(INL), WCLREL(INL)

*============================================================*
*  Calculation of actual transpiration rates, and of stress  *
*  water contents.                                           *
*============================================================*
*------Reset transpiration rates in all soil compartments to 0
        DO 5 I=1,NL
            TRWL(I) = 0.
```

```
5     CONTINUE

      ZR = ZRT

      TRRM = TRC/(ZR+1.0E-10)

      TRW = 0.
      ZLL = 0.
      WCRTZ = 0.
      WCRTZR = 0.
      WCRTZW = 0.

      DO 30 I=1,NL
            ZRTL = MIN(TKL(I),MAX((ZR-ZLL),0.0))
            WCRTZ = WCRTZ + (ZRTL/(ZR+1.0E-10))*WCLQT(I)
            WCRTZR = WCRTZR + (ZRTL/(ZR+1.0E-10))*WCREF(I)
            WCRTZW = WCRTZW + (ZRTL/(ZR+1.0E-10))*WCWP(I)
            WCLREL(I)=(WCLQT(I)-WCWP(I))/(WCREF(I)-WCWP(I))
            DSETR = LIMIT(0.,1.,(WCLREL(I)-LLRT)/(ULRT-LLRT))
            WLA = MAX (0.0, (WCLREL(I)-LLDL)*TKL(I)*1000.)
            TRWL(I) = MIN(DSETR*ZRTL*TRRM, WLA/DELT)
            TRW = TRW+TRWL(I)
            ZLL = ZLL + TKL(I)
30    CONTINUE

*-----Calibrate the rootzone water content for lowland soils
         IF (SWIWLP .EQ. 0 .OR. SWIWLP .EQ. 1) THEN
           IF ((WCRTZR-WCRTZW) .EQ. 0.) THEN
             WCRREL = 1.
           ELSE
             WCRREL = (WCRTZ-WCRTZW)/(WCRTZR-WCRTZW)
           END IF
         ELSE IF (SWIWLP .EQ. 2) THEN
           WCRREL = WCRTZ
         END IF

*======================================================================*
*  Calculation of effects of water stress on crop growth              *
*  and development                                                    *
*======================================================================*

      PCEW = TRW/(TRC+1.E-10)

*--   Set 'drought'
      IF (WCRREL.LE.ULLG .AND. WCLQT(1).LT.0.95*WCREF(1)) THEN
         DROUT = .TRUE.
         ICNT = 1
      END IF

      LSTRS = LIMIT (0., 1., (WCRREL-LLLS)/(ULLS-LLLS))
      LSTRS = 0.5*LSTRS + 0.5

      IF (WCRREL.LE.ULLG .AND. WCLQT(1).LT.0.95*WCREF(1)) THEN
        DVEW = LIMIT (0., 1., (DVS-0.25)/(1.0-0.25))
      ELSE
        DVEW = 1.
      END IF
```

```
      RETURN
      END

*======================================================================*
*  SUBROUTINE ASTRO                                                   *
*  Purpose: This subroutine calculates astronomic daylength,          *
*           diurnal radiation characteristics such as the daily       *
*           integral of sine of solar elevation and solar constant.   *
*                                                                     *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)    *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  DOY     R4  Daynumber (Jan 1st = 1)                      -       I  *
*  LAT     R4  Latitude of the site                       degrees   I  *
*  SC      R4  Solar constant                             J m-2 s-1 O  *
*  DS0     R4  Daily extraterrestrial radiation           J m-2 d-1 O  *
*  SINLD   R4  Seasonal offset of sine of solar height      -       O  *
*  COSLD   R4  Amplitude of sine of solar height            -       O  *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)      h       O  *
*  DSINB   R4  Daily total of sine of solar height          s       O  *
*  DSINBE  R4  Daily total of effective solar height        s       O  *
*                                                                     *
*  FATAL ERROR CHECKS (execution terminated, message)                 *
*  condition: LAT > 67, LAT < -67                                     *
*                                                                     *
*  FILE usage : none                                                  *
*---------------------------------------------------------------------*
      SUBROUTINE ASTRO (DOY, LAT,
     &                  SC , DS0, SINLD, COSLD, DAYL, DSINB, DSINBE)
      IMPLICIT REAL (A-Z)
      SAVE
*-----PI and conversion factor from degrees to radians
      PI    = 3.141592654
      RAD   = PI/180.

*-----check on input range of parameters
      IF (LAT.GT.67.)  STOP 'ERROR IN ASTRO: LAT> 67'
      IF (LAT.LT.-67.) STOP 'ERROR IN ASTRO: LAT>-67'

*-----declination of the sun as function of daynumber (DOY)
      DEC   = -ASIN (SIN (23.45*RAD)*COS (2.*PI*(DOY+10.)/365.))

*-----SINLD, COSLD and AOB are intermediate variables

      SINLD = SIN (RAD*LAT)*SIN (DEC)
      COSLD = COS (RAD*LAT)*COS (DEC)
      AOB   = SINLD/COSLD

*-----daylength (DAYL)
      DAYL   = 12.0*(1.+2.*ASIN (AOB)/PI)

      DSINB  = 3600.*(DAYL*SINLD+24.*COSLD*SQRT (1.-AOB*AOB)/PI)
      DSINBE = 3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
     &         12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT (1.-AOB*AOB)/PI)

*-----solar constant (SC) and daily extraterrestrial radiation (DS0)
      SC  = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      DS0 = SC*DSINB
```

```
      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE TOTASS                                                   *
*  Purpose: This subroutine calculates daily total gross               *
*           assimilation (DTGA) by performing a Gaussian integration   *
*           over time. At three different times of the day,            *
*           radiation is computed and used to determine assimilation   *
*           whereafter integration takes place.                        *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  DOY     R4  Daynumber (January 1 = 1)                    -      I   *
*  LAT     R4  Latitude of the site                      degrees   I   *
*  DTR     R4  Daily total of global radiation            J/m2/d   I   *
*  SCP     R4  Scattering coefficient of leaves for visible            *
*              radiation (PAR)                              -      I   *
*  AMAX    R4  Assimilation rate at light saturation      kg CO2/  I   *
*                                                        ha leaf/h     *
*  EFF     R4  Initial light use efficiency              kg CO2/J/ I   *
*                                                        ha/h m2 s     *
*  KDF     R4  Extinction coefficient for diffuse light            I   *
*  LAI     R4  Leaf area index                             ha/ha   I   *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)       h     O   *
*  DTGA    R4  Daily total gross Assimilation          kg CO2/ha/d O   *
*  DSO     R4  Daily extraterrestrial radiation          J m-2 s-1 O   *
*                                                                      *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIM                     *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE TOTASS (DOY,  LAT , DTR, SCP, AMAX, EFF, KDF, LAI,
     &                  DAYL, DTGA, DSO)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, IGAUSS
      SAVE

      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/
      PI   = 3.141592654

      CALL ASTRO(DOY,LAT,SC,DSO,SINLD,COSLD,DAYL,DSINB,DSINBE)

*-----assimilation set to zero and three different times of the day (HOUR)
      DTGA = 0.

      DO 10 I1=1,IGAUSS

*--------at the specified HOUR, radiation is computed and used to compute
*        assimilation
         HOUR = 12.0+DAYL*0.5*XGAUSS(I1)

*--------sine of solar elevation
         SINB  = AMAX1 (0., SINLD+COSLD*COS (2.*PI*(HOUR+12.)/24.))

*--------diffuse light fraction (FRDF) from atmospheric
*        transmission (ATMTR)
         PAR   = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
         ATMTR = PAR/(0.5*SC*SINB)

         IF (ATMTR.LE.0.22) THEN
            FRDF = 1.
         ELSE IF (ATMTR.GT.0.22 .AND. ATMTR.LE.0.35) THEN
            FRDF = 1.-6.4*(ATMTR-0.22)**2
         ELSE
            FRDF = 1.47-1.66*ATMTR
         END IF

         FRDF = AMAX1 (FRDF, 0.15+0.85*(1.-EXP (-0.1/SINB)))

*--------diffuse PAR (PARDF) and direct PAR (PARDR)
         PARDF = PAR * FRDF
         PARDR = PAR - PARDF

         CALL ASSIM (SCP,AMAX,EFF,KDF,LAI,SINB,PARDR,PARDF,FGROS)

*--------integration of assimilation rate to a daily total (DTGA)
         DTGA = DTGA+FGROS*WGAUSS(I1)

10    CONTINUE

      DTGA = DTGA * DAYL

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE ASSIM                                                    *
*  Purpose: This subroutine performs a Gaussian integration over       *
*           depth of canopy by selecting three different LAI's and     *
*           computing assimilation at these LAI levels. The            *
*           integrated variable is FGROS.                              *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  SCP     R4  Scattering coefficient of leaves for visible            *
*              radiation (PAR)                              -      I   *
*  AMAX    R4  Assimilation rate at light saturation      kg CO2/  I   *
*                                                        ha leaf/h     *
*  EFF     R4  Initial light use efficiency              kg CO2/J/ I   *
*                                                        ha/h m2 s     *
*  KDF     R4  Extinction coefficient for diffuse light            I   *
*  LAI     R4  Leaf area index                             ha/ha   I   *
*  SINB    R4  Sine of solar height                         -      I   *
*  PARDR   R4  Instantaneous flux of direct radiation (PAR) W/m2   I   *
*  PARDF   R4  Instantaneous flux of diffuse radiation(PAR) W/m2   I   *
*  FGROS   R4  Instantaneous assimilation rate of         kg CO2/  O   *
*              whole canopy                              ha soil/h     *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : none                             *
```

```
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*
      SUBROUTINE ASSIM (SCP, AMAX, EFF, KDF, LAI, SINB, PARDR, PARDF,
     &                  FGROS)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, I2, IGAUSS
      SAVE

*-----Gauss weights for three point Gauss
      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

*-----reflection of horizontal and spherical leaf angle distribution
      SQV  = SQRT(1.-SCP)
      REFH = (1.-SQV)/(1.+SQV)
      REFS = REFH*2./(1.+2.*SINB)

*-----extinction coefficient for direct radiation and total direct flux
      CLUSTF = KDF / (0.8*SQV)
      KBL    = (0.5/SINB) * CLUSTF
      KDRT   = KBL * SQV

*-----selection of depth of canopy, canopy assimilation is set to zero
      FGROS = 0.

      DO 10 I1=1,IGAUSS
         LAIC = LAI * XGAUSS(I1)

*---------absorbed fluxes per unit leaf area: diffuse flux, total direct
*        flux, direct component of direct flux.
         VISDF = (1.-REFH)*PARDF*KDF  *EXP (-KDF  *LAIC)
         VIST  = (1.-REFS)*PARDR*KDRT *EXP (-KDRT *LAIC)
         VISD  = (1.-SCP) *PARDR*KBL  *EXP (-KBL  *LAIC)

*---------absorbed flux (J/M2 leaf/s) for shaded leaves and assimilation of
*        shaded leaves
         VISSHD = VISDF + VIST - VISD
         IF (AMAX.GT.0.) THEN
            FGRSH  = AMAX * (1.-EXP(-VISSHD*EFF/AMAX))
         ELSE
            FGRSH = 0.
         END IF

*---------direct flux absorbed by leaves perpendicular on direct beam and
*        assimilation of sunlit leaf area

         VISPP  = (1.-SCP) * PARDR / SINB
         FGRSUN = 0.
         DO 20 I2=1,IGAUSS
            VISSUN = VISSHD + VISPP * XGAUSS(I2)
            IF (AMAX.GT.0.) THEN
               FGRS = AMAX * (1.-EXP(-VISSUN*EFF/AMAX))
            ELSE
               FGRS = 0.
            END IF
            FGRSUN = FGRSUN + FGRS * WGAUSS(I2)
20       CONTINUE

*---------fraction sunlit leaf area (FSLLA) and local assimilation
*        rate (FGL)
         FSLLA = CLUSTF * EXP(-KBL*LAIC)
         FGL   = FSLLA  * FGRSUN + (1.-FSLLA) * FGRSH

*---------integration of local assimilation rate to canopy
*        assimilation (FGROS)
         FGROS = FGROS + FGL * WGAUSS(I1)

10    CONTINUE
      FGROS = FGROS * LAI

      RETURN
      END

*-----------------------------------------------------------------------*
*  SUBROUTINE SAHEL                                                     *
*  Author : Daniel van Kraalingen (DRL2SU)                              *
*           adapted by: B.A.M. Bouman                                   *
*  Version: 1.2                                                         *
*  Date   : November 1993                                               *
*  Purpose: This subroutine is a simple soil water balance for freely  *
*           draining upland soils.                                      *
*                                                                       *
*  Reference: - Penning de Vries, F.W.T, D.M. Jansen, H.F.M. ten Berge *
*           and A. Bakema, 1989, Simulation of ecophysiological        *
*           processes of growth in several annual crops. Simulation    *
*           Monographs 29, Pudoc, Wageningen, The Netherlands.         *
*             - . . . . . . . . .                                       *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  ITASK   I4  Determines action of the subroutine,                    *
*  IUNITD  I4  Unit number of soil data file,               -     C,IN *
*  IUNITO  I4  Unit number of output file                   -     C,IN *
*  IUNITL  I4  Unit number of log file                      -     C,IN *
*  FILEI2  C*  Name of soil data file                       -     C,IN *
*  OUTPUT  L4  Flag that indicates if output to file is                *
*              required,                                    -     C,I  *
*  TERMNL  L4  Flag that indicates if simulation should                *
*              terminate                                    -    C,I,O *
*  TIME    R4  Time of simulation                           d      T   *
*  DELT    R4  Time step of integration                     d      T   *
*  SWIWLP  I   Switch to determine production environment   -      I   *
*  RAIN    R4  Rainfall / irrigation rate                  mm/d    I   *
*  RAINN   R4  Rainfall / irrigation rate of next day      mm/d    I   *
*  EVSC    R4  Potential evaporation rate                  mm/d    I   *
*  TRWL    R4  Array of actual transpiration per layer   cm3/cm3   I   *
*  NL      I4  No of soil layers from soil water balance    -      O   *
*  TKL     R4  Array of thicknesses of soil layers          m      O   *
*  TKLT    R4  Depth of simulated soil                      m      O   *
*  ZRTMS   R4  Maximum rooting depth of soil                m      O   *
*  WCWP    R4  Array of water contents at wilting point  cm3/cm3   O   *
*  WCFC    R4   ,,   ,,  ,,       ,,    ,, field capacity cm3/cm3   O   *
*  WCST    R4   ,,   ,,  ,,       ,,    ,, saturation     cm3/cm3   O   *
```

```
*  WCLQT    R4  Array of actual water contents           cm3/cm3    O  *
*  WLO      R4  Amount of ponded water                     mm       O  *
*                                                                      *
*  FATAL ERROR CHECKS (execution terminated, message):                 *
*  Certain sequences of ITASK, see subroutine CHKTSK                   *
*  DELT < 1                                                            *
*  Water balance check                                                 *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called: FUWCHK                            *
*  from TTUTIL : CHKTSK, OUTCOM, OUTDAT, OUTPLT,RDINIT,RDSREA, ERROR,  *
*                INSW, INTGRL                                          *
*                                                                      *
*  FILE usage : - Soil definition file FILEI2                          *
*               - Output file with unit IUNITO for output and warnings *
*----------------------------------------------------------------------*
      SUBROUTINE SAHEL (ITASK, IUNITD, IUNITO, IUNITL, FILEI2,
     &       OUTPUT, TERMNL, TIME, DELT, SWIWLP, RAIN, RAINN,
     &       EVSC, TRWL, NL, TKL, TKLT, ZRTMS, WCWP, WCFC, WCST,
     &       WCLQT, WL0)

      IMPLICIT REAL (A-Z)

*     Formal parameters
      INTEGER   ITASK,   IUNITD,  IUNITO, IUNITL, NL, SWIWLP
      REAL      TKL(3),  WCWP(3), WCFC(3), WCST(3)
      REAL      TRWL(3), WCLQT(3)
      LOGICAL OUTPUT, TERMNL
      CHARACTER*(*)   FILEI2

*(JJ)-The required soil file type recognition marker
      CHARACTER*80    SOILUP

*     Standard local variables
      INTEGER ITOLD

      SAVE

      DATA ITOLD /4/

*     The task that the subroutine should do (ITASK) against the task
*     ..........................
*     after initialization.

      CALL CHKTSK ('SAHEL', IUNITO, ITOLD, ITASK)

      TRWL1 = TRWL(1)
      TRWL2 = TRWL(2)
      TRWL3 = TRWL(3)
      TRW = TRWL1+TRWL2+TRWL3

      IF (ITASK.EQ.1) THEN

        IF (SWIWLP.EQ.1) THEN
         CALL OUTCOM ('SAHEL, water balance SAHEL for free drainage')
        END IF

*        Initialization section
```

```
         IF (DELT.LT.1.0) CALL ERROR
     &      ('SAHEL','DELT too small for SAHEL')

         CALL RDINIT (IUNITD, IUNITO, FILEI2)

*--------The quick-and-dirty patch to provide the user with a
*        recognisable error if the wrong types of soilfiles were
*        supplied at the start of the simulation
         CALL RDSCHA ('SOILUP', SOILUP)

*--------Initialization of states
         CALL RDSREA ('FRNOF', FRNOF)
         CALL RDSREA ('ZRTMS', ZRTMS)
         CALL RDSREA ('EES', EES)
         CALL RDSREA ('WCFC1', WCFC1)
         CALL RDSREA ('WCFC2', WCFC2)
         CALL RDSREA ('WCFC3', WCFC3)
         CALL RDSREA ('WCAD1', WCAD1)
         CALL RDSREA ('WCAD2', WCAD2)
         CALL RDSREA ('WCAD3', WCAD3)
         CALL RDSREA ('WCWP1', WCWP1)
         CALL RDSREA ('WCWP2', WCWP2)
         CALL RDSREA ('WCWP3', WCWP3)
         CALL RDSREA ('WCST1', WCST1)
         CALL RDSREA ('WCST2', WCST2)
         CALL RDSREA ('WCST3', WCST3)
         CALL RDSREA ('FWCLI1', FWCLI1)
         CALL RDSREA ('FWCLI2', FWCLI2)
         CALL RDSREA ('FWCLI3', FWCLI3)
         CALL RDSREA ('TKL1', TKL1)
         CALL RDSREA ('TKL2', TKL2)
         CALL RDSREA ('TKL3', TKL3)

         CLOSE (IUNITD, STATUS='DELETE')

         TKLT = TKL1+TKL2+TKL3

         WCLI1 = FWCLI1*(WCFC1-WCAD1) + WCAD1
         WCLI2 = FWCLI2*(WCFC2-WCAD2) + WCAD2
         WCLI3 = FWCLI3*(WCFC3-WCAD3) + WCAD3

         WL1I = WCLI1*TKL1*1.0E4
         WL2I = WCLI2*TKL2*1.0E4
         WL3I = WCLI3*TKL3*1.0E4
         WL1  = WL1I
         WL2  = WL2I
         WL3  = WL3I
         WCUM = (WL1+WL2+WL3)/10.0

         WCL1 = WL1/(TKL1*1.E4)
         WCL2 = WL2/(TKL2*1.E4)
         WCL3 = WL3/(TKL3*1.E4)

         WCLQT(1) = WCL1
         WCLQT(2) = WCL2
         WCLQT(3) = WCL3

         NL = 3
```

```
         TKL(1) = TKL1
         TKL(2) = TKL2
         TKL(3) = TKL3

         WCWP(1) = WCWP1
         WCWP(2) = WCWP2
         WCWP(3) = WCWP3

         WCFC(1) = WCFC1
         WCFC(2) = WCFC2
         WCFC(3) = WCFC3

         WCST(1) = WCST1
         WCST(2) = WCST2
         WCST(3) = WCST3

         DSLR  = 1.0
         CKWFL = 0.0
         RAINCU = 0.
         RIICU = 0.
         FEVLT = 0.
         EVSWCU = 0.
*--------for interface with ORYZA above-ground
         WL0 = 0.0

*-------------------------------------------------------------*
*        rate calculation section
*-------------------------------------------------------------*
      ELSE IF (ITASK.EQ.2) THEN

*        Available and total soil water
         WLFL1 = RAIN*(1.0-FRNOF)
         WLFL2 = MAX (0.0, WLFL1-(WCFC1*TKL1*1000.-WL1*0.10)/DELT)
         WLFL3 = MAX (0.0, WLFL2-(WCFC2*TKL2*1000.-WL2*0.10)/DELT)
         WLFL4 = MAX (0.0, WLFL3-(WCFC3*TKL3*1000.-WL3*0.10)/DELT)

*        Evaporation
         EVSH = MIN (EVSC, (WL1*0.0001-WCAD1*TKL1)*1000./DELT+WLFL1)
         EVSD = MIN (EVSC, 0.6*EVSC*(SQRT(DSLR)-SQRT(DSLR-1.))+WLFL1)
         EVSW = INSW (DSLR-1.1, EVSH, EVSD)

         FEVL1 = MAX (WL1-WCAD1*TKL1*1.0E4, 0.0)*
     &               EXP(-EES*(0.25*TKL1))
         FEVL2 = MAX (WL2-WCAD2*TKL2*1.0E4, 0.0)*
     &               EXP(-EES*(TKL1+(0.25*TKL2)))
         FEVL3 = MAX (WL3-WCAD3*TKL3*1.0E4, 0.0)*
     &               EXP(-EES*(TKL1+TKL2+(0.25*TKL3)))
         FEVLT = FEVL1+FEVL2+FEVL3

*-------Routine to avoid divisions by 0!
         IF (FEVLT .EQ. 0.) THEN
           EVSW1 = 0.
           EVSW2 = 0.
           EVSW3 = 0.
           EVSW = 0.
         ELSE
           EVSW1 = EVSW*(FEVL1/FEVLT)
           EVSW2 = EVSW*(FEVL2/FEVLT)
           EVSW3 = EVSW*(FEVL3/FEVLT)
         END IF

         IF (OUTPUT) THEN
            CALL OUTDAT (2, 0, 'RAINCU',RAINCU)
            CALL OUTDAT (2, 0, 'EVSW', EVSW)
            CALL OUTDAT (2, 0, 'WCL1', WCL1)
            CALL OUTDAT (2, 0, 'WCL2', WCL2)
            CALL OUTDAT (2, 0, 'WCL3', WCL3)
         END IF

*-----------------------------------------------------------------*
*        integration section
*-----------------------------------------------------------------*
      ELSE IF (ITASK.EQ.3) THEN

         WL1  = INTGRL (WL1, (WLFL1-WLFL2-EVSW1-TRWL1)*10.0, DELT)
         WL2  = INTGRL (WL2, (WLFL2-WLFL3-EVSW2-TRWL2)*10.0, DELT)
         WL3  = INTGRL (WL3, (WLFL3-WLFL4-EVSW3-TRWL3)*10.0, DELT)
         WCUM = (WL1+WL2+WL3)/10.0

         WCL1 = WL1/(TKL1*1.E4)
         WCL2 = WL2/(TKL2*1.E4)
         WCL3 = WL3/(TKL3*1.E4)

         DSLR = INTGRL (DSLR, INSW (RAINN-0.5, 1.0, 1.00001-DSLR)/
     &                  DELT, DELT)
         RAINCU = INTGRL (RAINCU, RAIN, DELT)
         EVSWCU = INTGRL (EVSWCU, EVSW, DELT)

*        Water balance check
         CKWFL = INTGRL (CKWFL, (WLFL1-EVSW-TRW-WLFL4)*10.0, DELT)
         CKWIN = WL1-WL1I+WL2-WL2I+WL3-WL3I
*         CKWRD = FUWCHK (CKWFL, CKWIN, TIME)

*------------------------------------------------------------------*
*------Terminal section
*------------------------------------------------------------------*
      ELSE IF (ITASK.EQ.4) THEN

*-------Store end-of-year data
        CALL OPSTOR ('RIICU',RIICU)
        CALL OPSTOR ('RAINCU',RAINCU)
        CALL OPSTOR ('EVSWCU', EVSWCU)

      END IF

      WCLQT(1) = WCL1
      WCLQT(2) = WCL2
      WCLQT(3) = WCL3

      ITOLD = ITASK

      RETURN
      END

*--------------------------------------------------------------------*
```

```
*  SUBROUTINE LOWBAL                                                    *
*  Author : B.A.M. Bouman                                               *
*  Version: 2.0                                                         *
*  Date   : November 1993                                               *
*                                                                       *
*  Purpose: simple water balance for puddled rice soils in irrigated   *
*  and rainfed lowland environments.                                    *
*                                                                       *
* Reference: Bouman, B.A.M., M.S.C. Wopereis & J.J. Riethoven, 1994.    *
*        Crop growth modelling in agro-ecological zonation of rice,     *
*        SARP Research Proceedings, AB-DLO, Wageningen,                 *
*        The Netherlands.                                               *
*  Info  : B.A.M. Bouman, DLO-Research Institute for Agrobiology        *
*          and Soil Fertility, P.O. Box 14, 6700 AA Wageningen,         *
*          The Netherlands. email: bouman@cabo.agro.nl                  *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
*  name   type meaning                                   units  class   *
*  ----   ---- -------                                   -----  -----   *
* ITASK   I4   Task that subroutine should perform         -    C,IN    *
* IUNITD  I4   Unit that can be used for input files       -    C,IN    *
* IUNITO  I4   Unit used for output file                   -    C,IN    *
* IUNITL  I4   Unit used for log  file                     -    C,IN    *
* FILEI2  C*   Name of input file no. 2                    -    C,IN    *
* OUTPUT  L4   Flag to indicate if output should be done   -    C,IN    *
* TERMNL  L4   Flag to indicate if simulation is to stop   -     I/O    *
* DELT    R    Time step of integration                    d      T     *
* SWIWLP  I    Switch for production environment           -      C     *
* ITIM    I    Time of simulation                          d      T     *
* ITRT    I    Time of transplanting                       d      T     *
* DVS     R    Development stage                           -      I     *
* TRWL    R    Array of actual transpiration per layer    mm/d    I     *
* EVSC    R    Potential soil evaporation rate            mm/d    I     *
* RAIN    R    Rainfall rate                              mm/d    I     *
* RAINN   R    Rainfall rate next day                     mm/d    I     *
* NL      I    Number of soil layers                       -      O     *
* TKL     R    Array of layer thicknesses                  m      O     *
* TKLT    R    Total soil thickness                        m      O     *
* ZRTMS   R    Maximum rooting set by puddled layer        m      O     *
* WCWP    R    Array of water content wilting point/layer cm3/cm3 O     *
* WCFC    R    Array of water content field capacity/layer cm3/cm3 O    *
* WCLQT   R    Array of actual water content/layer       cm3/cm3  O     *
* WL0     R    Amount of ponded water                      mm     O     *
*                                                                       *
*  Subroutines called: From library TTUTIL: OUTCOM, CHKTSK,             *
*                      RDSREA, RDSINT, RDSCHA, OUTDAT, OPSTOR           *
*  Data files needed: soil definition file FILEI2 (as specified in     *
*                     in the fiel CONTROL.DAT)                          *
*-----------------------------------------------------------------------*
      SUBROUTINE LOWBAL (ITASK, IUNITD, IUNITO, IUNITL,
     &   FILEI2, OUTPUT, TERMNL, DELT, SWIWLP, ITIM, ITRT,
     &   DVS, TRWL, EVSC, RAIN, RAINN, NL, TKL, TKLT, ZRTMS,
     &   WCWP, WCFC, WCST, WCLQT, WL0)

      IMPLICIT REAL(A-H,K-Z)

      INTEGER  ITASK, IUNITD, IUNITO, IUNITL, SWIWLP
      INTEGER  NL, ITIM, ITRT
```

```
      REAL WCAD(1), WCWP(1), WCFC(1), WCST(1), WCLQT(1)
      REAL TKL(1), TRWL(1)
      REAL INTGRL, INSW

      LOGICAL  OUTPUT, TERMNL, CRACK
      CHARACTER*(*)  FILEI2
      CHARACTER*80   SOILOW

*-----Standard local variables
      INTEGER ITOLD

      SAVE

      DATA ITOLD/4/

      CALL CHKTSK ('LOWBAL', IUNITO, ITOLD, ITASK)

*=================================================================*
*------Initialization section
*=================================================================*
      IF (ITASK .EQ. 1) THEN

       CRACK = .FALSE.

*------Send title to output file if irrigated production
       IF (SWIWLP .EQ. 0) THEN
         CALL OUTCOM ('LOWBAL: water balance irrigated rice')
       ELSE IF (SWIWLP .EQ. 1) THEN
         CALL OUTCOM ('LOWBAL: water balance rainfed rice')
       END IF

       IF (DELT.LT.1.0) CALL ERROR
     &     ('LOWBAL', 'DELT too small for LOWBAL')

*------Initialization of states
*------Reading data from file
       CALL RDINIT (IUNITD, IUNITO, FILEI2)
       CALL RDSCHA ('SOILOW', SOILOW)
       CALL RDSREA ('WL0MXI', WL0MXI)
       CALL RDSREA ('TKLPI', TKLPI)
       CALL RDSREA ('SPSOIL', SPSOIL)
       CALL RDSREA ('DDR', DDR)
       CALL RDSREA ('WL0I', WL0I)
       CALL RDSREA ('WL0MIN', WL0MIN)
       CALL RDSREA ('SHRINK', SHRINK)
       CALL RDSREA ('WCCRAC', WCCRAC)
       CALL RDSREA ('WCSTP', WCSTP)
       CALL RDSREA ('WCFCP', WCFCP)
       CALL RDSREA ('WCWPP', WCWPP)
       CALL RDSREA ('WCADP', WCADP)
       CALL RDSREA ('RIGIFT', RIGIFT)
       CALL RDSREA ('RIPUD', RIPUD)
       CALL RDSREA ('DVSIE', DVSIE)

       CLOSE (IUNITD, STATUS='DELETE')

*------Initializing state variables
       WL0 = WL0I
```

```
       WLOMX = WLOMXI
       TKLP = TKLPI
       TKLPM = TKLPI*SHRINK
       WLP = (WCSTP*TKLPM)+(TKLPI-TKLPM)
       WCLP = WLP/TKLP
       DSLR = 1.
       RII = 0.
       RUNOF = 0.
       RNOFCU = 0.
       SP = SPSOIL
       RAINCU = 0.
       RIICU = 0.
       RIICSB = 0.
       EVSWCU = 0.
       SPCU = 0.

*------For communication with ORYZA subroutine
       NL = 1
       ZRTMS = TKLPI/1000.
       WCWP(1) = WCWPP
       WCFC(1) = WCFCP
       WCST(1) = WCSTP
       WCAD(1) = WCADP
       TKL(1) = TKLPI/1000.
       TKLT = TKLPI/1000.
       WCLQT(1) = WCLP

*============================================================*
*-----Rate calculation section
*============================================================*
      ELSE IF (ITASK .EQ. 2) THEN
      TRWP = TRWL(1)
*------Uncracked situation
       IF (.NOT. CRACK) THEN
*--------Percolation only when ponded water is present
         IF (WLO .LE. 0) THEN
            SP = 0.
         ELSE
           IF ((WLO/DELT) .GE. SPSOIL) THEN
             SP = SPSOIL
           ELSE
             SP = WLO/DELT
           END IF
         END IF
       END IF

*------Reduction of EVSC when no more ponded water
       IF (WLO .LE. 0) THEN
          EVSH = MIN(EVSC, (WLP-WCADP*TKLP)/DELT+RAIN+RII)
          EVSD = MIN(EVSC, 0.6*EVSC*(SQRT(DSLR)-SQRT(DSLR-1.))+RAIN+RII)
          EVSW = INSW(DSLR-1.1, EVSH, EVSD)
       ELSE
          EVSW = EVSC
       END IF

*------In irrigated lowland, it is assumed that the seed-bed is
*      continuously (daily) irrigated.
*------If irrigated lowland, supply constant irrigation gift to
*      the main field when water level drops below WLOMIN, and
*      when the crop is not yet in ripening phase.
       IF (SWIWLP .EQ. 0) THEN
         IF (ITIM .LT. ITRT) THEN
           RII = SP + TRWP + EVSW - RAIN
         ELSE IF (ITIM .EQ. ITRT) THEN
           RII = 0.
         ELSE IF (ITIM .GT. ITRT) THEN
            IF (WLO .LE. WLOMIN .AND. DVS .LT. DVSIE) THEN
              RII = RIGIFT
            ELSE
              RII = 0.
            END IF
         END IF
       ELSE IF (SWIWLP .EQ. 1) THEN
         IF (ITIM .LT. ITRT) THEN
           RII = SP + TRWP + EVSW - RAIN
         ELSE IF (ITIM .GE. ITRT) THEN
           RII = 0.
         END IF
       END IF

*------Cracked situation
       IF (CRACK) THEN
         IF ((RAIN+WLO) .LE. DDR) THEN
            IF (WLO .LE. 0. .AND. RAIN .EQ. 0.) THEN
              SP= 0.
              ELSE IF (WLO.LE.0. .AND. RAIN.GT.0.) THEN
              SP = MAX(RAIN-EVSW, 0.)
              ELSE
              SP = WLO + RAIN
            END IF
         ELSE
            SP = DDR
         END IF
       END IF

       IF (OUTPUT) THEN
         CALL OUTDAT (2, 0, 'WLO', WLO)
         CALL OUTDAT (2, 0, 'TKLP', TKLP)
         CALL OUTDAT (2, 0, 'WCLP', WCLP)
         CALL OUTDAT (2, 0, 'EVSW', EVSW)
         CALL OUTDAT (2, 0, 'RAINCU',RAINCU)
         CALL OUTDAT (2, 0, 'RIICU', RIICU)
       END IF

*============================================================*
*-----Integration section
*============================================================*
      ELSE IF (ITASK .EQ. 3) THEN

*-----Surface draingae is standard zero
      RUNOF =0.
*-----1. Situation with ponded water
       IF (WLO .GT. 0) THEN
          WLO = INTGRL(WLO, (RAIN+RII-EVSW-TRWP-SP), DELT)
*--------1.1 bund overflow
         IF (WLO .GT. WLOMX) THEN
```

```
           RUNOF = WLO - WLOMX
           WLO = WLOMX
*--------1.2 no more ponded water; soil not yet completely shrunken
         ELSE IF (WLO.LT.0 .AND. TKLP.GT.TKLPM) THEN
*---------1.2.1 further shrinkage of puddled layer
          IF (WLO .GE. (TKLPM-TKLP)) THEN
            WLOMX = WLOMX - WLO
            TKLP = TKLP + WLO
            WLP = (WCSTP*TKLPM)+(TKLP-TKLPM)
            WCLP = WLP/TKLP
            WLO = 0.
*---------1.2.2 complete shrinkage of puddled layer
          ELSE IF (WLO .LT. (TKLPM-TKLP)) THEN
            WLOMX = (WLOMXI+TKLPI)-TKLPM
            TKLP = TKLPM
            WLP = (WCSTP*TKLP)+(WLO-(TKLPM-TKLP))
            WCLP = WLP/TKLP
            WLO = 0.
          END IF
*--------1.3 no more ponded water; soil already completely shrunken
         ELSE IF (WLO.LT.0. .AND. TKLP.EQ.TKLPM) THEN
          WLP = WLP + WLO
          WCLP = WLP/TKLP
          WLO = 0.
         END IF

*------2. Situation with no ponded water
       ELSE IF (WLO .LE. 0) THEN
         WLP = INTGRL (WLP, (RAIN+RII-EVSW-TRWP-SP), DELT)
*--------2.1 completely shrunken puddled layer
         IF (WLP .LE. (TKLPM*WCSTP)) THEN
           TKLP = TKLPM
           WLOMX = (WLOMXI+TKLPI)-TKLP
           WCLP = WLP/TKLP
           WLO = 0.
*--------2.2 more water than maximum in completely shrunken layer
         ELSE IF (WLP .GT. (TKLPM*WCSTP)) THEN
*----------2.2.1 formation of ponded water layer
           IF (WLP .GE. ((TKLPM*WCSTP)+(TKLP-TKLPM))) THEN
             WLOD = WLP - ((TKLPM*WCSTP)+(TKLP-TKLPM))
             IF (WLOD .GT. WLOMX) THEN
               WLO = WLOMX
               RUNOF = WLOD - WLOMX
             ELSE
               WLO = WLOD
             END IF
             WLP = (TKLPM*WCSTP)+(TKLP-TKLPM)
             WCLP = WLP/TKLP
*----------2.2.2 further shrinkage of puddled layer
           ELSE IF (WLP .LT. ((TKLPM*WCSTP)+(TKLP-TKLPM))) THEN
             TKLP = WLP-(TKLPM*WCSTP)+TKLPM
             WLOMX = (WLOMXI+TKLPI)-TKLP
             WCLP = WLP/TKLP
             WLO = 0.
           END IF
         END IF
       END IF
```

```
       DSLR = INTGRL(DSLR, INSW(RAINN-0.5, 1.0, 1.00001-DSLR)/
     &                DELT, DELT)

*------Summation of some water management states only
*      for main field, i.e. after transplanting only.
       IF (ITIM .LT. ITRT) THEN
         RIICU = 0.
         RIICSB = INTGRL (RIICSB, RII, DELT)
         RNOFCU = 0.
         EVSWCU = 0.
         SPCU = 0.
       ELSE IF (ITIM .EQ. ITRT) THEN
         IF (SWIWLP .EQ. 0) THEN
           RIICU = RIPUD
         ELSE IF (SWIWLP .EQ. 1) THEN
           RIICU = 0.
         END IF
         RAINCU = INTGRL (RAINCU, RAIN, DELT)
         RNOFCU = 0.
         EVSWCU =  INTGRL (EVSWCU, EVSW, DELT)
         SPCU = INTGRL (SPCU, SP, DELT)
       ELSE IF (ITIM .GT. ITRT) THEN
         RIICU = INTGRL (RIICU, RII, DELT)
         RAINCU = INTGRL (RAINCU, RAIN, DELT)
         RNOFCU = INTGRL (RNOFCU, RUNOF, DELT)
         EVSWCU =  INTGRL (EVSWCU, EVSW, DELT)
         SPCU = INTGRL (SPCU, SP, DELT)
       END IF

*------For communication with ORYZA subroutine
       TKL(1) = TKLP/1000.
       TKLT = TKLP/1000.
       WCLQT(1) = WCLP

       IF (WCLP .LT. WCCRAC) CRACK = .TRUE.

*=============================================================*
*------Terminal section
*=============================================================*
       ELSE IF (ITASK .EQ. 4) THEN
          CLOSE (15)
          CLOSE (16)
*---------Store end-of-year data to a special file.
          CALL OPSTOR ('RIICU',RIICU)
          CALL OPSTOR ('RAINCU',RAINCU)
          CALL OPSTOR ('EVSWCU', EVSWCU)
          CALL OPSTOR ('SPCU', SPCU)
       END IF

       ITOLD = ITASK

       RETURN

       END
```

1.2 Input files

1.2a Control data

```
*******************************************************************
* CONTROL.DAT; to control input and output file names             *
*******************************************************************
FILEON    = 'RESULTS.OUT'
FILEIR    = 'RERUNS.DAT'
FILEIT    = 'TIMER.DAT'
FILEI1    = 'C:\USR\ORYZA_W\RICE_W.DAT'
FILEI2    = 'C:\USR\ORYZA_W\PUDS05.DAT'
FILEOL    = 'RESULTS.LOG'
```

1.2b Crop data

```
*******************************************************************
* RICE_W.DAT                                                      *
* R Torres, 1992;  LINE; IRRI DS at 225 kg N                      *
* Plant data for rice (Oryza) IR72                                *
* Drought stress characteristics by Wopereis                      *
*******************************************************************
NPLH      = 3.
NH        = 25.
NPLSB     = 1000.
NPLDS     = 75.
SHCKL     = 0.25
SHCKD     = 0.4
DVRV      = 0.000625
DVRR      = 0.001629
RGRL      = 0.0090
FSTR      = 0.40

FLVTB     = 0.0,0.55, 0.203,0.589, 0.478,0.407, 0.730,0.388,
             0.895, 0.034, 1.274,0.0, 1.774,0.0, 2.1,0.0
FSTTB     = 0.0,0.45, 0.203,0.411, 0.478,0.593, 0.730,0.612,
             0.895,0.537, 1.274,0.0, 1.774,0.0, 2.1,0.0

FSOTB     = 0.0,0.0, 0.183,0.0, 0.471,0.0, 0.730,0.0, 0.895,0.429,
             1.274,1.0, 1.774,1.0, 2.1,1.0
KDFTB     = 0., 0.4, 0.2, 0.4, 0.6, 0.6, 2.1, 0.6, 3.0, 0.6
KDF       = 0.6

EFFTB     = 10.,0.54, 40.,0.36
SSGATB    = 0.,0.0003, 0.9,0.0003, 2.1,0.
SCP       = 0.2

REDFTT    = -10.,0., 10.,0., 20., 1., 37.,1., 43.,0.
NPROFT    = 0.0,1.0, 0.4,1.0, 1.0,1.6, 1.8,1.5, 2.,1.2, 2.2,1.0

TBD       = 8.
TBLV      = 8.
MAINLV    = 0.02
MAINST    = 0.015
MAINSO    = 0.003
```

```
MAINRT    = 0.01
CRGLV     = 1.326;  CRGST    = 1.326
CRGSO     = 1.462;  CRGRT    = 1.326
CRGSTR    = 1.11
FCSTR     = 0.444;  FCLV     = 0.419;  FCST    = 0.431
FCRT      = 0.431;  FCSO     = 0.487
LRSTR     = 0.947;  TCLSTR = 10.

FSHTB     = 0.0,0.50, 0.43,0.75, 1.0,1.0 , 2.1,1.
FRTTB     = 0.0,0.50, 0.43,0.25, 1.0,0.0,  2.1, 0.
DRLVT     = 0.,0., 0.6,0.,  1.,0.015, 1.6,0.025, 2.1,0.05

LAP0      = 0.0001
XNFLVT    =  0.,0.487, 16.,0.487, 34.,1.740,    70.,1.460,
            79.,1.336, 98.,1.076, 114.,1.192, 128.,0.773
NFLVTB    =  0.,0.487, 0.127,0.487, .279,1.740, .678,1.460,
            0.781,1.336, 1.009,1.076, 1.539,1.192, 2.1, 0.773
SLATB     =  0.,.0054,16.,.0054,  34.,.0030,  70.,.0019, 79.,.0019,
             98.,.0020, 114.,.0016, 128.,0.0014
NSLATB    =  0.,.0054, .127,.0054, .279,.0030, .678, .0019,
            .781,.0019, 1.009,.0020, 1.539,.0016, 2.1,0.0014

ZRTMC     = 0.7
GZRT      = 0.02
DRWT      = 0.0,1.0, 1.,1.0, 2.,1.0
WSET      = -1.0,0.0, 0.0,0.0, 1.0,1.0, 2.0,1.0

ULLGTR    = 1.1
LLLGTR    = 1.1
ULLSTR    = 0.51
LLLSTR    = 0.26
ULDLTR    = 0.31
LLDLTR    = 0.14
ULRTTR    = 0.63
LLRTTR    = 0.0
ULLGTF    = 0.94
LLLGTF    = 0.94
ULLSTF    = 0.77
LLLSTF    = 0.34
ULDLTF    = 0.43
LLDLTF    = 0.14
ULRTTF    = 0.77
LLRTTF    = 0.14
```

1.2c Soil data

Example of soil data for LOWBAL water balance module

```
*****************************************************************
* PUDS05.DAT; soil parameters for the water balance module      *
*             LOWBAL for puddled, lowland rice soils.           *
*  NON-CRACKING; LOW SP RATE (5 MM/DAY)                         *
*****************************************************************
** All data in mm or mm/day

WLOMXI = 100.00     ! bundheight (mm)
TKLPI  = 200.00     ! thickness puddled layer (mm)
SPSOIL = 5.00       ! fixed seepage & percolation rate (mm/d)
DDR    = 2000.00    ! deep drainage rate of the subsoil (mm/d)

WLOI   = 50.00      ! depth of ponded water layer (mm)
WLOMIN = 10.00      ! minumum depth of WL0 at which irrigation
                    ! is supplied (mm)
SHRINK = 0.7        ! linear shrinkage factor (-)

WCCRAC = 0.00       ! water content puddled layer at which cracks
                    ! penetrate the compacted (plough) layer (cm3/cm3)
WCSTP  = 0.52       ! water content at saturat., puddled layer (cm3/cm3)
WCWPP  = 0.01       ! water content at wilting point "     "
                    ! dummy variable for puddled soils!
WCFCP  = 0.01       ! water content at field capacity      "
                    ! dummy variable for puddled soils!
WCADP  = 0.01       ! water content at air-dryness  "      "
                    ! dummy variable for puddled soils!

RIGIFT = 50.00      ! irrigation gift (mm)
RIPUD  = 200.       ! water requirement for land-preparation (mm)
DVSIE  = 1.85       ! development stage after which no more
                    ! irrigation is applied (-)

SOILOW    = 'Lowland, puddled soil type'
```

Example of soil data for SAHEL water balance module

```
*****************************************************************
*   LOAM.DAT; Soil characteristics for a standard loam soil.    *
*   The moisture characteristics (water content values) are     *
*  calculated from the data in Penning de Vries et al., 1989    *
*  (p. 151-152) derived from measurements on Dutch soils        *
*   (Wösten et al., .1987)                                      *
*****************************************************************
* Thicknesses of the soil compartments (m)
TKL1   = 0.2;  TKL2   = 0.3;  TKL3   = 0.5

* Water contents at field capacity (WCFC), wilting point (WCWP),
* air-dryness (WCAD) and saturation (WCST) for the three soil
* compartments (cm3/cm3):
WCFC1 = 0.355; WCWP1 = 0.108; WCAD1 = 0.007; WCST1 = 0.503
WCFC2 = 0.355; WCWP2 = 0.108; WCAD2 = 0.007; WCST2 = 0.503
WCFC3 = 0.355; WCWP3 = 0.108; WCAD3 = 0.007; WCST3 = 0.503

* Initial water content as fraction of WCFC, per layer:
FWCLI1 = 1.0; FWCLI2 = 1.0; FWCLI3 = 1.0
```

```
**SURFACE AND OTHER SOIL CHARACTERISTICS
* Fraction runoff:
FRNOF = 0.0

* Maximum rooting depth of soil (m)
ZRTMS = 0.9

* Evaporation extinction coefficient (1/m):
EES   = 20.
SOILUP    = 'Upland, non-puddled soil type'


-------------------------------------------------------------------
```

The following soil files contain average moisture characteristics (water content at saturation, WCST, at field capacity, WCFC, at wilting point, WCWP, and at air-dryness, WCAD) as calculated from the data in Penning de Vries et al., 1989 (p. 151-152) derived from measurements on Dutch soils (Wösten et al., .1987) for the water balance module SAHEL:

Texture description	File name
Coarse sand	CSAND.DAT
Medium coarse sand	MCSAND.DAT
Medium fine sand	MFSAND.DAT
Fine sand	FSAND.DAT
Humous loamy medium course sand	HLMCSAND.DAT
Loamy medium coarse sand	LLMCSAND.DAT
Light loamy medium coarse sand	LMCSAND.DAT
Loamy fine sand	LFSAND.DAT
Sandy loam	SLOAM.DAT
Loess loam	LLOAM.DAT
Fine sandy loam	FSLOAM.DAT
Silt loam	SILOAM.DAT
Loam	LOAM.DAT
Sandy clay loam	SCLOAM.DAT
Silty clay loam	SICLOAM.DAT
Caly loam	CLOAM.DAT
Light clay	LCLAY.DAT
Silty clay	SICLAY.DAT

File name	WCST	WCFC	WCWP	WCAD
CSAND.DAT	0.3950	0.0647	0.0001	0.0000
MCSAND.DAT	0.3650	0.1405	0.0054	0.0000
MFSAND.DAT	0.3500	0.1611	0.0113	0.0000
FSAND.DAT	0.3640	0.2120	0.0334	0.0005
HLMCSAND.DAT	0.4700	0.3530	0.1326	0.0141
LLMCSAND.DAT	0.3940	0.2848	0.0939	0.0074
LMCSAND.DAT	0.3010	0.1798	0.0309	0.0005
LFSAND.DAT	0.4390	0.2328	0.0266	0.0002
SLOAM.DAT	0.4650	0.2731	0.0443	0.0007
LLOAM.DAT	0.4550	0.3268	0.1055	0.0079
FSLOAM.DAT	0.5040	0.3397	0.0882	0.0040
SILOAM.DAT	0.5090	0.3587	0.1084	0.0070
LOAM.DAT	0.5030	0.3552	0.1082	0.0071
SCLOAM.DAT	0.4320	0.3487	0.1677	0.0313
SICLOAM.DAT	0.4750	0.3778	0.1726	0.0287
CLOAM.DAT	0.4450	0.3994	0.2759	0.1183
LCLAY.DAT	0.4530	0.3783	0.2043	0.0498
SICLAY.DAT	0.5070	0.4474	0.2917	0.1095

1.2d Timer data

```
******************************************************************
*  TIMER.DAT; Timer and run control parameters for ORYZA_W       *
******************************************************************
* Switch for production environment
SWIWLP    = 0
* Weather data specification
WTRDIR    = 'C:\USR\WEATHER\'
CNTR      = 'PHIL'
ISTN      = 1
IFLAG     = 1101
MULTIP    = 1.
* Time variables
YEAR      = 1991.
DELT      = 1.
* Output options
COPINF    = 'N'
PRDEL     = 1.
IPFORM    = 4
DELTMP    = 'N'
* Angstrom parameters
ANGA      = 0.25
ANGB      = 0.45
* Time variables
STTIME    = 160.
FINTIM    = 1000.
DTRP      = 12.
* Note:in upland situation, IDOYTR is automatically set to STTIME for
* rainfed upland simulation
```

1.2e Weather data

```
******************************************************************
* Station name: IRRI wet station site
* Year: 1980
* Author: Daniel van Kraalingen            -99.000: NIL VALUE
* Source: Agroclimate Service Unit of IRRI
* Comments: Original name of data used in IRRI: ORWET
* Longitude: 121 15'' E, latitude: 14 11'' N, altitude: 21 m.
*
* Column  Daily value
* 1       station number
* 2       year
* 3       day
* 4       irradiation                      (kJm-2d-1) or (mJm-2 d-1)
* 5       minimum temperature              (degrees Celsius)
* 6       maximum temperature              (degrees Celsius)
* 7       early morning vapour pressure    (kPa)
* 8       mean wind speed (height: 2 m)    (m s-1)
* 9       precipitation                    (mm d-1)
******************************************************************
 121.25  14.18    21. 0.00 0.00
   1 1980   1 14004.  20.5  29.5   2.790   0.6   0.0
   1 1980   2 12528.  21.5  29.5   2.970   0.3   0.5
   1 1980   3 17136.  21.0  29.7   2.630   0.6   0.0
   1 1980   4 18360.  19.5  29.9   2.650   0.6   0.2
   1 1980   5 13140.  20.8  28.9   2.990   1.0   0.0
    . . . . . . . . . . . . . .
   1 1980 364  7740.  21.7  26.3   2.770   1.8   0.8
```

```
   1 1980 365  5220.  22.0  25.4   2.810   1.8   1.0
   1 1980 366 10656.  22.6  26.8   2.650   2.8   0.0
```

1.2f Rerun data

```
*******************************************************************
*   RERUNS.DAT                                                    *
*******************************************************************
* This is rerun set 1
STTIME = 1.
SPSOIL = 2.
WL0MXI = 100.
YEAR   = 1980.

* This is rerun set 2
STTIME = 10.
SPSOIL = 3.
WL0MXI = 100.
YEAR   = 1980.

* This is rerun set 3
STTIME = 1.
SPSOIL = 2.
WL0MXI = 150.
YEAR   = 1981.

* This is rerun set 4
STTIME = 1.
SPSOIL = 2.
WL0MXI = 150.
YEAR   = 1982.

* This is rerun set 5
STTIME = 10.
SPSOIL = 3.
WL0MXI = 150.
YEAR   = 1981.
```

1.3 Output files

1.3a End-of-season values

```
********************************************************************
*    OP.DAT                                                        *
********************************************************************
RUNNUM RIICU  RAINCU TRCCU  SPCU   GRDUR  WAG    WRR    WLVG
1      750.00 1157.6 205.68 493.60 117.00 13793. 8275.1 924.79
TRWCU
 913.42
```

1.3b Dynamic values

```
********************************************************************
*  RESULTS.OUT                                                     *
********************************************************************
Data file   T\PUDS05.DAT with  16 variables parsed by RDINDX
*-----------------------------------------------------------------
* Output table number  :  0 (=first output table)
* Output table format  : Table output
* Simulation results
* LOWBAL: water balance irrigated rice
* ORYZA_W: Irrigated lowland rice production

TIME      DOY    WL0    TKLP   WCLP   EVSW   RAINCU RIICU  DVS
160.000   160.00 50.000 200.00 .66400 .00000 .00000 .00000 .00000
165.000   165.00 50.000 200.00 .66400 5.2162 .00000 .00000 .06693
170.000   170.00 50.000 200.00 .66400 6.0621 .00000 .00000 .12788
........  ...... .....  .....  ...... ...... ....   ...... ......
275.000   275.00 .81750 192.79 .65144 1.4423 1155.1 750.00 1.9454
277.000   277.00 .00000 176.18 .61857 1.5845 1157.6 750.00 2.0090

TIME      LAI    WAG    WLVG   WRR    WCRREL    TRW    TRC
160.000   .10000 .00000 .00000 .00000 1.2824    .54012  .5401
165.000   .22479 19.270 10.712 .00000 1.2824    1.0558 1.0558
170.000   .50532 57.615 32.515 .00000 1.2824    2.5997 2.5997
.......   ...... .....  .....  ...... ......    ...... ......
275.000   2.2403 13512. 1009.9 7960.6 1.2577    7.7493 7.7493
277.000   2.0758 13793. 924.79 8275.1 1.1933    8.1548 8.1548
```

1.4 List of variable names

1.4a ORYZAW

Name	Description	Units
ALB	Albedo, reflection coefficient for short-wave radiation	-
ALBC	Albedo, reflection coefficient for crop	-
ALBDS	Albedo, reflection coefficient for dry soil syrface	-
ALBS	Albedo, reflection coefficient for moist soil surface	-
ALBOW	Albedo, reflection coefficient for open water	-
AMAX	Actual CO_2 assimilation rate at light saturation for individual leaves	kg CO_2 ha^{-1}leaf h^{-1}
ANGA	Parameter in Angstrom formula	-
ANGB	Parameter in Angstrom formula	-
AOB	Intermediate variable	-
ASIN	Arcsine function (intrinsic FORTRAN function)	-
ASSIM	Subroutine to calculate FGROS	-
ASTRO	Subroutine to compute e.g. daylength	-
ATMTR	Atmospheric transmission coefficient	-
BBRAD	Black body radiation	J m^{-2} s^{-1}
BOLTZM	Stefan-Boltzman constant	J m^{-2} d^{-1} $^0K^{-4}$
CBCHK	User defined function to check crop carbon balance	-
CKCIN	Carbon in the crop accumulated since simulation started	kg C ha^{-1}
CKCFL	Sum of integrated carbon fluxes into and out of the crop	kg C ha^{-1}
CKCRD	Difference between carbon added to the crop since initialization and the net total of integrated carbon fluxes, relative to their sum	-
CKCDIF	Same as CKCRD	-
CLEAR	Penman's original clearness factor	-
CLUSTF	Cluster factor	-
COS	Cosine function (intrinsic FORTRAN function)	-
COSLD	Intermediate variable in calculating solar height	-

CO2LV	CO_2 production factor for growth of leaves	kg CO_2 kg^{-1} DM
CO2RT	CO_2 production factor for growth of roots	kg CO_2 kg^{-1} DM
CO2SO	CO_2 production factor for growth of storage organs	kg CO_2 kg^{-1} DM
CO2ST	CO_2 production factor for growth of stems	kg CO_2 kg^{-1} DM
CO2STR	CO_2 production factor for growth of stem reserves	kg CO_2 kg^{-1} DM
CRGCR	Carbohydrate (CH_2O) requirement for dry matter production	kg CH_2O kg^{-1} DM
CRGLV	Carbohydrate requirement for leaf dry matter production	kg CH_2O kg^{-1} DM leaf
CRGRT	Carbohydrate requirement for root dry matter production	kg CH_2O kg^{-1} DM root
CRGSO	Carbohydrate requirement for stor. organ dry matter production	kg CH_2O kg^{-1} DM stor.organ
CRGST	Carbohydrate requirement for stem dry matter production	kg CH_2O kg^{-1} DM stem
CRGSTR	Carbohydrate requirement for stem reserves production	kg CH_2O kg^{-1} DM
DAYL	Daylength	h d^{-1}
DEC	Declination of the sun	radians
DELT	Time interval of integration	d
DLDR	Death rate leaves caused by drought	kg DM ha^{-1} d^{-1}
DLDRT	Total death rate leaves caused by drought	kg DM ha^{-1} d^{-1}
DLEAF	Control variable for start of leaf senescence by drought	-
DOY	Day number since 1 January (day of year)	d
DOYS	Day of year at seeding	d
DRLVT	Table for leaf death coefficient as function of DVS	d^{-1}, -
DROUT	Control variable indicating drought/no drought	-
DS0	Daily extra-terrestrial radiation	J m^{-2} d^{-1}
DSERT	Effect of drought stress on water uptake	-
DSINB	Integral of SINB over the day	s d^{-1}
DSINBE	As DSINB, but with a correction for lower atmospheric transmission at lower solar elevations	s d^{-1}
DSTRS	Stress factor for death of leaves caused by drought	-
DTGA	Daily total gross CO_2 assimilation of the crop	kg CO_2 ha^{-1} d^{-1}
DTR	Daily solar radiation (RDT)	J m^{-2} d^{-1}
DTRP	Number of days in seed-bed	d
DVEW	Effect of water stress on development rate in vegetative phase	-
DVR	Development rate of the crop	d^{-1}
DVRV	DVR in the vegetative phase (pre-anthesis)	(°C d)$^{-1}$

DVRR	DVR in the reproductive phase (post-anthesis)	$(^{o}C\ d)^{-1}$
DVS	Development stage of the crop	-

EES	Extinction coefficiemt for evaporation in bare soil	m^{-1}
EFF	Initial light use efficiency for individual leaves	kg CO_2 ha^{-1}leaf h^{-1} $(J\ m^{-2}\ leaf\ s^{-1})^{-1}$
EFFTB	Table of EFF as a function of temperature	EFF, °C
EVD	Penman evapotranspiration due to drying power of air for a crop/soil system	mm d^{-1}
EVDOW	Same as EVD, for open water layer	mm d^{-1}
EVR	Penman evapotransp. due to radiation for a crop/soil system	mm d^{-1}
EVROW	Same as EVR, for open water layer	mm d^{-1}
EVRWL	Same as EVR, for a crop/water layer system	mm d^{-1}
EVSCS	Potential soil evaporation	mm d^{-1}
EVSCOW	Potential evaporation from open water layer	mm d^{-1}
EVSD	Actual evaporation rate soil on dry days	mm d^{-1}
EVSH	Actual evaporation rate soil on humid days	mm d^{-1}

FCLEAR	Sky clearness function in calculation of net long-wave radiation	-
FCLV	Mass fraction carbon in the leaves	kg C kg^{-1} DM
FCRT	Mass fraction carbon in the roots	kg C kg^{-1} DM
FCSO	Mass fraction carbon in the storage organs	kg C kg^{-1} DM
FCST	Mass fraction carbon in the stems	kg C kg^{-1} DM
FCSTR	Mass fraction carbon in the stem reserves	kg C kg^{-1} DM
FGL	CO_2 assimilation rate at a specific depth in the canopy	kg CO_2 ha^{-1}leaf h^{-1}
FGRAIN	Fraction grain in the panicle	-
FGROS	Instantaneous canopy CO_2 assimilation	kg CO_2 ha^{-1} h^{-1}
FGRS	Intermediate variable for calculation of assimilation of sunlit leaves	-
FGRSH	CO_2 assimilation rate at one depth in the canopy for shaded leaves	kg CO_2 ha^{-1}leaf h^{-1}
FGRSUN	CO_2 assimilation rate at one depth in the canopy for sunlit leaves	kg CO_2 ha^{-1}leaf h^{-1}
FINTIM	Period of simulation	d
FLV	Fraction of shoot dry matter allocated to leaves	-
FLVTB	Table of FLV as function of DVS	-, -
FRDF	Fraction diffuse in incoming radiation	-
FRT	Fraction of total dry matter allocated to roots	-

FRTTB	Table of FRT as function of DVS	-, -
FSH	Fraction of total dry matter allocated to shoots	-
FSHTB	Table of FSH as function of DVS	-, -
FSLLA	Fraction of sunlit leaf area	-
FSO	Fraction of shoot dry matter allocated to storage organs	-
FSOTB	Table of FSO as function of DVS	-, -
FST	Fraction of shoot dry matter allocated to stems	-
FSTTB	Table of FST as function of DVS	-, -
FSTR	Fraction carbohydrates allocated to the stems, that is stored as reserves	-
FVAP	Vapour pressure effect on RLWN (Brunt equation)	-
GCR	Gross growth rate of crop dry matter, including translocation	kg DM ha^{-1} d^{-1}
GLV	Dry matter growth rate of leaves	kg DM ha^{-1} d^{-1}
GRDUR	Growth duration	d
GRLAI	Self-defined function to calculate the leaf area index	-
GRPOOL	Growth rate of 'excess' carbohydrates	kg DM ha^{-1} d^{-1}
GRT	Dry matter growth rate of roots	kg DM ha^{-1} d^{-1}
GSO	Dry matter growth rate of storage organs	kg DM ha^{-1} d^{-1}
GST	Dry matter growth rate of stems	kg DM ha^{-1} d^{-1}
GSTR	Dry matter growth rate of the stem reserves	kg DM ha^{-1} d^{-1}
GZRT	Growth rate roots	m d^{-1}
HOUR	Selected hour during the day	h
HU	Daily heat units for phenological development	(^{o}C d) d^{-1}
HULV	Daily heat units for leaf area development	(^{o}C d) d^{-1}
I1	Do-loop counter	-
I2	Do-loop counter	-
ICNT	Control variable for drought stress	-
IDATE	Integer value of day of year	d
IDOYTR	Integer value of day of year at transplanting	d
IGAUSS	Do-loop counter	-
INSD	Counter for non-drought stress days	-
ISTD	Counter for consecutive drought stress days	-
KBL	Extinction coefficient for direct component of direct PAR flux	ha ground ha^{-1} leaf

KDF	Extinction coefficient for leaves	ha ground ha^{-1} leaf
KDFTB	Table of extinction coefficients as function of DVS	ha ground ha^{-1} leaf
KDRT	Extinction coefficient for total direct PAR flux	ha ground ha^{-1} leaf
LAP0	Initial leaf area per plant at emergence	m^2 plant^{-1}
LAPI	Leaf area per plant in seedbed	m^2 plant^{-1}
LAI	Total area index (leaves + stems)	ha leaf ha^{-1} ground
LAIC	Leaf area index above selected height in canopy	ha leaf ha^{-1} ground
LAIEXP	Leaf area index at end of exponential leaf area growth phase	ha leaf ha^{-1} ground
LAIEXS	Leaf area index at end of exponential leaf area growth phase in seedbed	ha leaf ha^{-1} ground
LAII	Initial leaf area index at tranplanting	ha leaf ha^{-1} ground
LAIL	Leaf area index (simulated)	ha leaf ha^{-1} ground
LAT	Latitude of the weather station	degrees
LHVAP	Latent heat of evaporation of water	J kg^{-1} H_2O
LLDL	Lower limit dying leaves	-
LLDLTF	Lower limit dying leaves up to transplanting (or DVS 0.5)	-
LLDTLR	Lower limit dying leaves after transplanting (or DVS 0.5)	-
LLLG	Lower limit leaf growth	-
LLLGTF	Lower limit leaf growth after transplanting (or DVS 0.5)	-
LLLGTR	Lower limit leaf growth up to transplanting (or DVS 0.5)	-
LLLS	Lower limit leaf rolling	-
LLLSTF	Lower limit leaf rolling up to transplanting (or DVS 0.5)	-
LLLSTR	Lower limit leaf rolling after transplanting (or DVS 0.5)	-
LLRT	Lower limit reduction transpiration rate	-
LLRTTF	Lower limit reduction transpiration rate up to trans. (or DVS 0.5)	-
LLRTTR	Lower limit reduction transpiration rate after trans. (or DVS 0.5)	-
LLV	Loss of leaves	kg leaf ha^{-1} d^{-1}
LRSTR	Fraction (1 - 5.3%) of allocated stem reserves that is available for growth (5.3% loss due to membrane passages)	-
LSTR	Loss rate of stem reserves	kg stem res.ha^{-1} d^{-1}
LSTRS	Stress factor for leaf rolling	-
MAINLV	Maintenance respiration coefficient of leaves	kg CH_2O kg^{-1} DM d^{-1}
MAINRT	Maintenance respiration coefficient of roots	kg CH_2O kg^{-1} DM d^{-1}

MAINSO	Maintenance respiration coefficient of storage organs	kg CH_2O kg^{-1} DM d^{-1}
MAINST	Maintenance respiration coefficient of stems	kg CH_2O kg^{-1} DM d^{-1}
MNDVS	Factor accounting for effect of DVS on maintenance respiration	-
NFLV	Nitrogen fraction in the leaves	g N m^{-2} leaf
NFLVTB	Table of NFLV as function of development stage	
NH	Number of hills	hills m^{-2}
NL	Number of soil compartments (layers)	-
NPLH	Number of plants per hill	plants $hill^{-1}$
NPLDS	Number of plants direct seeded	plants m^{-2}
NPLSB	Number of plants in seedbed	plants m^{-2}
NPROF	Nitrogen profile in the crop	-
NPROFT	Table of NPROF as a function of DVS	-, -
NRAD	Net radiation	J m^{-1} d^{-1}
PAR	Instantaneous flux of photosynthetically active radiation	J m^{-2} ground s^{-1}
PARDF	Instantaneous diffuse flux of incoming PAR	J m^{-2} ground s^{-1}
PARDR	Instantaneous direct flux of incoming PAR	J m^{-2} ground s^{-1}
PCEW	Effect of water stress on daily total gross CO_2 assimilation of the crop DTGA	-
PENMAN	Penman reference value for potential evapotranspiration mm	d^{-1}
PI	Ratio of circumference to diameter of circle	-
PRDEL	Time interval for tabular printed output	d
PSYCH	Psychrometic instrument constant mbar	$^{o}C^{-1}$
Q10	Factor accounting for increase of maintenance respiration with a 10 ^{o}C rise temperature	-
RAD	Factor to convert degrees to radians	radians $degree^{-1}$
RAIN	Precipitation rate	mm d^{-1}
RAINCU	Cumulative precipitation	mm
RAINN	Precipitation rate next day	mm d^{-1}
RDT	Daily solar radiation	J m^{-2} d^{-1}
RDTT	Table of RDT as function of day of the year	J m^{-2} d^{-1}, d
REDFT	Factor accounting for effect of temperature on AMAX	-

REDFTT	Table of REDFT as function of temperature	-, °C
REFH	Reflection coefficient for diffuse PAR	-
REFS	Reflection coefficient for direct PAR	-
RGCR	Growth respiration rate of the crop	kg CO_2 ha^{-1} d^{-1}
RGRL	Relative growth rate of leaf area during exponential growth	(°C d)$^{-1}$
RLWN	Net long-wave radiation	J m^{-1} d^{-1}
RMCR	Maintenance respiration rate of the crop	kg CH_2O ha^{-1} d^{-1}

SAI	Stem area index	ha ha^{-1}
SC	Solar constant, corrected for varying distances between sun-earth	J m^{-2} s^{-1}
SCP	Scattering coefficient of leaves for PAR	-
SIN	Sine function (intrinsic FORTRAN function)	-
SINB	Sine of solar elevation	-
SINLD	Intermediate variable in calculating solar declination	-
SHCKD	Parameter indicating relation between seedling age and delay in phenological development	°C d (°C d)$^{-1}$
SHCKL	Parameter indicating relation between seedling age and delay in leaf area development	°C d (°C d)$^{-1}$
SLA	Specific leaf area	ha leaf kg^{-1} leaf
SLATB	Table of SLA as function of DVS	-
SLOPE	Tangent of the relation between saturated vapour pressure and temperature	mbar $^{0}C^{-1}$
SQV	Intermediate variable in calculation of reflection coefficient	-
SSGA	Specific green stem area	ha kg^{-1} stem
SSGATB	Table of SSGA as function of DVS	-, -
SVP	Saturated vapour pressure	mbar
SWILAI	Switch to use as input measured (0) or simulated (1) LAI	-
SWINLV	Switch to use as input NFLV vs DOY (0) or vs DVS (1)	-
SWIWLP	Switch to select irrigated lowland (0), rainfed lowland (1), or rainfed upland (2)	-

TAV	Daily average temperature	°C
TAVD	Daily average daytime temperature	°C
TBD	Base temperature for development	°C
TBLV	Base temperature for juvenile leaf area growth	°C
TCLSTR	Time coefficient for loss of stem reserves	d^{-1}

TEFF	Factor accounting for effect of temperature on maintenance respiration	-
TIME	Daynumber start simulation	d
TKL	Array fof thicknesses of soils compartments	m
TKLT	Thickness of combined soil compartments	m
TMAXT	Table daily maximum temperature as function of day of the year	°C, d
TMD	Maximum temperature for phenological development	°C
TMINT	Table daily minimum temperature as function of day of the year	°C, d
TMLV	Maximum temperature for leaf area development	°C
TNASS	Total net CO_2 assimilation	kg CO_2 ha^{-1}
TOTASS	Subroutine to calculate gross CO_2 assimilation of the crop	-
TRC	Potential transpiration rate canopy/soil system	mm d^{-1}
TRCT	Cumulative potential transpiration (after transplanting)	mm
TRCWL	Potential transpiration rate canopy/water layer system	mm d^{-1}
TREF	Reference temperature	°C
TRRM	Potential transpiration rate canopy per united rooted length	mm d^{-1} m^{-1}
TRW	Actual transpiration rate canopy	mm d^{-1}
TRWCU	Cumulative actual transpiration (after transplanting)	mm
TRWL	Array of TRW per soil compartment	mm d^{-1}
TS	Temperature sum for phenological development	°C d
TSHCKD	Transplanting shock for phenological development	°C d
TSHCKL	Transplanting shock for leaf area development	°C d
TSLV	Temperature sum for leaf area development	°C d
TSLVTR	Temperature sum for leaf area development at tranplanting	°C d
TSTR	Temperature sum for phenological development at tranplanting	°C d
ULDL	Upper limit dying leaves	-
ULDLTF	Upper limit dying leaves up to transplanting (or DVS 0.5)	-
ULDTLR	Upper limit dying leaves after transplanting (or DVS 0.5)	-
ULLG	Upper limit leaf growth	-
ULLGTF	Upper limit leaf growth after transplanting (or DVS 0.5)	-
ULLGTR	Upper limit leaf growth up to transplanting (or DVS 0.5)	-
ULLS	Upper limit leaf rolling	-
ULLSTF	Upper limit leaf rolling up to transplanting (or DVS 0.5)	-
ULLSTR	Upper limit leaf rolling after transplanting (or DVS 0.5)	-
ULRT	Upper limit reduction transpiration rate	-
ULRTTF	Upper limit reduction transpiration rate up to trans. (or DVS 0.5)	-

ULRTTR	Upper limit reduction transpiration rate after trans. (or DVS 0.5)	-
VAPOR	Actual vapour pressure	kpa
VISD	Absorbed direct component of direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISDF	Absorbed diffuse flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISPP	Absorbed light flux by leaves perpendicular on direct beam	J m^{-2} leaf s^{-1}
VISSHD	Total absorbed flux for shaded leaves) per unit leaf area (at depth LAIC	J m^{-2} leaf s^{-1}
VISSUN	Total absorbed flux for sunlit leaves in one of three Gauss point classes	J m^{-2} leaf s^{-1}
VIST	Absorbed total direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
WAG	Total above-ground dry matter	kg DM ha^{-1}
WCAD	Array of volumetric water content per soil compartment, air dry	m^{-3} m^{-3}
WCFC	Array of volumetric water content per soil compartment, field capacity	m^{-3} m^{-3}
WCL	Array of actual volumetric water content per soil compartment	m^{-3} m^{-3}
WCLQT	Same as WCL	m^{-3} m^{-3}
WCLREL	Array of relative water contents per soil compartment	m^{-3} m^{-3}
WCR	Total biomass	kg DM ha^{-1}
WCRDR	Critical soil water content for start of leaf death caused by drought	-
WCREF	Array of refernce water contents at which drought stress occurs, per soil compartment	m^{-3} m^{-3}
WCRREL	Total relative water content in root zone	m^{-3} m^{-3}
WCRTZ	Total water content in root zone	m^{-3} m^{-3}
WCRTZR	Water content in root zone at which drought stress occurs	m-3 m-3
WCRTZW	Water content in root zone at wilting point (pF 4.2)	m-3 m-3
WCST	Array of volumetric water content per soil compartment, at saturation	m^{-3} m^{-3}
WCSTUP	Volumetric water content at saturation of upper soil layer	m^{-3} m^{-3}
WCUP	Volumetric water content of upper soil layer	m^{-3} m^{-3}
WCWP	Array of volumetric water content per soil compartment, at wilting point	m^{-3} m^{-3}
WDF	Wind function	mm d^{-1} mbar^{-1}
WGAUSS	Array containing weights to be assigned to Gauss points	-

WIND	Wind speed	$m\ s^{-1}$
WL	Array of amounts of soil water per soil compartment	$m^3\ ha^{-1}$
WLA	Water available to the crop for uptake	mm
WLFL	array of fluxes of water from compartment I to I+1	$mm\ d^{-1}$
WLPOOL	Pool of 'excess' carbohydrates	$kg\ ha^{-1}$
WLVD	Dry weight of dead leaves	$kg\ ha^{-1}$
WLVEXP	Weight of leaves at end of exponential leaf growth phase	$kg\ ha^{-1}$
WLVEXS	Weight of leaves at end of exp. leaf growth phase in seedbed	$kg\ ha^{-1}$
WLVG	Dry weight of green leaves	$kg\ ha^{-1}$
WLVGI	Initial dry weight of the leaves	$kg\ ha^{-1}$
WLVGIT	Dry weight of green leaves	$kg\ ha^{-1}$
WRR	Dry weight rough rice	$kg\ ha^{-1}$
WRT	Dry weight of the roots	$kg\ ha^{-1}$
WRTI	Initial dry weight of the roots	$kg\ ha^{-1}$
WSO	Dry weight of storage organs	$kg\ ha^{-1}$
WST	Dry weight of the stems	$kg\ ha^{-1}$
WSTI	Initial dry weight of the stems	$kg\ ha^{-1}$
WSTR	Dry weight of stems reserves	$kg\ ha^{-1}$
WSTS	Dry weight of structural stems	$kg\ ha^{-1}$
XGAUSS	Array containing Gauss points	-
ZLL	Depth upper boundary compartment	m
ZR	Actual rooting depth	m
ZRT(I)	Rooting depth (initial)	m
ZRT	Array of ZRT differentiated per soil compartment	m
ZRTL	Same as ZR	m
ZRTM	Maximum for ZRT	m
ZRTMC	Maximum rooting depth of crop	m
ZRTMS	Maximum rooting depth of soil	m

1.4b LOWBAL

Name	Description	Units
WL0MX(I)	Bund height (initial), also maximum level of WL0	mm
DDR	Deep drainage rate of the subsoil	mm s^{-1}
DSLR	Number of days since last rain	-
DVSIE	Development stage after which no more irrigation is applied	-
EVSC	Potential soil evaporation rate for current weather conditions and crop	mm d^{-1}
EVSD	Actual evaporation rate soil on dry days	mm d^{-1}
EVSH	Actual evaporation rate soil on humid days	mm d^{-1}
EVSW	Actual evaporation rate soil	mm d^{-1}
EVSWCU	Cumulative EVSW after transplanting	mm
NL	Number of soil compartments (= 1)	-
RAIN	Precipitation rate	mm d^{-1}
RAINCU	Cumulative precipitation since transplanting	mm
RAINN	Precipitation rate next day	mm d-1
RIGIFT	Constant irrigation gift	mm
RII	Actual irrigation gift (either 0 or RIGIFT)	mm
RIICU	Cumulative irrigation gift after transplanting	mm
RIICSB	Cumulative irrigation gift in seed-bed	mm
RNOFCU	Cumulative RUNOF after transplanting	mm
RUNOF	Surface drainage (bund overflow)	mm
SHRINK	Linear shrinkage factor for puddled layer	-
SP	Actual seepage & percolation rate	mm s^{-1}
SPCU	Cumulative SP after transplanting	mm
SPSOIL	Potential seepage & percolation rate	mm s-1
TKLP(I)	Thickness puddled layer (initial)	mm
TKLPM	Thickness of shrunken soil	mm

TRWP	Actual transpiration rate canopy from puddled layer	mm d^{-1}
WCAD(1)	Same as WCADP	m^{-3} m^{-3}
WCADP	Volumetric water content of shrunken puddled layer, at air dryness (pF 7)	m^{-3} m^{-3}
WCCRAC	Water content of shrunken puddled layer at which cracks penetrate the impermeable layer	m^{-3} m^{-3}
WCFC(1)	Same as WCFCP	m^{-3} m^{-3}
WCFCP	Volumetric water content of shrunkne puddled layer, at field capacity (pF 2)	m^{-3} m^{-3}
WCLP	Actual volumetric water content of puddled layer	m^{-3} m^{-3}
WCLQT(1)	Same as WCLP	m^{-3} m^{-3}
WCST(1)	Same as WCSTP	m^{-3} m^{-3}
WCSTP	Volumetric water content of shrunken puddled layer, at saturation	m^{-3} m^{-3}
WCWP(1)	Same as WCWPP	m^{-3} m^{-3}
WCWPP	Volumetric water content of shrunken puddled layer, at wilting point (pF 4.2)	m^{-3} m^{-3}
WL0(I)	Depth of ponded water layer (initial)	mm
WL0MIN	Minimum depth of WL0 at which irrigation is supplied	mm
WLP	Actual amount of water in puddled layer	mm

1.4c SAHEL

Name	Description	Units
CKWFL	Sum of integrated water fluxes in/out of soil compartments	mm
DSLR	Number of days since last rain	d
EES	Evaporation extinction coefficient	m^{-1}
EVSC	Potential soil evaporation rate for current weather conditions and crop	mm d^{-1}
EVSD	Actual evaporation rate soil on dry days	mm d^{-1}
EVSH	Actual evaporation rate soil on humid days	mm d^{-1}
EVSW	Actual evaporation rate soil (indexed per soil compartment)	mm d^{-1}
EVSWCU	Cumulative EVSW since sowing	mm
FEVL	Array of fraction of EVSW, per soil compartment	-
FEVLT	Total of FEVL over all soil compartments	-
FRNOF	Fraction runoff	-
FWCLI	Initial soil water content as fraction of WCFC, indexed per soil compartment	-
NL	Number of soil compartments (= 1)	-
RAIN	Precipitation rate	mm d^{-1}
RAINCU	Cumulative precipitation since sowing	mm
RAINN	Precipitation rate next day	mm d-1
RIICU	Cumulative irrigation gift (= always 0)	mm
TKL	Thickness os soil compartment, indexed	mm
TKLT	Total thickness of all soil compartments	mm
WCAD	Volumetric water content , at air dryness (pF 7), indexed per soil compartment 1-NL	m^{-3} m^{-3}

WCFC	Volumetric water content, at field capacity (pF 2), indexed per soil compartment 1-NL	$m^{-3}\ m^{-3}$
WCL(I)	Actual volumetric water content, indexed per soil compartment 1-NL (initial)	$m^{-3}\ m^{-3}$
WCLQT	Same as WCL	$m^{-3}\ m^{-3}$
WCST	Volumetric water content at saturation, indexed per soil compartment 1-NL	$m^{-3}\ m^{-3}$
WCUM	Cumulative WL over all soil compartments	mm
WCWP	Volumetric water content, at wilting point (pF 4.2), indexed per soil compartment 1-NL	$m^{-3}\ m^{-3}$
WL(I)	Actual amount of water, indexed per soil compartment 1-NL (Note: WL0 is amount of ponded water)	mm
WLFL	Fluxes of water in/out soil compartments, indexed per compartment	$mm\ d^{-1}$
ZRTMS	Maximum rooting depth of soil	m

Appendix 2. Listing of RIGAUS with input and output files

2.1 RIGAUS

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*==============================================================*
* PROGRAM RIGAUS                                               *
* Authors: B.A.M. Bouman (AB-DLO) & M.J.W. Jansen (GLW-DLO)    *
* Date: December 1993                                          *
* Version: 1.1 (Changes made: no more maximum on rerun numbers *
*                but maximum on ILPREP; see RDDATA subroutine; *
*                error messages also sent to ERROR.LOG file)   *
* Purpose: program to draw at random (parameter) values from   *
*     statistical distributions and from measured data sets    *
*     for Monte Carlo simulation with simulation models.       *
*     The distributions are: UNIFORM, BETA and NORMAL.         *
*     Note: no more than 10000 total drawn values (ILPREP);    *
*           no more than 999 number of drawings (NDRAW);no more*
*           than 25 variables per statistical distrib. type,   *
*           no more than 5 measured variables, and no more     *
*           than 500 measured data per variable.               *
*     The correlation between soil moisture parameters WCFC,   *
*     WCWP and WCST (soil water balance SAHEL) is optionaly    *
*     included (switch ISWI).                                  *
*                                                              *
* PARAMETERS (Type: I=integer, R=real, C=character)            *
*            (Class: I=input, L=local, O=output)               *
* Name       type meaning                              class   *
* ----       ---- -------                              -----   *
* ISWI         I  Switch to take into account the correlation  *
*                 between WCFC, WCST and WCWP            I     *
* NL           I  Number of soil layers                  L     *
* TND          I  Total number of draws                  I     *
* ISEED        I  Seed for random generators             I/O   *
* NDU          I  Number of variables for Uniform drawing I    *
* NDB          I  Number of variables for Beta drawing   I     *
* NDN          I  Number of variables for Normal drawing I     *
* NMV          I  Number of measured variables           I     *
* VUNI(I)      C  Name of variable for Uniform drawing   I     *
* VBETA(I)     C  Name of variable for Beta drawing      I     *
* VNORM(I)     C  Name of variable for Normal drawing    I     *
* NMVAR(I)     R  Name of measured variable              I     *
* UNILO(I)     R  Lower boundary for Uniform distribution I    *
* UNIUP(I)     R  Upper boundary for Uniform distribution I    *
* ABETA(I)     R  Parameter A for Beta distributon       I     *
* BBETA(I)     R  Parameter B for Beta distribution        I   *
* BETALO(I)    R  Lower boundary for Beta distribution     I   *
* BETAUP(I)    R  Upper boundary for Beta distribution     I   *
* MEANU(I)     R  Mean value for Normal distribution       I   *
* VARU(I)      R  Variance for Normal distribution         I   *
* MDATA1-5(I)  R  Measured data for variable 1, 2 or 3     I   *
* DRAWU(J)     R  Random value from Uniform distribution   O   *
* DRAWB(J)     R  Random value from Beta distribution      O   *
* DRAWN(J)     R  Random value from Normal distribution    O   *
* DDATA1-5     R  Random value from measured data          O   *
*                                                              *
* Subroutines and functions called:                            *
* - from TTUTIL: RDINIT,RDSINT,RDSREA,RDAREA,RDSCHA             *
*                                                              *
* - FUNCTION RUNI, RGAU, RBET                                  *
*                                                              *
* Inputfiles: DRAW.IN                                          *
* Outputfiles: RERUNS.DAT, COLUMN.DAT                          *
*                                                              *
* Error messages: fatal errors in consistency check input data *
*                 messages in consistency check input data     *
*============================================================= *

      PROGRAM RIGAUS

      IMPLICIT REAL(A-H,L-Z)
      IMPLICIT INTEGER(I-K)
      PARAMETER (JMNP=25)
*-----Especially for ORYZA_W:
      PARAMETER (ILPREP=10000)
      PARAMETER (NDRAW = 999)
      PARAMETER (KMNP=500)
      PARAMETER (INMVAR=5)
      LOGICAL SWI

      CHARACTER*80 FILIN
      CHARACTER*6  VUNI, VBETA, VNORM, NMVAR
      CHARACTER*6 CWCFC, CWCST, CWCWP, CFWCI
      DIMENSION VUNI(JMNP), VBETA(JMNP), VNORM(JMNP), NMVAR(INMVAR)

      INTEGER TND, NDU, NDB, NDN, NMV, NL
      REAL UNILO(JMNP), UNIUP(JMNP), ABETA(JMNP), BBETA(JMNP)
      REAL VARU(JMNP), MEANU(JMNP), BETALO(JMNP), BETAUP(JMNP)
      REAL DRAWU(JMNP), DRAWB(JMNP), DRAWN(JMNP)
      REAL DDATA(INMVAR)

      REAL MDATA1(KMNP), MDATA2(KMNP), MDATA3(KMNP)
      REAL MDATA4(KMNP), MDATA5(KMNP)
      INTEGER IDATA1, IDATA2, IDATA3, IDATA4, IDATA5

      IUNITD = 10
      IUNITO = 40
      FILIN = 'RIGAUS.IN'

      NL = 3

      CWCFC = 'WCFC'
      CWCST = 'WCST'
```

```
      CWCWP = 'WCWP'
      CFWCI = 'FWCLI'

*--------------------------------------------------------------*
*     Reading data from input file                             *
*--------------------------------------------------------------*
*-----Open output file to write fatal error messages
      OPEN(52,FILE='ERROR.LOG',STATUS='UNKNOWN')
      WRITE(52,*) 'Error messages from RIGAUS program'
*-----Switch for closing status of ERROR.LOG
      IFILE = 0

*-----open outputfile to write log messages to
      OPEN(40, FILE='RIGAUS.LOG', STATUS='UNKNOWN')

      CALL RDINIT (IUNITD, IUNITO, FILIN)

      CALL RDSINT ('ISWI', ISWI)
      CALL RDSINT ('TND', TND)
*     Check on number of drawings:
      IF (TND .GT. NDRAW) THEN
        WRITE(*,*) 'ERROR: number of drawings >', NDRAW
        WRITE(52,*) 'ERROR: number of drawings >', NDRAW
        IFILE=1
        GO TO 100
      END IF

      CALL RDSINT ('ISEED', ISEED)
      CALL RDSINT ('NDU', NDU)
*     Check on number of UNIFORM variables:
      IF (NDU .GT. JMNP) THEN
        WRITE(*,*) 'ERROR: number of UNIFORM variables >', JMNP
        WRITE(52,*) 'ERROR: number of UNIFORM variables >', JMNP
        IFILE=1
        GO TO 100
      END IF

      CALL RDSINT ('NDB', NDB)
*     Check on number of BETA variables:
      IF (NDB .GT. JMNP) THEN
        WRITE(*,*) 'ERROR: number of BETA variables >', JMNP
        WRITE(52,*) 'ERROR: number of BETA variables >', JMNP
        IFILE=1
        GO TO 100
      END IF

      CALL RDSINT ('NDN', NDN)
*     Check on number of NORMAL variables:
      IF (NDN .GT. JMNP) THEN
        WRITE(*,*) 'ERROR: number of NORMAL variables >', JMNP
        WRITE(52,*) 'ERROR: number of NORMAL variables >', JMNP
        IFILE=1
        GO TO 100
      END IF

      CALL RDSINT ('NMV', NMV)
*     Check on number of MEASURED variables:
      IF (NMV .GT. INMVAR) THEN
        WRITE(*,*) 'ERROR: number of MEASURED variables >', INMVAR
        WRITE(52,*) 'ERROR: number of MEASURED variables >', INMVAR
        IFILE=1
        GO TO 100
      END IF

*     Check on total number of draws times parameters,
*     especially for ORYZA_W simulation model:
      TOTDR = TND *(NDU + NDB + NDN + NMV)
      IF (TOTDR .GT. ILPREP) THEN
        WRITE(*,*) 'ERROR: number of draws x parameters >', ILPREP
        WRITE(*,*) '=> reduce number of draws TND'
        WRITE(52,*) 'ERROR: number of draws x parameters >', ILPREP
        IFILE=1
        GO TO 100
      END IF

*-----Reading data for UNIFORM distribution
      CALL RDACHA ('VUNI', VUNI, JMNP, IVUNI)
      CALL RDAREA ('UNILO', UNILO, JMNP, IUNILO)
      CALL RDAREA ('UNIUP', UNIUP, JMNP, IUNIUP)
*     Check on consistency in supplied number of data values
      IF (IUNILO .NE. IUNIUP .OR. IUNILO .NE. IVUNI
     $    .OR. IUNIUP .NE. IVUNI) THEN
        WRITE(*,*) 'ERROR in data UNIFORM distribution'
        WRITE(*,*) 'inconsistency in number of data'
        WRITE(52,*) 'ERROR in data UNIFORM distribution'
        WRITE(52,*) 'inconsistency in number of data'
        IFILE=1
        GO TO 100
      END IF
      IF (IVUNI .LT. NDU) THEN
        WRITE(*,*) 'ERROR in data UNIFORM distribution'
        WRITE(*,*) 'number of supplied data < NDU'
        WRITE(52,*) 'ERROR in data UNIFORM distribution'
        WRITE(52,*) 'number of supplied data < NDU'
        IFILE=1
        GO TO 100
      ELSE IF (IVUNI .GT. JMNP) THEN
        WRITE(*,*) 'Error in data UNIFORM distribution'
        WRITE(*,*) 'number of supplied data >', JMNP
        WRITE(52,*) 'Error in data UNIFORM distribution'
        WRITE(52,*) 'number of supplied data >', JMNP
        IFILE=1
        GO TO 100
       END IF
      IF (IVUNI .GT. NDU) THEN
        WRITE(*,*) 'Message: in data UNIFORM distribution'
        WRITE(*,*) 'number of supplied data > NDU'
      END IF
*     Check on upper and lower boundary values
      DO 25 J=1,NDU
      IF (UNILO(J) .GE. UNIUP(J)) THEN
        WRITE(*,*) 'ERROR in boundaries UNIFORM distribution:'
        WRITE(*,*) 'in variable no:',J
        WRITE(52,*) 'ERROR in boundaries UNIFORM distribution:'
        WRITE(52,*) 'in variable no:',J
        IFILE=1
```

```
        GO TO 100
      END IF
25    CONTINUE

*-----Reading data for BETA distribution
      CALL RDACHA ('VBETA', VBETA, JMNP, IVBETA)
      CALL RDAREA ('ABETA', ABETA, JMNP, IABETA)
      CALL RDAREA ('BBETA', BBETA, JMNP, IBBETA)
      CALL RDAREA ('BETALO', BETALO, JMNP, IBETLO)
      CALL RDAREA ('BETAUP', BETAUP, JMNP, IBETUP)
*     Check on consistency in supplied number of data values
      IF (IBETLO .NE. IBETUP .OR. IABETA .NE. IBBETA) THEN
        WRITE(*,*) 'ERROR in data BETA distribution:'
        WRITE(*,*) 'inconsistency in number of data'
        WRITE(52,*) 'ERROR in data BETA distribution:'
        WRITE(52,*) 'inconsistency in number of data'
        IFILE=1
        GO TO 100
      END IF
      IF (IVBETA .NE. IABETA .OR. IVBETA .NE. IBETLO
     $    .OR. IABETA .NE. IBETLO) THEN
        WRITE(*,*) 'ERROR in data BETA distribution:'
        WRITE(*,*) 'inconsistency in number of data'
        WRITE(52,*) 'ERROR in data BETA distribution:'
        WRITE(52,*) 'inconsistency in number of data'
        IFILE=1
        GO TO 100
      END IF
      IF (IVBETA .LT. NDB) THEN
        WRITE(*,*) 'ERROR in data BETA distribution:'
        WRITE(*,*) 'number of supplied data < NDB'
        WRITE(52,*) 'ERROR in data BETA distribution:'
        WRITE(52,*) 'number of supplied data < NDB'
        IFILE=1
        GO TO 100
      ELSE IF (IVBETA .GT. JMNP) THEN
        WRITE(*,*) 'Error in data BETA distribution'
        WRITE(*,*) 'number of supplied data >', JMNP
        WRITE(52,*) 'Error in data BETA distribution'
        WRITE(52,*) 'number of supplied data >', JMNP
        IFILE=1
        GO TO 100
      END IF
      IF (IVBETA .GT. NDB) THEN
        WRITE(*,*) 'Message: in data BETA distribution:'
        WRITE(*,*) 'number of supplied data > NDB'
      END IF
*     Check on upper and lower boundary values
      DO 26 J=1,NDB
      IF (BETALO(J) .GE. BETAUP(J)) THEN
        WRITE(*,*) 'ERROR in boundaries BETA distribution:'
        WRITE(*,*) 'in variable no:',J
        WRITE(52,*) 'ERROR in boundaries BETA distribution:'
        WRITE(52,*) 'in variable no:',J
        IFILE=1
        GO TO 100
      END IF
26    CONTINUE
```

```
*-----Reading data for NORMAL distribution
      CALL RDACHA ('VNORM', VNORM, JMNP, IVNORM)
      CALL RDAREA ('MEANU', MEANU, JMNP, IMEANU)
      CALL RDAREA ('VARU', VARU, JMNP, IVARU)
*     Check on consistency in supplied number of data values
      IF (IVNORM .NE. IMEANU .OR. IVNORM .NE. IVARU
     $    .OR. IMEANU .NE. IVARU) THEN
        WRITE(*,*) 'ERROR in data NORMAL distribution'
        WRITE(*,*) 'inconsistency in number of data'
        WRITE(52,*) 'ERROR in data NORMAL distribution'
        WRITE(52,*) 'inconsistency in number of data'
        IFILE=1
        GO TO 100
      END IF
      IF (IVNORM .LT. NDN) THEN
        WRITE(*,*) 'ERROR in data NORMAL distribution'
        WRITE(*,*) 'number of supplied data < NDU'
        WRITE(52,*) 'ERROR in data NORMAL distribution'
        WRITE(52,*) 'number of supplied data < NDU'
        IFILE=1
        GO TO 100
      ELSE IF (IVNORM .GT. JMNP) THEN
        WRITE(*,*) 'Error in data VNORM distribution'
        WRITE(*,*) 'number of supplied data >', JMNP
        WRITE(52,*) 'Error in data VNORM distribution'
        WRITE(52,*) 'number of supplied data >', JMNP
        IFILE=1
        GO TO 100
      END IF
      IF (IVNORM .GT. NDN) THEN
        WRITE(*,*) 'Message: in data NORMAL distribution'
        WRITE(*,*) 'number of supplied data > NDU'
      END IF

*-----Reading measured data
      CALL RDACHA ('NMVAR', NMVAR, JMNP, INVAR)
*     Consistency check on number of supplied variable names
      IF (INVAR .LT. NMV) THEN
        WRITE(*,*) 'ERROR in MEASURED data'
        WRITE(*,*) 'number of variable names < NMV'
        WRITE(52,*) 'ERROR in MEASURED data'
        WRITE(52,*) 'number of variable names < NMV'
        IFILE=1
        GO TO 100
      ELSE IF (INVAR .GT. NMV) THEN
        WRITE(*,*) 'Message: in MEASURED data'
        WRITE(*,*) 'number of variable names > NMV'
      END IF
      IF (NMV .GE. 1) THEN
        CALL RDAREA ('MDATA1', MDATA1, KMNP, IDATA1)
*       Check on maximum number of measured data
        IF (IDATA1 .GT. KMNP) THEN
          WRITE(*,*) 'ERROR in MEASURED data'
          WRITE(*,*) 'number of data 1st variable >', KMNP
          WRITE(52,*) 'ERROR in MEASURED data'
          WRITE(52,*) 'number of data 1st variable >', KMNP
        IFILE=1
```

```
          GO TO 100
        END IF
      END IF
      IF (NMV .GE. 2) THEN
      CALL RDAREA ('MDATA2', MDATA2, KMNP, IDATA2)
        IF (IDATA2 .GT. KMNP) THEN
          WRITE(*,*) 'ERROR in MEASURED data'
          WRITE(*,*) 'number of data 2nd variable >', KMNP
          WRITE(52,*) 'ERROR in MEASURED data'
          WRITE(52,*) 'number of data 2nd variable >', KMNP
        IFILE=1
          GO TO 100
        END IF
      END IF
      IF (NMV .GE. 3) THEN
      CALL RDAREA ('MDATA3', MDATA3, KMNP, IDATA3)
        IF (IDATA3 .GT. KMNP) THEN
          WRITE(*,*) 'ERROR in MEASURED data'
          WRITE(*,*) 'number of data 3thd variable >', KMNP
          WRITE(52,*) 'ERROR in MEASURED data'
          WRITE(52,*) 'number of data 3thd variable >', KMNP
          IFILE=1
          GO TO 100
        END IF
      END IF
      IF (NMV .GE. 4) THEN
      CALL RDAREA ('MDATA4', MDATA4, KMNP, IDATA4)
        IF (IDATA4 .GT. KMNP) THEN
          WRITE(*,*) 'ERROR in MEASURED data'
          WRITE(*,*) 'number of data 4th variable >', KMNP
          WRITE(52,*) 'ERROR in MEASURED data'
          WRITE(52,*) 'number of data 4th variable >', KMNP
          IFILE=1
          GO TO 100
        END IF
      END IF
      IF (NMV .GE. 5) THEN
      CALL RDAREA ('MDATA5', MDATA5, KMNP, IDATA5)
        IF (IDATA5 .GT. KMNP) THEN
          WRITE(*,*) 'ERROR in MEASURED data'
          WRITE(*,*) 'number of data 5th variable >', KMNP
          WRITE(52,*) 'ERROR in MEASURED data'
          WRITE(52,*) 'number of data 5th variable >', KMNP
          IFILE=1
          GO TO 100
        END IF
      END IF

      CLOSE (IUNITD, STATUS='DELETE')

*--------------------------------------------------------------*
*     Opening output files                                     *
*--------------------------------------------------------------*
*-----Open output file RERUNS.DAT
      OPEN(50,FILE='RERUNS.DAT',STATUS='UNKNOWN')
*-----Open output file COLUMN.DAT:
      OPEN(51,FILE='COLUMN.DAT',STATUS='UNKNOWN')
```

```
*--------------------------------------------------------------*
*     Random drawing, plus writing to output file RERUNS.DAT   *
*     Note: if the switch ISWI is set to 1, then:              *
*           - When the variable name WCFC is found, the water  *
*           content values at wilting point (WCWP) and at      *
*           saturation (WCST) are calculated and written for   *
*           the three soil layers of SAHEL                     *
*           - When the variable name FWCLI is found, values    *
*           written for all three soil layers of SAHEL         *
*--------------------------------------------------------------*
      SWI = .FALSE.

*-----Run RUNI(ISEED) as dummy to get ISEED if supplied
*     ISEED in RIGAUS.IN = 0
      DUMMY = RUNI(ISEED)
      WRITE (50, '(A10,I7)') '* ISEED =', ISEED

      DO 50 I=1,TND

*-----Write info on run number to file RERUNS.DAT
      WRITE (50,'(A20,I5)') '* This is rerun set', I

*-------Drawing from uniform distribution
        DO 15 J=1,NDU
          DRAWU(J)=RUNI(ISEED)*(UNIUP(J)-UNILO(J)) + UNILO(J)
*         Optionaly: calculate correlated soil moisture contents and
*         fraction initial moisture content of all three layers
*         of the SAHEL water balance.
          IF (ISWI .EQ. 1) THEN
            IF (VUNI(J) .EQ. 'WCFC') THEN
*             Test on upper and lower boundaries WCFC  (limits of
*             derived relationship between the water content params)
              IF (UNIUP(J) .GT. 0.6) THEN
                WRITE(*,*) 'Error; upper boundary WCFC > 0.6'
                WRITE(52,*)'Error; upper boundary WCFC > 0.6'
                IFILE=1
                GO TO 100
               ELSE IF (UNILO(J) .LT. 0.05) THEN
                WRITE(*,*) 'Error; lower boundary WCFC < 0.05'
                WRITE(52,*) 'Error; lower boundary WCFC < 0.05'
                IFILE=1
                GO TO 100
               END IF
              WCFC   = LIMIT(0.001, 0.999, DRAWU(J))
5             WCSTI  = 0.025*RGAU(ISEED) + (0.347-0.164*WCFC +
     $                 1.217*WCFC**2)
              WCST  = LIMIT(0.001, 0.999, WCSTI)
              IF (WCST .LE. WCFC) GO TO 5
6             WCWPI  = 0.032*RGAU(ISEED) + (MAX(0.015, 0.050-0.535 *
     $                 WCFC+2.027*WCFC**2))
              WCWP = LIMIT(0.001, 0.999, WCWPI)
              IF (WCWP .GE. WCFC) GO TO 6
              DO 101, K=1,NL
                WRITE (CWCFC(5:5), '(I1)') K
                WRITE (CWCST(5:5), '(I1)') K
                WRITE (CWCWP(5:5), '(I1)') K
                WRITE(50,'(A6,A1,E10.4)') CWCFC, '=', WCFC
                WRITE(50,'(A6,A1,E10.4)') CWCST, '=', WCST
```

```
                WRITE(50,'(A6,A1,E10.4)') CWCWP, '=', WCWP
101           CONTINUE
              SWI = .TRUE.
            ELSE IF (VUNI(J) .EQ. 'FWCLI') THEN
*             Test on limits of UNIUP and UNILO
              IF (UNIUP(J).GT.1.0 .OR. UNILO(J).LT.0.0) THEN
                WRITE(*,*) 'ERROR; limits FWCLI out of bounds:'
     $                      ,UNIUP(J), UNILO(J)
                WRITE(52,*) 'ERROR; limits FWCLI out of bounds:'
     $                      ,UNIUP(J), UNILO(J)
                IFILE=1
                GO TO 100
              END IF
              FWCLI  = DRAWU(J)
              DO 501, K=1,NL
              WRITE (CFWCI(6:6), '(I1)') K
              WRITE(50,'(A6,A1,E10.4)') CFWCI, '=', FWCLI
501           CONTINUE
            ELSE
            WRITE(50,'(A6,A1,E10.4)') VUNI(J),'=',DRAWU(J)
            END IF
          ELSE
          WRITE(50,'(A6,A1,E10.4)') VUNI(J),'=',DRAWU(J)
          END IF
15      CONTINUE

*-------Drawing from beta distribution
        DO 20 J=1,NDB
          A = ABETA(J)
          B = BBETA(J)
          DRAWB(J)=RBET(A,B,ISEED)*(BETAUP(J)-BETALO(J)) + BETALO(J)
*         Optionaly: calculate correlated soil moisture contents
          IF (ISWI .EQ. 1) THEN
            IF (VBETA(J) .EQ. 'WCFC') THEN
*             Test on upper and lower boundaries WCFC (limits of
*             derived relationship between the water content params)
              IF (BETAUP(J) .GT. 0.6) THEN
                WRITE(*,*) 'Error: upper boundary WCFC > 0.6'
                WRITE(52,*) 'Error: upper boundary WCFC > 0.6'
                IFILE=1
                GO TO 100
               ELSE IF (BETALO(J) .LT. 0.05) THEN
                WRITE(*,*) 'Error; lower boundary WCFC < 0.05'
                WRITE(52,*) 'Error; lower boundary WCFC < 0.05'
                IFILE=1
                GO TO 100
               END IF
              WCFC  = LIMIT (0.001, 0.999, DRAWB(J))
7             WCSTI  = 0.025*RGAU(ISEED) + (0.347-0.164*WCFC  +
     $                  1.217*WCFC **2)
              WCST = LIMIT(0.001, 0.999, WCSTI)
              IF (WCST  .LE. WCFC) GO TO 7
8             WCWPI  = 0.032*RGAU(ISEED) + (MAX(0.015, 0.050-0.535 *
     $                  WCFC +2.027*WCFC**2))
              WCWP = LIMIT(0.001, 0.999, WCWPI)
              IF (WCWP .GE. WCFC) GO TO 8
              DO 102, K=1,NL
                WRITE (CWCFC(5:5), '(I1)') K
                WRITE (CWCST(5:5), '(I1)') K
                WRITE (CWCWP(5:5), '(I1)') K
                WRITE(50,'(A6,A1,E10.4)') CWCFC, '=', WCFC
                WRITE(50,'(A6,A1,E10.4)') CWCST, '=', WCST
                WRITE(50,'(A6,A1,E10.4)') CWCWP, '=', WCWP
102           CONTINUE
              SWI = .TRUE.
            ELSE IF (VBETA(J) .EQ. 'FWCLI') THEN
*             Test on limits of BETAUP and BETALO
              IF (BETAUP(J).GT.1.0 .OR. BETALO(J).LT.0.0) THEN
                WRITE(*,*) 'ERROR; limits FWCLI out of bounds:'
     $                      ,BETAUP(J), BETALO(J)
                WRITE(52,*) 'ERROR; limits FWCLI out of bounds:'
     $                      ,BETAUP(J), BETALO(J)
                IFILE=1
                GO TO 100
              END IF
              FWCLI = DRAWB(J)
              DO 601, K=1,NL
              WRITE (CFWCI(6:6), '(I1)') K
              WRITE(50,'(A6,A1,E10.4)') CFWCI, '=', FWCLI
601           CONTINUE
              ELSE
              WRITE(50,'(A6,A1,E10.4)') VBETA(J),'=',DRAWB(J)
            END IF
          ELSE
          WRITE(50,'(A6,A1,E10.4)') VBETA(J),'=',DRAWB(J)
          END IF
20      CONTINUE

*-------Drawing from normal distribution
        DO 30 J=1,NDN
          DRAWN(J)=RGAU(ISEED)*VARU(J) + MEANU(J)
*         Optionaly: calculate correlated soil moisture contents
          IF (ISWI .EQ. 1) THEN
            IF (VNORM(J) .EQ. 'WCFC') THEN
*             Test on upper and lower boundaries WCFC  (limits of
*             derived relationship between the water content params)
              IF (DRAWN(J) .GT. 0.6) THEN
                WRITE(*,*) 'Error; upper boundary WCFC > 0.6'
                WRITE(*,*) '-> choose other mean/variance'
                WRITE(*,*) '-> choose other probability distribution'
                WRITE(*,*) 'So far, ',I,' random values have been drawn'
                WRITE(52,*) 'Error; upper boundary WCFC > 0.6'
                WRITE(52,*) '-> choose other mean/variance'
                WRITE(52,*) '-> choose other probability distribution'
                IFILE=1
                GO TO 100
               ELSE IF (DRAWN(J) .LT. 0.05) THEN
                WRITE(*,*) 'Error; lower boundary WCFC < 0.05'
                WRITE(*,*) '-> choose other mean/variance'
                WRITE(*,*) '-> choose other probability distribution'
                WRITE(*,*) 'So far, ',I,' random values have been drawn'
                WRITE(52,*) 'Error; lower boundary WCFC < 0.05'
                WRITE(52,*) '-> choose other mean/variance'
                WRITE(52,*) '-> choose other probability distribution'
                IFILE=1
                GO TO 100
```

```
             END IF
             WCFC = LIMIT(00.1, 0.999, DRAWN(J))
9            WCSTI  = 0.025*RGAU(ISEED) + (0.347-0.164*WCFC +
     $                1.217*WCFC**2)
             WCST= LIMIT(0.001, 0.999, WCSTI)
             IF (WCST .LE. WCFC) GO TO 9
10            WCWPI  = 0.032*RGAU(ISEED) + (MAX(0.015, 0.050-0.535 *
     $                WCFC+2.027*WCFC**2))
             WCWP= LIMIT(0.001, 0.999, WCWPI)
             IF (WCWP .GE. WCFC) GO TO 10
             DO 103, K=1,NL
               WRITE (CWCFC(5:5), '(I1)') K
               WRITE (CWCST(5:5), '(I1)') K
               WRITE (CWCWP(5:5), '(I1)') K
               WRITE(50,'(A6,A1,E10.4)') CWCFC, '=', WCFC
               WRITE(50,'(A6,A1,E10.4)') CWCST, '=', WCST
               WRITE(50,'(A6,A1,E10.4)') CWCWP, '=', WCWP
103          CONTINUE
             SWI = .TRUE.
           ELSE IF (VNORM(J) .EQ. 'FWCLI') THEN
             IF (DRAWN(J).GT.1.0 .OR. DRAWN(J).LT.0.0) THEN
             WRITE(*,*) 'ERROR; random value FWCLI out of bounds:'
     $                  ,DRAWN(J)
             WRITE(*,*) '-> choose other mean/variance'
             WRITE(*,*) '-> choose other probability distribution'
             WRITE(*,*) 'So far, ',I,' random values have been drawn'
             WRITE(52,*) 'ERROR; random value FWCLI out of bounds:'
     $                  ,DRAWN(J)
             WRITE(52,*) '-> choose other mean/variance'
             WRITE(52,*) '-> choose other probability distribution'
             IFILE=1
             GO TO 100
             END IF
             FWCLI = DRAWN(J)
             DO 701, K=1,NL
             WRITE (CFWCI(6:6), '(I1)') K
             WRITE(50,'(A6,A1,E10.4)') CFWCI, '=', FWCLI
701          CONTINUE
           ELSE
           WRITE(50,'(A6,A1,E10.4)') VNORM(J),'=',DRAWN(J)
           END IF
         ELSE
         WRITE(50,'(A6,A1,E10.4)') VNORM(J),'=',DRAWN(J)
         END IF
30      CONTINUE

*-------Drawing at random from measured data
        IF (NMV .GE. 1) THEN
201       ICOUNT = INT(RUNI(ISEED)*IDATA1 + 1.)
          IF (ICOUNT .GE. (IDATA1+1) .OR. ICOUNT .EQ. 0) GO TO 201
          DDATA(1) = MDATA1(ICOUNT)
          WRITE(50, '(A6,A1,E10.4)') NMVAR(1), '=', MDATA1(ICOUNT)
        END IF
        IF (NMV .GE. 2) THEN
202       ICOUNT = INT(RUNI(ISEED)*IDATA2 + 1.)
          IF (ICOUNT .GE. (IDATA2+1) .OR. ICOUNT .EQ. 0) GO TO 202
          DDATA(2) = MDATA2(ICOUNT)
          WRITE(50, '(A6,A1,E10.4)') NMVAR(2), '=', MDATA2(ICOUNT)
```

```
        END IF
        IF (NMV .GE. 3) THEN
203       ICOUNT = INT(RUNI(ISEED)*IDATA3 + 1.)
          IF (ICOUNT .GE. (IDATA3+1) .OR. ICOUNT .EQ. 0) GO TO 203
          DDATA(3) = MDATA3(ICOUNT)
          WRITE(50, '(A6,A1,E10.4)') NMVAR(3), '=', MDATA3(ICOUNT)
        END IF
        IF (NMV .GE. 4) THEN
204       ICOUNT = INT(RUNI(ISEED)*IDATA4 + 1.)
          IF (ICOUNT .GE. (IDATA4+1) .OR. ICOUNT .EQ. 0) GO TO 204
          DDATA(4) = MDATA4(ICOUNT)
          WRITE(50, '(A6,A1,E10.4)') NMVAR(4), '=', MDATA4(ICOUNT)
        END IF
        IF (NMV .GE. 5) THEN
205       ICOUNT = INT(RUNI(ISEED)*IDATA5 + 1.)
          IF (ICOUNT .GE. (IDATA5+1) .OR. ICOUNT .EQ. 0) GO TO 205
          DDATA(5) = MDATA5(ICOUNT)
          WRITE(50, '(A6,A1,E10.4)') NMVAR(5), '=', MDATA5(ICOUNT)
        END IF


        WRITE(50,'(A)')

*-------Writing column names to file COLUMN.DAT
        IF (I .EQ. 1) THEN
          IF (SWI) THEN
            WRITE (51,'(32A10)') (VUNI(J), J=1,NDU),
     $      (VBETA(J), J=1,NDB), (VNORM(J), J=1,NDN),
     $      'WCST', 'WCWP', (NMVAR(J), J=1,NMV)
          ELSE
            WRITE (51,'(32A10)') (VUNI(J), J=1,NDU),
     $      (VBETA(J), J=1,NDB), (VNORM(J), J=1,NDN),
     $      (NMVAR(J), J=1,NMV)
          END IF
        END IF

*---------------------------------------------------------------*
*       Writing to output file COLUMN.DAT                        *
*---------------------------------------------------------------*
        IF (SWI) THEN
          WRITE(51,'(32E10.4)') (DRAWU(J), J=1,NDU),
     $    (DRAWB(J), J=1,NDB), (DRAWN(J), J=1,NDN),
     $    WCST, WCWP, (DDATA(J), J=1,NMV)
        ELSE
          WRITE(51,'(32E10.4)') (DRAWU(J), J=1,NDU),
     $    (DRAWB(J), J=1,NDB), (DRAWN(J), J=1,NDN),
     $    (DDATA(J), J=1,NMV)
        END IF

50    CONTINUE

      CLOSE(40)
      CLOSE(50)
      CLOSE(51)
      IF (IFILE .EQ. 0) THEN
        CLOSE(52, STATUS='DELETE')
      END IF
```

```
      STOP  'Program RIGAUS successfully finished'

100   CONTINUE
      IF (IFILE .EQ. 1) THEN
         CLOSE(52)
      END IF

      STOP  'Program RIGAUS aborted; error status'

      END

**********************************************************************
*     FUNCTION RUNI
*     Uniform(0,1) random generator
*     RUNI - pseudo-random uniformly distributed variate            O
*     ISEED - integer seed                                        I/O
*
*     Modification of UNIFL() by Kees Rappoldt (October 1989)
*     Author: Michiel Jansen, november 1993
*     The modification consists of the addition of the
*     I/O argument ISEED, used to (re)initialize the generator
*
*     At first call with ISEED.NE.0 the absolute value of ISEED
*     is used to seed the generator, negative ISEED is made positive
*     At first call with ISEED.EQ.0, integer function TSEED is called
*     to produce a seed value, passed to ISEED, enabling
*     reproduction of the random sequence if necessary.
*
*     At later calls zero and positive values of ISEED do not
*     disrupt the random sequence, moreover ISEED remains unaltered
*     At later calls, negative values of ISEED, will reinitialize
*     the generator, seeded with -ISEED, which value is passed to ISEED.
*
*     UNIFL() is equivalent to RUNI(ISEED) with ISEED.EQ.1122334455.
*
*     The algorithm originates from L'Ecuyer (1986). It is implemented
*     in Bratley et al., 1983, (UNIFL), and in Press et al., 1992 (RAN2)
*     RAN2 implements an additional shuffling, to enhance the generator,
*     shuffling is not done in RUNI() for compatibility with UNIFL().
*
*     References:
*     Bratley, P., B.L. Fox, L.E. Schrage. 1983. A guide to simulation
*         Springer-Verlag New York Inc. 397 pp.
*     L'Ecuyer,P. (1986). Efficient and portable combined pseudo-
*         random number generators. Commun. ACM (...).
*     Press, W., et al. (1992), Numerical Recipes, second edition,
*         Cambridge University Press.
**********************************************************************

      REAL FUNCTION RUNI(ISEED)

*     formal parameter
      INTEGER ISEED
**    local variables
      INTEGER JX,K
      INTEGER TSEED
      DIMENSION JX(3)
      LOGICAL INIT
      SAVE
      DATA INIT/.FALSE./

      IF ((ISEED .LE. -2147483563) .OR. (ISEED .GE. 2147483563)) THEN
         CALL ERROR('RUNI', 'INVALID ISEED')
      END IF
      IF (.NOT.INIT) THEN
*        initialize generator
         IF (ISEED .EQ. 0) ISEED = TSEED()
         IF (ISEED .LT. 0) ISEED = -ISEED
         JX(2) = ISEED
         JX(3) = 1408222472
         INIT = .TRUE.
      END IF

      IF (ISEED .LT. 0) THEN
*        reinitialize generator
         ISEED = -ISEED
         JX(2) = ISEED
         JX(3) = 1408222472
      END IF

*     get next term in first stream = 40014 * JX(2) mod 2147483563
      K = JX(2) / 53668
      JX(2) = 40014 * (JX(2) - K * 53668)  -  K * 12211
      IF (JX(2).LT.0)  JX(2) = JX(2) + 2147483563
*     get next term in the second stream = 40692 * JX(3) mod 2147483399
      K = JX(3) / 52774
      JX(3) = 40692 * (JX(3) - K * 52774)  -  K * 3791
      IF (JX(3).LT.0)  JX(3) = JX(3) + 2147483399
*     set JX(1) = ((JX(3) + 2147483562 - JX(2)) mod 2147483562) + 1
      K = JX(3) - JX(2)
      IF (K.LE.0)  K = K + 2147483562
      JX(1) = K
*     put it on the interval (0,1)
      RUNI = K * 4.656613E-10
      RETURN
      END


**********************************************************************
*     FUNCTION TSEED
*     produces a seed in the range 1...86412
*     based on the system time (in seconds) from midnight
*     authors: Jacques Withagen and Michiel Jansen
*     date: november 1993
*     warning: time-calculation is compiler-dependent
*
*     VAX compiler calculation of time
*     TSEED = INT(SECNDS(0.))
*     end of VAX compiler specific part
*
*     Microsoft compiler calculation of time
**********************************************************************
      INTEGER FUNCTION TSEED()

      INTEGER TIM(4)
      CALL GETTIM(TIM(1), TIM(2), TIM(3), TIM(4))
```

```
      TSEED = 3600*TIM(1) + 60*TIM(2) + TIM(3)
*     end of Microsoft compiler specific part
*     prevent zero seed
      IF (TSEED .EQ. 0) TSEED = 86400
*     scramble (one-to-one, since 86413 is a prime)
      TSEED = MOD(241*MOD(239*TSEED, 86413), 86413)
      RETURN
      END

************************************************************************
*     FUNCTION RGAU
*     Generates unit normal deviate by Box-Muller method
*     RGAU - pseudo-random standard normal deviate                    O
*     ISEED - integer seed                                          I/O
*     Modification of BOXMUL by Kees Rappoldt, October 1989
*     Author: Michiel Jansen, november 1993
*     The modification consists of the addition of the
*     I/O argument ISEED, used to (re)initialize the
*     basic generator RUNI(ISEED)
*
*     Subroutines and/or functions called:
*      - RUNI
*     Some remarks:
*     Trigonometric function calls could be obviated, as shown
*     for instance in GASDEV() of Press et al. (1992).
*     This should slightly speed up the generator.
*     Not done in RGAU for compatibility with BOXMUL.
*     BOXMUL() is equivalent to RGAU(ISEED) with ISEED.EQ.1122334455.
*
*     References:
*     Box, G.E.P., and M.E.Muller. (1958). A note on the
*         generation of random normal deviates.
*         Ann.Math.Stat. 29:610-611.
*     Bratley,P., B.L.Fox and L.E.Schrage. 1983. A guide to
*         simulation. Springer-Verlag New York Inc. 397 pp.
*     Press, W., et al. (1992), Numerical Recipes, second edition,
*         Cambridge University Press.
************************************************************************
      REAL FUNCTION RGAU(ISEED)

*     formal parameters
      INTEGER ISEED
**    local variables + function called
      REAL ANGLE,PI,U2,VECTOR,X,Y,RUNI
      PARAMETER (PI=3.14159265)
      LOGICAL NEWSET
      SAVE
      DATA NEWSET/.FALSE./

      IF ((ISEED .LE. -2147483563) .OR. (ISEED .GE. 2147483563)) THEN
         CALL ERROR('RGAU', 'INVALID ISEED')
      END IF

      IF (.NOT.NEWSET) THEN
*        generate random radius vector length and angle
         U2     = RUNI(ISEED)
         VECTOR = SQRT (-2.0 * ALOG(U2))
         ANGLE  = 2.0 * PI * RUNI(ISEED)

*        find the two normal deviates
         X = COS (ANGLE) * VECTOR
         Y = SIN (ANGLE) * VECTOR

*        at first X is returned
         RGAU   = X
         NEWSET = .TRUE.

      ELSE
*        in previous call X was returned ; now Y
         RGAU   = Y
         NEWSET = .FALSE.
      END IF

      RETURN
      END

************************************************************************
*     FUNCTION RBET
*     Beta random generator
*     RBET - random variable from beta(A,B) distribution  O
*     A - parameter .GT.0                                 I
*     B - parameter .GT.0                                 I
*     ISEED - integer seed                              I/O
*
*     Author:      Walter Rosssing
*     Date  :      August 1990
*     Modified by: Michiel Jansen
*     Date   :     November 1993
*
*     Purpose:
*     The beta distribution has two parameters, A and B.
*     Mean of the distribution is A/(A+B),
*     variance is AB/[(A+B+1)(A+B)**2].
*     This pseudo random generator is fully based on FUNCTION
*      BETACH in the second edition (1987) of:
*     Bratley, P., B.L. Fox and L.E. Schrage. 1983. A guide
*        to simulation. Springer Verlag. New York. 397 pp.
*     Previous values of A and B are saved in AA and BB
*     which are initialized at impossible values
*     If A and B are not equal to AA and BB
*     the working array CON is (re)initialized.
*     The program has been adapted for the use of the RUNI
*     function for the generation of uniformly distributed
*     variates.
*
*
*     Subroutines and functions called:
*     - from library TTUTIL: ERROR
*     - RUNI
************************************************************************
      REAL FUNCTION RBET(A, B, ISEED)

*     formal parameters
      REAL A,B
```

```
      INTEGER ISEED
*     local variables and used function
      REAL AA, BB, CON(3),U1,U2,RUNI,V,W
      PARAMETER (LN4 = 1.3862944)
      SAVE
      DATA AA/-1./, BB/-1./

      IF ((A.LE.0) .OR. (B.LE.0)) THEN
        CALL ERROR('RBET', 'INVALID ARGUMENTS')
      END IF
      IF ((ISEED .LE. -2147483563) .OR. (ISEED .GE. 2147483563)) THEN
         CALL ERROR('RBET', 'INVALID ISEED')
      END IF

      IF ((A.NE.AA) .OR. (B.NE.BB)) THEN
*        (re)intialize
         AA = A
         BB = B
         CON(1) = AMIN1(A,B)
         IF (CON(1) .GT. 1.) THEN
             CON(1) = SQRT((A + B - 2.)/(2.*A*B - A - B))
         ELSE
             CON(1) = 1./CON(1)
         END IF
         CON(2) = A + B
         CON(3) = A + 1./CON(1)
      END IF
*     generation
10    U1 = RUNI(ISEED)
      U2 = RUNI(ISEED)
      V  = CON(1)*ALOG( U1/(1.-U1) )
      W  = A*EXP(V)
      IF (CON(2)*ALOG(CON(2)/(B+W)) + CON(3)*V - LN4
     $    .LT. ALOG(U1*U1*U2) ) GO TO 10
      RBET = W/(B+W)
      RETURN
100   END
```

2.2 Input file

```
************************************************************
*   RIGAUS.IN: file contains input data for the program    *
*   RIGAUS to draw at random variables from statistical    *
*   and measured distributions (December-1993)             *
************************************************************
* First, choose if the special provisions for the soil water
* balance model SAHEL have to be taken into account:
ISWI = 1    ! 0=do not take into acount; 1=take into acount

TND = 5  ! Number of Draws

ISEED = 27426  ! Seed for random drawing

********** UNIFORM ***************************
NDU = 2    ! Number of variables for drawing from UNIFORM
           ! distribution  (MAXIMUM = 10)

* Names of variables for UNIFORM distribution
VUNI = 'WCFC', 'FWCLI', 'RDT', 'SLA'

* Give lower and upper boundary, in sequence of the
* variables specified above.
UNILO = 0.10, 0.0, 5000.0, 0.15
UNIUP = 0.60, 1.0, 25000.0, 0.35

*********** BETA ***************************************
NDB = 0    ! Number of variables for drawing from BETA
           ! distribution (MAXIMUM = 10)

* Names of variables for BETA distribution
VBETA = 'BETA1', 'BETA2', 'BETA3', 'BETA4', 'BETA5',
        'BETA6'
* Give A and B parameters for BETA distribution, in sequence
* of the variables specified above.
ABETA = 1.0, 2.0, 4.0, 6.0, 8.0, 10.0
BBETA = 1.0, 1.0, 1.0, 1.0, 1.0, 1.0
* Give lower and upper boundary, in sequence of the
* variables specified above.
BETALO = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0
BETAUP = 1.0, 1.0, 1.0, 1.0, 1.0, 1.0

*********** NORMAL ******************************************
NDN = 2     ! Number of variables for drawing from NORMAL
            ! distribution (MAXIMUM = 10)

* Names of variables for NORMAL distribution
VNORM = 'STTIME', 'DTRP', 'NORM3', 'NORM4', 'NORM5'

* Give mean and variance for the NORMAL distribution,
* in sequence of the variables specified above.
```

```
MEANU =  150., 12.0, 0.0, 30.0, 60.0
VARU  =  10., 2.0, 100.0, 10.0, 10.0

************* MEASURED DATA ********************************
NMV = 0       ! Number of measured variables (MAXIMUM = 3)

* Names of measured variables
NMVAR = 'MVAR1', 'MVAR2', 'MVAR3'

* Give measured data of the above variables (MAX = 500)
MDATA1 = 1., 2., 3., 4., 5.
MDATA2 = 6., 7., 8., 9., 10.
MDATA3 = 10., 20., 30., 40., 50.
```

2.3 Output files

2.3a RERUNS.DAT

```
 * ISEED =  27426
 * This is rerun set
1
WCFC1 =  .169E+00
WCST1 =  .288E+00
WCWP1 =  .825E-02
WCFC2 =  .169E+00
WCST2 =  .288E+00
WCWP2 =  .825E-02
WCFC3 =  .169E+00
WCST3 =  .288E+00
WCWP3 =  .825E-02
FWCLI1=  .880E+00
FWCLI2=  .880E+00
FWCLI3=  .880E+00
STTIME=  .164E+03
DTRP  =  .125E+02

 * This is rerun set
2
WCFC1 =  .239E+00
WCST1 =  .361E+00
WCWP1 =  .377E-01
WCFC2 =  .239E+00
WCST2 =  .361E+00
WCWP2 =  .377E-01
WCFC3 =  .239E+00
WCST3 =  .361E+00
WCWP3 =  .377E-01
FWCLI1=  .368E-01
FWCLI2=  .368E-01
FWCLI3=  .368E-01
STTIME=  .136E+03
DTRP  =  .132E+02

 * This is rerun set
3
WCFC1 =  .484E+00
WCST1 =  .602E+00
WCWP1 =  .282E+00
WCFC2 =  .484E+00
WCST2 =  .602E+00
WCWP2 =  .282E+00
WCFC3 =  .484E+00
WCST3 =  .602E+00
WCWP3 =  .282E+00
FWCLI1=  .595E+00
FWCLI2=  .595E+00
FWCLI3=  .595E+00
STTIME=  .156E+03
DTRP  =  .117E+02

 * This is rerun set
4
WCFC1 =  .383E+00
WCST1 =  .467E+00
WCWP1 =  .128E+00
WCFC2 =  .383E+00
WCST2 =  .467E+00
WCWP2 =  .128E+00
WCFC3 =  .383E+00
WCST3 =  .467E+00
WCWP3 =  .128E+00
FWCLI1=  .461E+00
FWCLI2=  .461E+00
FWCLI3=  .461E+00
STTIME=  .147E+03
DTRP  =  .114E+02

 * This is rerun set
5
WCFC1 =  .217E+00
WCST1 =  .361E+00
WCWP1 =  .273E-01
WCFC2 =  .217E+00
WCST2 =  .361E+00
WCWP2 =  .273E-01
WCFC3 =  .217E+00
WCST3 =  .361E+00
WCWP3 =  .273E-01
FWCLI1=  .694E+00
FWCLI2=  .694E+00
FWCLI3=  .694E+00
STTIME=  .159E+03
DTRP  =  .714E+01
```

2.3b COLUMN.DAT

```
    WCFC       FWCLI      STTIME     DTRP          WCST        WCWP
 .169E+00  .880E+00  .164E+03  .125E+02  .288E+00  .825E-02
 .239E+00  .368E-01  .136E+03  .132E+02  .361E+00  .377E-01
 .484E+00  .595E+00  .156E+03  .117E+02  .602E+00  .282E+00
 .383E+00  .461E+00  .147E+03  .114E+02  .467E+00  .128E+00
 .217E+00  .694E+00  .159E+03  .714E+01  .361E+00  .273E-01
```