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ORYZA_W:
Rice growth model for irrigated and rainfed environments

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Preface

This volume of the SARP Research Proceedings presents ORYZA_W version 3.0, a simulation model for irrigated and rainfed rice production. The above-ground crop growth part of ORYZA_W is based on ORYZA1, version 1.3, described in another volume of this series.

ORYZA_W provides the user with a choice of three one-dimensional soil-water balance modules: PADDY, SAHEL and LOWBAL. SAHEL and LOWBAL are already familiar to researchers in the SARP network. Use of these two modules is, however, limited to specific environments. SAHEL was developed for freely draining 'upland' rice soils with a deep groundwater table and LOWBAL for 'lowland' rice soils with a hard plow sole (impenetrable for roots) and a deep groundwater table. Because of their frequent use in SARP, SAHEL and LOWBAL are explained in detail in this volume. PADDY was especially developed to provide the user with a universal soil-water balance module. It can handle any soil condition (puddled / non-puddled, free draining / impeded drainage, cracking / non-cracking) in irrigated and rainfed rice growing environments, and can also be used in rice / non-rice rotations. All soil-water balance modules presented here work with time steps of 1 day. We hope that ORYZA_W will prove to be of value for your research.

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Contents

1 Introduction

One of the major limitations to rice production in Asia is water supply and availability. A rice crop may need 1000 - 4000 mm of water (Tabbal et al., 1992). In both irrigated and rainfed areas there is a need to optimize water use efficiency at the regional level. This can be done through (*i*) improvement of irrigation facilities, (*ii*) introduction of water-saving techniques, (*iii*) optimization of planting time or adapting the cropping system. For any of these approaches, a thorough understanding of the system is needed. Systems analysis and simulation can be used to evaluate the potentials of different solutions for different environments.

Process-based simulation models are increasingly being used to assess attainable yields on a regional scale (van Keulen and Wolf, 1986; van Diepen et al., 1991; Hammer and Muchow, 1991). They allow detailed analysis of experimental data, extrapolation of research findings to other environments and can provide probability distributions of yield that can be used for an economic evaluation of strategies to optimize water use efficiency (Anderson, 1991). Different levels of systems approaches can be chosen to analyze water-limited environments. The question which approach to use depends on the required output of the study, on data needs and on data availability. If an approach is selected, data needs are defined. If data requirements are not met, data may be measured or estimated from databases or expert knowledge.

This manual introduces the ORYZA_W version 3.0 model, a rice growth simulation model that can simulate growth and development of rice in irrigated and rainfed *lowland* and *upland* environments. Definitions of these environments were given by IRRI (1989):

(*i*) Irrigated rice lands are those areas that have assured irrigation for one or more crops per year, with some areas served only by supplementary irrigation in the wet season

(*ii*) Rainfed lowland rice is grown in bunded fields where water depth does not exceed 50 cm for more than 10 consecutive days and the fields are inundated for at least part of the season. Such fields have no access to an irrigation system but may have on-farm rain water conservation facilities.

(*iii*) Upland rice is grown in rainfed unbunded fields with naturally well-drained soils and no surface water accumulation.

In Asia, rainfed and irrigated lowland rice soils are mostly puddled prior to direct-seeding or transplanting of rice seedlings. Puddling usually comprises one or two plowings, one or two harrowings and a final levelling under water-submerged soil conditions. Puddling reduces percolation rate, hampers weed growth and provides a soft medium for roots. After harvesting of the rice crop, sometimes an upland crop is grown, profiting from residual soil water, late season rainfall and sometimes capillary rise from a groundwater table. In case of water shortage, drying will cause a puddled soil to transfer from a muddy layer to a compact soil, a process that can be called 'soil ripening'. In upland rice ecosystems rice is grown in non-puddled soil.

ORYZA_W 3.0 is programmed under the FORTRAN Simulation Environment (FSE, version 2.0) as developed by van Kraalingen (1991). 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 initialization; `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 initialization and rate and state calculations, the reader is referred to text books on crop growth simulation modelling (e.g. Penning de Vries and van Laar, 1982; van Keulen and Wolf, 1986; Leffelaar, 1993). FSE also facilitates in- and output data handling. The WEATHER system (van Kraalingen et al., 1991) is used to read weather data. Utilities from the library TTUTIL (Rappoldt and van Kraalingen, 1990) are extensively used for specific tasks such as reading input data, writing output data, and integration of states.

The crop growth part of ORYZA_W 3.0 (ORYWAT) is based on version 1.3 of the ORYZA1 model (Kropff et al., 1994), a model for irrigated rice production, which is based on the Wageningen / IRRI models MACROS and SUCROS. ORYZA1 was modified to enable the linkage to a soil water balance module and include effects of drought on plant growth and renamed to ORYWAT.

ORYZA_W provides the user with the option to use three different soil-water balance modules: LOWBAL, SAHEL or PADDY. PADDY is a universal multiple layer (up to 10) model that can be used for both puddled and non-puddled conditions, for naturally free-draining soils and for soils with impeded drainage. PADDY also takes into account the effect of soil cracking on the water balance and can be easily adapted for rotation studies, involving fallow periods and upland crops grown after rice, provided a suitable model for the upland crop is available. Use of LOWBAL (a single layer model for lowland soils) and SAHEL (a three-layer model for upland soils) is restricted to specific environments. Details on when LOWBAL and SAHEL can be used are given in Chapter 2. PADDY can be used for any soil condition (puddled / non-puddled, free draining / impeded drainage, cracking / non-cracking) in irrigated and rainfed rice growing environments. The reader is, therefore, encouraged to use PADDY.

The soil-water balance modules explained here are all one-dimensional. Tuong et al. (1994) showed that for rice grown in puddled soil, lateral percolation losses toward and into bunds, and the effect of poorly puddled spots may largely determine the water balance in areas with a relatively permeable subsoil. More complex numerical models that allow for lateral flow into the bunds (e.g. Walker and Rushton, 1984) can be used to simulate these processes in a detailed way. One-dimensional models can still be used, provided a constant percolation rate is assumed, incorporating both vertical and lateral percolation losses (Bouman et al., 1994; Wopereis et al., 1994).

The structure of ORYZA_W 3.0 under the FSE system is schematically indicated in Figure 1.1. The ITASK succession, the reading of weather data, and the handling of input and output files are performed by the FSE system, using the libraries TTUTIL.LIB and WEATHER.LIB. This information is passed on to the subroutine MODELS. This subroutine calls ORYWAT, which is the actual above-ground growth module, and a number of crop growth subroutines in the library ORYWSUB.LIB. The three soil-water balance modules (LOWBAL for lowland soils, SAHEL for upland soils and PADDY for both lowland and upland soils) are included in the library SOILBAL.LIB.

The switch SWIWLP (set in the TIMER.DAT input file) is used to select the production environment and to combine ORYWAT with either LOWBAL, PADDY or SAHEL: SWIWLP = 0 for irrigated lowland; SWIWLP = 1 for rainfed lowland using LOWBAL; SWIWLP = 2 for rainfed upland using SAHEL and SWIWLP = 3 for irrigated or rainfed lowland or upland rice or rice-upland crop rotations using PADDY. The modules ORYWAT, LOWBAL, PADDY and SAHEL are the core of the actual growth model ORYZA_W.

In Chapter 2, differences between the three soil-water balance modules are explained. SAHEL, LOWBAL and PADDY are then introduced separately in Chapters 3, 4 and 5 respectively. Three experiments that were conducted at IRRI to investigate drought stress responses of lowland rice for model development are briefly discussed in Chapter 6. The results of these experiments were the basis for the changes made in ORYZA1, version 1.3.

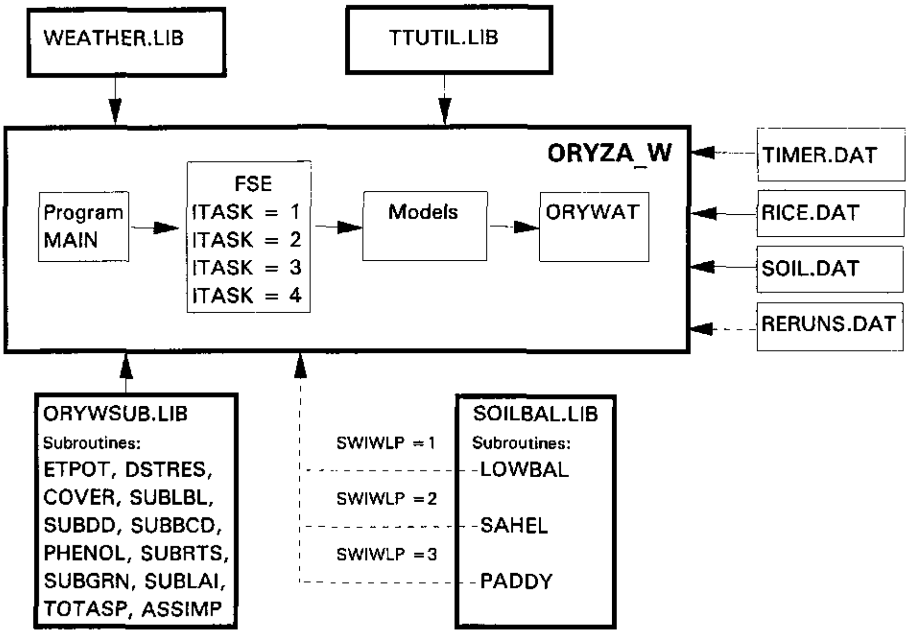

Figure 1.1 Main components of the rice growth model ORYZA_W 3.0.

The resulting rainfed rice growth module, ORYWAT is presented in Chapter 7. In Chapter 8, calculation procedures for potential and actual canopy transpiration and soil evaporation are given. In Chapter 9 editing and running of ORYZA_W is discussed. A complete listing of the model with input and output files is given in Appendices 1 - 5.

2 Choosing between the soil-water balance modules PADDY, LOWBAL and SAHEL

The ORYZA_W model contains three soil-water balance modules: PADDY, LOWBAL and SAHEL. PADDY is a universal soil-water balance module and can be used in any rice growing environment. Use of LOWBAL is restricted to lowland rice and use of SAHEL to upland rice ecosystems. Moreover, a number of simplifications have been introduced in LOWBAL and SAHEL that may make these models unsuitable under certain growing conditions. This Chapter explains such restrictions and highlights differences between PADDY and SAHEL for upland rice and PADDY and LOWBAL for lowland rice. Detailed descriptions of the three modules follow in Chapters 3, 4 and 5.

2.1 Using PADDY or SAHEL in the upland rice environment

IRRI (1988) defined the upland rice ecosystem as follows: 'Upland rice is grown in rainfed bunded or unbunded fields with naturally well-drained soils and no surface water accumulation'. If no layer is restricting water flow, modeling of water flow becomes relatively simple. An important soil characteristic is the soil water retention curve, relating soil pressure potential h to volumetric water content θ ($m^3\ m^{-3}$). The root zone can be seen as a 'box' which contains water within two predefined critical soil pressure potentials h: field capacity ($h = -10$ kPa; pF = log(|10*h|) = 2) and wilting point ($h = -1500$ kPa; pF = 4.2). When water is applied to the soil, it is assumed to be rapidly redistributed if the water content is above field capacity. The excess water flows downward. The crop can extract water up to the wilting point; water held at lower pressure heads is unavailable for plants. The soil-water balance module SAHEL is based on these simple principles. PADDY works in a similar way if a switch in the soil data file indicates that the soil profile is freely draining (`SWITFD = 1`). Soils in upland rice environments are always non-puddled. A switch in the soil data input file for PADDY indicates puddled or non-puddled conditions: `SWITPD = 0` (non-puddled) and `SWITPD = 1` (puddled). For upland soils `SWITPD` is, therefore, always equal to 0.

Figure 2.1 schematically illustrates the processes of the water balance that need to be considered in freely draining upland environments. Soils are typically of sandy to loamy texture and have a deep ground water table (> 1 m below the root zone). This type of soil has a high saturated hydraulic conductivity (around 0.1 m d^{-1} or more), permitting fast downward water transport, so that saturation of soil layers does not occur. The water balance processes considered are infiltration, percolation, evaporation, transpiration and downward distribution. Upward water flow (capillary rise) is disregarded. Lateral in- or outflow of water is always fully negligible in these situations. In SAHEL, the soil profile is divided into three layers and each is considered to be homogeneous. Thickness and physical characteristics of each layer are model inputs. The upper layer should be 0.1 - 0.2 m thick, the second 0.2 - 0.4 m, and the third 0.4 - 1.0 m. Their sum should slightly exceed the maximum rooted depth. In PADDY, a maximum of 10 layers may be defined without

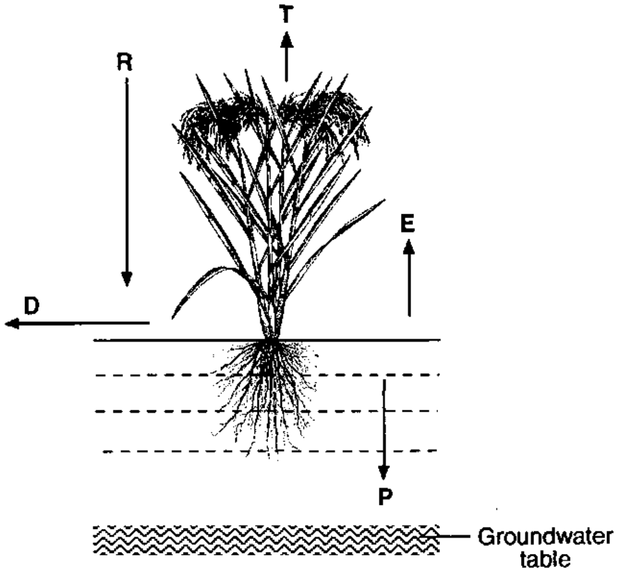

Figure 2.1 Vertical soil profile and components of the water balance that are considered in the module SAHEL and the module PADDY for freely draining rainfed upland environments. PADDY can be used for such environments if a switch (SWITFD) is set to 1 in the soil data input file. D = surface drainage, E = evaporation, P = percolation, R = rainfall, T = transpiration.

restrictions to their thickness. The (vertical) inflow and outflow of water in each layer is simulated on a daily basis. Inflow into the first layer is from rainfall. Field capacity is the highest water content that a layer can obtain. The amount of water that can not be stored in one layer, drains into the next layer or out of the profile. Water is extracted from the layers by evaporation and water uptake by the roots (transpiration). Soil evaporation loss in SAHEL is divided over the three layers. In PADDY, evaporation losses occur in the top layer only. This may result in slight differences in model outcome if all input parameters for both models are equal.

Use of SAHEL for soils with impeded internal drainage or in the presence of a shallow groundwater table is discouraged. For such conditions PADDY can be used. If the soil profile is not freely draining, the switch SWITFD should be set to 0 in the soil data input file. In doing so, the data needs of PADDY increase: knowledge of the saturated hydraulic conductivity of each layer is now needed. Water is redistributed as follows: incoming rainfall is partitioned by calculating gain and loss terms for all compartments, starting with the top compartment. Every compartment can be filled up to field capacity. Any excess water is drained at a maximum rate equal to the saturated hydraulic conductivity of the compartment. If this conductivity is too low, excess water will fill up the soil compartment itself, and may even be distributed upward, reaching compartments at shallower depth, creating a 'perched' water table.

In case of a shallow groundwater table, capillary rise to the root zone may be an important water resource for the plant. SAHEL ignores capillary rise. In PADDY, a switch `SWITGW` indicates if groundwater is present in the profile. If `SWITGW = 1`, groundwater depths are specified by the user in the soil data input file. If `SWITGW = 2`, they are calculated from downward fluxes and two empirical site-specific coefficients. If `SWITGW = 0`, groundwater is assumed to be absent in the profile. Capillary rise is calculated using a 'window structure', i.e. flow due to capillary rise between compartments is not simulated. To calculate capillary rise, knowledge of the hydraulic conductivity curve of the soil compartments is needed.

An overview of data needs and restrictions for use of PADDY and SAHEL in rainfed upland environments is given in Table 2.1.

2.2 Using PADDY or LOWBAL in the lowland rice environment

In Asia, contributing 90 - 95% of world production (Pathak and Gomez, 1991), rice in lowland environments is mostly grown under flooded conditions. To achieve this, fields are bunded and soils are puddled by plowing, followed by harrowing and levelling at water-saturated conditions. Puddling leads to destruction of soil aggregates and macropore volume and to a large increase in micropore space (Moormann and van Breemen, 1978). The vertical profile of an irrigated puddled rice soil can schematically be described by a layer of ponded water, a muddy layer with little resistance to water flow, a 'plow sole' with large resistance to water flow, and the non-puddled subsoil (Wopereis et al., 1992), as shown in Figure 2.2. The water balance of a puddled rice field is determined by the following components (Figure 2.2): irrigation supply, rainfall, evaporation, transpiration, seepage, percolation and capillary rise. Rainfall in excess of bund height leaves the system as surface runoff. This surface runoff can be an input for a neighbouring field, but in a sequence of fields, neighbouring fields will pass-on the surface runoff until it is lost in a drain, creek or ditch. Transpiration by the rice crop withdraws water from the puddled layer (which is replenished with ponded water) and from the non-puddled subsoil, if rice roots are growing sufficiently deep.

Percolation is the vertical movement of water beyond the root zone to the water table, while seepage is the lateral movement of subsurface water (IRRI, 1965). In practice, the two are often inseparable (Wickham and Singh, 1978). The amount of seepage is determined by piezometer head differences between fields. The difference in piezometer head is large near drains, ditches or creeks and in terraced rice-fields with considerable difference in elevation. Seepage loss from rice terraces in the middle of a toposequence to lower lying fields may be offset by incoming seepage from higher fields. Top-end terraces

Table 2.1. Soil data needs for modeling of the soil-water balance in upland rice growing environments. Switches for PADDY (i.e. `SWITPD`, `SWITFD`, `SWITGW`) are set in the soil data input file. `SWITPD = 0`: not puddled; `SWITPD = 1`: puddled; `SWITFD = 1`: freely draining; `SWITFD = 0`: impeded drainage; `SWITGW = 0`: groundwater table not in profile; `SWITGW = 1`: groundwater in profile, depths specified by user; `SWITGW = 2`: groundwater in profile, depths calculated.

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1. Non-puddled, freely draining soils with deep groundwater table

Model(s): SAHEL or PADDY (`SWITPD = 0, SWITFD = 1, SWITGW = 0`)

Data needs:
- thickness of the soil layers
- water retention characteristics (i.e. soil water content as a function of soil-water pressure potential *h*) for each layer
- initial soil-water content per layer
- fraction runoff
- maximum rootable depth

2. Non-puddled, freely draining soils with shallow groundwater table

Model(s): PADDY (`SWITPD = 0, SWITFD = 1, SWITGW = 1` or `SWITGW = 2`)

Data needs: As 1, but with:
- hydraulic conductivity characteristics (i.e. hydraulic conductivity *k* as a function of soil-water pressure potential *h*, including saturated hydraulic conductivity) for each layer
- groundwater table depth (if `SWITGW = 1`)
- coefficients for calculation groundwater table depth (if `SWITGW = 2`)

3. Non-puddled soils with impeded drainage and deep groundwater table

Model(s): PADDY (`SWITPD = 0, SWITFD = 0, SWITGW = 0`)

Data needs: As 1, but with:
- saturated hydraulic conductivity for each layer

4. Non-puddled soils with impeded drainage and shallow groundwater table

Model(s): PADDY (`SWITPD = 0, SWITFD = 0, SWITGW = 1` or `SWITGW = 2`)

Data needs: As 2

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will experience net seepage-loss; bottom-end terraces net seepage gain. Another possible water loss is leakage through the bunds: water moving laterally into the bunds and then down to the water table (Tuong et al., 1994). Here, under-bund flow losses are not dealt with separately but are considered part of the seepage component.

The amount of seepage is affected by the soil-physical characteristics of the field and bunds, the state of maintenance, the relative length of the bunds compared with the surface area of the field, and by the depth of the water table in the field and in the drain, ditch or creek (Wickham and Singh, 1978). The percolation rate of puddled rice fields is affected by a variety of soil factors (Wickham and Singh, 1978): structure, texture, bulk density, mineralogy, organic matter content and concentration of salts in soil solution. In general, a heavy texture, montmorillonitic clay mineralogy, high sodium content of irrigation water, and a high bulk density are favorable for effective puddling and low percolation rates. The percolation rate is further influenced by the water regime in and around the field. Increased depths of ponded water increase percolation due to the larger gradient in hydraulic head imposed (Ferguson, 1970; Sanchez, 1973; Wickham and Singh, 1978). In a field survey in the Philippines, Kampen (1970) found, for the same reason, that percolation rates were larger in fields with a deep water table (> 2 m depth) than in fields with a shallow water table (0.5 - 2 m).

A general representation of a puddled rice field water balance is:

$$dW = I + R + C - E - T - S - P - D \qquad (2.1)$$

in which (all units in mm d^{-1}):

dW = change in stored water
I = irrigation supply
R = rainfall
C = capillary rise
E = evaporation
T = transpiration
S = seepage
P = percolation
D = surface drainage (bund overflow)

In LOWBAL, Eqn 2.1 is simplified. Capillary rise is neglected. It is assumed that, in most situations, there is no or little upward flow of water through the plow sole against the water pressure in the puddled layer. The upward flow that might be present is accounted for by using a net, field-average seepage & percolation rate (see below). Secondly, the percolation rate P is assumed to be independent of water regime (ponded water depth, moisture content, ground water table). Sensitivity analyses using the detailed differential soil water balance model SAWAH (ten Berge et al., 1992) showed that this assumption is valid for most lowland situations except for a poorly puddled topsoil overlying a relatively permeable subsoil (Bouman et al., 1994). The third simplification was to combine seepage S and percolation P in a field-average constant SP. Seepage and percolation are difficult to separate in the field, and their combination into one variable is justified by the fact that both are governed by the same hydraulic principles. The constant SP can easily be determined in the field from sloping gauge readings (corrected for R, E and T). Using field-average SP rates, problems with spatial variation in location-specific S and P in the field (such as measured using double ring-infiltrometers) are overcome. P measured near a

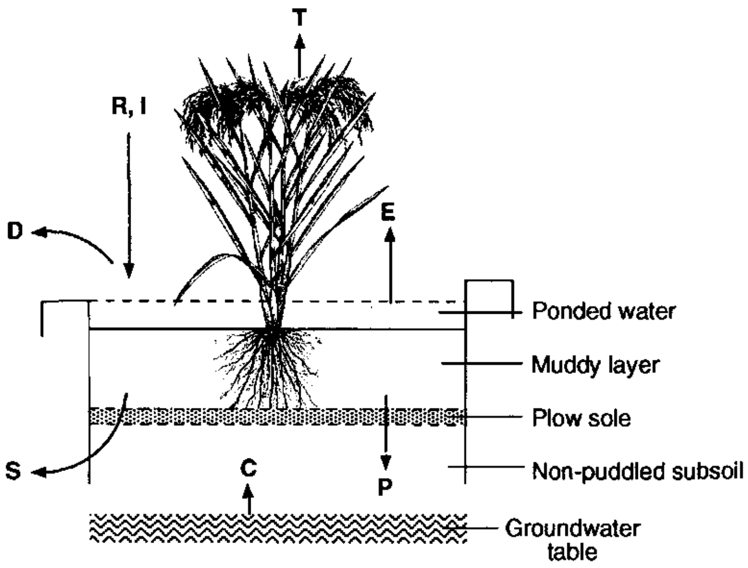


Figure 2.2 Vertical profile of puddled soil in lowland environment. D = surface drainage, E = evaporation, I = irrigation, P = percolation, R = rainfall, S = seepage, T = transpiration, C = capillary rise from the groundwater table.

bund is often much higher than *P* measured in the middle of the field, as a result of poorly puddling. Moreover, the *SP* rate measured with sloping gauges is a net value integrating water losses through vertical and lateral percolation (under bund flow) and lateral seepage to neighbouring fields, and water gains through capillary rise and lateral inflow (seepage) from neighbouring fields. The last simplification was to assume that roots do not penetrate the plow sole, and that there is no water extraction from the non-puddled subsoil.
The simplified model of the water balance used in LOWBAL becomes:

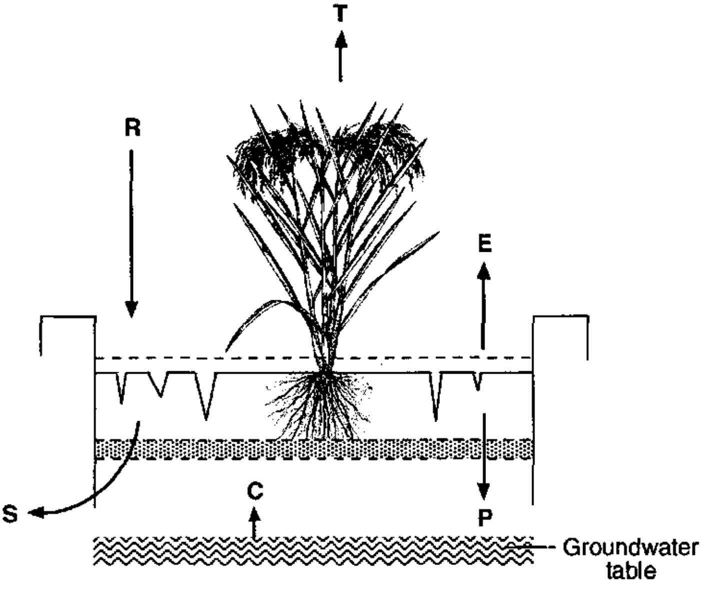
$$dW = I + R - E - T - SP - D \qquad (2.2)$$

I, *R*, *E* and *T* are input variables, and *dW* and *D* are output variables of the module. *R* is measured at meteorological stations, *I* is externally controlled, and *E* and *T* are calculated from meteorological conditions (in the subroutines ETPOT and DSTRES of ORYZA_W; see Chapters 7 and 8). *SP* is measured in the field, or estimated from soil texture data, using a suitable 'pedotransfer function' (Bouma et al., 1993; Wopereis et al., 1992).

In irrigated situations, and generally in the beginning of the season under rainfed conditions, a layer of ponded water is present in the field. Direct water loss from this ponded water layer is through evaporation, *E*. Water losses from the puddled layer by transpiration, *T*, and seepage & percolation, *SP*, are replenished using this ponded water.

In *fully irrigated* situations, irrigation is usually applied if the depth of the ponded

(a)



(b)

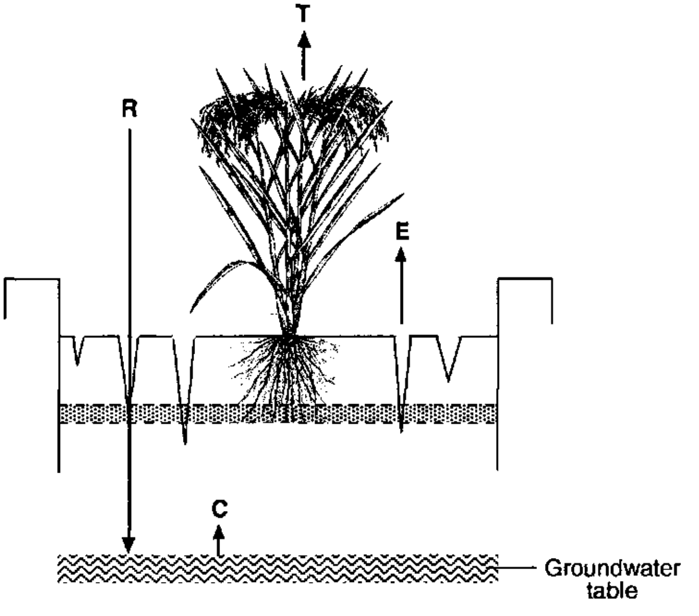


Figure 2.3 Vertical profiles of a puddled soil in a rainfed lowland environment. In (a), cracks have not yet extended through the plow sole; in (b) cracks have penetrated into the subsoil. E = evaporation, P = percolation, R = rainfall, S = seepage, C = capillary rise and T = transpiration.

Table 2.2. Soil data needs for modeling of the soil-water balance in lowland rice growing environments. Switches for PADDY (i.e. SWITPD, SWITFD, SWITGW) are set in the soil data input file. SWITPD = 0: not puddled; SWITPD = 1: puddled; SWITFD = 1: freely draining; SWITFD = 0: impeded drainage; SWITGW = 0: groundwater table not in profile; SWITGW = 1: groundwater in profile, depths specified by user; SWITGW = 2: groundwater in profile, depths calculated.

1. Puddled soils with hard plow pan impenetrable for roots and deep groundwater table

Model(s):	LOWBAL or PADDY (SWITPD = 1, SWITFD = 0, SWITGW = 0)
Data needs:	- bund height - initial depth of ponded water - thickness of soil layer(s) - saturated volumetric water content for both puddled and shrunken soil - water retention characteristics (i.e. soil water content as a function of soil-water pressure potential *h*) for each layer of the shrunken soil - initial soil-water content per layer - seepage & percolation rate - deep drainage rate subsoil (LOWBAL) - saturated hydraulic conductivity for each layer (PADDY) - water content or pressure potential at which cracks break through the plow sole - maximum rootable depth (PADDY)

2. All other puddled soils

Model(s):	PADDY (SWITPD = 1, SWITFD = 0, SWITGW = 0, 1 or 2)
Data needs:	As 1 but in case of a shallow groundwater table (SWITGW = 1 or 2): - hydraulic conductivity characteristics (i.e. hydraulic conductivity *k* as a function of soil-water pressure potential *h*, including saturated hydraulic conductivity) for each layer - groundwater table depth (if SWITGW = 1) - coefficients for calculation groundwater table depth (if SWITGW = 2)

water layer reaches a minimum value (close to 0). The amount of water in the puddled layer remains, therefore, constant throughout the growing season in irrigated systems. Farmers usually add about 5-10 cm of water during every application.

In *rainfed* lowland situations, the layer of ponded water disappears if rainfall is not sufficient to meet *E*, *T* and *SP* losses. Without ponded water, there is no hydraulic pressure to 'force' water through the plow sole and the *SP* rate is, therefore, zero. Further water loss through *E* and *T*, will cause the muddy puddled layer to dry out. The 'suspended' soil particles settle and the puddled layer shrinks. If drying-out of the puddled layer continues, cracks may develop that will broaden and widen in time (Figure 2.3a). Eventually, the cracks may extend through the puddled layer and plow sole into the subsoil (Figure 2.3b). Depending on the drainage capacity of the subsoil, water from rainfall may drain immediately through the cracks in the subsoil without replenishing the (rooted) puddled layer. In heavy clay soils with a low drainage capacity, rainfall water can still get ponded on the surface, but in case of a relatively permeable subsoil, rainfall will drain quickly. The capacity for shrinkage and cracking are soil properties that mainly depend on texture and degree of puddling; the degree of shrinkage and cracking are determined by water content or pressure head in the puddled layer. Shrinking and cracking are irreversible, i.e. the puddled layer will not resume its earlier properties (until renewed puddling in the next season).

The model LOWBAL was developed based on Eqn 2.2. For convenience, all depths of soil layers and amounts of water are expressed in mm, and all rates in mm d^{-1}. The surface of the puddled layer is the reference level from which the depth of ponded water and the height of the bunds are measured. Another simplification in LOWBAL is the use of only one soil layer. This soil layer comprises both the muddy layer and the plow sole shown in Figures 2.2 and 2.3. The non-puddled subsoil is represented by a drainage rate. If the subsoil is permeable, this value is set to a high value and vice versa. More details on LOWBAL are given in Chapter 4.

In PADDY, the number of layers is not restricted to 1 as in LOWBAL. Instead a maximum of 10 (NL) soil compartments may be defined, and the number of soil compartments within the puddled topsoil (NLPUD, including the plow sole) can be varied. For example, NL and NLPUD can be set to 8 and 3 respectively, i.e. a soil profile with three puddled soil compartments (of which the third represents the plow sole) and 5 compartments in the non-puddled subsoil. Puddled soils are not freely draining. If PADDY is used for puddled soils (`SWITPD = 1`), switch `SWITFD` should be set to 0. If `SWITPD = 1` and `SWITFD = 1`, the program will stop and an error message will occur.

Capillary rise can be included in the water balance, but this will require knowledge of the hydraulic conductivity characteristics of each soil compartment. Such hydraulic conductivity characteristics need to be specified in parameterized format, using either van Genuchten parameters (van Genuchten, 1980; van Genuchten et al., 1991) or a simple power function. Van Genuchten's equations can be written as follows:

$$S = (\theta - \theta_r) / (\theta_s - \theta_r) = [1 + |\alpha h|^n]^{-m} \quad (2.3)$$

and

$$k(S) = k_s S^l [1 - (1 - S^{1/m})^m]^2 \quad (2.4)$$

The parameter S is the degree of saturation; θ_r (-) and θ_s (-) refer to the residual and saturated values of the volumetric water content θ (-); k_s is the saturated hydraulic conductivity (cm d^{-1}); α (cm^{-1}), n (-), m (-), and l (-) are parameters which determine the shape of the functions and $m = 1 - 1/n$. Programs for parameterization of soil hydraulic properties using van Genuchten equations can be obtained via van Genuchten et al. (1991) and Wopereis et al. (1994). A power function can be written as:

$$k(h) = k_s |h|^n \tag{2.5}$$

where k_s is the saturated hydraulic conductivity (cm d^{-1}); h is the pressure potential (kPa), and n is a soil-specific dimensionless constant. The switch `SWITKH`, defined in the soil data input file is used to define the parameterization method used, i.e. `SWITKH = 1` for van Genuchten functions and `SWITKH = 2` for power functions.

Wopereis et al. (1992) showed that the percolation rate through a puddled soil is affected by both the characteristics of the non-puddled subsoil, through its hydraulic conductivity curve, and by the physical properties (i.e. hydraulic resistance) of the least permeable layer in the puddled topsoil, i.e. the plow sole. Via the switch `SWITVP`, defined in the soil data input file, PADDY provides two options for dealing with percolation rates. A constant percolation and seepage rate can be used (`SWITVP = 0`) or percolation rates can be derived using an iterative Newton-Raphson procedure (Wolfram, 1991) from hydraulic conductivity characteristics of the plow sole and the non-puddled subsoil (`SWITVP = 1`).

If a puddled soil dries out, its volume shrinks, cracks appear, and a 'soil ripening' process occurs, gradually changing the muddy topsoil into real soil. PADDY provides a subroutine SHRINK to simulate this process. It is assumed that soil shrinkage is irreversible, i.e. the total porosity of a dried, previously puddled soil layer cannot increase in case of rewetting.

3 SAHEL: three layer soil-water balance module for upland rice

The module SAHEL (Soils in semi-Arid Habitats that Easily Leach) is a three layer soil-water balance module, developed for non-puddled freely draining upland rice soils with a deep groundwater table. Capillary rise is ignored. For any other soil conditions PADDY should be used (see Chapter 5). For more details on when to use SAHEL see Chapter 2.

The soil water balance model SAHEL is based on models described by van Keulen (1975), Stroosnijder (1982) and Jansen and Gosseye (1986). The version of SAHEL used in ORYZA_W is described by Penning de Vries et al. (1989; pp. 155-160) and by van Kraalingen and Penning de Vries (1990). A complete listing of the model, list of variable names used and the soil data file needed are included in Appendix 2. Compared to the version of SAHEL as described by Penning de Vries et al. (1989) and by van Kraalingen and Penning de Vries (1990), the initialization of the water content of the soil is changed in the ORYZA_W version of SAHEL. The initial water content WCLI of each layer is not read from input file, but calculated as initial water content fraction FWCLI times the field capacity WCFC (the same way as it was defined from the water content at wilting point, WCWP, in the 'original' version of SAHEL, by van Keulen, 1975).

```
WCLI = FWCLI * WCFC
```

FWCLI is the initial water content expressed as a fraction of the water content at field capacity, and is read from input file.

3.1 Communication with the crop growth model ORYWAT

To pass-on to ORYWAT:

NL	= number of layers (-)
TKL	= array of thicknesses of soil layers (m)
TKLT	= depth of soil (m)
ZRTMS	= maximum rooting depth of soil (m)
WCWP	= array of water contents at wilting point (cm^3 cm^{-3})
WCFC	= array of water contents at field capacity (cm^3 cm^{-3})
WCST	= array of water contents at saturation (cm^3 cm^{-3})
WCLQT	= array of actual water contents (cm^3 cm^{-3})
WL0	= amount of ponded water (mm)

To get from ORYWAT:

EVSC	= potential evaporation rate (mm d^{-1})
TRWL	= array of actual transpiration rates per layer (mm d^{-1})

3.2 Model data needs

For SAHEL, the following input parameters are read from the soil data file:

TKL(1-3) = thicknesses of the soil layers (m)
WCST(1-3) = volumetric water content at saturation for each layer (-)
WCFC(1-3) = volumetric water content at field capacity (pF 2.0) for each layer (-)
WCWP(1-3) = volumetric water content at wilting point (pF 4.2) for each layer (-)
WCAD(1-3) = volumetric water content at air-dryness (pF 7) for each layer (-)
FWCLI(1-3) = initial volumetric water content as fraction of WCFC for each layer (-)
FRNOF = fraction runoff (-)
ZRTMS = maximum rootable depth (m)
EES = evaporation extinction coefficient (-)

3.3 Model validation

The SAHEL model described here was validated with a dataset presented by Wopereis et al. (1993a). The water content of the 0 - 40 cm topsoil of a non-puddled dry-seeded rice field was simulated. Good agreement between measured and simulated data were obtained (Figure 3.1). A description of the source code of SAHEL is given in Appendix 2.

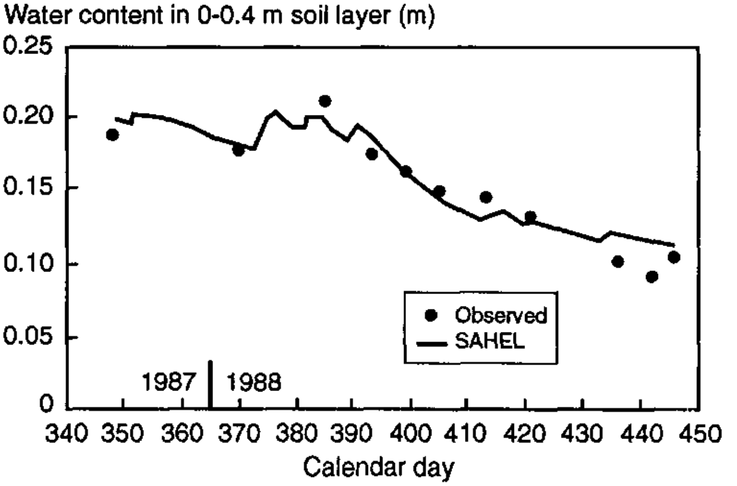


Figure 3.1 Simulated and observed soil water content in the 0-0.4 m soil layer of a dry-seeded rice field in the Philippines, non-monsoon season 1987-1988. Simulation were conducted with the SAHEL soil water balance module.

4 LOWBAL: one layer soil-water balance module for lowland rice

The module LOWBAL is a one-layer soil-water balance module, developed for puddled lowland rice soils with a plow pan impenetrable for roots and for soils with a deep groundwater table. Capillary rise is ignored. For any other soil conditions PADDY should be used (see Chapter 5). For more details on when to use LOWBAL see Chapter 2. The source code of LOWBAL is explained in detail below.

4.1 Percolation and seepage

Without cracks, the seepage and percolation rate, SP, gets the value of SPSOIL, which is read from the soil data input file. In case the ponded water depth (WL0) is not adequate, SP is set equal to WL0/DELT:

```
*------Uncracked situation
       IF (.NOT. CRACK) THEN
*--------Percolation only when ponded water is present
         IF (WL0 .LE. 0) THEN
            SP = 0.
         ELSE
           IF ((WL0/DELT) .GE. SPSOIL) THEN
             SP = SPSOIL
           ELSE
             SP = WL0/DELT
           END IF
         END IF
       END IF
```

When there is no ponded water, the soil dries out and cracks may develop. In LOWBAL, it is assumed that cracks will penetrate through the plow sole if the water content of the shrunken puddled layer drops below a critical value, WCCRAC. The value of WCCRAC depends on the soil type and is read from an input file. If the soil does not crack (or if cracks do not extend through the plow sole), WCCRAC should be set to 0 in the soil input file (Appendix 3). Cracking only affects the seepage & percolation rate, SP. If the water content in the shrunken puddled layer, WCLP, drops below WCCRAC, the seepage & percolation rate of the soil is determined by the drainage rate of the subsoil, DDR. Two situations are distinguished: The amount of ponded water and rainfall on a certain day is smaller than the amount of water that can be drained through the subsoil (DDR) (1), or the amount of ponded water and rainfall on a certain day is larger than DDR (2).

Water loss through seepage & percolation can never be larger than the combined amounts of ponded water and rainfall. If there is no ponded water and no rain, there is no seepage & percolation: SP = 0. If there is no ponded water, but there is rainfall that day, SP is equal to the amount of rainfall minus the amount of water that is 'intercepted' and evaporated from the surface:

```
*------Cracked situation
       IF (CRACK) THEN
         IF ((RAIN+WL0) .LE. DDR) THEN
            IF (WL0 .LE. 0. .AND. RAIN .EQ. 0.) THEN
              SP= 0.
            ELSE IF (WL0.LE.0. .AND. RAIN.GT.0.) THEN
              SP = MAX(RAIN-EVSW, 0.)
```

If there is some ponded water, both the amount of ponded water and rainfall are lost by seepage & percolation.

```
            ELSE
              SP = WL0 + RAIN
            END IF
```

Seepage & percolation is limited to the maximum value DDR (the surplus of WL0+RAIN fills-up the shrunken puddled layer and/or results in ponded water).

```
       ELSE
            SP = DDR
       END IF
```

Note that root growth through the cracks into the subsoil, to 'explore' for water, is not considered in LOWBAL.

4.2 Effects of shrinkage on redistribution of water

At the start of the growing season, a layer of ponded water, WL0, may be present on top of the puddled layer. The amount of water in the puddled layer itself is calculated by comparing the initial thickness of the puddled layer, just after puddling, with its thickness when it is completely dried-out. The initial thickness of the puddled layer is TKLPI. When the puddled layer dries-out, the layer will gradually shrink to a minimum value TKLPM = TKLPI*SHRINK. The factor SHRINK is soil specific and read from an input file (Appendix 3). After complete shrinkage, it is assumed here that the shrunken puddled layer is saturated with water (i.e. its water content is WCSTP). The amount of water WLP in the original puddled layer can thus be calculated as the amount of water that can be stored in the puddled soil after complete shrinkage, i.e. TKLPM*WCST, plus the difference in height between the initial thickness, TKLPI and the final thickness TKLPM:

```
WLP = (TKLPM*WCSTP) + (TKLPI-TKLPM)
```

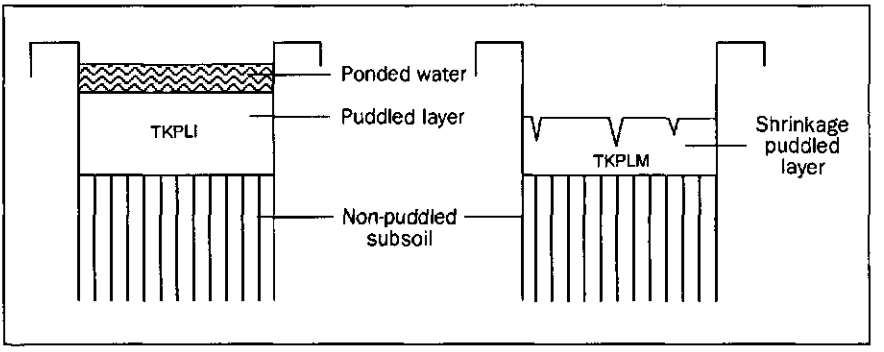


Figure 4.1 Principles of soil shrinkage modelling in LOWBAL. TKPLI = initial thickness puddled layer; TKPLM = thickness puddled layer after complete shrinkage. The difference in height between TKPLI and TKPLM is referred to as 'muddy suspension layer'.

In fact it is assumed here that a freshly puddled layer is composed of a 'muddy suspension' with thickness TKLPI-TKLPM and a saturated soil layer of thickness TKLPM (Figure 4.1). In reality, soil particles will settle upon drying, and the muddy puddled layer will gradually turn into 'real soil', a process that is called soil ripening (Wopereis, 1993). The water content of the puddled layer, WCLP, is calculated by dividing the amount of water in the puddled layer by its thickness, TKLP:

```
WCLP = WLP/TKLP
```

LOWBAL keeps track of the amount of water in both the ponded water layer and the puddled layer. Two situations are considered: ponded water is either present or not. The source code of LOWBAL is given in Appendix 3 and is discussed below, using the same numbering as in the source code listing.

Ponded water

Water loss from the ponded water layer is by evaporation, EVSW, transpiration, TRWP, and seepage & percolation, SP (SP = water flux out of puddled layer). Note that in fact, TRWP and SP are withdrawn from the puddled layer which is immediately replenished from the layer of ponded water. SP is set to the minimum of the (measured) rate allowed by the soil, SPSOIL, and the thickness of the ponded water layer that can percolate that day, WLO/DELT. Water input in the ponded layer is by rainfall, RAIN, and irrigation, RII. The depth of the ponded water layer, WLO, is the integral of the previous depth and the above rates.

```
*==============================================================*
*-----Integration section
*==============================================================*
      ELSE IF (ITASK .EQ. 3) THEN
*-----Surface drainage is standard zero
      RUNOF =0.
*-----1. Situation with ponded water
       IF (WL0 .GT. 0) THEN
         WL0 = INTGRL(WL0, (RAIN+RII+RIDUM-EVSW-TRWP-SP), DELT)
```

If the new WL0 calculated above is larger than the bund height, WL0MX, bund overflow is calculated as surface runoff, RUNOF, and WL0 is reset to bund height.

```
*--------1.1 bund overflow
         IF (WL0 .GT. WL0MX) THEN
           RUNOF = WL0 - WL0MX
           WL0 = WL0MX
```

If the new WL0 is negative (i.e. there is a shortage of ponded water), a corresponding amount of water is withdrawn from the puddled layer and WL0 is reset to 0. Again, two situations can be distinguished: the puddled layer has not yet shrunk to its minimum thickness (i.e. 1.2: actual thickness, TKLP, is larger than minimum thickness, TKLPM), and the puddled layer has shrunk completely (i.e. 1.3: TKLP = TKLPM).

If the puddled layer has not yet reached its minimum thickness, the water that is withdrawn from this puddled layer causes it to shrink further. Shrinkage can either be partial (1.2.1) or complete (1.2.2).

If the amount of water withdrawn (i.e. WL0, negative value) is not large enough to cause complete shrinkage, TKLP is reduced with the amount of lost water. The reduction of TKLP causes the lowering of the surface of the puddled layer, and hence an increase in bund height (with respect to the surface level). The amount of water in the puddled layer can still be calculated as the sum of water that can be stored in a completely shrunken layer plus the muddy suspension layer on top, with thickness TKLP-TKLPM:

```
*-------1.2 no more ponded water; soil not yet completely shrunk
         ELSE IF (WL0.LT.0 .AND. TKLP.GT.TKLPM) THEN
*---------1.2.1 further shrinkage of puddled layer
          IF (WL0 .GE. (TKLPM-TKLP)) THEN
            WL0MX = WL0MX - WL0
            TKLP = TKLP + WL0
            WLP = (WCSTP*TKLPM)+(TKLP-TKLPM)
            WCLP = WLP/TKLP
            WL0 = 0.
```

If the amount of water withdrawn (i.e. WL0, negative value) is large enough to cause complete shrinkage, TKLP shrinks to its minimum value TKLPM and further water loss is taken from the water content of the shrunken soil:

```
*---------1.2.2 complete shrinkage of puddled layer
          ELSE IF (WL0 .LT. (TKLPM-TKLP)) THEN
            WL0MX = (WL0MXI+TKLPI)-TKLPM
            TKLP = TKLPM
            WLP = (WCSTP*TKLP)+(WL0-(TKLPM-TKLP))
            WCLP = WLP/TKLP
            WL0 = 0.
          END IF
```

When the puddled layer has already shrunk to its minimum value, the amount of water that is drawn from this puddled layer (i.e. WL0, negative value) is taken will affect its water content:

```
*--------1.3 no more ponded water; soil already completely shrunken
         ELSE IF (WL0.LT.0. .AND. TKLP.EQ.TKLPM) THEN
          WLP = WLP + WL0
          WCLP = WLP/TKLP
          WL0 = 0.
         END IF
```

No ponded water

Water loss from the puddled layer is by evaporation from its surface, EVSW, and by transpiration, TRWP. Seepage & percolation, SP, is zero. Water input is by rainfall, RAIN, and irrigation, RII. The amount of water in the puddled layer is the integral of the previous amount and the above rates:

```
*------2. Situation with no ponded water
       ELSE IF (WL0 .LE. 0) THEN
         WLP = INTGRL (WLP, (RAIN+RII+RIDUM-EVSW-TRWP-SP), DELT)
```

Two situations can be considered next: the water storage capacity of the completely shrunken puddled layer is either adequate (2.1) or inadequate (2.2): i.e. WLP is either smaller or larger than (TKLPM*WCSTP).

In the completely shrunken situation, the thickness of the puddled layer is minimal, and bund height has reached its maximum value. Upon further drying, its water content will drop below saturation and is calculated by dividing the amount of water stored by the thickness of the completely shrunken layer.

```
*--------2.1 completely shrunken puddled layer


         IF (WLP .LE. (TKLPM*WCSTP)) THEN
```

```
      TKLP = TKLPM
      WL0MX = (WL0MXI+TKLPI)-TKLP
      WCLP = WLP/TKLP
      WL0 = 0.
```

The amount of water in the puddled layer consists of the amount of water that could be stored in case of complete shrinkage, TKLPM*WCSTP, plus the muddy suspension layer on top, with thickness TKLP-TKLPM.

If the new amount WLP is larger than the old amount, (TKLPM*WCSTP)+(TKLP-TKLPM), a new layer of ponded water is formed on the puddled layer and WLP is reset to its old value (since the shrinkage of the puddled layer is irreversible, TKLP can not increase). The thickness of the new ponded water layer is equal to the new amount of water minus the old amount, with a maximum determined by the bund height.

```
*--------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
        WL0D = WLP - ((TKLPM*WCSTP)+(TKLP-TKLPM))
        IF (WL0D .GT. WL0MX) THEN
          WL0 = WL0MX
          RUNOF = WL0D - WL0MX
        ELSE
          WL0 = WL0D
        END IF
        WLP = (TKLPM*WCSTP)+(TKLP-TKLPM)
        WCLP = WLP/TKLP
```

If the new amount WLP is smaller than the old amount, (TKLPM*WCSTP)+(TKLP-TKLPM), further shrinkage of the puddled layer will occur. Water is taken from the muddy suspension layer, i.e. TKLP will decrease and bund height WL0MX will increase.

```
*----------2.2.2 further shrinkage of puddled layer

      ELSE IF (WLP .LT. ((TKLPM*WCSTP)+(TKLP-TKLPM))) THEN
        TKLP = WLP-(TKLPM*WCSTP)+TKLPM
        WL0MX = (WL0MXI+TKLPI)-TKLP
        WCLP = WLP/TKLP
        WL0 = 0.
      END IF
```

4.3 Irrigation

In *rainfed* lowland (switch SWIWLP = 1), the amount of irrigation is set to zero: RII = 0. In *irrigated* lowland (SWIWLP = 0), irrigation is simulated as a dynamic variable, i.e. the (timing of) irrigation is simulated as function of the depth of ponded water. In the seed-bed, it is assumed that the crop is nearly continuously irrigated: a daily amount of irrigation, RIDUM, is applied that equals the losses by seepage & percolation and by evaporation and transpiration:

```
RIDUM = SP + TRWP + EVSW - RAIN
```

On the day of transplanting, the amount of irrigation water so far needed for the main field is initialized as RIPUD: the total amount of water needed for land preparation, puddling and any evaporation of the bare field until transplanting. This amount should be empirically determined and is read from an input file (Appendix 3).

```
RIICU = RIPUD
```

In the main field after transplanting, a fixed amount of irrigation, RIGIFT, is applied to the field when the depth of ponded water drops below a critical, minimum level, WL0MIN. This irrigation is applied until the crop reaches the growth stage, DVSIE, when no more irrigation is given, because of ripening of the crop.

```
IF (WL0 .LE. WL0MIN .AND. DVS .LT. DVSIE) THEN
RII = RIGIFT
```

RIGIFT and WL0MIN depend on management practices of farmers and are read from an input file (Appendix 3).

4.4 Integration of water balance components

The following components of the water balance are integrated over the period between transplanting and the end of the season (i.e. for the main field): cumulative irrigation, RIICU, cumulative runoff as bund overflow, RNOFCU, cumulative rain, RAINCU, cumulative seepage & percolation, SPCU, and cumulative evaporation, EVSWCU:

```
RIICU  = INTGRL (RIICU, RII, DELT)
RNOFCU = INTGRL (RNOFCU, RUNOF, DELT)
RAINCU = INTGRL (RAINCU, RAIN, DELT)
SPCU   = INTGRL (SPCU, SP, DELT)
EVSWCU = INTGRL (EVSWCU, EVSW, DELT)
```

If the crop is direct-seeded, the above state variables are integrated from sowing onward.

4.5 Communication with ORYWAT

Some variables are introduced in LOWBAL for communication with the above-ground growth module ORYWAT.

To pass-on to ORYWAT:

```
NL        = 1
```
(note: only one soil layer in LOWBAL)

```
WCWP(1)   = WCWPP
WCFC(1)   = WCFCP
WCST(1)   = WCSTP
WCAD(1)   = WCADP
WCLQT(1)  = WCLP
TKL(1)    = TKLPI/1000.
```
(note: in ORYWAT, layer thickness is in m!)

```
TKLT      = TKLPI/1000.
```

To get from ORYWAT:

```
TRWP      = TRWL(1)
EVSC
```

4.6 Model data needs

The following parameters are read from the soil data input file (all units in mm or mm d^{-1}):

WL0MXI	=	initial bund height (maximum thickness of 'first' layer)
TKLPI	=	initial thickness of the puddled layer
SPSOIL	=	potential seepage & percolation rate
DDR	=	deep drainage rate subsoil
WL0I	=	initial depth of ponded water
WL0MIN	=	critical depth of ponded water below which irrigation is applied
SHRINK	=	linear shrinkage factor
WCCRAC	=	volumetric water content shrunken puddled layer below which cracks extend through the plow sole
WCSTP	=	volumetric water content at saturation of shrunken puddled layer
WCFCP	=	volumetric water content at field capacity of shrunken puddled layer (pF 2)
WCWPP	=	volumetric water content at wilting point of shrunken puddled layer (pF 4.2)
WCADP	=	volumetric water content at air-dryness of shrunken puddled layer (pF 7)
RIGIFT	=	irrigation application
RIPUD	=	amount of water needed for land preparation (puddling) at the start of the growing season, plus water losses from the main field between land preparation and transplanting

DVSIE = development stage of the crop at which no more irrigation is applied.

Values for the above parameters depend on soil type (mainly texture, mineralogy, organic matter content, bulk density), soil preparation (e.g. the manner and effectiveness of puddling), general land preparation (e.g. bunding, plowing), and irrigation management. Some indicative values are:

WL0MXI = 100 - 200 mm, as measured from the top of the puddled soil.

TKLPI = 150 - 200 mm.

SPSOIL = with well-puddled, clayey soils, generally reported values are about 1-5 mm d^{-1} (Wickham and Singh, 1978). In more unfavorable areas, SP rates can increase to 25 mm d^{-1} and more

DDR = depends on soil type: in heavy, compact clay soils, values may be as low as 1 - 10 mm d^{-1}; in coarse loamy or sandy soils, values may be as high as 100 - 1000 mm d^{-1} or more. Usually, values of the saturated hydraulic conductivity of the soil will be used for DDR.

WL0I = 50 mm.

WL0MIN = if possible, farmers will prevent the drying of the puddled layer to avoid shrinkage and cracking; values may be around 0 - 10 mm. Note: because of the time step of one day in ORYWAT, a rather high value should be chosen if shrinkage is to be prevented, e.g. 10 mm.

SHRINK = not many data on the shrinkage characteristics of puddled soils are available. In field observations in Tarlac Province, the Philippines, the following values have been found for the ratio of total porosity of puddled top soil over total porosity of shrunken, ripened top soil, for soils with different texture:

0.65 for sand:silt:clay = 23:43:54 %
0.70 for sand:silt:clay = 33:41:26 %
0.73 for sand:silt:clay = 9:27:64 %
0.74 for sand:silt:clay = 27:28:45 %
0.78 for sand:silt:clay = 36:37:27 %
0.79 for sand:silt:clay = 74: 3:23 %
0.81 for sand:silt:clay = 23:23:54 %
0.93 for sand:silt:clay = 33:24:43 %

The average ratio is 0.77. As first approximation, these data can be used for the linear shrinkage factor.

WCCRAC = Measurements at the IRRI farm in the Philippines revealed that cracks penetrated the plow sole if the average pressure potential of the puddled topsoil dropped below –0.1 MPa (Wopereis, 1993; p. 121 and Tuong, unpublished data); the corresponding water content can be calculated using the soil's water retention curve. For non-cracking soils, WCCRAC is set to 0. WCCRAC is very soil specific and information on this soil parameter is scarce. To determine WCCRAC for a specific site, depth of

		cracking and soil-water contents in the topsoil should be monitored during a soil drying cycle.
WCST-WCAD	=	As a first approximation, data of non-puddled soil can be used. In reality, these values will depend on the degree of drying of the puddled soil (Taylor, 1972).
RIGIFT	=	depends on the irrigation management practice. A typical value is 50 mm.
RIPUD	=	should be empirically determined for the area under consideration. Typical values are 200 - 300 mm.
DVIE	=	in general, irrigation is stopped near the end of the growing season to allow ripening of the crop; development stage 1.8 - 2.0.

4.7 Model validation

The model LOWBAL was validated for irrigated lowland conditions using data from field experiments conducted at IRRI (Figure 4.2), and with model simulations using the detailed soil water balance model SAWAH (Bouman et al., 1994). The model performs accurately if seepage & percolation rates, SP, have been measured and do not change in time. Field average SP rates can easily be measured using sloping gauges placed in the field. Percolation rates may change if the plow sole at the bottom of the puddled layer is disturbed, as e.g. occurred in an IRRI field experiment by hand weeders (Wopereis, 1993; pp. 108-109). Seepage may occur where it was originally not present when neighbouring fields are drained at the end of the growing season, thus inducing water flow through and underneath bunds. Seepage may also change if water levels in neighbouring ditches, creeks or drains vary. These changes of seepage rates 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 general, the changes in seepage rate as mentioned above will mostly occur at the end of the growing season; for the main part of the growing season, LOWBAL will, therefore, be applicable.

For rainfed lowland situations, LOWBAL has not been tested explicitly. However, the process description of shrinkage and cracking is similar to the one used in PADDY (see Chapter 5). The model PADDY was validated with field experiments at IRRI. In LOWBAL, shrinkage is treated as a linear decrease of soil pores, and hence of puddled soil depth, with loss of water. In reality, shrinkage of puddled soil follows three phases: linear shrinkage, residual shrinkage and zero-shrinkage (Bronswijk, 1988; Ishiguro, 1992). It is expected that this simplification in LOWBAL will not lead to serious errors in estimating the water balance. In LOWBAL, soil cracking is treated in an empirical way: if the soil moisture content of the ripened top soil drops below a critical value, cracks are assumed to break through the plow sole. It is expected that simulations will be more crude for cracking soils than for non-cracking soils. More research is needed on ripening and cracking of puddled soils of different texture. Finally, in LOWBAL it is assumed that roots do not penetrate the plow sole. This simplification is not always warranted: e.g. at the IRRI farm, it was found that roots penetrated the plow sole and extended up to 0.40 m depth (i.e. 20 cm below the puddled top soil) with drying of the puddled layer. Under such conditions, modelling of the soil water content below the puddled layer, and the extraction of water by the roots becomes important, as can be done with the soil water balance module PADDY explained in Chapter 5.

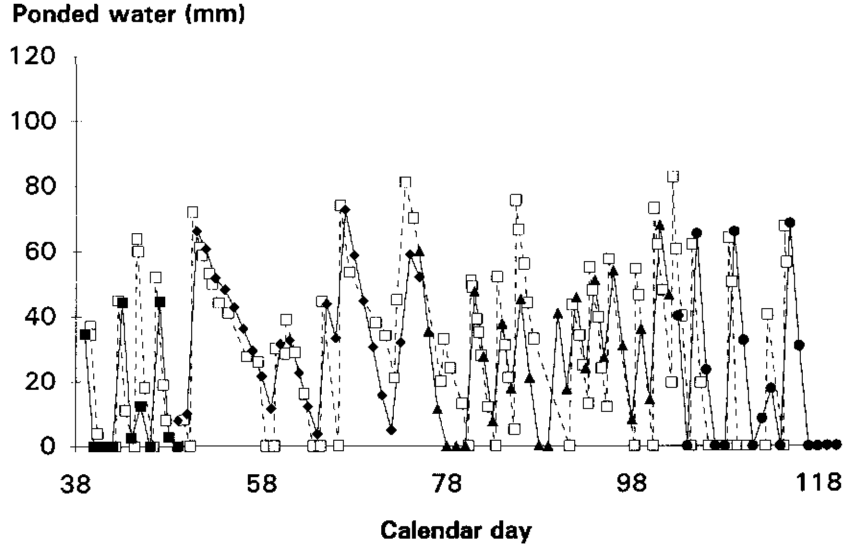


Figure 4.2 Simulated (black dots) and observed (white dots) depths of ponded water in a field experiment conducted at the IRRI farm, Los Baños, Philippines (Bouman et al., 1994).

5 PADDY: soil-water balance module for lowland and upland rice and for rice-upland crop rotations

The model PADDY was developed to simulate the soil-water balance for all rice growing conditions (with / without water limitations, puddled / non-puddled, free draining / impeded drainage) and for upland crops grown after rice. The program is written in FORTRAN and makes use of the Fortran Simulation Environment (FSE, van Kraalingen, 1991). PADDY is a multi-layer (up to 10) integral soil-water balance model. A complete listing of the source code, an explanation of variable names used and an overview of input files needed is given in Appendix 4.

Switches set in the soil data input file (Appendix 4) define if the soil profile is freely draining (SWITFD = 1) or not (SWITFD = 0). In PADDY, this switch is translated into a logical FREEDR for easy reading. If SWITFD = 1 then FREEDR = .TRUE., else FREEDR = .FALSE. Another switch in the soil data input file defines if the topsoil is puddled (SWITPD = 1) or not (SWITPD = 0). In PADDY, this switch is translated into a logical PUDDLD. If SWITPD = 1 then PUDDLD = .TRUE., else PUDDLD = .FALSE. Combining (SWITFD = 1) and (SWITPD = 1) is not possible, as puddled soils are assumed not to be freely draining.

A typical soil profile of a puddled rice soil consists of a muddy layer with little resistance to water flow, an often compacted layer with large resistance to water flow (plow sole) and the non-puddled subsoil (Figure 2.2). In the soil data input file the number of puddled soil compartments (including the plow sole!) is defined as NLPUD. Usually NLPUD will be set to 3, i.e. the 2 first soil compartments comprise the muddy layer and the third compartment represents the plow sole. If NLPUD is set to 4 than the fourth compartment represents the plow sole and so on. Thickness of each soil compartment is defined by the user in the soil data file. Percolation rate through the puddled topsoil (i.e. muddy layer and plow sole) is either calculated using an iteration procedure (see Section 5.1) or assumed to be constant. The maximum number of soil layers is 10.

Continued drying of a puddled soil results in the formation of soil shrinkage cracks and subsidence of the soil surface. During this process the muddy layer gradually transforms in a soil layer, a process that can be called 'soil ripening'. In PADDY this soil ripening process is modelled using a separate subroutine. A simple subroutine with limited data needs is available (see Section 5.2). In contrast to LOWBAL, subsidence of the soil surface is not simulated. Cracks penetrate through a soil layer if its pressure head h drops below a critical value, which is defined in the soil data input file (Appendix 4). The soil's water balance may change radically if cracks penetrate through the plow sole, breaking its function as a barrier to downward flow.

A third switch in the soil data input file determines if groundwater is present in the soil profile (SWITGW). In PADDY this switch is translated into a logical GRWAT. If SWITGW = 1 or SWITGW = 2, then GRWAT = .TRUE., else GRWAT = .FALSE.. Groundwater table depth is either an input into the model (SWITGW = 1) or is calculated from downward fluxes (SWITGW = 2). Capillary rise to soil compartments above the groundwater table is calculated using a 'window-structure', i.e. water flow to each soil compartment is calculated separately. No flow due to capillary rise occurs between boundaries of soil compartments. Time step of integration of PADDY is one day. The source code of PADDY and associated subroutines, a list of variables, explanations and dimensions and the soil data file needed are included in Appendix 4.

5.1 Percolation and seepage

Ponded water drains in the soil profile via percolation or seepage. A switch SWITVP, defined in the soil data file, determines if a combined percolation and seepage rate (PERCOL) is read from the soil data file (SWITVP = 0). If seepage losses can be neglected, the user can choose for an option to calculate the percolation rate through the puddled topsoil (SWITVP = 1). For freely draining non-puddled soils (SWITFD = 1), ponded water is quickly drained to the subsoil and the value for SWITVP is ignored.

The subroutine SATFLX is called if SWITVP = 1. It can calculate percolation rates provided the saturated hydraulic conductivity of the plow sole (soil layer NLPUD, see above) and the hydraulic conductivity curve of the subsoil directly below the plow sole (soil layer NLPUD + 1) are known. Wopereis et al. (1992) showed that the percolation rate through a puddled soil is affected by both the characteristics of the non-puddled subsoil, through its hydraulic conductivity curve, and by the physical properties (i.e. hydraulic resistance) of the least permeable layer in the puddled topsoil, i.e. the plow sole. The switch SWITKH in PADDY, can be used to define hydraulic conductivity characteristics with van Genuchten parameters (SWITKH = 1) or using a power function (SWITKH = 2). These functions are given in Chapter 2.

Using an iterative Newton-Raphson procedure (Wolfram, 1991) fluxes through the plow sole and the non-puddled subsoil are calculated in a separate subroutine SATFLX and compared until the difference between both fluxes become negligible. The procedure is illustrated in Figure 5.1. SATFLX starts with taking a random value for the pressure head h in the non-puddled subsoil (1). The difference between the flux through the puddled topsoil (f_t) and the non-puddled subsoil (f_s) at that pressure head is then calculated (2). The flux through the puddled topsoil equals (Wopereis et al., 1992):

$$f_t = -k_s (h_t - h_b + z_l) \ / \ z_l) \tag{5.1}$$

where k_s is the hydraulic conductivity of the soil layer (cm d^{-1}), and h_t and h_b pressure head (cm) at top and bottom of the plow sole respectively. Assuming gravity flow in the subsoil, the flux in the subsoil can be written as (Wopereis et al., 1992):

$$f_s = -k(h_b) \tag{5.2}$$

If the difference between f_t and f_s is too large, the intersection of the tangent line with the x-axis is calculated, which yields a new value for h_b (3). A new difference between fluxes f_t and f_s is calculated (4) etc. The calculations continue until the difference between f_t and

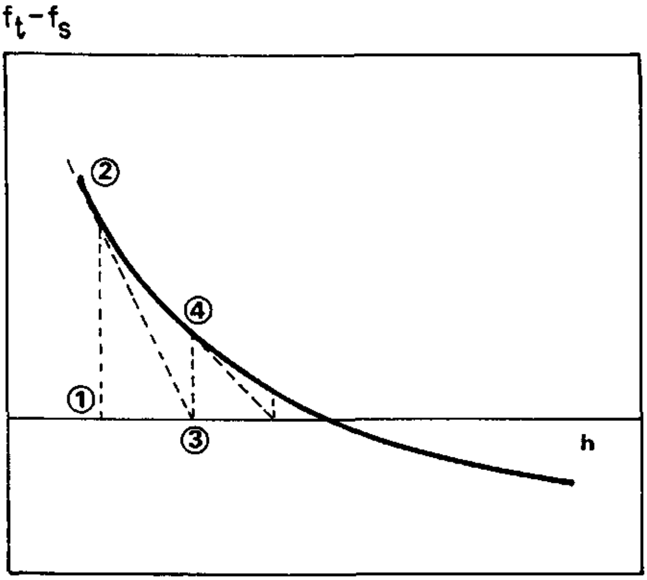


Figure 5.1 Iterative procedure used in the subroutine SATFLX to calculate percolation rates for a puddled soil by minimizing the difference between the fluxes through the plow sole (f_t) and the non-puddled subsoil (f_s).

f_s becomes close to zero. A listing of the subroutine SATFLX is given in Appendix 4.

The module SATFLX was validated by comparing steady state percolation rates calculated with the one-dimensional dynamic soil-water balance model SAWAH (ten Berge et al., 1992) and PADDY. SAWAH simulates fluxes between compartments using small variable time steps. From Table 5.1 it can be seen that SAWAH and PADDY predictions are close if the plow sole conductivity is small, regardless of groundwater table depth. SWITVP should not be used if the conductivity of the plow sole is known to be larger than 0.1 cm d^{-1} (for more details see Bouman et al., 1994). Under such circumstances percolation rates predicted by PADDY may be too small and a constant percolation and seepage rate should be defined instead.

5.2 Soil ripening and cracking of a puddled topsoil

If a puddled soil dries out, its volume shrinks, cracks appear, and a 'soil ripening' process occurs, gradually changing the muddy topsoil into real soil. PADDY provides one subroutine to simulate this process (subroutine SHRINK). It is assumed that soil shrinkage is irreversible, i.e. the total porosity of a dried, previously puddled soil layer cannot increase in case of rewetting, unless intensive re-puddling is carried out. The approach is similar to the one used in LOWBAL. A shrinkage factor, defined as the ratio of total porosity of puddled and non-puddled soil is used to calculate volume change. It is assumed

Table 5.1. Steady-state percolation rates calculated using PADDY and SAWAH, at a constant ponded water depth of 15 cm. k_s is the saturated hydraulic conductivity of the plow sole. Hydraulic conductivity characteristics of the subsoil taken from Wopereis et al. (1993b).

k_s ($cm\ d^{-1}$)	SAWAH (groundwater table at 1 m) infiltration rate ($mm\ d^{-1}$)	SAWAH (groundwater table at 5 m) infiltration rate ($mm\ d^{-1}$)	PADDY infiltration rate ($mm\ d^{-1}$)
0.03	1.4	1.4	1.7
0.1	4.5	4.5	5.2
0.3	33.4	149.5	14.9

that the puddled soil remains saturated during shrinkage, i.e. water loss equals volume change, until the total porosity is equal to that of non-puddled soil. From that moment on the soil pressure potential decreases and the rice plant may start to suffer from drought stress. Important differences with LOWBAL are that more than one shrinking soil layer can be defined and that subsidence of the soil surface is neglected. Inputs to the subroutine SHRINK are: volume of water in soil compartment `I`, `WL(I)` in mm, thickness `TKL(I)` in mm, and saturated volumetric water content after puddling and ripening (`WCST(I)` and `WCSTRP(I)` respectively, in $m^3\ m^{-3}$). Outputs are volumetric water content `WCL(I)` in $m^3\ m^{-3}$, and total porosity, `TOTPOR(I)` in $m^3\ m^{-3}$, and new thickness of the soil layer after shrinkage, `VL(I)` in mm.

```
                 CALL SHRINK (ITASK,I,WL(I),TKL(I),WCST(I),WCSTRP(I),
     &              WCL(I),TOTPOR(I),VL(I))
```

SHRINK is not used to simulate the depth of soil cracks. This would be possible by dividing the puddled topsoil into a large number of small compartments, and by calculating the water content and volume change of each small compartment. If water loss in the soil profile is determined by evaporation and incoming rainfall only (no crop) this is feasible, as was shown by Bronswijk (1989). If a rice crop is grown, the situation is a lot more complex as the uptake of water by the crop as a function of depth is unknown. In PADDY a more empirical approach is therefore used. Bronswijk (1988) presented the simulation model FLOCR, in which shrinkage characteristics of soils are included as hydraulic parameters that can be specified for each soil layer. In this version of PADDY a simplified approach to shrinkage is followed as it is expected that data on soil shrinkage characteristics of puddled soil material will be rarely available.

The soil's water balance may change radically if cracks penetrate through the plow sole. Field experiments conducted at the International Rice Research Institute (IRRI) showed that cracks penetrated through the plow sole if the pressure potential of the topsoil dropped below −100 kPa (IRRI, 1992). In PADDY, cracks are assumed to have penetrated through a soil compartment if its simulated water content drops below a value, corresponding to a critical pF value. This critical pF value is defined in the soil data file (PFCR), see Appendix 4. A corresponding soil water content WCCR is calculated using the subroutine SUWCMS2 if SWITPF = 1 or via linear interpolation if SWITPF = 0. This subroutine is derived from SUWCMS (ten Berge et al., 1992), see Section 5.9.

```
      IF (PUDDLD) THEN
*------- Initialize SHRINK subroutine

*------- Calculate water content when cracks penetrate through a
*------- soil compartment
         IF (SWITPF.EQ.1) THEN
            CALL SUWCMS2(NLPUD,2,WCST(NLPUD),WCCR,10**PFCR)
         ELSE
            IF (PFCR.LE.4.2.AND.PFCR.GE.0) THEN
               WCCR = WCWP(NLPUD)+((WCFC(NLPUD)-WCWP(NLPUD))/2.2)*
     &                                (4.2-PFCR)
            ELSEIF (PFCR.GT.4.2.AND.PFCR.LE.7) THEN
               WCCR = WCAD(NLPUD)+((WCWP(NLPUD)-WCAD(NLPUD))/2.8)*
     &                                (7.0-PFCR)
            ELSE
               STOP 'PLEASE CHECK VALUE PFCR IN SOIL DATA FILE'
            END IF
         END IF
```

If cracks break through a soil compartment, its saturated hydraulic conductivity value KSAT is set to an arbitrarily chosen high value (1000 cm d^{-1}). A message is sent to the screen if cracks break through a soil compartment. The actual water content of a soil layer WCL(I) is compared with the value of WCCR.

```
     IF (PUDDLD) THEN
         I = 1
         DO WHILE (I.LE.NL. AND. I.LE.NLPUD)
             CALL SHRINK (ITASK,I,WL(I),TKL(I),WCST(I),WCSTRP(I),
     &                    WCL(I),TOTPOR(I),VL(I))
            IF (WCL(I).LT.WCCR) THEN
               KSAT(I) = 1000.
               PRINT *,'CRACKS REACHED BOTTOM COMPARTMENT ',I
            END IF
            IF (WCL(NLPUD).LT.WCCR) CRACKS = .TRUE.
```

The new saturated storage capacity of the soil layer `I`, `WLST(I)` (unit: mm) is calculated by multiplying new thickness `VL(I)` (unit: mm) by the new total porosity `TOTPOR(I)` (unit: -). The storage capacity at field capacity of layer `I`, `WLFC(I)` (unit: mm) is assumed to be equal to the saturated storage capacity:

```
            WLST(I) = VL(I)*TOTPOR(I)
            WLFC(I) = WLST(I)
          I = I + 1
        END DO

      END IF
```

This last assumption is not backed by any data or literature reference but is assumed to be a reasonable estimate for most puddled soils.

5.3 Redistribution of water in the soil profile

If the soil profile is freely draining (`SWITFD = 1`), redistribution of soil-water is modeled in PADDY in a similar way as in SAHEL (see Chapters 2 and 3). It is assumed that the hydraulic conductivity of each soil layer, when wet, is very high, and that water between saturation and field capacity is drained within the time step of 1 day used in the model. Data on hydraulic conductivity are not an input for PADDY if `SWITFD = 1`. Instead, in PADDY the saturated hydraulic conductivity of each soil layer is automatically set to an arbitrarily chosen high value (1000 cm d^{-1}). If the soil profile is not freely draining (`SWITFD = 0`), the saturated hydraulic conductivity of each soil layer needs to be specified. The maximum flux through a soil layer is then equal to this saturated hydraulic conductivity. If the soil profile is puddled (`SWITPD = 1`), one of the soil layers in the topsoil (the plow sole) will usually have a low saturated hydraulic conductivity. The combination of `SWITPD = 1` and `SWITFD = 1` cannot be used in PADDY as it is assumed that puddled soils are not freely draining. If groundwater is present in the profile (`SWITGW = 1`), capillary rise to soil layers above the one containing the groundwater table is considered, if their soil water content is below field capacity. The water contents of the soil layer that contains the groundwater table and those at greater depth are reset to saturation. The initial moisture content of the soil profile is defined by the user:

```
      CALL RDAREA ('WCLI',WCLI,10,NL)
```

The drying sequence in a rainfed rice system can be divided into two stages:

1. Ponded water
2. No ponded water

Phase 1 will never occur for freely draining soils. For *puddled* systems, phase 2 can be subdivided into:

2.1 No ponded water and shallow soil cracks

2.2 No ponded water and deep soil cracks

'Shallow' soil cracks (phase 2.1) are cracks that have not yet penetrated through the plow sole (Figure 2.3a). 'Deep' soil cracks (phase 2.2) have (Figure 2.3b), which, depending on the subsoil's permeability, may lead to a radical change in the soil's water balance. If there is ponded water (phase 1), the ponded water level will change according to:

$$\mathrm{d}W_\mathrm{p} = I + R + C - E - P - T - D \qquad (5.1)$$

where (all dimensions in mm d^{-1}):

$\mathrm{d}W_\mathrm{p}$ = change in ponded water depth
I = irrigation supply
R = rainfall
C = capillary rise
E = evaporation
T = transpiration
P = percolation
D = bund overflow / surface runoff

1. Ponded water

In PADDY, the amount of ponded water is the starting point of calculations at the beginning of each day. If there is ponded water, three situations can be considered: ponded water can sustain both evaporation and transpiration demands (1.1); ponded water can sustain evaporation but only partly transpiration demand (1.2) and ponded water can sustain only part of the evaporation demand (1.3).

1.1 Ponded water can sustain both evaporation and transpiration demands

The ponded water level in the field, WL0, possibly augmented with rainfall RAIN and/or irrigation IR, is sufficient to sustain both evaporation (EVSC) and transpiration (TRW) demands. EVSC and TRW are calculated in the subroutine ETPOT (Chapter 8) and are an input to PADDY. A change in ponded water level WL0CH is calculated comparing gains (RAIN+IR) and losses of water (EVSC+TRW). Note that WL0 is a state variable (unit: mm); WL0/DELT and WL0CH are rate variables (unit: mm d^{-1}).

A counter DSPW resets the number of days without ponded water back to 1. This counter is used for calculation of evaporation from the soil, as will be explained later.

```
*------- 1. Ponded water on field
      IF (WL0.GE.TINY) THEN
```

```
*---------- reset number of days after ponded water
         DSPW = 1

*---------- 1.1 Ponded water can sustain evaporation and transpiration
         IF (WL0/DELT+RAIN+IR.GE.EVSC+TRW) THEN
*------------- calculate change in ponded water depth (mm/d)
            WL0CH = RAIN+IR-EVSC-TRW
```

The total transpiration requirement TRW is calculated in the subroutine ETPOT and is divided equally over the various soil compartments within the root zone (array TRWL(I), where I is the soil compartment number). Both TRW and TRWL(I) are input variables for PADDY. In this case, however, transpiration loss TRW can be covered completely from ponded water present on the soil surface. No water is, therefore, taken from the soil and transpiration losses per soil compartment are reset to zero.

```
*------------- reset transpiration losses per soil compartment to zero
*------------- as transpiration is taken from ponded water
            I = 1
            DO WHILE (I.LE.NL)
            TRWL(I) = 0
            I = I + 1
            END DO
*------------- for water balance check
            EVSW = EVSC
            EVSWS = 0.
```

If the soil is not freely draining (SWITFD = 0) and if, in case of a puddled soil, cracks have not yet reached the plow sole, downward water flow is determined by a percolation rate.

```
            IF ((.NOT.FREEDR).AND.(.NOT.CRACKS)) THEN
*------------- calculate percolation rate (mm/d)
```

The switch SWITVP determines if the percolation rate, PERC, is calculated using the subroutine SATFLX (SWITVP=1) or read from an input file (PERC = PERCOL if SWITVP=0). PERC can never be larger than the amount of ponded water left on the soil surface, after subtraction of transpiration and evaporation losses (WL0/DELT+WL0CH). The in's and out's of SATFLX are explained in Section 5.1. For non-puddled soils SWITVP must be 0. If this is not the case, the program is stopped and a warning is sent to the screen.

```
            IF (SWITVP .EQ. 0) THEN
                  IF (WL0/DELT+WL0CH.GE.PERCOL) THEN
                     PERC = PERCOL
                  ELSE
                     PERC = WL0/DELT+WL0CH
```

```
                  END IF
               ELSE
                  IF (.NOT.PUDDLD)
     &               STOP 'SWITVP MUST BE 0 FOR NON-PUDDLED SOIL'
                  IF (NLPUD.LT.NL) THEN
                     CALL SATFLX (TKL,NLPUD,WL0,PERC)
                  ELSE
                     STOP 'SWITVP MUST BE 0 IF NL = NLPUD'
                  END IF
                  IF (WL0/DELT+WL0CH.LE.PERC)
     $                PERC = WL0/DELT + WL0CH
               END IF
```

After assessment of the percolation rate, the change in ponded water depth is recalculated.

```
*------------- recalculate change in ponded water depth (mm/d)
            WL0CH = WL0CH - PERC
```

The amount of water in excess of bund height, WL0MX, is lost from the soil profile as runoff, RUNOF.

```
*------------- calculate runoff (mm/d) if ponded water depth
*------------- exceeds bund height

            IF (WL0+WL0CH*DELT.GE.WL0MX) THEN
               RUNOF = (WL0+WL0CH*DELT-WL0MX)/DELT
               WL0CH = WL0CH-RUNOF
            END IF
```

In total, NL+1 flow rates are used in PADDY, where NL = number of soil compartments. WLFL(1) is the flow rate at the ponded water - soil surface interface; WLFL(2) is the flow rate at the soil layer (1) - soil layer (2) boundary etc. In this case all flow rates are assumed to be equal to the percolation rate.

```
            I = 1
            DO WHILE (I.LE.NL+1)
               WLFL(I) = PERC
               I = I + 1
            END DO
```

For non-puddled soils and for puddled soils with cracks deeper than the plow sole, the ponded water on the soil surface will flow downward with a rate that depends on the hydraulic characteristics of the subsoil. In this case the concept of percolation rate cannot be used. Instead, two subroutines determine the fate of water flow: DOWNFL and BACKFL.

```
         ELSE
*---------- calculate flow through boundaries of soil compartments

            WLFL(1) = RAIN + IR - EVSC - TRW
            I = 1
            DO WHILE (I.LE.NL)
               CALL DOWNFL(I,KSAT(I),WLFL(I),TRWL(I),EVSWS,WL(I),
     &                  WLFC(I),DELT,WLFL(I+1))
               I = I + 1
            END DO

            IF (.NOT. FREEDR) THEN
               I = NL
               DO WHILE (I.GE.1)
                  CALL BACKFL(I,WL(I),WLFL(I),WLFL(I+1),EVSWS,
     &              TRWL(I),WLST(I),DELT,FLNEW,REST)
                  WLFL(I) = FLNEW
                  I = I - 1
               END DO
```

Using the subroutine DOWNFL, incoming rainfall is redistributed by calculating for all compartments gain and loss terms, starting with the top compartment. All water in excess of field capacity is drained from the compartment, with a maximum rate equal to the saturated hydraulic conductivity of the compartment, `KSAT(I)`. If the rate is low, the water content of the compartment may reach saturation, i.e. a perched water table may develop. Note that `KSAT(I)` is multiplied by a factor 10 to convert from cm d^{-1} to mm d^{-1}.

```
      SUBROUTINE DOWNFL(I,KSAT,FLIN,TRWL,EVSWS,WL,WLFC,DELT,FLOUT)

      IMPLICIT REAL (A-H,J-Z)

      IF (I.EQ.1) THEN
         FLOUT = MIN(10*KSAT,MAX(0.,FLIN-EVSWS-TRWL+(WL-WLFC)/DELT))
      ELSE
         FLOUT = MIN(10*KSAT,MAX(0.,FLIN-TRWL+(WL-WLFC)/DELT))
      END IF
      RETURN
      END
```

If the soil profile is not freely draining, one or more soil layers in the profile restrict water flow. Using the subroutine BACKFL and starting with the last compartment, in- and outflow fluxes are then compared. If the outflow flux for a given compartment is too low (i.e. the resulting water content of the compartment would be higher than its saturated water content), the excess water is redistributed upward. This means that, although the cracked topsoil is freely draining, water may still start ponding on the soil surface because of a layer with a low saturated hydraulic conductivity deeper in the soil profile. Ponding of water will occur if the REST term (HLP in subroutine BACKFL) for I = 1 is larger than the water holding capacity of the first soil compartment (WLST(1)).

```
      SUBROUTINE BACKFL(I,WL,FLIN,FLOUT,EVSWS,TRWL,WLST,DELT,
     &                   FLNEW,HLP)

      IMPLICIT REAL (A-H,J-Z)

      HLP = 0.
      IF (I.EQ.1) THEN
         HLP = WL+(FLIN-FLOUT-EVSWS-TRWL)*DELT
      ELSE
         HLP = WL+(FLIN-FLOUT-TRWL)*DELT
      END IF
      IF (HLP.GT.WLST) THEN
         FLNEW = FLIN - (HLP-WLST)/DELT
      ELSE
         FLNEW = FLIN
      END IF
      RETURN
      END
```

Water in excess of bund height is lost from the soil profile through runoff:

```
                  WL0CH = MAX(0.,(REST-WLST(1))/DELT )

                  IF (WL0+WL0CH*DELT.GE.WL0MX) THEN
                     RUNOF = (WL0 + WL0CH*DELT-WL0MX)/DELT
                     WL0CH = WL0CH - RUNOF
                  END IF
               END IF
            END IF
```

1.2 Ponded water depth can sustain evaporation but only part of transpiration

If the ponded water level and the incoming amount of water via rain and irrigation (WL0/DELT+RAIN+IR) are not sufficient to meet transpiration and evaporation demands (EVSC+TRW), all ponded water will be consumed (WL0CH = -WL0/DELT).

```
*---------- 1.2 Ponded water depth can sustain evaporation but
*----------     only part of transpiration

         ELSE IF ((WL0/DELT+RAIN+IR.GE.EVSC).AND.
     $                     (WL0/DELT+RAIN+IR.LT.EVSC+TRW)) THEN
```

```
*------------- calculate change in ponded water depth (mm/d)
          WL0CH = -WL0/DELT
```

Percolation rate PERC is assumed to be zero in this case, as no ponded water is left. This also holds for the flow from the rest of the soil compartments (WLFL(I)).

```
*------------- percolation is zero because no ponded water left
          PERC = 0.
          I=1
          DO WHILE (I.LE.NL+1)
             WLFL(I) = PERC
             I = I + 1
          END DO
```

The part of transpiration not yet accounted for (TRW+EVSC-RAIN-IR-WL0/DELT) is covered by water taken from the soil profile. These losses are divided equally over the root zone soil compartments I. The transpiration loss per soil compartment, TRWL(I), an input to PADDY, is corrected with the factor ((TRW+EVSC-RAIN-IR-WL0/DELT)/ TRW):

```
*------------- correct transpiration losses per soil compartment as
*------------- transpiration losses are partly covered by ponded water

          I = 1
          DO WHILE (I.LE.NL)
             TRWL(I) = ((TRW+EVSC-RAIN-IR-WL0/DELT)/TRW)
     $                                               *TRWL(I)*DELT
             I = I + 1
          END DO

*------------- for water balance check
          EVSW = EVSC
          EVSWS = 0.
```

1.3 Ponded water can only sustain part of evaporation demand

As all ponded water is used to cover the evaporation demand, percolation rate is assumed to be zero. The flux at the soil surface WLFL(1) is equal to incoming rainfall and irrigation, RAIN + IR. Transpiration losses are covered completely by water taken from the soil profile. These losses (TRWL(I)) are an input to PADDY.

```
*---------- 1.3 Ponded water can sustain part of evaporation only
        ELSE IF (WL0/DELT+RAIN+IR.LT.EVSC) THEN
*---------- calculate change in ponded water depth (mm/d)
          WL0CH = -WL0/DELT
          PERC = 0.
          WLFL(1) = RAIN + IR
```

```
            I = 2
            DO WHILE (I.LE.NL+1)
               WLFL(I) = PERC
               I = I + 1
            END DO
```

The evaporation demand not yet accounted for, EVSC+WLOCH is taken from incoming rainfall and irrigation (RAIN+IR) and, from water available in the topsoil compartment i.e. actual water content, WL(1), minus water content when air dry, WLAD(1). Because EVSC, WLOCH, RAIN and IR are all rate variables, these water contents need to be divided by the time step DELT. The sum of the amount of water available in the topsoil compartment plus rainfall and irrigation sets a limit to the value of EVSW.

```
*---------- calculate contribution of first soil compartment to
*---------- evaporation
            EVSW = MIN(EVSC+WLOCH,WL(1)/DELT-
     $                                   WLAD(1)/DELT+RAIN+IR)
            EVSWS = EVSW
*------------- for water balance check
            EVSW = WL0/DELT+EVSWS
         END IF
```

2. *No ponded water*

If there is no ponded water, the evaporative demand is met by taking water from the first soil layer. Actual soil evaporation is calculated by assuming that the cumulative evaporation is proportional to the square root of time. The rate of evaporation on the first day without ponded water is assumed to be 60% of the potential soil evaporation. A counter DSPW keeps track of the number of days that have passed without ponded water. A similar approach was used by Penning de Vries et al. (1989).

```
      ELSE
*------- 2. No ponded water on surface
*------- calculate evaporation rate from soil surface (mm/d)
         EVSH = MIN(EVSC,MAX(0.,(WL(1)-WLAD(1))/DELT+RAIN+IR))
         EVSD = MIN(EVSC,0.6*EVSC*(SQRT(DSPW)-SQRT(DSPW-1.))+RAIN+IR)
         EVSW = INSW(DSPW-1.1,EVSH,EVSD)
         EVSW = MIN(EVSW,MAX(0.,RAIN+IR+(WL(1)-WLAD(1))/DELT))
         EVSWS = EVSW
         DSPW = DSPW + 1
```

The subroutines DOWNFL and BACKFL are again used to redistribute water in the soil profile. The subroutine BACKFL is only called if the profile is not freely draining (SWITFD = 0).

```
         I = 1
         DO WHILE (I.LE.NL)
            CALL DOWNFL(I,KSAT(I),WLFL(I),TRWL(I),EVSWS,WL(I),
```

```
&                             WLFC(I),DELT,WLFL(I+1))
            I = I + 1
         END DO

         IF (.NOT.FREEDR) THEN
            I = NL
            DO WHILE (I.GE.1)
               CALL BACKFL(I,WL(I),WLFL(I),WLFL(I+1),EVSWS,
&                            TRWL(I),WLST(I),DELT,FLNEW,REST)
               WLFL(I) = FLNEW
               I = I - 1
            END DO
```

Water in excess of bund height is lost from the soil profile through runoff:

```
            WL0CH = MAX(0.,(REST-WLST(1))/DELT )
            IF (WL0+WL0CH*DELT.GE.WL0MX) THEN
               RUNOF = (WL0 + WL0CH*DELT-WL0MX)/DELT
               WL0CH = WL0CH - RUNOF
            END IF
         END IF
      END IF
```

5.4 Groundwater table

The switch SWITGW, defined in the soil data file (Appendix 4) determines if groundwater is present in the soil profile. This switch is translated into a logical GRWAT in PADDY: GRWAT = .TRUE. if SWITGW = 1 or SWITGW = 2, else GRWAT = .FALSE.. The new groundwater table depth is read from a table (SWITGW = 1) or calculated (SWITGW = 2). In both cases the subroutine GWTAB is used.

```
      IF (GRWAT) THEN
*------- new groundwater table depth
         ZWPREV = ZW
         CALL GWTAB(ITASK,SWITGW,NL,DOY,DELT,WLFL,TKL,ZWPREV,
&                   IGW,ZW)
      END IF
```

Input to subroutine GWTAB are: ITASK (1: initialization; 3: integration), SWITGW (if SWITGW = 1: input from table, if SWITGW = 2, groundwater table is calculated), NL (number of soil layers), DOY (day of year), DELT (time step of integration, usually 1 day), WLFL (array containing fluxes at soil layer boundaries), TKL (array of thickness soil layers) and ZWPREV (previous groundwater table depth). Output are IGW (shallowest soil compartment in groundwater) and ZW (new groundwater table depth). If SWITGW = 1, groundwater table depth is read from the table ZWTB. If SWITGW = 2, it is assumed that the groundwater table depth is receding with a constant speed, ZWA. The flux at the bottom of the soil layer IGW, WLFL(IGW), multiplied with a sensitivity factor ZWB brings the water table closer to the soil surface (following lines taken from subroutine GWTAB):

```
      IF (SWITGW.EQ.1) THEN
         ZW = LINT(ZWTB,IZWTB,DOY)
      ELSE
         ZW = ZW + ZWA - ZWB*10*WLFL(IGW)*DELT
         IF (ZW.LT.MINGW) ZW = MINGW
         IF (ZW.GT.MAXGW) ZW = MAXGW
      END IF
```

In PADDY, it is assumed that soil layers I in the subsoil, that are saturated with water because of the presence of a groundwater table, drain to their field capacity water content, WLFC(I) within the time step DELT (one day). The flux from each soil compartment I, WLFL(I+1) is calculated taking into account drainage to field capacity, DRAIN, losses due to transpiration (TRWL(I)), and the flux into this soil compartment, WLFL(I). The shallowest soil compartment containing groundwater is known via calls to the subroutine GWTAB (stores this compartment number in the variable IGP, see above).

```
   IF (GRWAT) THEN
*------- drain compartments in groundwater
      I = IGW
      DO WHILE (I.LE.NL)
         IF (WL(I).GE.WLFC(I)) THEN
            DRAIN = (WL(I)-WLFC(I))/DELT
            WLFL(I+1) = DRAIN+MAX(0.,WLFL(I)-TRWL(I))
         ELSE
            WLFL(I+1) = MAX(0.,WLFL(I)-TRWL(I)+
     $                  (WL(I)-WLFC(I))/DELT)
         END IF
         I = I + 1
      END DO
```

After resetting the soil water contents to field capacity, the current groundwater table depth ZW obtained from a call to the subroutine GWTAB (see above) is used to fill soil compartments up to saturation:

```
   I = NL
      GWTOT = 0.
      DO WHILE (I.GE.1)
         GWFILL(I) = 0.
*---------- check if groundwater in soil compartment
         GWCHK = MAX(0.,ZW-ZL(I)-0.5*TKL(I)/10.)
         IF (GWCHK.EQ.0) THEN
```

```
            PRINT *,'Groundwater in compartment ',i
            IF (I.EQ.1) THEN
               GWFILL(I) = MAX(0,(WLST(I)-WL(I))/DELT+TRWL(I)+
     $                    WLFL(I+1)+EVSWS-WLFL(I))
            ELSE
               GWFILL(I) = MAX(0,(WLST(I)-WL(I))/DELT+TRWL(I)+
     $                    WLFL(I+1)-WLFL(I))
            END IF
            GWTOT = GWTOT + GWFILL(I)
         END IF
```

5.5 Capillary rise

Capillary rise to soil compartments above the groundwater table is calculated using a "window-structure", i.e. water flow to each soil compartment is calculated separately. No flow due to capillary rise occurs between boundaries of soil compartments. Capillary rise from the groundwater table to a soil compartment is assumed to occur only if the soil moisture content of this compartment is below field capacity. The soil pressure head, MS (in mbar or cm H_2O), prevailing in the soil compartment is calculated with the subroutine SUWCMS2, derived from SUWCMS (ten Berge et al., 1992). Field capacity water content is assumed to occur if `MS = 100` mbar (pF = 2).

```
*---------- only capillary rise if compartment is below field
*---------- capacity (MS > 100 mbar)
         MS = 0.
         FLOW = 0.
         IF (WL(I).GT.WLAD(I).AND.WL(I).LT.WLFC(I).AND.
     $       ZW.GT.ZL(I)+TKL(I)/10.) THEN
            IF (SWITKH.NE.0) THEN
               CALL SUWCMS2(I,1,WCST(I),WCL(I),MS)
               IF (MS.GT.100.) THEN
```

Capillary rise is calculated using the WOFOST routine SUBSOL (van Diepen et al., 1988), which is slightly changed to allow for the use of Van Genuchten parameters. The routine is, to avoid confusion, renamed to SUBSL2. Input to SUBSL2 is the soil pressure head `MS` calculated with the subroutine SUWCMS2:

```
                  CALL SUBSL2(LOG10(MS),ZW-ZL(I)+
     &                  0.5*TKL(I)/10.,I,WCST(I),FLOW)
               END IF
c if flow negative (percolation) then reset to zero
               IF (FLOW.LT.0) FLOW = 0.
               IF (I.EQ.1) THEN
                  CAPRI(I) = MIN(FLOW,(WLST(I)-WL(I))/DELT+
```

```
&                                  EVSWS+TRWL(I)+WLFL(I+1)-WLFL(I))
                  ELSE
                     CAPRI(I) = MIN(FLOW,(WLST(I)-WL(I))/DELT+
&                                      TRWL(I)+WLFL(I+1)-WLFL(I))
                  END IF
               END IF
            END IF
```

Capillary rise can only decrease with increasing distance from the groundwater table. If the calculated capillary rise of a compartment higher in the profile is larger than the compartment below, the capillary rise is reset to the value of the compartment closer to the groundwater table:

```
            IF (I.LT.NL) THEN
               IF (CAPRI(I).GT.CAPRI(I+1).AND.CAPRI(I+1).GT.0)
&                                       CAPRI(I) = CAPRI(I+1)
            END IF
            CAPTOT = CAPTOT + CAPRI(I)
            I = I - 1
         END DO
```

5.6 Changes in soil water content

At the end of the dynamic section of the module, changes in water content of the soil compartments (WLCH(I)) are calculated.

```
      I = 1
      DO WHILE (I.LE.NL)
         IF (I.EQ.1) THEN
            WLCH(I) = WLFL(I)-WLFL(I+1)-TRWL(I)-
$                     EVSWS+CAPRI(I)
         ELSE
            WLCH(I) = WLFL(I)-WLFL(I+1)-TRWL(I)+CAPRI(I)
         END IF
         WCUMCH = WCUMCH + WLCH(I)
         I = I + 1
      END DO
```

During the integration phase of the module, changes in state variables are integrated using a time step of one day.

```
*---- integration of state variables
      WL0 = INTGRL(WL0,WL0CH,DELT)
      I = 1
      DO WHILE (I.LE.NL)
```

```
      WL(I) = INTGRL(WL(I),WLCH(I),DELT)
      WCL(I) = WL(I)/TKL(I)
      I = I + 1
   END DO
```

For puddled soils `WCL(I)` is recalculated using the subroutine SHRINK as explained in Section 5.2.

5.7 Water balance check

At the end of the integration section, a water balance check is carried out. First cumulative amounts of water balance components are calculated:

```
*---- cumulative amounts
      DRAICU = DRAICU - WLFL(NL+1)*DELT
      UPRICU = UPRICU + CAPTOT*DELT
      EVSWCU = EVSWCU - EVSW*DELT
      RAINCU = RAINCU + (RAIN+IR)*DELT
      RNOFCU = RNOFCU - RUNOF*DELT
      TRWCU = TRWCU - TRW*DELT
```

Changes in soil water content and ponded water depth are compared with inflow and outflow at the boundaries of the soil profile, using the module SUWCHK (ten Berge et al., 1992). SUWCHK compares the total change in system water content `CKWIN` with the total of external contributions to system water content, `CKWFL`.

```
*----- water balance check
      WCUM = WCUM + WCUMCH*DELT

*----- contribution of profile to water balance, since start
      PROREL = WCUMCH
      WCUMCO = WCUMCO + PROREL*DELT

*----- contribution of surface water to water balance, since start
      SURREL = WLOCH
      WLOCO = WLOCO+SURREL*DELT

*----- total change in system water content
      CKWIN = WCUMCO + WLOCO

*----- total of external contributions to system water content
      CKWFL = RAINCU + RNOFCU + EVSWCU + TRWCU + UPRICU + DRAICU
*----- check this
      CALL SUWCHK (CKWFL,CKWIN,TIME)
```

5.8 Irrigation

A switch SWITIR, set in the soil data file, determines if the soil is irrigated if the ponded water depth on the soil profile WL0 drops below a minimum value WL0MIN (SWITIR = 2). Irrigation can also be read from a table defined in the soil data file (Appendix 4), RIRRIT, if SWITIR = 1.

```
*------- if irrigated, supply constant irrigation (mm/d) if ponded water
*------- level is below minimum
      IF (SWITIR.EQ.1) IR = LINT(RIRRIT, IRIRR, DOY)
      IF (WL0 .LE. WL0MIN.AND.SWITIR.EQ.2) THEN
         IR = IRRI
      END IF
```

If an irrigation table is used it is important to realize that IR for a specific day is calculated via linear interpolation. Each irrigation day should be preceded by a day without irrigation and should be followed by a day without irrigation. If for example irrigation is applied on calendar days 10, 50 and 100 (50 mm) than a correct RIRRIT table would be:

```
RIRRIT = 1., 0., 9., 0., 10., 50., 11., 0., 49., 0., 50., 50., 51., 0.,
99., 0., 100., 50., 101., 0., 400., 0.
```

and not simply:

```
RIRRIT = 10., 50., 50., 50., 100., 50.
```

as this would result in irrigation on calendar days between 10 and 50 and 50 and 100 as well. It is assumed that the seedbed is continuously irrigated. Water losses due to percolation (PERC), evaporation (EVSC) and transpiration (TRW) are covered by an irrigation application IR:

```
      IF (ITIM .LT. ITRT) THEN
         IR = PERC + EVSC + TRW
      END IF
```

5.9 Other subroutines used by PADDY

Besides the subroutines SATFLX, SHRINK and SUBSL2 explained above, PADDY uses the following subroutines from SAWAH (ten Berge et al., 1992): SUERR, SUWCHK, SUMSKM and SUWCMS. SUERR checks if a value of a variable is within a specified domain. SUWCHK checks the soil-water balance by comparing time-integrated boundary fluxes versus changes in the total amount of water contained in the system. SUMSKM calculates the hydraulic conductivity at given suction for compartment I on the basis of a chosen option. SUWCMS calculates volumetric soil-water content from soil-water suction and vice versa. Both SUMSKM and SUWCMS were adapted slightly and renamed to SUMSK2 and SUWCMS2 respectively. SUWCMS2 works with Van Genuchten parameters only (see Chapter 2). SUMSK2 works with Van Genuchten parameters and power functions (see Chapter 2).

5.10 Important switches

Switch	Meaning
SWITFD	profile is freely draining (1); layers are impeding water flow (0)
SWITPD	topsoil is puddled (1); soil is not puddled (0)
SWITPF	water retention data given at saturation, field capacity, wilting point and when air dry (0); water retention data parameterized via Van Genuchten function (1)
SWITKH	no hydraulic conductivity characteristics available (0); hydraulic conductivity data parameterized via van Genuchten function (1); hydraulic conductivity data parameterized via power function (2)
SWITGW	groundwater not present in profile (0); groundwater depth read from input file (1); groundwater depth calculated (2)
SWITVP	percolation rate read from input file (0); percolation rate calculated (1)
SWITIR	no irrigation (0); irrigation read from table (1); irrigation if ponded water depth drops below minimum value (2)

5.11 Communication with ORYWAT

Some variables are introduced in PADDY for communication with the above-ground module ORYWAT.

To pass-on to ORYWAT:

NL	=	number of soil compartments	-
TKLP(I)	=	array with thicknesses of soil compartments	m
TKLT	=	total depth soil profile	m
ZRTMS	=	maximum rooting depth soil	m
WCL(I)	=	array with actual soil water contents per soil layer I	$cm^3\ cm^{-3}$
WL0	=	ponded water depth	mm
WCWP(I)	=	array with volumetric soil moisture contents at wilting point	$cm^3\ cm^{-3}$
WCFC(I)	=	array with soil moisture contents at field capacity	$cm^3\ cm^{-3}$
WCST(I)	=	array with soil moisture contents at saturation	$cm^3\ cm^{-3}$

To get from ORYWAT:

TRWL(I)	=	array with actual transpiration rates per soil layer I	$mm\ d^{-1}$
EVSC	=	potential evaporation rate	$mm\ d^{-1}$

5.12 Model data needs

Data needs for PADDY are (depending on soil condition, i.e. free draining, impeded drainage, puddled, non-puddled):

NL	number of soil compartments	-
TKL	array of thicknesses of soil compartments	m
WCLI	initial volumetric water content of soil compartment	$m^3\ m^{-3}$
RIRRIT	irrigation table	$mm\ d^{-1}$
IRRI	irrigation applied if ponded water depth lower than minimum value	$mm\ d^{-1}$
SWITIR	irrigation switch	
SWITPD	puddled / non-puddled switch	
SWITPF	water retention switch	
SWITKH	hydraulic conductivity switch	
SWITFD	free drainage / impeded drainage switch	
SWITGW	groundwater switch	

If SWITPD = 1 (soil is puddled):

SWITVP	percolation rate switch	-
NLPUD	number of puddled soil compartments	-
WCSTRP	saturated volumetric water content of ripened soil	$m^3\ m^{-3}$
PFCR	critical pF value where cracks break through compartment	-

If SWITPF = 0 (water retention data from table):

WCST	saturated volumetric soil water content	$m^3\ m^{-3}$
WCFC	volumetric water content at 'field capacity'	$m^3\ m^{-3}$
WCWP	volumetric water content at 'wilting point'	$m^3\ m^{-3}$
WCAD	volumetric water content when 'air-dry'	$m^3\ m^{-3}$

If SWITPF = 1 (water retention curve is parameterized using Van Genuchten function):

VGA	Van Genuchten alpha parameter	cm^{-1}
VGL	Van Genuchten lambda parameter	-
VGN	Van Genuchten n parameter	-
VGR	Van Genuchten residual water content	-
WCST	saturated volumetric soil water content of puddled topsoil	$m^3\ m^{-3}$

If SWITKH = 1 (conductivity curve is parameterized using Van Genuchten function):

KST	saturated hydraulic conductivity	$cm\ d^{-1}$
VGA	Van Genuchten alpha parameter	cm^{-1}
VGL	Van Genuchten lambda parameter	-
VGN	Van Genuchten n parameter	-
VGR	Van Genuchten residual water content	-

If SWITKH = 2 (conductivity curve is parameterized using power function):

KST	saturated hydraulic conductivity	cm d^{-1}
PN	parameter n in power function for hydraulic conductivity	-

If SWITFD = 0 (profile is not freely draining):

- Percolation rates and saturated hydraulic conductivity:

PERCOL	percolation rate from soil data input file	mm d^{-1}
KST	saturated hydraulic conductivity	cm d^{-1}

-Bund heights and ponded water depths:

WL0I	amount of initial ponded water	mm
WL0MIN	minimum amount of ponded water before start of irrigation	mm
WL0MX	maximum amount of ponded water (= bund height)	mm

If SWITGW = 1 or SWITGW = 2 (groundwater table is present in profile):

- If groundwater table depth is read from table (SWITGW = 1):

ZWI	initial depth of groundwater table below soil surface	cm
ZWTB	table with groundwater table data	-

- If groundwater table depth is calculated (SWITGW = 2):

MAXGW	maximum groundwater table depth	cm
MINGW	minimum groundwater table depth	cm
ZWA	depth groundwater table is receding in case of no recharge	cm
ZWB	sensitivity factor of recharge	-
ZWTBI	initial depth of groundwater table below soil surface	cm

Methods to measure soil hydraulic properties were described in details by Wopereis et al. (1994).

5.13 Model validation

For non-puddled soil conditions, PADDY was tested using data from a drought experiment conducted by Hasegawa and Yoshida (1982) at IRRI. Average soil hydraulic characteristics at various depths were taken from Wopereis et al. (1993b). Potential transpiration rates, calculated by the subroutine ETPOT were multiplied by a factor 1.3 to allow for the high evapotranspiration rate measured in the experimental field caused by its isolated location (Hasegawa and Yoshida, 1978). LAI was simulated. All other crop parameters were taken from Kropff et al. (1994). Observed and simulated water contents were in excellent agreement (Figure 5.2).

For flooded puddled soil conditions, PADDY was tested using data from a field experiment (field experiment 1) conducted at IRRI in the dry season of 1991 (cv. IR72) and described in detail by Wopereis et al. (1994) and Bouman et al. (1994). Input variables were rainfall, irrigation, evapotranspiration rates from daily weighing of pots installed in the field and groundwater table depths measured using piezometers. Average and upper and lower extreme values for measured hydraulic conductivity of the plow sole (k_s) and the non-puddled subsoil were used. Simulated and observed changes in ponded water depth were compared. For non-flooded soil conditions, the ORYZA_W model was tested using data from a second experiment (field experiment 2), conducted in the dry season of 1992 on a 2000m^2 field (cv IR72). For details see Wopereis (1993).

PADDY accurately predicted the changes in ponded water depth for field experiment 1 if average hydraulic conductivity data were used (k_s = 0.082 cm d^{-1}, see Figure 5.3). Discrepancies after calendar day 80 were due to disturbance of the plow sole by hand weeders. Wopereis et al. (1992) tested the differential SAWAH soil water balance module (ten Berge et al., 1992) with the same field data. Results from this study showed that the iteration procedure using in PADDY to calculate the flux through the soil profile under flooded soil conditions was as effective as the small time step calculations used in SAWAH. Observed and simulated root zone water content (Figure 5.4) were compared. The results indicated that the model could satisfactorily explain differences in soil water content across drought treatments.

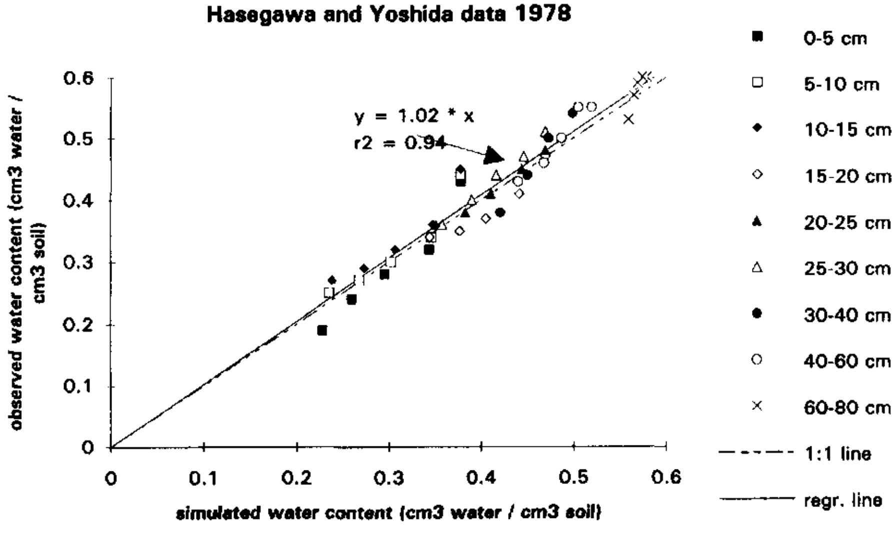


Figure 5.2 Simulated and observed soil water contents at various depths in the soil profile using the soil-water balance module PADDY and data from Hasegawa and Yoshida (1978).

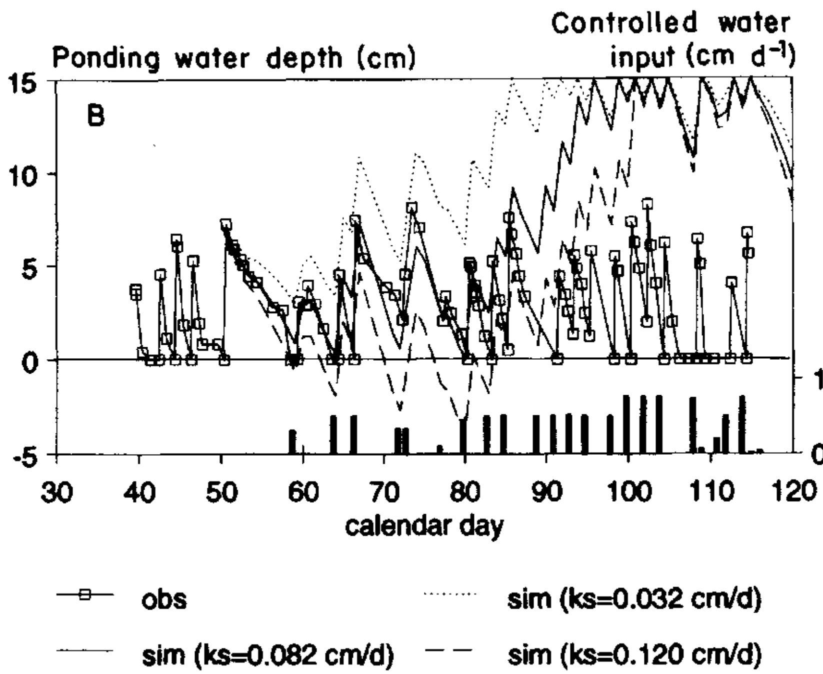


Figure 5.3 Simulated and observed changes in ponded water depth in field experiment 1 using soil water balance module PADDY.

5.14 Rice-upland crop rotations

Puddling of soil, often practised in lowland rice cultivation destroys soil structure and creates a muddy toplayer, impeding water flow and hampering growth of weeds. Often an upland crop, like wheat or a legume is grown after rice profiting from residual moisture. PADDY was developed to simulate the dynamics of soil water content in the root zone of rice and takes into account the changes that occur in volume and porosity of a drying, previously puddled soil layer. The current version of PADDY can be used for crop rotations if a suitable model for the upland crop is available. A variable `WBINIT` can be added to the timer file, indicating if the soil-water balance model PADDY will be initialized or not. If `WBINIT = 0`, the model is not initialized, and `ITASK = 1` in PADDY is skipped. This option can be used for example if an upland crop is grown after rice. Fallow periods can be simulated by introducing a logical `FALLOW`. If `FALLOW = .TRUE.` the crop model is not called. If a rice crop is grown again after the upland crop, initialization is needed and `WBINIT` should again be 1. Introducing `WBINIT` in a RERUNS file allows running of ORYZA_W for an unlimited number of cropping seasons. The necessary adjustments needed in ORYZA_W are already incorporated, but currently 'commented out' by an asterix * in the first column of the FSE program. A search for the text string *For crop rotations* can be used to find these lines in the source code.

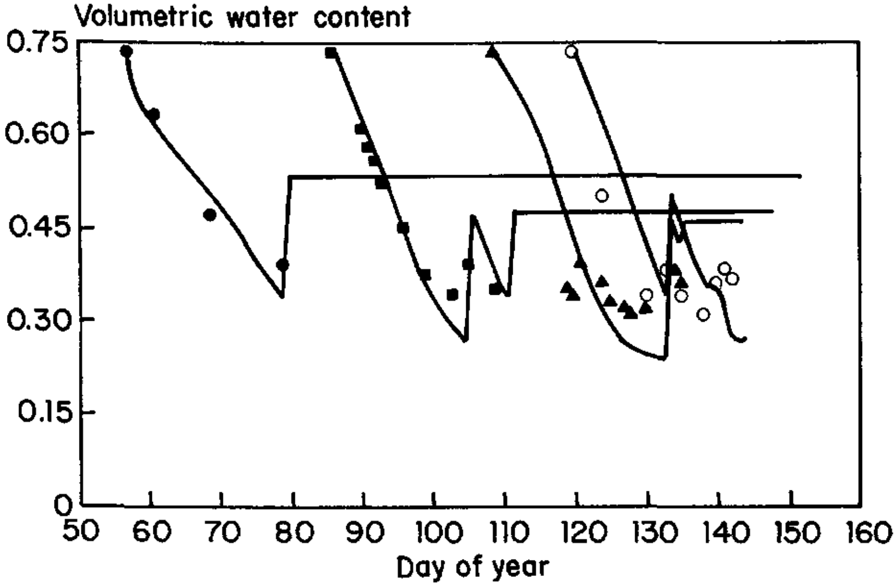


Figure 5.4 Simulated (lines) and observed (symbols) soil water content (m^3 m^{-3}) for cv. IR72 in field experiment 2 for drought at transplanting (0-5 cm, late recovery, closed circles), drought at mid-tillering (0-10 cm, late recovery, squares), drought at panicle initiation (0-10 cm, late recovery, triangles), and drought at flowering (0-10 cm, no recovery, open circles).

6 Drought stress responses of two lowland rice cultivars to soil-water status

Quantification of physiological and morphological responses of rice to drought stress is essential to predict the impact of soil and weather conditions on rice production using process based crop simulation models. Drought may delay the phenological development of the rice plant (Turner et al., 1986; Puckridge and O'Toole, 1981; Inthapan and Fukai, 1988), and affects physiological processes like transpiration, photosynthesis, respiration and translocation of assimilates to the grains (e.g. Fukai et al., 1985; Turner, 1986). Drought strongly affects the morphology of the rice plant. Leaf area development may be hampered due to reduced leaf expansion, leaf rolling and early senescence, and tillering and panicle development may be reduced (e.g. O'Toole and Cruz, 1980; O'Toole and Baldia, 1982). On the other hand, drought may induce more rapid root growth (e.g. O'Toole and Chang, 1979; O'Toole and Moya, 1981).

For lowland rice, grown in puddled soil, hardly any information on the relation between root zone soil-water status and physiological and morphological responses to drought is available. Because of the lack of such data, rainfed rice simulation models often use standard relationships that have been derived for other crops (Penning de Vries et al., 1989).

6.1 Description of the greenhouse experiments

At IRRI, three greenhouse experiments were conducted to study the physiological and morphological responses of two semi-dwarf lowland rice varieties (IR20 and IR72), grown in puddled clay soil and non-puddled sandy soil, to temporary drought at different growth stages. Responses during the drought period itself and after re-irrigation were investigated. The experiments aimed at finding relationships between root zone soil-water status and drought stress responses of the plant, for incorporation in rainfed rice simulation models. Drought was initiated at different growth stages and morphological and physiological responses were monitored. Results of these experiments are briefly reported here because they formed the basis of the modifications made to the crop growth module ORYZA1 for use in rainfed environments, explained in Chapter 7.

The experiments were conducted in greenhouses at the International Rice Research Institute (IRRI) in Los Baños, Philippines (14°30' N, 121°15' E). The climate at the study area is characterized by two pronounced seasons: a dry season (DS) from December to May and a wet season (WS) from June to November, which mainly differ in the levels of radiation and rainfall. Temperatures are similar. Experiment 1 was conducted from 30 January to 6 June 1992 (DS1992); Experiment 2 from 26 September 1992 to 26 January 1993 (WS1992) and Experiment 3 from 13 April 1994 to 29 July 1994 (DS1994). Two cultivars of rice (*Oryza sativa* L.), IR20 and IR72 were grown in pvc pots (20 cm diameter and 25 cm height). Three seedlings (DS1992: 21-day old; WS1992: 22-day old; DS1994: 21-day old) were planted in the center of each pot. In 1992, all pots were filled with saturated puddled Maahas clay soil (saturated volumetric water content: 0.73 cm^3 water cm^{-3} soil) taken from a submerged field at the IRRI farm that was plowed and harrowed 5 days before. The soil material comprised 13% sand, 39% silt and 48% clay. In 1994, pots were filled with non-puddled sandy soil material, comprising 70% sand, 17% silt and 13% clay (saturated volumetric water content: 0.42 cm^3 water cm^{-3} soil). High fertilizer inputs were imposed to ensure that reduced growth of stressed plants was caused by drought only. During the experiments, occasional spraying of insecticides against whorl maggot and green leaf hopper was needed to avoid pest damage.

In each of the three experiments, drought was imposed at different growth stages by simply withholding water application and by removing any ponded water from the soil surface. In 1992, drought was induced at transplanting (A), two weeks after transplanting (B), mid-tillering (D), panicle initiation (E) and first flowering (F). In 1994, the number of drought treatments was restricted to drought at three weeks after transplanting (C) and first flowering (F). Panicle initiation was defined as the first day when a white feathery cone was present inside the leaf sheath of the rice plant. First flowering was defined as the moment when 90% of the plants subjected to a certain treatment had at least one flowering panicle. For comparison, a number of pots for each variety was kept well-watered (WW). The degree of leaf rolling was monitored as a stress indicator. A 0 to 5 rolling factor was used (O'Toole and Cruz, 1980). A leaf rolling factor of 1 indicates a first sign of leaf rolling, whereas score 5 means that the leaf has completely rolled up.

In 1992, the duration of drought was varied as well to investigate the responses and the ability of the rice plant to recover from different drought intensities. In the short duration treatments (or early recovery, ER), stressed plants were recovered when plants reached leaf rolling score 5. In the long duration treatment (or highly stressed, late recovery: LR) plants were recovered when they were close to dying, i.e. leaf rolling score 5 and roughly 50% dead leaves. Recovery was achieved by re-irrigating the pots to bring the dried soil to saturation. In 1994, only treatment ER was included. After the onset of the recovery period, plants were kept well-watered until maturity. In the 1992 experiments, drought was maintained in a number of pots.

Transpiration measurements

Pots with well-watered and stressed plants were weighed daily (early morning) to estimate transpiration losses, using a balance with a resolution of 1 g. Transpiration rate was calculated as the difference in pot weight between successive days. If drought stress results in a reduction of LAI, the measured potential transpiration of well-watered plants will be higher than the potential transpiration rate of stressed plants. Radiation is the main driving force for differences in transpiration between the well-watered and stressed canopies. The potential transpiration of the stressed plants was, therefore, calculated from the transpiration of the well-watered plants, using the ratio of calculated absorbed fraction of global radiation in stressed and well-watered plants as a weighing factor:

$$T_p(D) = T_p(WW) * (1 - e^{-0.4LAI(D)}) / (1 - e^{-0.4LAI(WW)}) \quad (6.1)$$

where:

T_p(D) is the potential transpiration rate of stressed plants,

T_p(WW) the potential transpiration rate of well-watered plants,

LAI(D) the LAI of stressed plants, and

LAI(WW) the LAI of well-watered plants.

The factor 0.4 used in Eqn 6.1 is the extinction coefficient for global radiation in rice plants (Kropff and van Laar, 1993). Relative transpiration (RT) used here is the ratio of the actual transpiration of stressed plants, T_a(D), over that of well-watered plants corrected for differences in LAI using Eqn 6.1, i.e. T_a(D) / T_p(D).

6.2 Results of the greenhouse experiments

For reasons of brevity only the results obtained for IR20 in Experiments 1 and 2 are reported here. Very similar results were, however, obtained for IR72 in Experiments 1, 2 and 3, regardless of the soil material (puddled / non-puddled) used.

Evaporative demand of the air

The evaporative demand of the air in the various experiments was estimated from the transpiration rates of the well-watered plants between 40 and 80 days after transplanting (closed canopy situation). Average transpiration rate in DS1992 was 16 mm d^{-1} (standard deviation, SD: 3 mm d^{-1}), in WS1992: 6 mm d^{-1} (SD: 2 mm d^{-1}) and in DS1994: 11 mm d^{-1} (SD: 3 mm d^{-1}).

Impact of drought on physiological processes

Transpiration rates of stressed and well-watered plants were converted into relative transpiration rates (RT) using Eqn 6.1 and expressed as a function of soil-water pressure potential h. Variation of RT below and above 1 at low absolute values of h (moist soil) can be explained by micro-environmental variation in and between experiments and error in estimating daily LAI values for well-watered and stressed plants from a limited number of observations.

For reasons of brevity, only the results obtained for cultivar IR20 in Experiments 1 and 2 are reported here (Figure 6.1). Observations for the A and B treatments start at pressure potentials near −100 kPa only, because the pots were initially left uncovered. Logistic curves fitted the data reasonably well. A similar result was obtained by Sinclair and Ludlow (1986) for four tropical grain legumes, relating fraction of transpirable soil water (FTSW) to RT, defining total transpirable soil water as the difference between initial pot weight and its weight when RT reached 0.1.

Differences between dry and wet season data for similar drought treatments were relatively minor given the contrast in evaporative demand between both seasons. Plant age had a more pronounced effect on the relation between RT and soil-water pressure potential h. Differences in rooting pattern may have had some influence in the early drought

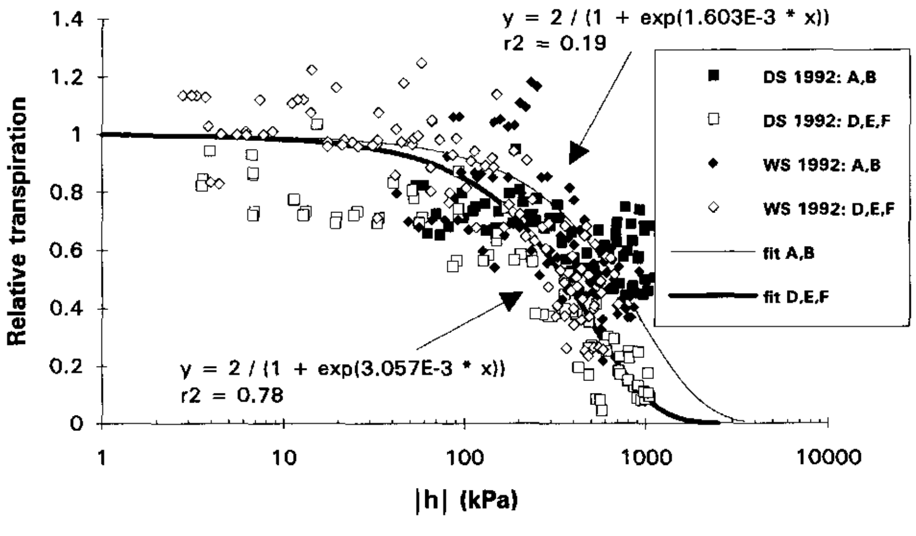


Figure 6.1 Relative transpiration rates of IR20 in Experiments 1 and 2 as a function of soil-water pressure potential, resulting from drought at different growth stages. A: drought at transplanting, B: drought two weeks after transplanting, C: drought three weeks after transplanting, D: drought at mid-tillering, E: drought at panicle initiation; F: drought at first flowering.

treatments (A, B). However, at the moment of recovery, roots extended throughout the (shrunken) soil volume for all treatments, indicating no restrictions on availability of soil-water at greater depths in the pots.

For both varieties and for all treatments, plants transpired roughly at potential rate, corrected for differences in LAI, until the soil-water pressure potential h reached the range −70 to −100 kPa (Figure 6.1). At lower soil pressure potentials, RT declined rapidly, especially if drought was induced at a later growth stage (D, E, F). RT values declined more or less linearly with log(h). Decline in RT started earlier for the D, E, F treatments than for the A, B treatments. This is probably due to the larger size and higher transpiration demand of the older plants.

Relationships between leaf morphology and soil-water status

Leaf elongation rate of plants stressed in the vegetative phase decreased rapidly after an initial period of normal growth. Tanguilig et al. (1987) also found an abrupt decrease in leaf elongation rate 11 days after initiation of drought stress in IR36. The critical soil-water pressure potential at which leaf expansion in the vegetative phase stopped completely (zero leaf expansion) was estimated from graphs of plant height. Because plant height measurements were done at weekly intervals, results should be interpreted as rough estimates only. In the dry season of 1992, critical pressure potentials ranged from −50 kPa (IR72, DLR) to −160 kPa (IR72, BER). Critical pressure potentials were lower in the wet season of 1992, ranging from −50 kPa (IR72, ELR) to −260 kPa (IR72, AER), probably due to the lower evaporative demand in the wet season. For younger plants, leaf expansion stopped at lower pressure potentials, which may also be attributed to a lower evaporative demand of a small leaf canopy.

As soil-water status declined further, ($h < -200$ kPa) leaf rolling started in all treatments and for both varieties (Figure 6.2). Decrease in the leaf rolling factor from 1 (no leaf rolling) to 0 (complete leaf rolling) was observed if pressure potentials dropped further to −1MPa or lower. As drought progressed, the percentage of dead leaves increased rapidly as well (Figure 6.3). Both leaf rolling and dead leaves factors were linearly related with log(h).

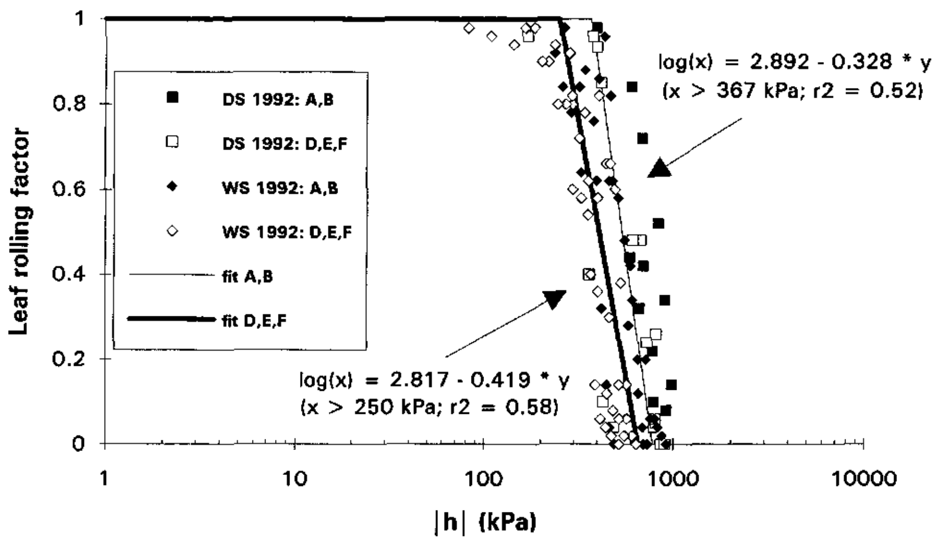


Figure 6.2 Leaf rolling factors of IR20 in Experiments 1 and 2 as a function of soil-water pressure potential, resulting from drought at different growth stages. A leaf rolling factor of 1 indicates no leaf rolling, a leaf rolling factor of 0 indicates that leaves are completely rolled up. A: drought at transplanting, B: drought two weeks after transplanting, C: drought three weeks after transplanting, D: drought at mid-tillering, E: drought at panicle initiation; F: drought at first flowering.

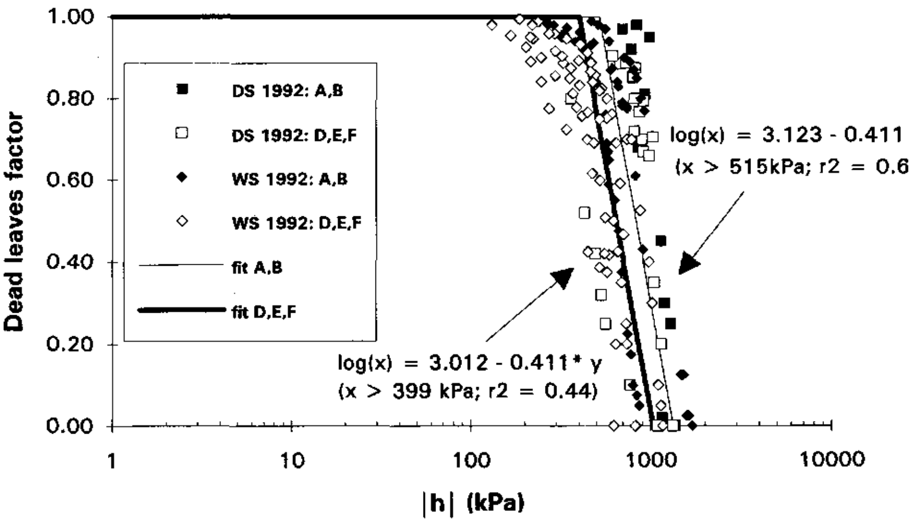


Figure 6.3 Dead leaves factors of IR20 in Experiments 1 and 2 as a function of soil-water pressure potential, resulting from drought at different growth stages. A dead leaves factor of 1 indicates that no dead leaves are present, a dead leaves factor of 1 indicates that all leaves are dead. A: drought at transplanting, B: drought two weeks after transplanting, C: drought three weeks after transplanting, D: drought at mid-tillering, E: drought at panicle initiation; F: drought at first flowering.

The younger the plant, the lower the soil-water potential before leaf rolling started. Leaves rolled and dead leaves appeared relatively quickly if drought was initiated at flowering, probably because of the added effect of natural senescence. Summarizing the results of the three experiments, the response of leaf morphology to drought may be separated into three more or less sequential phases:

1. Decline in leaf expansion (vegetative phase only),
2. Leaf rolling and
3. Early leaf senescence.

For most treatments phases 2 and 3 showed some overlap, i.e. dead leaves appeared at leaf rolling scores below 5. Results obtained for the puddled clay and non-puddled sandy soil were remarkably similar, indicating the potential of the soil-water pressure potential to act as an indicator for drought in different soil types. Most drought responses started if the soil pressure potential dropped below −100 kPa.

Impact of drought on phenology

Early drought postponed the date of 50% flowering as compared to that of well-watered plants by a maximum of 22 days. The delay in flowering was reduced if drought was

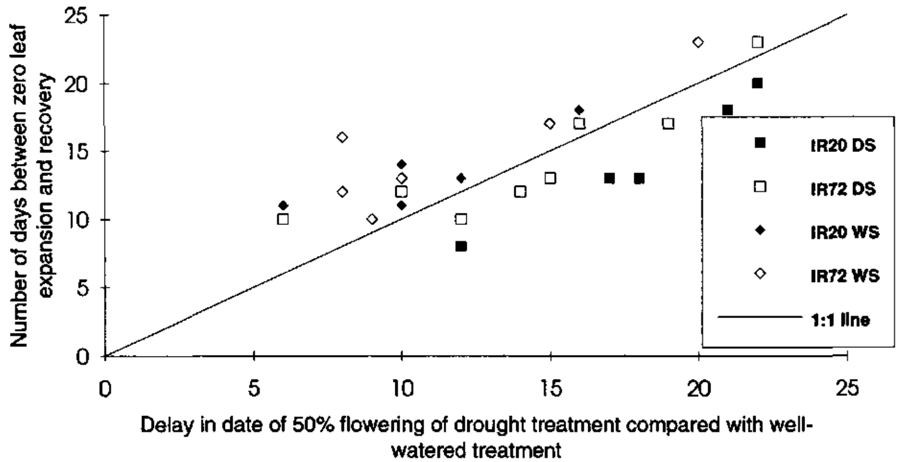


Figure 6.4 Comparison between the delay in date of 50% flowering and the number of days between zero leaf expansion and recovery for all drought treatments in Experiments 1, 2 and 3.

induced at later growth stages. Postponement was in reasonable agreement with the number of days between the date of zero leaf expansion and the recovery date (Figure 6.4). This may indicate that if the soil is too dry to produce new leaves, the development rate of the crop is brought to a standstill as well.

Impact of drought on yield and yield components

For both varieties, yields obtained in early drought treatments (A and B) did not differ significantly from the well-watered yields. Drought at mid-tillering, panicle initiation and flowering strongly reduced yields to below 200 g m^{-2}, mainly caused by large percentages of unfilled grains and a reduction in 1000 grain weight.

Impact for modeling of rainfed rice production

The soil-water - drought response relationships presented above were used to modify ORYZA1 for use in rainfed rice environments. This modified ORYZA1 module was renamed to ORYWAT and is presented in the Chapter 7. Soil-water pressure potentials h, obtained from a soil-water balance module like PADDY may be translated into changes in leaf morphology, and relative transpiration. These responses can be defined as functions of $\log(h)$ as shown in Figures 6.1, 6.2 and 6.3. A similar approach, linking stress factors to soil extractable water, was taken for other crops by Sinclair (1986) and McCree and Fernandez (1989).

Results obtained from this study and from Tanguilig et al. (1987) for IR36 suggest that the decline in leaf elongation rate of semi-dwarf lowland rice varieties, stressed in the vegetative phase, is relatively abrupt. This could be tentatively modeled as a 'step function' declining from 1 (normal leaf expansion) to 0 (zero leaf expansion) if the soil-water pressure head drops below its critical value for zero leaf expansion.

The reasonable good agreement between delay in flowering and the number of days between the moment of zero leaf expansion and recovery (Figure 6.4) suggests that the development rate stops when the soil becomes too dry for further leaf expansion and resumes if drought stress is released. If the critical soil-water pressure potential for zero leaf expansion is reached, stressed plants will still be able to produce carbohydrates for growth, as transpiration has not yet ceased. This extra C may be used for root development to explore soil-water resources, may be stored in the stem or may result in thickening of leaves during drought stress. In a rainfed rice model, this may be modeled as a temporary storage pool for carbohydrates during drought, as was also done by McCree and Fernandez (1989). In ORYWAT, it is assumed that the extra C is used for root growth.

Plant size and evaporative demand of the air will influence the drought stress responses to some extent, as was also shown in this study. Results reported here are, however, not as distinct as reported by Doorenbos and Kassam (1979) for C_3 crops, despite the clear difference in evaporative demand of the air in the wet and dry season experiments.

Root distribution in the field is very important. Water uptake rate of rice roots from a top soil layer may decrease with decreasing soil-water potential, but roots at greater depth may make up for this difference by increasing water uptake, even if the soil-water potential at that depth is also decreasing (e.g. Hasegawa and Yoshida, 1982). In this experiment roots were limited to a cylinder of 20 cm height and 20 cm diameter. In reality roots may grow deeper, especially in the absence of a hard plow pan. For modeling purposes it is important to establish extraction rates at different depths in the root zone.

Results reported here are specific for two semi-dwarf lowland varieties. Dryland rice varieties are known to be more 'pessimistic' (Bradford and Hsiao, cited in Dingkuhn et al., 1989) in their drought responses as they show leaf rolling at higher leaf water potentials (e.g. Turner et al., 1986; Dingkuhn et al., 1989). They also tend to have a deeper root system than lowland rice varieties (Yoshida, 1981) and may therefore be more effective in exploring soil-water resources.

The advantage of expressing drought stress responses as a function of soil-water pressure potential is that they can be used for any soil type, even when the soil shrinks, provided a good soil-water balance model and knowledge of the soil's water retention and soil shrinkage curve, linking h to soil-water content θ, is available. If such drought responses are used as an input for a rice growth simulation model ORYZA1, predictions of rice yield under water-limited conditions can be made.

6.3 Conclusions

The results of the three greenhouse experiments can be summarized as follows: Three greenhouse experiments were conducted to investigate drought stress responses of two lowland rice cultivars, grown in puddled clay and non-puddled sandy soil. Results obtained for both varieties and for both soil materials were quite similar. Plant age had a more distinct effect on drought stress responses than differences in evaporative demand of the air between dry and wet seasons. Roots extended throughout the (shrunken) soil volume for all treatments. Differences in rooting pattern among drought treatments are therefore expected to be minor. Drought in the vegetative phase delayed phenological events but did not result in significant yield losses if drought occurred within 2 weeks after transplanting. Drought in the reproductive phase resulted in substantial yield losses.

Drought affected transpiration rates by closure of stomata and changes in leaf morphology of the rice plant. The first observed response, if drought was initiated in the vegetative phase, was a relatively abrupt decline in leaf expansion. Logistic functions could be used to describe the decline in relative transpiration, corrected for differences in LAI, as a function of $\log(h)$. Leaf rolling and rate of senescence were linearly related to $\log(h)$. These functions were used to modify the rice growth model ORYZA1. The resulting module, ORYWAT is explained in detail in Chapter 7.

7 The ORYWAT growth module

ORYWAT is based on ORYZA1, version 1.3 (Kropff et al., 1994), an ecophysiological model for fully irrigated rice production. ORYWAT simulates rice growth and development under fully irrigated and water limited conditions. Nutrient supply is considered non-limiting and any influence of pests, diseases or weeds is assumed absent. The main additions to ORYZA1, included in ORYWAT, are the calculation of root growth, potential and actual evapotranspiration and the effects of drought stress on growth and development. In this chapter, only these modifications will be described; the reader is referred to Kropff et al. (1994) for a description of the crop growth processes on potential production level.

The drought stress effects in ORYWAT on growth and development were derived from the pot experiments discussed in Chapter 6 and were related to critical pF values of the root zone. An overview of the dependency of drought stress factors on soil-water potential as observed for IR20 is given in Figures 7.1a and 7.1b. These functions are used in ORYWAT. Drought stress responses are defined as a function of the pF of the root zone. pF is defined as the logarithm of soil pressure potential: log $|10*h|$ = pF, with h in kPa. E.g. if the soil-water pressure potential is 100 kPa, the corresponding pF value is 3. For the sake of simplicity this was also done for the decrease in relative transpiration rate, although a logical curve was fitted to the data (Figures 7.1a and 7.1b, see also Chapter 6). For every response, critical pF values can be defined: an upper limit, that indicates the start of stress, and a lower limit, that indicates 100% stress:

ULLS: upper limit leaf rolling: start of leaf rolling (-)
LLLS: lower limit leaf rolling: leaves are completely rolled up (-)
ULDL: upper limit dying leaves: start of senescence (-)
LLDL: lower limit dying leaves: 100% dead leaves (-)
ULRT: upper limit reduction relative transpiration rate: start of reduction (-)
LLRT: lower limit reduction relative transpiration rate: transpiration rate is zero (-)

For leaf expansion, a step function was assumed in Chapter 6. For this reason only one limit, STLG is defined:

STLG: limit to leaf growth: inhibition of leaf expansion (-)

Drought stress factors apply for the whole crop growth duration, although in reality plant age influences drought stress responses as a function of soil-water pressure potential to some extent (see Chapter 6 and Figures 7.1a and 7.1b).

7.1 Root growth

Rooting depth is an important variable in calculating root zone water content and water uptake for transpiration by the plants. Roots of rice cultivars in lowland soils rarely grow

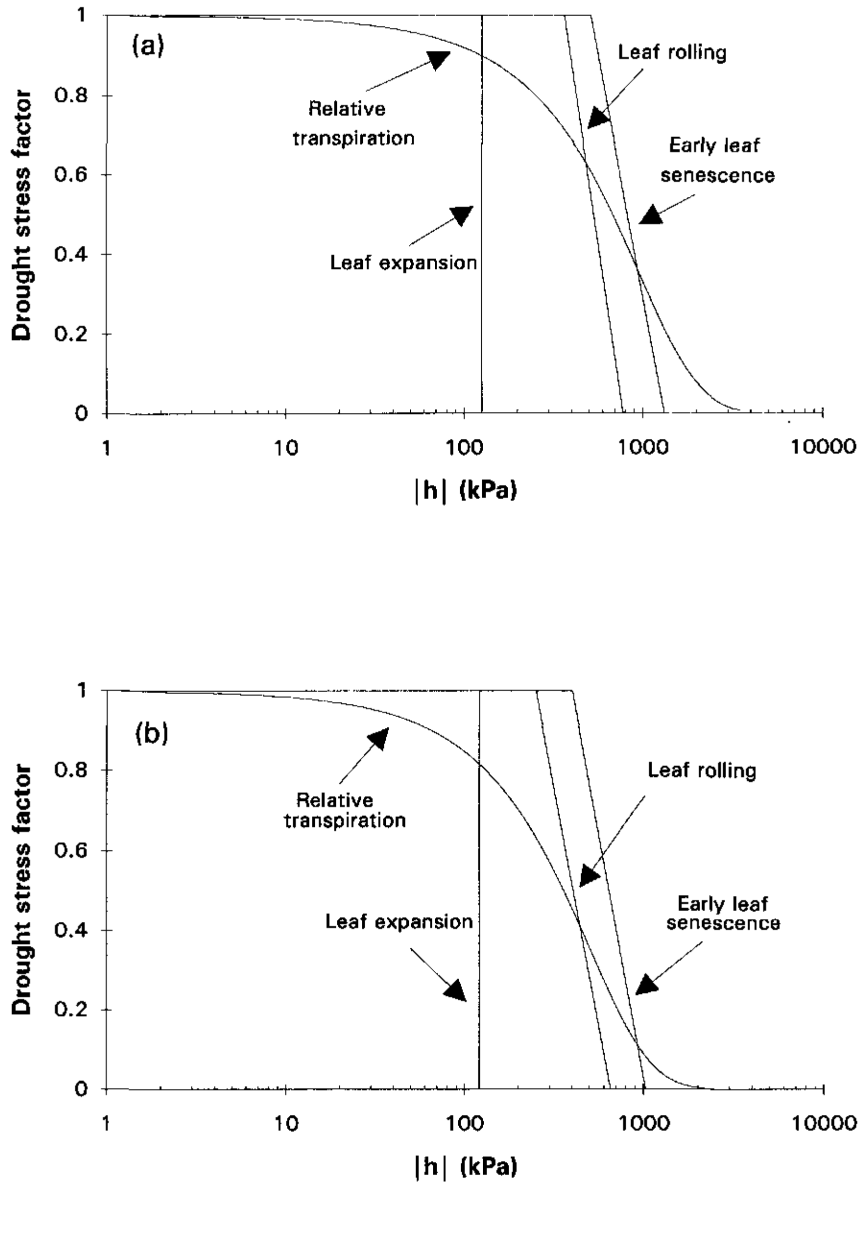


Figure 7.1 Relationship between soil-water pressure potential and drought stress factors for IR20; (a) shows results for treatments A and B, (b) shows results for treatments D, E and F. For explanation of the treatments see Section 6.1.

deeper than 40 cm; about 90% of the total root system is usually found in the top 20 cm. Roots of upland rice cultivars in light-textured upland soils may grow as deep as 0.8-1.0 m (Hasegawa and Yoshida, 1982). In ORYWAT, rooting depth, ZRT, is calculated as integral of ZRT on the previous day with the daily root growth rate, GZRT:

```
ZRT = INTGRL (ZRT, GZRT, DELT)
```

There is a wealth of literature showing root length densities of rice as a function of soil depth. From such data an estimate of GZRT can be made. Usually GZRT is in the range of 0.01 - 0.02 m d^{-1} depending, among others, on rice variety, soil texture, soil tillage and presence of hard layers.

- In LOWBAL (SWIWLP = 1) it is assumed that roots do not penetrate the plow sole, and the maximum rooted depth, ZRTM, is determined by the thickness of the puddled layer, TKLT.
- In SAHEL (SWIWLP = 2) ZRTM is determined by the maximum rooting depth of the rice crop itself, ZRTMC, or by the rootable depth of the soil profile, ZRTMS (e.g. as determined by an impermeable layer).
- In PADDY (SWIWLP = 3) rooting depth only increases beyond ZRTMCW, defined in the crop data file, in case of drought (i.e. soil water content of the root zone drops below the upper limit for inhibition of leaf expansion). In case of drought, the maximum rooting depth is determined by the maximum rooting depth of the rice crop, ZRTMCD, or by the rootable depth of the soil profile, ZRTMS.

```
      IF (SWIWLP .EQ. 3) THEN
         IF ((.NOT. DROUT).AND.(ZRT.LE.ZRTMCW)) THEN
            ZRTM = MIN(ZRTMCW, ZRTMS, TKLT)
         ELSE IF ((.NOT. DROUT) .AND. (ZRT.GT.ZRTMCW)) THEN
            ZRTM = MIN(ZRT, ZRTMS, TKLT)
         ELSE IF (DROUT) THEN
            ZRTM = MIN(ZRTMCD, ZRTMS, TKLT)
         END IF

* In all other cases, roots grow straight to max. length ZRTMC

      ELSE
         ZRTM = MIN(ZRTMC, ZRTMS, TKLT)
      END IF
      ZRT = INTGRL (ZRT, GZRT, DELT)
      ZRT = MIN (ZRT, ZRTM)
```

7.2 Root zone water content

Regardless of which soil water balance module is chosen, the total actual water content in the root zone, WCRREL is calculated as the sum of the water content of each individual soil layer in the root zone:

```
DO 30 I=1,NL
  ZRTL   = MIN(TKL(I),MAX((ZR-ZLL),0.0))
  WCRREL = WCRREL + (ZRTL/(ZR+1.0E-10))*WCLQT(I)
```

in which ZR is the total rooted depth , TKL(I) is the depth of soil layer I, ZLL is the depth of accumulated soil layers, ZRTL is the depth of the roots in the soil layer under consideration, and NL is the number of soil layers.

7.3 Critical soil water contents

In the subroutine DSTRES, the critical pF values defined in the crop data input file (Appendix 1) are converted into soil water contents per layer. The critical soil water contents per soil layer I, defining each drought stress response, are calculated from the water retention curve (SWITPF = 1) using subroutine SUWCMS2, or are derived via interpolation (SWITPF = 0) between volumetric water contents at field capacity (WCFC(I)) and wilting point (WCWP(I)).

```
IF (SWITPF.EQ.1) THEN
  CALL SUWCMS2(I,2,WCST(I),STLGW(I),10**STLG)
  CALL SUWCMS2(I,2,WCST(I),ULLSW(I),10**ULLS)
  CALL SUWCMS2(I,2,WCST(I),LLLSW(I),10**LLLS)
  CALL SUWCMS2(I,2,WCST(I),ULDLW(I),10**ULDL)
  CALL SUWCMS2(I,2,WCST(I),LLDLW(I),10**LLDL)
  CALL SUWCMS2(I,2,WCST(I),ULRTW(I),10**ULRT)
  CALL SUWCMS2(I,2,WCST(I),LLRTW(I),10**LLRT)
ELSE
  STLGW(I)=WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-STLG)
  ULLSW(I)=WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-ULLS)
  LLLSW(I)=WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-LLLS)
  ULDLW(I)=WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-ULDL)
  LLDLW(I)=WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-LLDL)
  ULRTW(I)=WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-ULRT)
  LLRTW(I)=WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-LLRT)
END IF
```

These individual soil water contents are then summed up over the root zone for leaf growth inhibition and for the appearance of dead leaves due to early senescence:

```
STLGWR = STLGWR + (ZRTL/(ZR+1.0E-10))*STLGW(I)
ULDLWR = ULDLWR + (ZRTL/(ZR+1.0E-10))*ULDLW(I)
LLDLWR = LLDLWR + (ZRTL/(ZR+1.0E-10))*LLDLW(I)
```

7.4 Actual transpiration and drought stress factors

Actual transpiration rate

In DSTRES, per layer I, the actual water content WCLQT(I) is compared with the upper and lower limits for transpiration (ULRTW(I) and LLRTW(I) respectively), via the factor DSETR:

```
      DSETR = LIMIT(0.,1.,
     $              (WCLQT(I)-LLRTW(I))/(ULRTW(I)-LLRTW(I)))
```

The amount of water available to the plants is the volume of water between actual water content and the lower limit of dead leaves, if roots can explore the root zone completely:

```
      WLA = MAX (0.0, (WCLQT(I)-LLDLW(I))*TKL(I)*1000.)
```

The volume of water taken up by the roots, i.e. the transpiration of the crop needs to be divided over the rooting depth. In DSTRES it is assumed that the maximum uptake S_{max} is constant over depth. This means that, under optimal water conditions, the transpiration load of the crop is divided equally over all soil layers. The water uptake TRRM at any depth x, is then equal to the potential transpiration rate, TRC, divided by the rooting depth, ZRT, i.e. TRRM = TRC/ZRT. The transpiration rate per layer I, TRWL(I) and the total transpiration rate TRW are calculated as follows:

```
      TRRM = TRC/(ZRT+1.0E-10)
      TRWL(I) = MIN(DSETR*ZRTL*TRRM, WLA/DELT)
      TRW = TRW+TRWL(I)
```

Another option would be to assume that S_{max} declines with increasing rooting depth. It can be derived that in that case at depth x, the water uptake TRRM is equal to: TRC*[2 / ZRT - (2 * x) / (ZRT)^2], which can easily be adopted in DSTRES.

Leaf rolling stress factor

In DSTRES, the leaf rolling score of every soil layer is calculated and a total leaf score LS over the root zone is derived:

```
      LS = LS + (ZRTL/ZRT)*LIMIT(0.,1.,
     $              (WCLQT(I)-LLLSW(I))/(ULLSW(I)-LLLSW(I)))
```

The leaf area index simulated in the main crop model is multiplied with the stress factor LSTRS. The maximum reduction of LAI due to leaf rolling is assumed to be 50%. LSTRS therefore varies between 0.5 and 1. LSTRS is derived in DSTRES as follows:

```
      LSTRS = 0.5*LS + 0.5
```

Early senescence stress factor

In DSTRES the dead leaves score of every soil layer is calculated and a total dead leaves score DS over the root zone is derived:

```
DS = DS + (ZRTL/ZRT)*LIMIT(0.,1.,
$          (WCLQT(I)-LLDLW(I))/(ULDLW(I)-LLDLW(I)))
```

The DSTRS factor used in the main crop growth model is equal to DS and varies between 0 and 1:

```
DSTRS = DS
```

Reduced development rate

In DSTRES, it is assumed that the development rate of the crop stops if the water content of the root zone drops below STLGWR. A factor DVEW is set to 0 in this case. No delay in development is simulated when drought occurs in the reproductive phase. When there is no drought stress, DVEW equals 1. If there is drought, a counter ICNT is set to 1. This counter is used in the crop growth module ORYWAT for calculation of LAI (see Section 7.5).

```
        IF (WCRREL.LE.STLGWR) THEN
            DROUT = .TRUE.
            ICNT  = 1
            DVEW  = 0.
        ELSE
            DVEW  = 1.
        END IF
END IF
```

Reduced CO_2 assimilation rate

In DSTRES, the reduction factor on daily total gross CO_2 assimilation of the crop is, PCEW, calculated as the ratio of actual canopy transpiration over potential canopy transpiration:

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

7.5 Drought stress effects simulated by ORYWAT

Inhibition of leaf growth

In ORYWAT, the LAI is modelled as exponential function of a relative growth rate, RGRL, when LAI is below 1 and the development stage DVS is below 0.6. If LAI is larger than 1 or DVS is larger than 0.6, the specific leaf area, SLA, concept is used and LAI is calculated from simulated leaf weight, WLVG, (see Kropff et al., 1994). However, when there has been drought stress as indicated by the counter ICNT, which is set in the subroutine DSTRES, the LAI at values lower than 1 are also simulated using the specific leaf area, SLA, concept:

```
IF (LAI .LT. 1.0 .AND. DVS .LT. 06 .AND. ICNT .EQ. 0) THEN
   LAI = LAII*NH*NPLH/NPLSB*(EXP(RGRL*(TSLV-TSLVTR-TSHCKL)))
ELSE
   LAI = 0.5*SAI + SLA*(WLVG-WLVEXP) + LAIEXP
```

```
      END IF
```

The counter ICNT = 0 indicates that there is no drought stress, and ICNT = 1 means drought stress. This effect of drought stress on leaf area production is 'permanent', i.e. when there has been drought stress at any time in the growing season, ICNT is set to 1 and will not be reset to 0 when there is no longer drought stress. Thus, during and after a drought spell, LAI will always be calculated from simulated leaf weight using the SLA concept. This approach was chosen because in a field experiment at IRRI it was found that rice that suffered from severe drought at transplanting was not able to grow exponentially up to LAI = 1 after recovery (Wopereis, 1993, page 129-130).

With drought stress, photosynthesis no longer leads to leaf production and the 'excess' carbohydrates are allocated to the roots, if the flowering stage has not been reached (DVS < 1):

```
      IF (WCRREL.LE.STLGWR.AND.DVS.LT.1.) THEN
         FSH = 0.
         FRT = 1.
      END IF
```

Reduced development rate

During the vegetative growth period, the development rate of the crop, DVR, is calculated from the vegetative development rate, DVRV, the daily heat units for phenological development, HU, and the stress factor for development rate, DVEW (as calculated in the subroutine DSTRES):

```
      DVR = DVRV*HU*DVEW
```

Leaf rolling

Leaf rolling affects the leaf area index LAI. The LAI is first calculated in the subroutine SUBLAI of ORYWAT and is then multiplied with the leaf rolling stress factor calculated by the subroutine DSTRES:

```
      LAI  = LAI*LSTRS
```

Leaf senescence

The effect of drought on dying of leaves (early senescence) is determined by the stress factor DSTRS, calculated in the subroutine DSTRES. If DSTRS is lower than 1, the variable WLVGIT registers what the current green leaf mass is. This amount cannot increase unless drought is released. The stress factor DSTRS determines the percentage of dead leaves. The variable DLDRT keeps track of the dead leaf mass due to this early senescence process. The rate of leaf death due to drought, DLDR, is calculated as:

```
      DLDR = 0.
*------- 7. Leaf death as caused by drought stress
          IF (DSTRS.EQ.1) THEN
             DLEAF = .FALSE.
             DLDRT = 0.
```

```
      END IF
      IF ((DSTRS.LT.1.).AND.(.NOT.DLEAF)) THEN
         WLVGIT = WLVG
         DLEAF = .TRUE.
         KEEP = DSTRS
      END IF
      IF (DLEAF) THEN
         IF (DSTRS.LE.KEEP) THEN
            DLDR = (WLVGIT/DELT)*(1.-DSTRS)-DLDRT/DELT
            KEEP = DSTRS
            DLDRT = DLDR*DELT + DLDRT
         END IF
      END IF
```

The weight of green leaves, WLVG, is calculated as the integral of the previous WLVG with the growth rate of leaves, GLV, the loss rate of leaves due to 'regular' senescence, LLV, and the death rate of leaves due to drought, DLDR. Similarly, the weight of dead leaves, WLVD, is calculated as the integral of the previous WLVD with the loss rate of leaves due to 'regular' senescence, LLV, and the death rate of leaves due to drought, DLDR.

```
      WLVG = INTGRL (WLVG, GLV - LLV - DLDR,   DELT)
      WLVD = INTGRL (WLVD, LLV + DLDR ,  DELT)
```

Reduced CO_2 assimilation rate
The gross daily assimilation rate, DTGA, is reduced by drought stress with the factor PCEW as calculated in the subroutine DSTRES:

```
      DTGA = DTGA * PCEW
```

7.6 Maximum drought stress duration

The effects of drought stress on growth and development of rice as implemented in ORYWAT were derived from pot- and field experiments at IRRI (Wopereis, 1993). The maximum duration of drought stress in these experiments was 25 days (Wopereis 1993, p. 125). The number of consecutive days with drought stress, ISTD, is counted in ORYWAT and the simulation is stopped when more than 25 stress days are accumulated. It is assumed that plants recover completely from drought stress when more than 3 consecutive non-drought days, INSD, are recorded. The counter for accumulated drought stress days is then reset to 0.

```
* If rel. water content greater than STLGWR: no more drought
* Reset stress-day counters to 0 if there are more than 3
* days without drought.
      IF (WCRREL.GT.STLGWR) THEN
         DROUT = .FALSE.
```

```
          INSD = INSD + INT(DELT)
          IF (INSD.GT.3) ISTD = 0
      END IF

* Count the drought stress days
      IF (WCRREL.LE.STLGWR) THEN
         ISTD = ISTD + INT(DELT)
         INSD = 0.
      END IF

* Stop the simulation when number of stress days exceeds maximum
* value (from greenhouse 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
```

The simulation is also stopped when the (relative) water content in the root zone drops below the lower limit of dead leaves, LLDLWR:

```
* Check if lower limit dead leaves is reached
      IF (WCRREL.LE.LLDLWR) THEN
         PRINT *,'Soil dryer than lower limit dead leaves'
         PRINT *,'=> Simulation stopped'
         CALL OUTCOM('soil dryer than LLDL - simulation stopped')
         TERMNL = .TRUE.
      END IF
```

7.7 Model validation

ORYZA_W was validated using data from a field experiment with four drought treatments conducted at IRRI in 1992 (Wopereis, 1993), conducted under optimal fertilizer supply and full control of pests and diseases. The model could satisfactorily explain differences in biomass production, LAI and yield across drought treatments. Yields ranged from 5 - 8.4 t ha^{-1}.

8 Evaporation and transpiration

In the subroutine ETPOT, the Penman reference evaporation and transpiration and the potential soil evaporation and canopy transpiration are calculated. Strictly speaking, transpiration is the loss of water from the plants, and evaporation is the loss of water from the soil or from a free-water surface. Evapotranspiration covers both transpiration and evaporation. The calculation of the Penman reference evapotranspiration, and the following explanatory text are largely based on van Laar et al., 1992.

8.1 Penman reference evapotranspiration

Penman (1948) calculated potential evaporation and evapotranspiration from free-water surfaces, bare soil and low grass swards (reference crop). Potential means that there are no limitations with respect to the supply of liquid water to the evaporating surface. This potential evapotranspiration is the sum of a radiation term EVR and a drying power term EVD (both in mm day^{-1}). These terms are different for soil, open water and for a (reference) crop. In a production system of rice, three situations can be discerned: open water (lowland environment, in the main field before transplanting), a crop with soil background (rainfed upland; rainfed lowland with dried-out soil) and a crop with a water layer underneath (lowland). For these situations, separate values for EVR and EVD are calculated.

Radiation term EVR

The radiation term EVR depends on net radiation, NRAD (J m^{-2} d^{-1}), the latent heat of evaporation, LHVAP (equal to 2.4 10^6 J kg^{-1} at 30°C with only a small temperature dependence) and a weighting factor (SLOPE/(SLOPE+PSYCH)), where SLOPE (mbar $°C^{-1}$) is the tangent of the relation between saturated vapour pressure (mbar) and temperature (°C) and PSYCH (0.67 mbar $°C^{-1}$ at 0 meter elevation) the psychrometer constant (Monteith, 1965):

```
LHVAP = 2.4E6
PSYCH = 0.67
EVR   = (1./LHVAP)*(SLOPE/(SLOPE+PSYCH))*NRAD
EVRWL = (1./LHVAP)*(SLOPE/(SLOPE+PSYCH))*NRADWL
EVROW = (1./LHVAP)*(SLOPE/(SLOPE+PSYCH))*NRADOW
```

In which EVR is the radiation term for crop/soil system, EVRWL is the radiation term for crop/water layer system, and EVROW is the radiation term for open water. SLOPE is calculated from daily average temperature, TAV:.

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

Net radiation, NRAD, depends on incoming short-wave radiation (RDT, J m^{-2} d^{-1}), the reflection or albedo value, ALB, ALBWL or ALBOW (unitless), and net outgoing long-wave radiation, RLWN:

```
NRAD   = (1.-ALB)*RDT-RLWN
NRADWL =(1.-ALBWL)*RDT-RLWN
NRADOW = (1.-ALBOW)*RDT-RLWN
```

Here, NRAD is the net radiation for crop/soil system (or of bare soil), NRADWL is the net radiation for a crop/water layer system, and NRADOW is the net radiation for a layer of open water. The albedo for soil, open water and crop/soil and crop/water layer systems is calculated as follows:

- The soil's albedo, ALBS, depends on the surface color and the moisture content. Albedo values for dry soil, ALBSD, vary from 0.15 (clay) to 0.40 (dune sand). The dependence on soil moisture is described in relation to the average water content of the top soil layer (ten Berge, 1989).

- The albedo of a layer of water, ALBOW, is about 0.05.

- The albedo of canopy/soil, ALB, is composed of that of the soil, ALBS, and that of the canopy, ALBC; the albedo of canopy/water layer, ALBWL, is composed of that of the water layer, ALBOW, and that of the canopy, ALBC. Here, a value of 0.25 is used for ALBC. The relative contributions of both albedos depend on the shading of the soil by the crop and is calculated on the basis of the leaf area index, LAI. An extinction coefficient (for short-wave radiation penetrating the crop) of 0.5 is used here. When LAI is 0, the albedo for bare soil or an open water layer is obtained.

```
ALBDS = 0.25
ALBOW = 0.05
ALBC  = 0.25
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))
```

Net long-wave radiation, LWN (J m^{-2} d^{-2}) is approximated by three semi-empirical functions, (Penman, 1956; derived from the original Brunt (1932) formula), accounting for temperature, BBRAD (J m^{-2} s^{-2}), vapour pressure in the atmosphere, FVAP (unitless) and sky clearness, FCLEAR (unitless).

```
BOLTZM = 5.668E-8
BBRAD  = BOLTZM*(TAV+273.)**4
FVAP   = 0.56-0.079*SQRT(VAPOR)
CLEAR  = LIMIT(0., 1., ((RDT/DS0)-ANGA)/ANGB)
FCLEAR = 0.1+0.9*CLEAR
```

```
RLWN   = BBRAD*FVAP*FCLEAR*86400.
```

Here, the sky clearness factor, CLEAR (unitless), is calculated using the Ångström formula, in which ANGA and ANGB are empirical constants and DSO is the extra-terrestrial radiation, i.e. the radiation intensity at the top of the atmosphere. The values for ANGA and ANGB are related to climatic conditions (see Table 8.1), and are read from the weather input file (see Chapter 9). The value of DSO depends on location on earth (latitude) and time of the year, and is calculated in the subroutine ASTRO. The actual vapour pressure, VAPOR (mbar (daily average)) to calculate FVAP is read from the weather input file.

Drying power term EVD

The drying power term is calculated from Penman's drying power term, DRYP for a reference crop and DRYPOW for an open water layer, and from SLOPE and PSYCH (see above):

```
EVD   = DRYP*PSYCH/(SLOPE+PSYCH)
EVDOW = DRYPOW*PSYCH/(SLOPE+PSYCH)
```

in which EVD is the drying power term for crop/soil or crop/water layer, and EVDOW is the drying power term for open water layer. DRYP and DRYPOW (mm d^{-1} mbar $^{o}C^{-1}$) are calculated from saturated vapour pressure, SVP (mbar), the actual vapour pressure, VAPOR (mbar), and a wind speed function, WDF for a reference crop and WDFOW for an open water layer (mm d^{-1} $^{o}C^{-1}$):

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

The wind function estimates the conductance for transfer of latent and sensible heat from the surface to the standard height and depends on roughness of the surface and atmospheric stability. In ETPOT, the wind function is calculated from wind speed WIND (m s^{-1}) which is read from the weather input file:

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

Table 8.1. Indicative values for empirical constants in the Ångström formula in relation to general climatic zones used by the FAO (Frère and Popov, 1979).

	ANGA	ANGB
Cold and temperate zones	0.18	0.55
Dry tropical countries	0.25	0.45
Humid tropical zones	0.29	0.42

8.2 Potential canopy transpiration and soil evaporation

The radiation term EVR and the drying power term EVD of the 'Penman' evapotranspiration, computed above, are used to calculate the potential transpiration of the canopy (with soil background or water layer) and the potential evaporation of the soil and open water layer.

Potential canopy transpiration

The potential transpiration of rice with a water layer is

```
TRCWL = EVRWL*(1.-EXP(-0.5*LAI))+EVD*(MIN(2.5,LAI))
```

and with a soil background

```
TRCS  = EVR*(1.-EXP(-0.5*LAI))+EVD*(MIN(2.5,LAI))
```

Only part of the radiation term, EVR, will be used by the crop, if not all radiation is intercepted by the canopy, which is exponentially related to leaf area. Radiation not used by the canopy will reach the soil or water layer and contribute to potential soil or water evaporation. The average extinction coefficient for visible and near infrared radiation is about 0.5.

The drying power of the air, EVD, is only effective up to a cumulative leaf area index of 2.5. Lower leaves do not contribute much to transpiration because little light penetrates deep into the canopy, hence their stomatal resistance is higher. Also air humidity is higher and wind speed is reduced. For this upper layer of the crop, the drying power term of the reference crop is used.

Potential soil and water evaporation

In lowland environments, rice is generally transplanted from seed-bed into the main field. Before transplanting, the main field is puddled and a layer of ponded water is present. The evaporation from this open water layer, EVSCOW, is:

```
EVSCOW = EVROW + EVDOW
```

Here, both the radiation term and the drying power term of an open water layer are used since there is no crop present. After transplanting, only radiation transmitted through the canopy is available for evaporation from the water layer (radiation term). The canopy also reduces the wind speed (drying power term). Evaporation from this 'shielded' water layer, EVSCWL, becomes:

```
EVSCWL = EXP(-0.5*LAI)*(EVRWL+EVD)
```

In upland environments with a non-puddled soil, and in lowland with a dried-out puddled layer at the end of the growing season, the potential evaporation from the soil, EVSCS, is:

```
EVSCS  = EXP(-0.5*LAI)*(EVR+EVD)
```

When there are no rice plants present (before emergence), LAI = 0, and EVSCS becomes the evaporation of bare soil.

Finally, in ETPOT, the potential values for transpiration, TRC, and evaporation, EVSC, are selected for the relevant production environment. The switch SWIWLP controls this selection: 0 = irrigated lowland; 1 = rainfed lowland; 2 = rainfed upland and 3 = any rice growing condition (both irrigated and rainfed upland or lowland).

In *lowland environments*, a layer of ponded water is generally present on the fields. However, under unfavourable weather conditions, this layer can disappear when the crop is not irrigated. The depth of ponded water, WL0, is used to select the appropiate transpiration and evaporation rates. WL0 is calculated in the PADDY and LOWBAL water balance and passed on to ETPOT.

```
IF (WL0 .GT. 0) THEN
   TRC  = TRCWL
   EVSC = EVSCWL
ELSE IF (WL0 .LT. 0) THEN
   TRC  = TRCS
   EVSC = EVSCS
END IF
```

Before transplanting, it is assumed that in both irrigated and rainfed lowland, a layer of ponded water is present in the main field. Evaporation is therefore evaporation from an open water layer:

```
EVSC = EVSCOW
```

In *rainfed upland* environments, a soil background is always present:

```
TRC  = TRCS
EVSC = EVSCS
```

9 Running and editing ORYZA_W

9.1 Input and output file control

Under the SARP-shell (Riethoven, 1994) the control over the input and output files is facilitated with a menu-system. 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 5). The content of this file is:

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
Crop data are the parameter values needed for the above-ground growth module ORYZAW. An example is given in Appendix 1 for crop data for IR72, derived from field experiments at IRRI (Kropff et al., 1993). Crop data should preferably be derived for the local rice variety under consideration, from field experiments under potential growth conditions.

Soil data
Soil data are the parameter values needed for the water balance modules PADDY, LOWBAL or SAHEL. It is important to select the right input file for each soil-water balance module. When the wrong file is supplied, ORYZA_W is aborted and gives an error message. Examples of soil files are given in Appendix 2. For the SAHEL water balance module, 18 example files are supplied 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 timing of the growing season. An example is given in Appendix 5. Important parameters in this file are:

Production environment

SWIWLP = switch to control the production environment:
0 = irrigated;
1 = rainfed lowland using LOWBAL;
2 = rainfed upland using SAHEL;
3 = irrigated or rainfed lowland or upland using PADDY

Weather data

The selection of files containing weather data is controlled by the 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

Also, the Angstrom parameters have to be given and a multiplication factor to convert radiation data from the weather file from kJ or mJ into J:

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

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 data in a weather file should be daily values of radiation, minimum temperature, maximum temperature, vapour pressure, wind speed and rainfall. The format of the data should adhere to strict rules. An example of a weather data file in the WEATHER format is given in Appendix 5.

Timer variables

IYEAR = year of weather data (= year of simulation), 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 preset and normally do not need changing.

IFLAG = indicates where weather error and warnings go, e.g. 1100 means errors and warnings only to log file, see WEATHER manual, van Kraalingen et al., 1990

COPINF = swich variable denoting what to 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 system provides a facility for reruns with ORYZA_W using changed model parameter and/or initial state variable values (van Kraalingen et al., 1991a). A reruns file with the name RERUNS.DAT contains the names and new values of any parameter and/or initial state variable for a model rerun. When ORYZA_W is executed, it will automatically search for the presence of a file with the name RERUNS.DAT. If such a file is not found, the model will be executed one single time, using the data from the standard data files. If a RERUNS.DAT is present, the parameter values will be read and the model will automatically be rerun with the (set of) new parameter values. The total number of runs made by the model is then always one more then the number of rerun sets. 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. 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 when the first variable is repeated. An example of a RERUNS.DAT file is given in Appendix 5.

The maximum number of parameter values for reruns 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. Otherwise, the output file RESULTS.OUT will become extremely large.

Output file

ORYZA_W creates one output file: e.g. RESULTS.OUT (exact file name defined in CONTROL.DAT, see above). 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})`.

Log files

Two log files are made. 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 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.

9.2 Editing ORYZA_W

ORYZA_W is written in the programming language FORTRAN-77 on an IBM compatible 486 PC. When the source code of the model is edited, ORYZA_W should be re-compiled and linked with the libraries included on the diskette before execution (see also Chapter 1).

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Appendix 1 ORYWAT crop growth module and subroutines ETPOT and DSTRES

A1.1 Listing ORYZA_W

```
*----------------------------------------------------------------------*
*                                                                      *
*                            ORYZA_W (3.0)                             *
*         A Model for Fully Irrigated and Rainfed Rice Production      *
*                                                                      *
* This version especially adapted from the FST-Version 1.3 of ORYZA1   *
* (April 1994) for use under the SARP-Shell.                           *
*                                                                      *
* Version: FSE-2.1                                                     *
* Date: October 1994                                                   *
*                                                                      *
* Documented in SARP Research Proceedings (1994):                      *
* ORYZA_W: Rice growth model for irrigated and rainfed                 *
*          environments                                                *
* MCS Wopereis, BAM Bouman, TP Tuong, HFM ten Berge, MJ Kropff         *
*                                                                      *
* International Rice Research Institute (IRRI), P.O. Box 933,          *
* 1099 Manila, The Philippines                                         *
*                                                                      *
* Department of Theoretical Production Ecology (TPE-WAU),              *
* Wageningen Agricultural University, P.O. Box 430, 6700 AK Wageningen,*
* The Netherlands                                                      *
*                                                                      *
* Research Institute for Agrobiology and Soil Fertility (AB-DLO),      *
* Agricultural Research Department, P.O. Box 14, 6700 AA Wageningen,   *
* The Netherlands                                                      *
*                                                                      *
* This model is based on the following models:                         *
* - INTERCOM    by Kropff, M.J. et al., 1993. In: Modelling crop-weed  *
*                  interactions. Forthcoming CAB, London               *
* - MACROS-L1D by Penning de Vries F.W.T. et al., 1989. Simulation of  *
*                  ecophysiological processes of growth in several     *
*                  annual crops. Simulation Monographs 29, Pudoc,      *
*                  Wageningen and IRRI, Los Banos, 271 pp.             *
* - SUCROS      by Laar, H.H. van, J. Goudriaan & H. van Keulen, 1992. *
*                  Simulation of crop growth for potential and water-  *
*                  limited production situations. Simulation Reports 27,*
*                  CABO-TPE, Wageningen, The Netherlands, 72 pp.       *
*                                                                      *
************************************************************************
      PROGRAM MAIN
      CALL FSE
      END

*----------------------------------------------------------------------*
* SUBROUTINE MODELS                                                    *
* 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                            *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* ITASK   I4  Task that subroutine should perform (-)              I   *
* IUNITD  I4  Unit that can be used for input files (-)            I   *
* IUNITO  I4  Unit number of output file (-)                       I   *
* IUNITL  I4  Unit number for log file messages (-)                I   *
* FILEIT  C*  Name of timer input 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  Daynumber (January 1 = 1) (-)                        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 (=day number) (d)           I   *
* FINTIM  R4  Finish time of simulation (=day number) (d)          I   *
* DELT    R4  Time step of integration (d)                         I   *
* LAT     R4  Latitude of site (dec.degr.)                         I   *
* LONG    R4  Longitude of site (dec.degr.)                        I   *
* ELEV    R4  Elevation of site (m)                                I   *
* WSTAT   C*  Status code from weather system (-)                  I   *
* WTRTER  L4  Flag whether weather can be used by model (-)        O   *
* RDD     R4  Daily shortwave radiation (J m-2 d-1)                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  Daily average windspeed (m s-1)                      I   *
* RAIN    R4  Daily amount of rainfall (mm d-1)                    I   *
*                                                                      *
* Fatal error checks: none                                             *
* Warnings          : none                                             *
* Subprograms called: models as specified by the user                  *
* File usage        : none                                             *
*----------------------------------------------------------------------*
      SUBROUTINE MODELS(ITASK,IUNITD,IUNITO,IUNITL,FILEIT,FILEI1,FILEI2,
     &                  FILEI3,FILEI4,FILEI5,OUTPUT,TERMNL,DOY,IDOY,
     &                  YEAR,IYEAR,TIME,STTIME,FINTIM,DELT,LAT,LONG,
     &                  ELEV,WSTAT,WTRTER,RDD,TMMN,TMMX,VP,WN,RAIN)
      IMPLICIT REAL(A-Z)

*     Formal parameters
      INTEGER ITASK,IUNITD,IUNITO,IUNITL,IDOY,IYEAR
      CHARACTER FILEIT*(*),FILEI1*(*),FILEI2*(*),FILEI3*(*)
```

```
      CHARACTER FILEI4*(*),FILEI5*(*)
      LOGICAL OUTPUT,TERMNL,WTRTER
      CHARACTER WSTAT*6
      CHARACTER WUSED*6

*     Local variables
      INTEGER SWIWLP,SWITPF
      INTEGER IDOYH,ISTAT2
      INTEGER IWVAR

*-----Standard local declarations
      INTEGER ITIM,ITRT
      INTEGER INL,I
      PARAMETER (INL=10)

*-----Declarations for water limited production
      REAL TKL(INL),WCWP(INL),WCFC(INL),WCST(INL)
*-----Declarations needed for PADDY module
      REAL TOTPOR(INL)
      REAL WCLQT(INL),TRWL(INL)

      INTEGER NL
      SAVE

*     code for the use of RDD, TMMN, TMMX, VP, WN, RAIN  (in that order)
*     a letter 'U' indicates that the variable is Used in calculations
      DATA WUSED/'UUUUUU'/

*     Check weather data availability
      IF (ITASK.EQ.1.OR.ITASK.EQ.2.OR.ITASK.EQ.4) THEN
         DO IWVAR = 1,6
*           is there an error in the IWVAR-th weather variable ?
            IF (WUSED(IWVAR:IWVAR).EQ.'U'.AND.WSTAT(IWVAR:IWVAR).EQ.'4')
     &          THEN
               WTRTER = .TRUE.
               TERMNL = .TRUE.
               RETURN
            END IF
10       END DO
      END IF

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

*-------Read values from TIMER file
         CALL RDINIT(IUNITD,IUNITL,FILEIT)
         CALL RDSINT('SWIWLP',SWIWLP)
         IF (SWIWLP.LT.0.OR.SWIWLP.GT.3)
     &       CALL ERROR('MODELS','wrong value for SWIWLP')

         CALL RDSREA('MULTIP',MULTIP)
         CLOSE (IUNITD)

         CALL RDINIT(IUNITD,IUNITL,FILEI1)
         CALL RDSREA('DTRP  ',DTRP)
         CLOSE (IUNITD)

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

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

*--------Set timer variables
         DTRP = ANINT(DTRP)
*        In upland: there is no transplanting!
         IF (SWIWLP.EQ.2) DTRP = 0.
         ITRT = NINT(STTIME+DTRP)

      END IF

      ITIM = NINT(TIME)

*-----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)

*-----Call water balances and crop growth subroutines
      IF (SWIWLP.EQ.2) THEN
         CALL SAHEL(ITASK,IUNITD,IUNITO,IUNITL,FILEI2,OUTPUT,TERMNL,
     &              TIME,DELT,SWIWLP,RAIN,RAINN,EVSC,TRWL,INL,NL,TKL,
     &              TKLT,ZRTMS,WCWP,WCFC,WCST,WCLQT,WL0)

      ELSE IF (SWIWLP.EQ.0.OR.SWIWLP.EQ.1) THEN
         CALL LOWBAL(ITASK,IUNITD,IUNITO,IUNITL,FILEI2,OUTPUT,TERMNL,
     &               DELT,SWIWLP,ITIM,ITRT,DVS,TRWL,EVSC,RAIN,RAINN,INL,
     &               NL,TKL,TKLT,ZRTMS,WCWP,WCFC,WCST,WCLQT,WL0)

      ELSE IF (SWIWLP.EQ.3) THEN
         CALL PADDY(ITASK,IUNITD,IUNITO,IUNITL,FILEI2,OUTPUT,TERMNL,
     &              WSTAT,WTRTER,DOY,DELT,TIME,ITIM,ITRT,RAIN,EVSC,TRWL,
     &              INL,NL,ZRTMS,TKL,TKLT,WCWP,WCFC,WCST,WCLQT,TOTPOR,
     &              WL0,SWITPF)
      END IF

      CALL ORYWAT(ITASK,IUNITD,IUNITO,IUNITL,FILEI1,FILEIT,SWIWLP,
     &            SWITPF,OUTPUT,TERMNL,DOY,IDOY,YEAR,IYEAR,TIME,STTIME,
     &            ITIM,ITRT,FINTIM,DELT,LAT,RDD,TMMN,TMMX,VP,WN,RAIN,NL,
     &            TKL,TKLT,ZRTMS,EVSC,WCWP,WCFC,WCST,WCLQT,TRWL,WL0,DVS,
     &            DTRP)
```

```
      RETURN
      END
```

A1.2 Listing ORYWAT

```
*----------------------------------------------------------------------*
* SUBROUTINE ORYWAT                                                    *
*                                                                      *
* Adapted from ORYZA1 (V1.3)                                           *
* Date   : October 1994                                                *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* ITASK   I4  Task that subroutine should perform (-)              I   *
* IUNITD  I4  Unit that can be used for input files (-)            I   *
* IUNITO  I4  Unit number of output file (-)                       I   *
* IUNITL  I4  Unit number for log file messages (-)                I   *
* FILEIN  C*  Name of file with input model data (-)               I   *
* FILEIT  C*  Name of timer input file (-)                         I   *
* SWIWLP  I4  Switch to select production environment (-)          I   *
* SWITPF  I4  Switch for pF data (-)                               I   *
* OUTPUT  R4  Flag to indicate if output should be done (-)        I   *
* TERMNL  R4  Flag to indicate if simulation is to stop (-)       I/O  *
* DOY     R4  Daynumber (January 1 = 1) (-)                        I   *
* IDOY    I4  Day number within year of simulation (INTEGER) (d)   I   *
* YEAR    R4  Year of simulation (REAL) (y)                        I   *
* IYEAR   R4  Year of simulation (INTEGER) (y)                     I   *
* TIME    R4  Time of simulation (d)                               I   *
* STTIME  R4  Start time of simulation (=day number) (d)           I   *
* ITIM    I4  Time of simulation (d)                               I   *
* ITRT    I4  Time of transplanting (d)                            I   *
* FINTIM  R4  Finish time of simulation (=day number) (d)          I   *
* DELT    R4  Time step of integration (d)                         I   *
* LAT     R4  Latitude of site (dec.degr.)                         I   *
* RDD     R4  Daily shortwave radiation (J m-2 d-1)                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  Daily average windspeed (m s-1)                      I   *
* RAIN    R4  Daily amount of rainfall (mm d-1)                    I   *
* NL      I4  Number of soil layers (-)                            I   *
* TKL     R4  Array of thicknesses soil layers (m)                 I   *
* TKLT    R4  Depth of simulated soil (m)                          I   *
* ZRTMS   R4  Maximum rooting depth of soil (m)                    I   *
* EVSC    R4  Potential soil evaporation rate (mm d-1)             I   *
* WCWP    R4  Array of water content at wilting point/layer (cm3       *
*             cm-3)                                                I   *
* WCFC    R4  Array of water content field capacity/layer (cm3         *
*             cm-3)                                                I   *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) I   *
* WCLQT   R4  Array of actual soil water contents/layer (cm3 cm-3) I   *
* TRWL    R4  Array of actual transpiration rate/layer (mm d-1)    O   *
* WL0     R4  Amount of ponded water (mm)                          I   *
* DVS     R4  Development stage of the crop (-)                    O   *
* DTRP    R4  Days in seedbed (J m-2 d-1)                          I   *
*                                                                      *
* Fatal error checks: if one of the characters of WSTAT = '4',         *
*                     indicates missing weather                        *
* Warnings          : none                                             *
* Subprograms called: models as specified by the user                  *
* File usage        : IUNITD,IUNITD+1,IUNITO,IUNITO+1,IUNITL           *
*----------------------------------------------------------------------*

      SUBROUTINE ORYWAT(ITASK,IUNITD,IUNITO,IUNITL,FILEIN,FILEIT,SWIWLP,
     &                  SWITPF,OUTPUT,TERMNL,DOY,IDOY,YEAR,IYEAR,TIME,
     &                  STTIME,ITIM,ITRT,FINTIM,DELT,LAT,RDD,TMMN,TMMX,
     &                  VP,WN,RAIN,NL,TKL,TKLT,ZRTMS,EVSC,WCWP,WCFC,
     &                  WCST,WCLQT,TRWL,WL0,DVS,DTRP)

*-----------------------------------------------------------------*
*     DECLARATION SECTION                                         *
*-----------------------------------------------------------------*
      IMPLICIT REAL(A-Z)

*     Formal parameters
      INTEGER ITASK,IUNITD,IUNITO,IUNITL,IDOY,IYEAR
      INTEGER NL
      LOGICAL OUTPUT,TERMNL
      CHARACTER*(*) FILEIN,FILEIT
      REAL DOY,YEAR,TIME,STTIME,FINTIM,DELT
      REAL LAT,RDD,TMMN,TMMX,VP,WN,RAIN
      REAL TKL(NL),WCWP(NL),WCFC(NL),WCST(NL)
      REAL WCLQT(NL),TRWL(NL)

*     Standard local declarations

      INTEGER SWIWLP,SWITPF,SWICOV,SWILAI,SWINLV,SWITMP
      CHARACTER*1 MLAI,MNFLV,MWTDM,MWLVG,MWLVD,MWST,MWPA

*     AFGEN functions
      INTEGER IMSLAT,ILSLAT
      PARAMETER (IMSLAT=40)
      DIMENSION SLATB(IMSLAT)
      INTEGER IMDRLV,ILDRLV
      PARAMETER (IMDRLV=40)
      DIMENSION DRLVT(IMDRLV)
      INTEGER IMEFFT,ILEFFT
      PARAMETER (IMEFFT=40)
      DIMENSION EFFTB(IMEFFT)
      INTEGER IMFLVT,ILFLVT
```

```
      PARAMETER (IMFLVT=40)
      DIMENSION FLVTB(IMFLVT)
      INTEGER IMFRTT,ILFRTT
      PARAMETER (IMFRTT=40)
      DIMENSION FRTTB(IMFRTT)
      INTEGER IMFSHT,ILFSHT
      PARAMETER (IMFSHT=40)
      DIMENSION FSHTB(IMFSHT)
      INTEGER IMFSOT,ILFSOT
      PARAMETER (IMFSOT=40)
      DIMENSION FSOTB(IMFSOT)
      INTEGER IMFSTT,ILFSTT
      PARAMETER (IMFSTT=40)
      DIMENSION FSTTB(IMFSTT)
      INTEGER IMKDFT,ILKDFT
      PARAMETER (IMKDFT=40)
      DIMENSION KDFTB(IMKDFT)
      INTEGER IMKNFT,ILKNFT
      PARAMETER (IMKNFT=40)
      DIMENSION KNFTB(IMKNFT)
      INTEGER IMNFLV,ILNFLV
      PARAMETER (IMNFLV=40)
      DIMENSION NFLVTB(IMNFLV)
      INTEGER IMREDF,ILREDF
      PARAMETER (IMREDF=40)
      DIMENSION REDFTT(IMREDF)
      INTEGER IMSSGA,ILSSGA
      PARAMETER (IMSSGA=40)
      DIMENSION SSGATB(IMSSGA)
      INTEGER IMTMCT,ILTMCT
      PARAMETER (IMTMCT=40)
      DIMENSION TMCTB(IMTMCT)
      INTEGER IMXLAI,ILXLAI
      PARAMETER (IMXLAI=40)
      DIMENSION XLAITB(IMXLAI)
      INTEGER IMXNFL,ILXNFL
      PARAMETER (IMXNFL=40)
      DIMENSION XNFLVT(IMXNFL)
      INTEGER IMXWLV,ILXWLV
      PARAMETER (IMXWLV=40)
      DIMENSION XWLVDT(IMXWLV)
      INTEGER IMXWL1,ILXWL1
      PARAMETER (IMXWL1=40)
      DIMENSION XWLVGT(IMXWL1)
      INTEGER IMXWPA,ILXWPA
      PARAMETER (IMXWPA=40)
      DIMENSION XWPATB(IMXWPA)
      INTEGER IMXWST,ILXWST
      PARAMETER (IMXWST=40)
      DIMENSION XWSTTB(IMXWST)
      INTEGER IMXWTD,ILXWTD
      PARAMETER (IMXWTD=40)
      DIMENSION XWTDMT(IMXWTD)

*     Used functions
      REAL LINT,INSW,NOTNUL

*     Declarations for water-limited production

      LOGICAL DLEAF,DROUT

      INTEGER ICNT
      INTEGER ITIM,ITRT
      INTEGER ISTD,INSD,ITMP1

      SAVE

*----------------------------------------------------------------------*
*     INITIALIZATION SECTION                                           *
*----------------------------------------------------------------------*
      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 IF (SWIWLP.EQ.2) THEN
            CALL OUTCOM('ORYZA_W: Rainfed, upland rice production')
         ELSE IF (SWIWLP.EQ.3) THEN
            CALL OUTCOM('ORYZA_W: Rainfed lowland rice production')
         END IF

*        Read Angstrom parameters from the TIMER file
         CALL RDINIT(IUNITD,IUNITL,FILEIT)
         CALL RDSREA('ANGA',ANGA)
         CALL RDSREA('ANGB',ANGB)
         CLOSE (IUNITD)

*        Open crop input file
         CALL RDINIT(IUNITD,IUNITL,FILEIN)

*        Read initial states
         CALL RDSREA('DVSI  ',DVSI)
         CALL RDSREA('WLVGI ',WLVGI)
         CALL RDSREA('WRTI  ',WRTI)
         CALL RDSREA('WSOI  ',WSOI)
         CALL RDSREA('WSTI  ',WSTI)
         CALL RDSREA('ZERO  ',ZERO)

*        Read model parameters
         CALL RDSREA('CO2   ',CO2)
         CALL RDSREA('CO2REF',CO2REF)
         CALL RDSREA('CRGLV ',CRGLV)
         CALL RDSREA('CRGRT ',CRGRT)
         CALL RDSREA('CRGSO ',CRGSO)
```

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      CALL RDSREA('CRGST ',CRGST)
      CALL RDSREA('CRGSTR',CRGSTR)
      CALL RDSREA('DVRI  ',DVRI)
      CALL RDSREA('DVRJ  ',DVRJ)
      CALL RDSREA('DVRP  ',DVRP)
      CALL RDSREA('DVRR  ',DVRR)
      CALL RDSREA('FCLV  ',FCLV)
      CALL RDSREA('FCRT  ',FCRT)
      CALL RDSREA('FCSO  ',FCSO)
      CALL RDSREA('FCST  ',FCST)
      CALL RDSREA('FCSTR ',FCSTR)
      CALL RDSREA('FSTR  ',FSTR)
      CALL RDSREA('LAPE  ',LAPE)
      CALL RDSREA('LRSTR ',LRSTR)
      CALL RDSREA('MAINLV',MAINLV)
      CALL RDSREA('MAINRT',MAINRT)
      CALL RDSREA('MAINSO',MAINSO)
      CALL RDSREA('MAINST',MAINST)
      CALL RDSREA('MOPP  ',MOPP)
      CALL RDSREA('NH    ',NH)
      CALL RDSINT('NPLH  ',ITMP1)
      NPLH = REAL (ITMP1)
      CALL RDSREA('NPLSB ',NPLSB)
      CALL RDSREA('PPSE  ',PPSE)
      CALL RDSREA('Q10   ',Q10)
      CALL RDSREA('RGRL  ',RGRL)
      CALL RDSREA('SCP   ',SCP)
      CALL RDSREA('SHCKD ',SHCKD)
      CALL RDSREA('SHCKL ',SHCKL)
      CALL RDSREA('SPGF  ',SPGF)
      CALL RDSREA('TBD   ',TBD)
      CALL RDSREA('TBLV  ',TBLV)
      CALL RDSREA('TCLSTR',TCLSTR)
      CALL RDSREA('TMD   ',TMD)
      CALL RDSREA('TOD   ',TOD)
      CALL RDSREA('TREF  ',TREF)
      CALL RDSREA('WGRMX ',WGRMX)

*     Read AFGEN functions
      CALL RDAREA('TMCTB ',TMCTB,IMTMCT,ILTMCT)
      CALL RDAREA('NFLVTB',NFLVTB,IMNFLV,ILNFLV)
      CALL RDAREA('REDFTT',REDFTT,IMREDF,ILREDF)
      CALL RDAREA('EFFTB ',EFFTB,IMEFFT,ILEFFT)
      CALL RDAREA('KDFTB ',KDFTB,IMKDFT,ILKDFT)
      CALL RDAREA('KNFTB ',KNFTB,IMKNFT,ILKNFT)
      CALL RDAREA('FSHTB ',FSHTB,IMFSHT,ILFSHT)
      CALL RDAREA('FRTTB ',FRTTB,IMFRTT,ILFRTT)
      CALL RDAREA('FLVTB ',FLVTB,IMFLVT,ILFLVT)
      CALL RDAREA('FSTTB ',FSTTB,IMFSTT,ILFSTT)
      CALL RDAREA('FSOTB ',FSOTB,IMFSOT,ILFSOT)
      CALL RDAREA('DRLVT ',DRLVT,IMDRLV,ILDRLV)
      CALL RDAREA('SSGATB',SSGATB,IMSSGA,ILSSGA)
      CALL RDAREA('SLATB',SLATB,IMSLAT,ILSLAT)

*     Read the switches
      CALL RDSINT('SWICOV',SWICOV)
      IF (SWICOV.NE.-1.AND.SWICOV.NE.1)
     &     CALL ERROR('ORYWAT','wrong value for SWICOV')
      CALL RDSINT('SWILAI',SWILAI)
      IF (SWILAI.NE.-1.AND.SWILAI.NE.1)
     &     CALL ERROR('ORYWAT','wrong value for SWILAI')
      CALL RDSINT('SWINLV',SWINLV)
      IF (SWINLV.NE.-1.AND.SWINLV.NE.1)
     &     CALL ERROR('ORYWAT','wrong value for SWINLV')
      CALL RDSINT('SWITMP',SWITMP)
      IF (SWITMP.NE.-1.AND.SWITMP.NE.1)
     &     CALL ERROR('ORYWAT','wrong value for SWITMP')

*     Read the measured data
      CALL RDSCHA('MLAI',MLAI)
      CALL UPPERC(MLAI)
      CALL RDSCHA('MNFLV',MNFLV)
      CALL UPPERC(MNFLV)
      CALL RDSCHA('MWTDM',MWTDM)
      CALL UPPERC(MWTDM)
      CALL RDSCHA('MWLVG',MWLVG)
      CALL UPPERC(MWLVG)
      CALL RDSCHA('MWLVD',MWLVD)
      CALL UPPERC(MWLVD)
      CALL RDSCHA('MWST',MWST)
      CALL UPPERC(MWST)
      CALL RDSCHA('MWPA',MWPA)
      CALL UPPERC(MWPA)

*     Test on consistency in supplied data (LAI)
      IF (SWILAI.EQ.-1.AND.MLAI.EQ.'N') THEN
         WRITE (*,*) 'Cannot use LAI as forcing function beacuse'
         WRITE (*,*) 'MLAI is set to "N" -> check crop data file!'
         TERMNL = .TRUE.
         WRITE (*,'(A)') ' Press <RETURN>'
         READ (*,'(A)') DUMMY
      END IF

      IF (MLAI.EQ.'Y') CALL RDAREA('XLAITB',XLAITB,IMXLAI,ILXLAI)
      IF (MNFLV.EQ.'Y') CALL RDAREA('XNFLVT',XNFLVT,IMXNFL,ILXNFL)
      IF (MWLVG.EQ.'Y') CALL RDAREA('XWLVGT',XWLVGT,IMXWL1,ILXWL1)
      IF (MWST.EQ.'Y') CALL RDAREA('XWSTTB',XWSTTB,IMXWST,ILXWST)
      IF (MWPA.EQ.'Y') CALL RDAREA('XWPATB',XWPATB,IMXWPA,ILXWPA)
      IF (MWLVD.EQ.'Y') CALL RDAREA('XWLVDT',XWLVDT,IMXWLV,ILXWLV)
      IF (MWTDM.EQ.'Y') CALL RDAREA('XWTDMT',XWTDMT,IMXWTD,ILXWTD)

*     Parameters for water-limited production
      CALL RDSREA('NPLDS',NPLDS)
      CALL RDSREA('ZRTI',ZRTI)
      IF (SWIWLP.LT.3) CALL RDSREA('ZRTMC',ZRTMC)
      IF (SWIWLP.EQ.3) CALL RDSREA('ZRTMCW',ZRTMCW)
```

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      IF (SWIWLP.EQ.3) CALL RDSREA('ZRTMCD',ZRTMCD)
      CALL RDSREA('GZRT',GZRT)
      CALL RDSREA('STLG',STLG)
      CALL RDSREA('ULLS',ULLS)
      CALL RDSREA('LLLS',LLLS)
      CALL RDSREA('ULDL',ULDL)
      CALL RDSREA('LLDL',LLDL)
      CALL RDSREA('ULRT',ULRT)
      CALL RDSREA('LLRT',LLRT)

      CLOSE (IUNITD)

*     Set sow date and transplanting date
      DOYS = STTIME
      DOYTR = REAL(ITRT)

*     Write captions to the output file
      IF (SWILAI.EQ.-1) THEN
         CALL OUTCOM('- Measured LAI used as forcing function')
      ELSE IF (SWILAI.EQ.1) THEN
         CALL OUTCOM('- Simulated LAI used')
      END IF
      IF (SWINLV.EQ.-1) THEN
         CALL OUTCOM('- Nitrogen content as function of DVS used')
      ELSE IF (SWINLV.EQ.1) THEN
         CALL OUTCOM('- Nitrogen content as function of DOY used')
      END IF
      IF (SWICOV.EQ.-1) THEN
         CALL OUTCOM('- No cover over seed-bed used')
      ELSE IF (SWICOV.EQ.1) THEN
         CALL OUTCOM('- Cover over seed-bed used')
      END IF
      IF (SWITMP.EQ.-1) THEN
         CALL OUTCOM('- No GCM temperature correction used')
      ELSE IF (SWITMP.EQ.1) THEN
         CALL OUTCOM('- GCM temperature correction used')
      END IF

*     Initialize state variables
      DVS = DVSI
      PARCUM = ZERO
      PARCM1 = ZERO
      WLVG = WLVGI
      WLVD = ZERO
      WSTS = WSTI
      WSTR = ZERO
      WST = WSTS+WSTR
      WSO = WSOI
      WRT = WRTI
      WRR = ZERO
      WRR14 = WRR/0.86
      NGR = ZERO
      NSP = ZERO
      DAS = ZERO
      TS = ZERO
      TSLV = ZERO
      TNASS = ZERO
      GRDUR = ZERO
      WLVGIT = ZERO
      LAISIM = 0.
      DVR = 0.
      TSHCKD = 0.
      TSHCKL = 0.
      TADRW = 0.

*     Water-limited production
      ZRT = ZRTI
      TRC = ZERO
      TRW = ZERO
      TRCT = ZERO
      TRWCU = ZERO
      DLDRT = ZERO
      ISTD = 0
      INSD = 0

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

*----------------------------------------------------------*
*   RATE CALCULATION SECTION                               *
*----------------------------------------------------------*
   ELSE IF (ITASK.EQ.2) THEN

*-------1. interpolation of observed Values
      IF (MWLVG.EQ.'Y') THEN
         XWLVG = LINT(XWLVGT,ILXWL1,DOY)
      ELSE
         XWLVG = -99.
      END IF
      IF (MWLVD.EQ.'Y') THEN
         XWLVD = LINT(XWLVDT,ILXWLV,DOY)
      ELSE
         XWLVD = -99.
      END IF
      IF (MWST.EQ.'Y') THEN
         XWST = LINT(XWSTTB,ILXWST,DOY)
      ELSE
```

```
      XWST = -99.
   END IF
   IF (MWPA.EQ.'Y') THEN
      XWPA = LINT(XWPATB,ILXWPA,DOY)
   ELSE
      XWPA = -99.
   END IF
   IF (MWTDM.EQ.'Y') THEN
      XWTDM = LINT(XWTDMT,ILXWTD,DOY)-XWLVD
   ELSE
      XWTDM = -99.
   END IF
   IF (MWTDM.EQ.'Y') THEN
      XWT = LINT(XWTDMT,ILXWTD,DOY)
   ELSE
      XWT = -99.
   END IF
   IF (MNFLV.EQ.'Y') THEN
      XNFLV = LINT(XNFLVT,ILXNFL,DOY)
   ELSE
      XNFLV = -99.
   END IF
   IF (MLAI.EQ.'Y') THEN
      XLAI = LINT(XLAITB,ILXLAI,DOY)
   ELSE
      XLAI = -99.
   END IF

*-------2. Computation of some weather variables
   RDAS = 1.
   DTR = RDD

   CALL COVER(SWICOV,DAS,DOYTR,DOYS,TMPCOV)

   TMAXC = INSW(REAL(SWITMP),0.,LINT(TMCTB,ILTMCT,DOY))
   TMINC = INSW(REAL(SWITMP),0.,TMAXC)
   TMAX = TMMX+TMAXC+TMPCOV
   TMIN = TMMN+TMINC
   TAV = (TMIN+TMAX)/2.
   TAVD = (TMAX+TAV)/2.
   TEFF = Q10**((TAV-TREF)/10.)

*--------3. Leaf area development
   SSGA = LINT(SSGATB,ILSSGA,DVS)
   SAI = SSGA*WST

   IF (MLAI.EQ.'Y'.AND.MWLVG.EQ.'Y') THEN
      SLA = XLAI/NOTNUL(XWLVG)
   ELSE
      SLA = LINT(SLATB,ILSLAT,DVS)
   END IF

*        'Unroll' leaves in caes of leaf-rolling before entering the
*        LAI-calculations
*         IF (LSTRS .LT. 1.) THEN
*            LAI = LAI/LSTRS
*         END IF

        CALL SUBLAI(SWILAI,DAS,DOYS,DOYTR,LAPE,RGRL,TSLV,NPLSB,WLVG,
     &              SLA,NH,NPLH,SHCKL,DVS,LAISIM,TSHCKL,DTRP,ICNT,
     &              NPLDS)

        LAI = INSW(REAL(SWILAI),XLAI,LAISIM)
*       Leaf rolling in case of drought stress
        IF (SWILAI.EQ.1) LAI = LAI*LSTRS
        ALAI = LAI+0.5*SAI

*--------4. Phenological development
        CALL SUBDD(TMAX,TMIN,TBD,TOD,TMD,HU)
        CALL SUBDD(TMAX,TMIN,TBLV,30.,42.,HULV)
        CALL SUBCD(DOY,DOYTR,TAV,TIME,NCOLD)

*------5. Calculation of evapotranspiration rate and drought
*       stress levels

*--------6. Daily dry matter production
        WAGT = WLVG+WST+WSO+WLVD
        WAG = WLVG+WST+WSO

***     6.1 Daily Gross Canopy CO2 Assimilation (DTGA)
        KDF = LINT(KDFTB,ILKDFT,DVS)
        REDFT = LINT(REDFTT,ILREDF,TAVD)
        KNF = LINT(KNFTB,ILKNFT,DVS)
        PARI1 = (1.-0.06)*DTR*0.5*(1.-EXP(-KDF*ALAI))/1.E6
        NFLV = INSW(REAL(SWINLV),LINT(NFLVTB,ILNFLV,DVS),XNFLV)
        CO2EFF = (1.-EXP(-0.00305*CO2-0.222))
     &           /(1.-EXP(-0.00305*CO2REF-0.222))
        EFF = LINT(EFFTB,ILEFFT,TAVD)*CO2EFF

        CALL TOTASP(DOY,LAT,DTR,SCP,EFF,REDFT,KDF,KNF,ALAI,CO2,NFLV,
     &              DAYL,AMAX,DTGA,DPAR,DPARI,DS0)

        CALL PHENOL(DVS,DAS,DVRJ,DVRI,DVRP,DVRR,HU,DAYL,MOPP,PPSE,TS,
     &              SHCKD,DOYTR,DOYS,DVR,TSHCKD,DVEW)

***    5.2 Calculation of potential transpiration and evaporation
        CALL ETPOT(SWIWLP,ITIM,ITRT,ANGA,ANGB,DTR,DS0,TAV,VP,WN,ALAI,
     &             WCLQT,WCST,WL0,TRC,EVSC)

***    5.3 Calculation of actual evapotranspiration and of the effects
*            of water stress on crop growth and development
        CALL DSTRES(TERMNL,SWIWLP,SWITPF,DELT,DVS,TRC,ZRT,TKL,NL,WCLQT,
     &              WCST,WCFC,WCWP,STLG,ULLS,LLLS,ULDL,LLDL,ULRT,LLRT,
     &              TRW,TRWL,WCRREL,ICNT,DROUT,LSTRS,DSTRS,PCEW,DVEW,
     &              STLGWR,ULDLWR,LLDLWR)
```

```
*         Effect of drought stress on DTGA
          DTGA = DTGA*PCEW

*         Effect of drought stress on development rate
          IF (DROUT.AND.DVS.LT.1.0) DVR = DVR*DVEW

***       6.2 Relative growth Rates of Plant Organs
*             (assimilate partitioning)
          FSH = LINT(FSHTB,ILFSHT,DVS)
          FRT = LINT(FRTTB,ILFRTT,DVS)
          FLV = LINT(FLVTB,ILFLVT,DVS)
          FST = LINT(FSTTB,ILFSTT,DVS)
          FSO = LINT(FSOTB,ILFSOT,DVS)

          IF (WCRREL.LE.STLGWR.AND.DVS.LT.1.) THEN
             FSH = 0.
             FRT = 1.
          END IF

***       6.3 Carbohydrate requirement for dry matter production
          CRGCR = FSH*(CRGLV*FLV+CRGST*FST*(1.-FSTR)+CRGSTR*FSTR*FST+
     &            CRGSO*FSO)+CRGRT*FRT

***       6.4 maintenance requirements
          MNDVS = WLVG/NOTNUL(WLVG+WLVD)
          RMCR = (WLVG*MAINLV+WST*MAINST+WSO*MAINSO+WRT*MAINRT)
     &           *TEFF*MNDVS

***       6.5. Gross and net growth rate of crop (GCR, NGCR)
          LSTR = INSW(DVS-1.,0.,WSTR/TCLSTR)

          GCR = ((DTGA*30./44.)-RMCR+(LSTR*LRSTR*FCSTR*30./12.))/CRGCR

          NGCR = MAX(0.,GCR-LSTR*LRSTR*FCSTR*30./12.)

***       6.6 Number of grains and spikelets
          PWRR = NGR*WGRMX

          CALL SUBGRN(GCR,FSH,FSO,DOY,DOYS,DOYTR,DVS,WRR,PWRR,SPGF,TAV,
     &                TMAX,NSP,TIME,GRAINF,GSO,GGR,GNSP,GNGR)

***       6.7 Growth rates of crop organs
          LLV = WLVG*LINT(DRLVT,ILDRLV,DVS)

          CALL SUBRTS(DOY,DOYTR,GCR,FRT,FSH,FLV,LLV,FST,FSTR,LSTR,WLVG,
     &                WSTR,WSTS,WRT,NPLH,NH,NPLSB,DELT,GLV,GSTR,RWLVG,
     &                GRT,RWSTR,GST,RWLVG1,GRT1,RWSTR1,GST1)

          DLDR = 0.
*-------- 7. Leaf death as caused by drought stress
          IF (DSTRS.EQ.1.) THEN
             DLEAF = .FALSE.
             DLDRT = 0.
          END IF
          IF ((DSTRS.LT.1.).AND.(.NOT.DLEAF)) THEN
             WLVGIT = WLVG
             DLEAF = .TRUE.
             KEEP = DSTRS
          END IF
          IF (DLEAF) THEN
             IF (DSTRS.LE.KEEP) THEN
                DLDR = (WLVGIT/DELT)*(1.-DSTRS)-DLDRT/DELT
                KEEP = DSTRS
                DLDRT = DLDR*DELT+DLDRT
             END IF
          END IF

*---------8. Carbon Balance Check
***       8.1 Growth respiration of the crop (RGCR)
          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)

          RGCR = (GRT+GRT1)*CO2RT+(GLV+RWLVG1)*CO2LV+(GST+GST1)
     &           *CO2ST+GSO*CO2SO+(GSTR+RWSTR1)*CO2STR+(1.-LRSTR)
     &           *LSTR*FCSTR*44./12.

          CTRANS = RWLVG1*FCLV+GST1*FCST+RWSTR1*FCSTR+GRT1*FCRT
          RTNASS = ((DTGA*30./44.-RMCR)*44./30.)-RGCR-(CTRANS*44./12.)
          CKCIN = (WLVG+WLVD-WLVGI)*FCLV+(WSTS-WSTI)*FCST+WSTR*FCSTR+
     &            (WRT-WRTI)*FCRT+WSO*FCSO
          CKCFL = TNASS*(12./44.)

          CALL SUBCBC(CKCIN,CKCFL,TIME,CBCHK,TERMNL)

*---------9. Output section
          IF (OUTPUT) THEN
             CALL OUTDAT(2,0,'DVS    ',DVS)
             CALL OUTDAT(2,0,'ZRT    ',ZRT)
             CALL OUTDAT(2,0,'PCEW   ',PCEW)
             CALL OUTDAT(2,0,'WCRREL',WCRREL)
             CALL OUTDAT(2,0,'STLGWR',STLGWR)
             CALL OUTDAT(2,0,'ULDLWR',ULDLWR)
             CALL OUTDAT(2,0,'LLDLWR',LLDLWR)
             CALL OUTDAT(2,0,'TRW    ',TRW)
             CALL OUTDAT(2,0,'TRC',TRC)
             CALL OUTDAT(2,0,'LSTRS',LSTRS)
             CALL OUTDAT(2,0,'DSTRS',DSTRS)
             IF (MLAI.EQ.'Y') CALL OUTDAT(2,0,'XLAI   ',XLAI)
             CALL OUTDAT(2,0,'LAI    ',LAI)
             CALL OUTDAT(2,0,'WRT    ',WRT)
             CALL OUTDAT(2,0,'WLVG   ',WLVG)
             CALL OUTDAT(2,0,'TADRW  ',TADRW)
             CALL OUTDAT(2,0,'WLVD   ',WLVD)
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         CALL OUTDAT(2,0,'WST    ',WST)
         CALL OUTDAT(2,0,'WSO    ',WSO)

      END IF

*-----------------------------------------------------------*
*     INTEGRATION SECTION                                   *
*-----------------------------------------------------------*
      ELSE IF (ITASK.EQ.3) THEN

         DVS = INTGRL(DVS,DVR,DELT)
         PARCUM = INTGRL(PARCUM,DPARI,DELT)
         PARCM1 = INTGRL(PARCM1,PARI1,DELT)
         WLVG = INTGRL(WLVG,RWLVG-DLDR,DELT)
         WLVD = INTGRL(WLVD,LLV+DLDR,DELT)
         WSTS = INTGRL(WSTS,GST,DELT)
         WSTR = INTGRL(WSTR,RWSTR,DELT)
         WSO = INTGRL(WSO,GSO,DELT)
         WRT = INTGRL(WRT,GRT,DELT)
         WRR = INTGRL(WRR,GGR,DELT)
         NGR = INTGRL(NGR,GNGR,DELT)
         NSP = INTGRL(NSP,GNSP,DELT)
         DAS = INTGRL(DAS,RDAS,DELT)
         TS = INTGRL(TS,HU,DELT)
         TSLV = INTGRL(TSLV,HULV,DELT)
         TNASS = INTGRL(TNASS,RTNASS,DELT)
*PATCH DVK
         TADRW = WRT+WLVG+WLVD+WST+WSO
* For PADDY
         IF (SWIWLP.EQ.3) THEN
            IF ((.NOT.DROUT).AND.(ZRT.LE.ZRTMCW)) THEN
               ZRTM = MIN(ZRTMCW,ZRTMS,TKLT)
            ELSE IF ((.NOT.DROUT).AND.(ZRT.GT.ZRTMCW)) THEN
               ZRTM = MIN(ZRT,ZRTMS,TKLT)
            ELSE IF (DROUT) THEN
               ZRTM = MIN(ZRTMCD,ZRTMS,TKLT)
            END IF
* In all other cases, roots grow straight to max. length ZRTMC
         ELSE
            ZRTM = MIN(ZRTMC,ZRTMS,TKLT)
         END IF
         ZRT = INTGRL(ZRT,GZRT,DELT)
         ZRT = MIN(ZRT,ZRTM)

         WRR14 = WRR/0.86
         WST = WSTS+WSTR
         GRDUR = TIME-DOYS

*---------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.-5..OR.WLVG.LT.-5..OR.WST.LT.-5.) THEN
            WRITE (*,*) 'Negative biomass=> simulation stopped'
            CALL OUTCOM('Negative biomass => simulation stopped')
            IF (WSO.LT.0.) WSO = 0.
            IF (WST.LT.0.) WST = 0.
            IF (WLVG.LT.0.) WLVG = 0.
            TERMNL = .TRUE.
         END IF

* If rel. water content greater than STLGWR: no more drought
* Reset stress-day counters to 0 if there are more than 3
* days without drought.
         IF (WCRREL.GT.STLGWR) THEN
            DROUT = .FALSE.
            INSD = INSD+INT(DELT)
            IF (INSD.GT.3) ISTD = 0
         END IF

* Count the drought stress days
         IF (WCRREL.LE.STLGWR) THEN
            ISTD = ISTD+INT(DELT)
            INSD = 0
         END IF

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

* Check if lower limit dead leaves is reached
         IF (WCRREL.LE.LLDLWR) THEN
            WRITE (*,*) 'Soil dryer than lower limit dead leaves'
            WRITE (*,*) '=> Simulation stopped'
            CALL OUTCOM('soil dryer than LLDL - simulation stopped')
            TERMNL = .TRUE.
         END IF

         IF (DVS.GT.2.) TERMNL = .TRUE.
         IF (NCOLD.GT.3.) TERMNL = .TRUE.
         IF (GRAINF.LT.0.) TERMNL = .TRUE.

*-----------------------------------------------------------*
*     TERMINAL SECTION                                      *
*-----------------------------------------------------------*
```

```
      ELSE IF (ITASK.EQ.4) THEN

*        Terminal calculations
         WGR = WRR/NOTNUL(NGR)

*        Terminal output

      END IF

      RETURN
      END
```

A1.3 Listing ETPOT

```
*----------------------------------------------------------------------*
* 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 (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* SWIWLP  I4  Switch to select production environment (-)          C  *
* ITIM    I4  Time of simulation (d)                               T  *
* ITRT    I4  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  *
* DS0     R4  Daily extraterstrial radiation (J m-2 d-1)           I  *
* TAV     R4  Average daily temperature (oC)                       I  *
* VP      R4  Early morning vapour pressure (kPa)                  I  *
* WN      R4  Daily average windspeed (m s-1)                      I  *
* LAI     R4  Apparent leaf area index (incl. stem area) (ha ha-1) I  *
* WCLQT   R4  Array of actual soil water contents/layer (cm3 cm-3) I  *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) I  *
* WL0     R4  Amount of ponded water (mm)                          I  *
* TRC     R4  Potential transpiration rate (mm d-1)                O  *
* EVSC    R4  Potential soil evaporation rate (mm d-1)             O  *
*                                                                      *
* FATAL ERROR CHECKS: none                                             *
* FILE usage : none                                                    *
*----------------------------------------------------------------------*
      SUBROUTINE ETPOT(SWIWLP,ITIM,ITRT,ANGA,ANGB,RDT,DS0,TAV,VP,WN,LAI,
     &                 WCLQT,WCST,WL0,TRC,EVSC)

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

*------Conversion from kpa -> mbar
      VAPOR = VP*10.
      WIND = WN

      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/DS0)-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.OR.SWIWLP.EQ.3) THEN
         IF (WL0.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) EVSC = EVSCOW

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

      RETURN
      END
```

A1.4 Listing DSTRES

```
*----------------------------------------------------------------------*
*  SUBROUTINE DSTRES                                                   *
*                                                                      *
*  Author: M.C.S. Wopereis and B.A.M. Bouman                           *
*  Version: 1.0                                                        *
*  Date: August 1994                                                   *
*  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 (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* TERMNL  R4  Flag to indicate if simulation is to stop (-)       I/O *
* SWIWLP  I4  Switch to select production environment (-)          C  *
* SWITPF  R4  Switch for pF data (-)                               I  *
* DELT    R4  Time step of integration (d)                         T  *
* DVS     R4  Development stage of the crop (-)                    I  *
* TRC     R4  Potential transpiration rate (mm d-1)                I  *
* ZRT     R4  Rooting depth (m)                                    I  *
* TKL     R4  Array of thicknesses soil layers (m)                 I  *
* NL      I4  Number of soil layers (-)                            I  *
* WCLQT   R4  Array of actual soil water contents/layer (cm3 cm-3) I  *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) I  *
* WCFC    R4  Array of water content field capacity/layer (cm3        *
*             cm-3)                                                I  *
* WCWP    R4  Array of water content at wilting point/layer (cm3      *
*             cm-3)                                                I  *
* STLG    R4  Upper/lower limit leaf growth (pF)                   I  *
* ULLS    R4  Upper limit leaf rolling (pF)                        I  *
* LLLS    R4  Lower limit leaf rolling (pF)                        I  *
* ULDL    R4  Upper limit dead leaves (pF)                         I  *
* LLDL    R4  Lower limit dead leaves (pF)                         I  *
* ULRT    R4  Upper limit relative transpiration rate (pF)         I  *
* LLRT    R4  Lower limit relative transpiration rate (pF)         I  *
* TRW     R4  Actual transpiration rate (mm d-1)                   O  *
* TRWL    R4  Array of actual transpiration rate/layer (mm d-1)    O  *
* WCRREL  R4  Relative water content in non-pud rootzone (cm3 cm-3) O *
* ICNT    I4  Counter for leaf growth stress (-)                   O  *
* DROUT   L4  Switch for leaf growth stress (-)                   C/O *
* LSTRS   R4  Stress factor for leaf rolling (-)                   O  *
* DSTRS   R4  Stress factor for dead leaves (?)                    O  *
* PCEW    R4  Stress factor for CO2 assimilation (-)               O  *
* DVEW    R4  Stress factor for development rate (-)               O  *
* STLGWR  R4  Limit for leaf growth averaged over non puddled root    *
*             zone (step function) (cm3 cm-3)                      O  *
* ULDLWR  R4  Actual upper limit dead leaves averaged over non        *
*             puddled root zone (vol. water content) (cm3 cm-3)    O  *
* LLDLWR  R4  Actual lower limit dead leaves averaged over non        *
*             puddled root zone (vol. water content) (cm3 cm-3)    O  *
*----------------------------------------------------------------------*
      SUBROUTINE DSTRES(TERMNL,SWIWLP,SWITPF,DELT,DVS,TRC,ZRT,TKL,NL,
     &                  WCLQT,WCST,WCFC,WCWP,STLG,ULLS,LLLS,ULDL,LLDL,
     &                  ULRT,LLRT,TRW,TRWL,WCRREL,ICNT,DROUT,LSTRS,
     &                  DSTRS,PCEW,DVEW,STLGWR,ULDLWR,LLDLWR)
```

```
      IMPLICIT REAL(A-Z)

*      Formal parameters
      INTEGER SWIWLP,SWITPF,NL
      LOGICAL TERMNL,DROUT
      REAL TRWL(NL),TKL(NL),WCLQT(NL),WCFC(NL),WCWP(NL)
      REAL WCST(NL)

*      Local variables
      INTEGER I,ICNT,INL
      PARAMETER (INL=10)
      REAL STLGW(INL)
      REAL ULLSW(INL),LLLSW(INL)
      REAL ULDLW(INL),LLDLW(INL)
      REAL ULRTW(INL),LLRTW(INL)

      SAVE

      IF (NL.GT.INL) CALL ERROR('DSTRES','too many layers')

      STLGWR = 0.
      ULDLWR = 0.
      LLDLWR = 0.


*================================================================*
*   Calculation of actual transpiration rates, and of stress     *
*================================================================*

      IF (SWIWLP.EQ.0.OR.SWIWLP.EQ.1) NL = 1
      IF (SWIWLP.EQ.2) NL = 3

*------Reset transpiration rates in all soil compartments to 0
      DO I = 1,NL
         TRWL(I) = 0.
5     END DO

      ZR = ZRT

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

      TRW = 0.
      ZLL = 0.
      LS = 0.
      DS = 0.
      WCRREL = 0.


      DO I = 1,NL
         ZRTL = MIN(TKL(I),MAX((ZR-ZLL),0.0))
         WCRREL = WCRREL+(ZRTL/(ZR+1.0E-10))*WCLQT(I)
         IF (SWITPF.EQ.1) THEN
            CALL SUWCMS2(I,2,WCST(I),STLGW(I),10**STLG)
            CALL SUWCMS2(I,2,WCST(I),ULLSW(I),10**ULLS)
            CALL SUWCMS2(I,2,WCST(I),LLLSW(I),10**LLLS)
            CALL SUWCMS2(I,2,WCST(I),ULDLW(I),10**ULDL)
            CALL SUWCMS2(I,2,WCST(I),LLDLW(I),10**LLDL)
            CALL SUWCMS2(I,2,WCST(I),ULRTW(I),10**ULRT)
            CALL SUWCMS2(I,2,WCST(I),LLRTW(I),10**LLRT)
         ELSE
            STLGW(I)  = WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-STLG)
            ULLSW(I)  = WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-ULLS)
            LLLSW(I)  = WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-LLLS)
            ULDLW(I)  = WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-ULDL)
            LLDLW(I)  = WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-LLDL)
            ULRTW(I)  = WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-ULRT)
            LLRTW(I)  = WCWP(I)+((WCFC(I)-WCWP(I))/2.2)*(4.2-LLRT)
         END IF
         STLGWR = STLGWR+(ZRTL/(ZR+1.0E-10))*STLGW(I)
         ULDLWR = ULDLWR+(ZRTL/(ZR+1.0E-10))*ULDLW(I)
         LLDLWR = LLDLWR+(ZRTL/(ZR+1.0E-10))*LLDLW(I)

         DSETR = LIMIT(0.,1.,(WCLQT(I)-LLRTW(I))/(ULRTW(I)-LLRTW(I)))
         WLA = MAX(0.0,(WCLQT(I)-LLDLW(I))*TKL(I)*1000.)
         TRWL(I) = MIN(DSETR*ZRTL*TRRM,WLA/DELT)
         TRW = TRW+TRWL(I)
         LS = LS+(ZRTL/ZRT)
     &        *LIMIT(0.,1.,(WCLQT(I)-LLLSW(I))/(ULLSW(I)-LLLSW(I)))
         DS = DS+(ZRTL/ZRT)
     &        *LIMIT(0.,1.,(WCLQT(I)-LLDLW(I))/(ULDLW(I)-LLDLW(I)))


         ZLL = ZLL+TKL(I)
30    END DO

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

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

*--   Set 'drought'

      IF (WCRREL.LE.STLGWR) THEN
         DROUT = .TRUE.
         ICNT = 1
         DVEW = 0.
      ELSE
         DVEW = 1.
      END IF

      LSTRS = 0.5*LS+0.5
      DSTRS = DS
```

```
      RETURN
      END
*
```

A1.5 Listing subroutines used in ORYWAT

```
*----------------------------------------------------------------------*
*  SUBROUTINE COVER                                                    *
*  Purpose : In this subroutine a temperature correction is made       *
*            in case a plastic cover is used in the seedbed.           *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* SWICOV  I4  Switch in case a cover is used in seedbed (-)        I  *
* DAS     R4  Days after sowing (d)                                I  *
* DOYTR   R4  Transplanting date, day of year (d)                  I  *
* DOYS    R4  Sowing date, daynumber of year (d)                   I  *
* TMPCOV  R4  Temperature correction if a cover is used (-)        O  *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE COVER(SWICOV,DAS,DOYTR,DOYS,TMPCOV)
      IMPLICIT REAL(A-Z)

*     Formal parameters
      INTEGER SWICOV
      REAL DAS,DOYTR,DOYS,TMPCOV

*     Local variables
      INTEGER IDAS,ISA
      SAVE

      IDAS = INT(DAS)
      ISA = INT(DOYTR)-INT(DOYS)
      IF (ISA.LT.0) THEN
         ISA = ISA+365
      ELSE
         ISA = ISA
      END IF

      IF (IDAS.LT.ISA.AND.SWICOV.GT.0) THEN
         TMPCOV = 9.5
      ELSE
         TMPCOV = 0.
      END IF

      RETURN
      END
```

```
*----------------------------------------------------------------------*
*  SUBROUTINE SUBCBC                                                   *
*  Purpose: This subroutine checks the Crop Carbon Balance             *
*           and stops the simulation if the difference between        *
*           CKCIN and CKCFL exceeds 0.1 %                              *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* CKCIN   R4  Accumulated C in the crop (kg C ha-1)                I  *
* CKCFL   R4  Sum of integrated C fluxes (kg C ha-1)               I  *
* TIME    R4  Time of simulation (d)                               T  *
* CBCHK   R4  Carbon balance check, relative value to the sums of     *
*             CKIN and CKCFL (-)                                   O  *
* TERMNL  R4  Flag to indicate if simulation is to stop (-)        O  *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE SUBCBC(CKCIN,CKCFL,TIME,CBCHK,TERMNL)
      IMPLICIT REAL(A-Z)
      LOGICAL TERMNL
      SAVE

      CBCHK = 2.0*(CKCIN-CKCFL)/(CKCIN+CKCFL+1.E-10)

      IF (ABS(CBCHK).GT.0.001) THEN
         WRITE (6,10) CBCHK,CKCIN,CKCFL,TIME
10       FORMAT (/,'* * *Error in Carbon Balance, please check* * *',/,
     &           ' CBCHK=',F8.3,', CKCIN=',F8.2,', CKCFL=',F8.2,
     &           ' at TIME=',F6.1)
         TERMNL = .TRUE.
      END IF

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBDD                                                    *
*  Purpose: This subroutine calculates the daily amount of heat units  *
*           for calculation of the phenological development rate and  *
*           early leaf area growth.                                    *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* TMAX    R4  Daily maximum temperature (oC)                       I  *
* TMIN    R4  Daily minimum temperature (oC)                       I  *
* TBD     R4  Base temperature for development (oC)                I  *
* TOD     R4  Optimum temperature for development (oC)             I  *
* TMD     R4  Maximum temperature for development (oC)             I  *
* HU      R4  Heat units (oCd d-1)                                 O  *
*                                                                      *
*  FILE usage : none                                                   *
```

```
*----------------------------------------------------------------------*
      SUBROUTINE SUBDD(TMAX,TMIN,TBD,TOD,TMD,HU)
      IMPLICIT REAL(A-Z)
      INTEGER I
      SAVE

      TM = (TMAX+TMIN)/2.
      TT = 0.
      DO I = 1,24
         TD = TM+0.5*ABS(TMAX-TMIN)*COS(0.2618*FLOAT(I-14))

         IF ((TD.GT.TBD).AND.(TD.LT.TMD)) THEN
            IF (TD.GT.TOD) TD = TOD-(TD-TOD)*(TOD-TBD)/(TMD-TOD)
            TT = TT+(TD-TBD)/24.
         END IF

10    END DO
      HU = TT

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBCD                                                    *
*  Purpose: This subroutine calculates number of days below a certain *
*           average temperature (TAV), which is used to terminate the *
*           simulation after a maximum number of cold days the crop    *
*           can survive.                                               *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* DOY     R4  Daynumber (January 1 = 1) (-)                         I  *
* DOYTR   R4  Transplanting date, day of year (d)                   I  *
* TAV     R4  Average daily temperature (oC)                        I  *
* TIME    R4  Time of simulation (d)                                T  *
* NCOLD   R4  Number of cold days (-)                               O  *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE SUBCD(DOY,DOYTR,TAV,TIME,NCOLD)
      IMPLICIT REAL(A-Z)
      SAVE

      IF (DOY.EQ.DOYTR) NCOLD = 0.
      IF (TAV.LT.12.) THEN
         NCOLD = NCOLD+1.
      ELSE
         NCOLD = 0.
      END IF

      IF (NCOLD.GT.3.) THEN
         WRITE (6,10) NCOLD,TIME
10       FORMAT (/,'* * *Number of cold days (<12 C) exceeded 3* * *',/,
     &           ' NCOLD',F8.3,' at TIME=',F6.1)
      END IF
      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE PHENOL                                                   *
*  Purpose: This subroutine calculates the rate of phenological        *
*           development of the crop based on photoperiod and           *
*           temperature.                                               *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* DVS     R4  Development stage of the crop (-)                     I  *
* DAS     R4  Days after sowing (d)                                 I  *
* DVRJ    R4  Development rate juvenile ((oCd)-1)                   I  *
* DVRI    R4  Development rate, photoperiod-sensitive phase         I  *
*             ((oCd)-1)                                                *
* DVRP    R4  Development rate, PI phase ((oCd)-1)                  I  *
* DVRR    R4  Development rate, reproductive phase ((oCd)-1)        I  *
* HU      R4  Heat units (oCd d-1)                                  I  *
* DAYL    R4  Astronomic daylength (base = 0 degrees) (h)           I  *
* MOPP    R4  Maximum optimum photoperiod (h)                       I  *
* PPSE    R4  Photoperiod sensitivity (h-1)                         I  *
* TS      R4  Temperature sum (oCd)                                 I  *
* SHCKD   R4  Delay parameter in phenology ((oCd)(oCd)-1)           I  *
* DOYTR   R4  Transplanting date, day of year (d)                   I  *
* DOYS    R4  Sowing date, daynumber of year (d)                    I  *
* DVR     R4  Development rate of the crop (d-1)                    O  *
* TSHCKD  R4  Transpl. shock for phenol. development (oCd)          O  *
* DVEW    R4  Stress factor for development rate (-)                O  *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE PHENOL(DVS,DAS,DVRJ,DVRI,DVRP,DVRR,HU,DAYL,MOPP,PPSE,
     &                  TS,SHCKD,DOYTR,DOYS,DVR,TSHCKD,DVEW)
      IMPLICIT REAL(A-Z)
      INTEGER IDAS,ISA
      SAVE

      IDAS = INT(DAS)
      ISA = INT(DOYTR)-INT(DOYS)
      IF (ISA.LT.0) THEN
         ISA = ISA+365
      ELSE
         ISA = ISA
      END IF

      IF (DVS.GE.0..AND.DVS.LT.0.40) DVR = DVRJ*HU*DVEW
      IF (DVS.GE.0.40.AND.DVS.LT.0.65) THEN
         DL = DAYL+0.9
```

```
         IF (DL.LT.MOPP) THEN
            PPFAC = 1.
         ELSE
            PPFAC = 1.-(DL-MOPP)*PPSE
         END IF
         PPFAC = MIN(1.,MAX(0.,PPFAC))
         DVR = DVRI*HU*PPFAC*DVEW
      END IF
      IF (DVS.GE.0.65.AND.DVS.LT.1.00) DVR = DVRP*HU*DVEW
      IF (DVS.GE.1.00) DVR = DVRR*HU

      IF (IDAS.EQ.ISA) TSTR = TS
      TSHCKD = SHCKD*TSTR
      IF (IDAS.GT.ISA.AND.TS.LT.(TSTR+TSHCKD)) DVR = 0.
      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBRTS                                                   *
*  Purpose: This subroutine calculates the growth rates of the organs. *
*           At the day of transplanting it calculates the weight       *
*           losses per area as a result of the change in plant density *
*           when plants are removed from the seedbed and planted in    *
*           the field.                                                 *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* DOY     R4  Daynumber (January 1 = 1) (-)                        I   *
* DOYTR   R4  Transplanting date, day of year (d)                  I   *
* GCR     R4  Growth crop rate (kg ha-1 d-1)                       I   *
* FRT     R4  Fraction dry matter allocated to roots (-)           I   *
* FSH     R4  Fraction dry matter allocated to the shoot (-)       I   *
* FLV     R4  Fraction shoot dry matter allocated to leaves (-)    I   *
* LLV     R4  Loss rate of leaves (kg ha-1 d-1)                    I   *
* FST     R4  Fraction shoot-DM allocated to the stems (-)         I   *
* FSTR    R4  Fraction CH2O allocated to stem reserves (kg ha-1        *
*             d-1)                                                 I   *
* LSTR    R4  Loss rate of stem reserves (kg ha-1 d-1)             I   *
* WLVG    R4  Weight of the green leaves (kg ha-1)                 I   *
* WSTR    R4  Weight of stem reserves (kg ha-1)                    I   *
* WSTS    R4  Weight of structural stems (kg ha-1)                 I   *
* WRT     R4  Weight of the roots (kg ha-1)                        I   *
* NPLH    I4  Number of plants per hill (pl/hill)                  I   *
* NH      R4  Number of hills (hills m-2)                          I   *
* NPLSB   R4  Number of plants in seedbed (pl/m2)                  I   *
* DELT    R4  Time step of integration (d)                         T   *
* GLV     R4  Growth rate leaves (kg ha-1 d-1)                     O   *
* GSTR    R4  Growth rate stem reserves (kg ha-1 d-1)              O   *
* RWLVG   R4  Net growth rate of green leaves (kg ha-1 d-1)        O   *
* GRT     R4  Growth rate of roots (kg ha-1 d-1)                   O   *
* RWSTR   R4  Net growth rate of stem reserves (kg ha-1 d-1)       O   *
* GST     R4  Growth rate of structural stems (kg ha-1 d-1)        O   *
* RWLVG1  R4  RWLVG at transplanting (kg ha-1 d-1)                 O   *
* GRT1    R4  GRT at transplanting (kg ha-1 d-1)                   O   *
* RWSTR1  R4  RWSTR at transplanting (kg ha-1 d-1)                 O   *
* GST1    R4  GST at transplanting (kg ha-1 d-1)                   O   *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE SUBRTS(DOY,DOYTR,GCR,FRT,FSH,FLV,LLV,FST,FSTR,LSTR,
     &                  WLVG,WSTR,WSTS,WRT,NPLH,NH,NPLSB,DELT,GLV,GSTR,
     &                  RWLVG,GRT,RWSTR,GST,RWLVG1,GRT1,RWSTR1,GST1)

      IMPLICIT REAL(A-Z)
      SAVE

      IF (DOY.EQ.DOYTR) THEN
         PLTR = NPLH*NH/NPLSB
      ELSE
         PLTR = 1.
      END IF

      RWLVG1 = (WLVG*(1.-PLTR))/DELT
      GST1 = (WSTS*(1.-PLTR))/DELT
      RWSTR1 = (WSTR*(1.-PLTR))/DELT
      GRT1 = (WRT*(1.-PLTR))/DELT

      GRT = GCR*FRT-GRT1
      GLV = GCR*FSH*FLV-RWLVG1
      RWLVG = GLV-LLV
      GST = GCR*FSH*FST*(1.-FSTR)-GST1
      GSTR = GCR*FSH*FST*FSTR-RWSTR1
      RWSTR = GSTR-LSTR

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBGRN                                                   *
*  Purpose: This subroutine calculates spikelet formation rate and     *
*           spikelet fertility as affected by low and high temperature *
*           and the grain growth rate.  Spikelet sterility component   *
*           is according to Horie et al., 1992.                        *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* GCR     R4  Growth crop rate (kg ha-1 d-1)                       I   *
* FSH     R4  Fraction dry matter allocated to the shoot (-)       I   *
* FSO     R4  Fraction shoot DM allocated to storage organs (-)    I   *
* DOY     R4  Daynumber (January 1 = 1) (-)                        I   *
* DOYS    R4  Sowing date, daynumber of year (d)                   I   *
* DOYTR   R4  Transplanting date, day of year (d)                  I   *
* DVS     R4  Development stage of the crop (-)                    I   *
* WRR     R4  Weight of rough rice (kg ha-1)                       I   *
```

```
* PWRR     R4  Potential weight of rough rice (kg ha-1)              I  *
* SPGF     R4  Spikelet growth factor (no kg-1)                     I  *
* TAV      R4  Average daily temperature (oC)                       I  *
* TMAX     R4  Daily maximum temperature (oC)                       I  *
* NSP      R4  Number of spikelets (no)                             I  *
* TIME     R4  Time of simulation (d)                               T  *
* GRAINF   R4  Sink limitation factor (-)                           O  *
* GSO      R4  Growth rate of storage organs (kg ha-1 d-1)          O  *
* GGR      R4  Rate of increase in grain weight (kg ha-1 d-1)       O  *
* GNSP     R4  Rate of increase in spikelet number (no ha-1 d-1)    O  *
* GNGR     R4  Rate of increase in grain number (no ha-1 d-1)       O  *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE SUBGRN(GCR,FSH,FSO,DOY,DOYS,DOYTR,DVS,WRR,PWRR,SPGF,
     &                  TAV,TMAX,NSP,TIME,GRAINF,GSO,GGR,GNSP,GNGR)
      IMPLICIT REAL(A-Z)
      LOGICAL GRAINS
      SAVE

      GRAINF = 1.
      IF (DOY.EQ.DOYS) GRAINS = .FALSE.

      GSO = GCR*FSH*FSO
      IF (DVS.GT.0.95) THEN
         GGR = GSO
      ELSE
         GGR = 0.
      END IF

      IF (GRAINS) THEN
         IF (WRR.GT.PWRR) GRAINF = -1.
         IF (GRAINF.LT.0.) THEN
            WRITE (6,10) GRAINF,TIME
10          FORMAT (/,' * * * Sink limitation before DVS=2 !!!! * * *',
     &              /,' GRAINF',F8.3,' at TIME=',F6.1)
         END IF
      END IF

* Grain formation
      DVSPI = 0.65
      DVSF = 1.
      IF ((DVS.GE.DVSPI).AND.(DVS.LE.DVSF)) THEN
         GNSP = GCR*SPGF
      ELSE
         GNSP = 0.
      END IF

* Grain formation from spikelets (GNGR)
      IF (DOY.EQ.DOYTR) COLDTT = 0.
      IF (DOY.EQ.DOYTR) TFERT = 0.
      IF (DOY.EQ.DOYTR) NTFERT = 0.

      IF ((DVS.GE.0.75).AND.(DVS.LE.1.2)) THEN
         CTT = MAX(0.,22.-TAV)
         COLDTT = COLDTT+CTT
      END IF
      IF ((DVS.GE.0.96).AND.(DVS.LE.1.2)) THEN
         TFERT = TFERT+TMAX
         NTFERT = NTFERT+1.
      END IF

      IF ((DVS.GE.1.2).AND.(.NOT.GRAINS)) THEN
         GRAINS = .TRUE.
         SF1 = 1.-(4.6+0.054*COLDTT**1.56)/100.
         SF1 = MIN(1.,MAX(0.,SF1))
         TFERT = TFERT/(NTFERT)
         SF2 = 1./(1.+EXP(0.853*(TFERT-36.6)))
         SF2 = MIN(1.,MAX(0.,SF2))
         SPFERT = MIN(SF1,SF2)
         GNGR = NSP*SPFERT
      ELSE
         GNGR = 0.
      END IF

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBLAI                                                   *
*  Purpose: This subroutine calculates the leaf area index of the      *
*           crop in the seedbed and after transplanting in the field.  *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* SWILAT  I4  Switch for simulated or measured LAI (-)               I *
* DAS     R4  Days after sowing (d)                                  I *
* DOYS    R4  Sowing date, daynumber of year (d)                     I *
* DOYTR   R4  Transplanting date, day of year (d)                    I *
* LAPE    R4  Leaf area of the plant at emergence (m2)               I *
* RGRL    R4  Relative growth rate for leaf development ((oCd)-1)    I *
* TSLV    R4  Temperature sum for leaf development (oC)              I *
* NPLSB   R4  Number of plants in seedbed (pl/m2)                    I *
* WLVG    R4  Weight of the green leaves (kg ha-1)                   I *
* SLA     R4  Specific leaf area (ha kg-1)                           I *
* NH      R4  Number of hills (hills m-2)                            I *
* NPLH    I4  Number of plants per hill (pl/hill)                    I *
* SHCKL   R4  Delay parameter in development ((oCd)(oCd)-1)          I *
* DVS     R4  Development stage of the crop (-)                      I *
* LAISIM  R4  Simulated leaf area index (ha ha-1)                    O *
* TSHCKL  R4  Transpl. shock for leaf area development (oCd)         O *
* DTRP    R4  Days in seedbed (J m-2 d-1)                            I *
* ICNT    I4  Counter for leaf growth stress (-)                     I *
* NPLDS   R4  Number of plants direct seeded (-)                     I *
*                                                                      *
```

```
*  FILE usage : none                                                  *
*---------------------------------------------------------------------*
      SUBROUTINE SUBLAI(SWILAI,DAS,DOYS,DOYTR,LAPE,RGRL,TSLV,NPLSB,WLVG,
     &                  SLA,NH,NPLH,SHCKL,DVS,LAISIM,TSHCKL,DTRP,ICNT,
     &                  NPLDS)
      IMPLICIT REAL(A-Z)
      INTEGER SWILAI,IDAS,ISA
      INTEGER ICNT
      SAVE

      IDAS = INT(DAS)
      ISA = INT(DOYTR)-INT(DOYS)
      IF (ISA.LT.0) THEN
         ISA = ISA+365
      ELSE
         ISA = ISA
      END IF

      LAIEXS = 0.
      WLVEXS = 0.

*-------- 1. Leaf area calculation for transplanted rice.
      IF (DTRP.GT.0) THEN
*-------- 1.1) Seed-bed
         IF (IDAS.LT.ISA) THEN
            IF (LAISIM.LT.1.) THEN
               LAPI = LAPE*(EXP(RGRL*TSLV))
               LAISIM = LAPI*NPLSB
               WLVEXS = WLVG
               LAIEXS = LAISIM
            ELSE
               LAISIM = SLA*(WLVG-WLVEXS)+LAIEXS
            END IF
*--------- 1.2) Transplanting effects: dilution and shock-setting
         ELSE
            IF (IDAS.EQ.ISA) THEN
               TSLVTR = TSLV
               TSHCKL = SHCKL*TSLVTR
               LAII = LAISIM*NH*NPLH/NPLSB
            END IF
*----------- 1.3) During transplanting shock-period
            IF (TSLV.LT.(TSLVTR+TSHCKL)) THEN
               LAISIM = LAII
*----------- 1.4) After transplanting shock-period
            ELSE
               IF ((LAISIM.LT.1.0).AND.(DVS.LT.1.0).AND.(ICNT.EQ.0))
     &              THEN
                  LAISIM = LAII*(EXP(RGRL*(TSLV-TSLVTR-TSHCKL)))
                  WLVEXP = WLVG
                  LAIEXP = LAISIM
               ELSE
                  LAISIM = LAIEXP+SLA*(WLVG-WLVEXP)
               END IF
            END IF
         END IF
*      WRITE(*,*) 'LAISIM=', LAISIM

*-------- 2. Leaf area calculation for direct-seeded rice.
      ELSE IF (DTRP.EQ.0.) THEN
         IF ((LAISIM.LT.1.0).AND.(DVS.LT.1.0).AND.(ICNT.EQ.0)) THEN
            LAPI = LAPE*(EXP(RGRL*TSLV))
            LAISIM = LAPI*NPLDS
            WLVEXP = WLVG
            LAIEXP = LAISIM
         ELSE
            LAISIM = LAIEXP+SLA*(WLVG-WLVEXP)
         END IF

      END IF

      IF (SWILAI.LT.0) LAISIM = 0.

      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 (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* DOY     R4  Daynumber (January 1 = 1) (-)                        I  *
* LAT     R4  Latitude of site (dec.degr.)                         I  *
* SC      R4  Solar constant (J m-2 s-1)                           O  *
* DS0     R4  Daily extraterstrial 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 TOTASP                                                   *
*  Purpose: This subroutine calculates daily total potential 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 (unit)                                   class *
* ----   ---- ---------------                                  ----- *
* DOY     R4  Daynumber (January 1 = 1) (-)                       I  *
* LAT     R4  Latitude of site (dec.degr.)                        I  *
* DTR     R4  Daily total of global radiation (J m-2 d-1)         I  *
* SCP     R4  Scattering coefficient of leaves for visible        I  *
*             radiation ((PAR))                                   I  *
* EFF     R4  Initial light use efficiency (kg CO2/J/ ha/h m2 s)  I  *
* REDFT   R4  Reduction factor, temp. effect on AMAX (-)          I  *
* KDF     R4  Extinction coefficient for diffuse light (-)        I  *
* KNF     R4  Extinction coefficient, N profile in canopy (-)     I  *
* LAI     R4  Apparent leaf area index (incl. stem area) (ha ha-1) I *
* CO2     R4  Ambient CO2 concentration (ppm)                     I  *
* NFLV    R4  Nitrogen fraction in the leaves (g m-2)             I  *
* DAYL    R4  Astronomic daylength (base = 0 degrees) (h)         O  *
* AMAX    R4  Assimilation rate at light saturation (kg ha-1 h-1) O  *
* DTGA    R4  Daily total gross Assimilation (kg ha-1 d-1)        O  *
* DPAR    R4  Daily incoming PAR (MJ m-2 d-1)                     O  *
* DPARI   R4  Intercepted DPAR (MJ m-2 d-1)                       O  *
* DS0     R4  Daily extraterstrial radiation (J m-2 d-1)          O  *
*                                                                    *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIMP                  *
*  FILE usage : none                                                 *
*--------------------------------------------------------------------*
      SUBROUTINE TOTASP(DOY,LAT,DTR,SCP,EFF,REDFT,KDF,KNF,LAI,CO2,NFLV,
     &                  DAYL,AMAX,DTGA,DPAR,DPARI,DS0)
      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,DS0,SINLD,COSLD,DAYL,DSINB,DSINBE)

*-----assimilation set to zero and three different times of the day (HOU
      DTGA = 0.
      DPAR = 0.
      DPARI = 0.

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

*-----diffuse PAR (PARDF) and direct PAR (PARDR)
```

```
         PARDF = PAR*FRDF
         PARDR = PAR-PARDF

         CALL ASSIMP(SCP,EFF,REDFT,KDF,KNF,LAI,SINB,PARDR,PARDF,NFLV,
     &               CO2,AMAX,FGROS,PARINT)

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

10    END DO

      DTGA = DTGA*DAYL

*-----calculation of daily incident PAR and intercepted PAR (MJ/m2/d)
      DPAR = DPAR*DAYL*3600/1.E6
      DPARI = DPARI*DAYL*3600/1.E6

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE ASSIMP                                                   *
*  Purpose: This subroutine performs a Gaussian integration over       *
*           depth of canopy by selecting three different LAI's and     *
*           computing potential assimilation at these LAI levels. The  *
*           integrated variable is FGROS. The routine accounts for     *
*           an exponential profile of leaf N in the canopy and         *
*           includes the effect of CO2 concentration.                  *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* SCP     R4  Scattering coefficient of leaves for visible             *
*             radiation ((PAR))                                    I   *
* EFF     R4  Initial light use efficiency (kg CO2/J/ ha/h m2 s)   I   *
* REDFT   R4  Reduction factor, temp. effect on AMAX (-)           I   *
* KDF     R4  Extinction coefficient for diffuse light (-)         I   *
* KNF     R4  Extinction coefficient, N profile in canopy (-)      I   *
* LAI     R4  Apparent leaf area index (incl. stem area) (ha ha-1) I   *
* SINB    R4  Sine of solar height (-)                             I   *
* PARDR   R4  Instantaneous flux of direct radiation (PAR) (W m-2) I   *
* PARDF   R4  Instantaneous flux of diffuse radiation(PAR) (W m-2) I   *
* NFLV    R4  Nitrogen fraction in the leaves (g m-2)              I   *
* CO2     R4  Ambient CO2 concentration (ppm)                      I   *
* AMAX    R4  Assimilation rate at light saturation (kg ha-1 h-1)  O   *
* FGROS   R4  Instantaneous assimilation rate of whole canopy (kg      *
*             CO2 ha-1 soil h-1)                                   O   *
* PARINT  R4  Intercepted PAR (J m-2 s-1)                          O   *
*                                                                      *
*  SUBROUTINES called : none                                           *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*
      SUBROUTINE ASSIMP(SCP,EFF,REDFT,KDF,KNF,LAI,SINB,PARDR,PARDF,NFLV,
     &                  CO2,AMAX,FGROS,PARINT)
      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

*-----calculate relative effect of CO2 level on AMAX
      CO2AMX = 49.57/34.26*(1.-EXP(-0.208*(CO2-60.)/49.57))
      CO2AMX = MAX(0.,CO2AMX)

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

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

*---------calculate leaf nitrogen for each layer,
*        based on exponential distribution
         IF (LAI.GT.0.01.AND.KNF.GT.0.) THEN
            SLNI = NFLV*LAI*KNF*EXP(-KNF*LAIC)/(1.-EXP(-KNF*LAI))
         ELSE
            SLNI = NFLV
         END IF

*---------calculate actual photosynthesis from SLN, CO2 and temperature
*        calculation of AMAX according to van Keulen & Seligman (1987):
*        AMAX = 32.4 * (SLNI-0.2) * REDFT * CO2AMX
         IF (SLNI.GE.0.5) THEN
*          according to Shaobing Peng (IRRI, unpublished data):
            AMAX = 9.5+(22.*SLNI)*REDFT*CO2AMX
         ELSE
            AMAX = MAX(0.,68.33*(SLNI-0.2)*REDFT*CO2AMX)
         END IF

*---------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
*        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.
         IASUN = 0.
         DO 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)
            IASUN = IASUN+VISSUN*WGAUSS(I2)
20       END DO

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

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

10    END DO
      FGROS = FGROS*LAI

*-----calculation of intercepted PAR (PARINT, J/m2/s)
      PARINT = PARINT*LAI

      RETURN
      END
*
```

A1.6 Crop data file

```
*****************************************************************************
*                          ORYZA_Wz.DAT                                     *
* Crop and management data for rice; model ORYZA-W (version 2.1)            *
* Experimental data: Parameters and Functions from: IRRI/APPA, 1992         *
* Oryza sativa cv.IR72, IRRI, Dry Season (M10) at 225 kg N                  *
* plus data from Wopereis drought stress experiments at IRRI.               *
* This data file is for zonation purposes.                                  *
*****************************************************************************

**********************************************************************
* 1. Management parameters                                           *
**********************************************************************
NPLH   = 5.      ! number of plants per hill
NH     = 25.     ! number of hills
NPLSB  = 1000.   ! number of plants in seed-bed
NPLDS  = 75.     ! number of plants/m2 direct-seeded
DTRP   = 12.     ! days in seed-bed (between sowing-transplanting)
**********************************************************************
* 2. Crop data                                                       *
**********************************************************************

* Initial data
LAPE   = 0.0001  ! initial leaf area per plant at emergence
DVSI   = 0.      ! initial development stage
WLVGI  = 0.      ! initial leaf weight
WSTI   = 0.      ! initial stem weight
WRTI   = 0.      ! initial stem weight
WSOI   = 0.      ! initial weight storage organs
ZERO   = 0.      ! zero condition for integrals

* Model parameters
SHCKL  = 0.25    ! parameter indicating relation between seedling-
                 ! age and delay in leaf area development
SHCKD  = 0.4     ! parameter indicating relation between seedling-
                 ! age and delay in phenological development
RGRL   = 0.00800  ! relative growth rate of leaf area
FSTR   = 0.20    ! fraction carbohydrates allocated to stems that
                 ! is stored as reserves
SCP    = 0.2     ! scattering coefficient of leaves for PAR
TBD    = 8.      ! base temperature for development (oC)
TBLV   = 8.      ! base temperature for juvenile leaf area growth
TMD    = 42.     ! maximum temperature for development
TOD    = 30.     ! optimum temperature for development
CO2REF = 340.    ! Reference level of atmospheric CO2
CO2    = 340.    ! Ambient CO2 concentration
TREF   = 25.     ! reference temperature
Q10    = 2.      ! factor accounting for increase of maintenance
                 ! respiration with a 10 oC rise in temperature
DVRJ   = 0.000773 ! development rate during juvenile phase
DVRI   = 0.000758 ! development rate during photoperiod-
                  ! sensitive phase
DVRP   = 0.000784 ! development rate during panicle development
DVRR   = 0.001784 ! development rate in reproductive phase
MOPP   = 11.30   ! maximum optimum photoperiod
PPSE   = 0.0     ! photoperiod sensitivity
SPGF   = 64900.000 ! spikelet growth factor
WGRMX  = 0.0000249 ! maximum individual garin weight

* table for GCM (General Circulation Model) temperature correction
TMCTB  = 0.,0., 366.,0.

* table of extinction coefficient of leaves (KDF) as function of development stage
KDFTB     =  0.,0.4,  0.65,0.4,  1.,0.6,  2.1,0.6

* table of extinction coefficeint of nitrogen profile in the canopy (KNF) as
* function of development stage (DVS)
KNFTB      = 0.,0.4,  2.1,0.4

* tables of 'fraction of total dry matter allocated to shoot'
* (FSH) and of 'fraction of total dry matter allocated to roots'
* (FRT) as function of development stage
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.

* table of specific leaf area as function of development stage
```

```
SLATB  =  0., 0.0047, 0.152, 0.0047, 0.336, 0.0033, 0.653,0.0028,
          0.787,0.0021, 1.011,0.0019, 1.431,0.0017, 2.10, 0.0017

* tables of partitioning factors for leaves (FLVTB), stems (FSTTB),
* and storage organs (FSOTB) as function of development stage.
 FLVTB  =
    0.000, 0.545,
    0.080, 0.545,
    0.245, 0.559,
    0.490, 0.542,
    0.720, 0.422,
    0.895, 0.053,
    1.230, 0.000,
    1.730, 0.,
    2.1, 0.
 FSTTB  =
    0.000, 0.455,
    0.080, 0.455,
    0.245, 0.441,
    0.490, 0.458,
    0.720, 0.578,
    0.895, 0.517,
    1.230, 0.000,
    1.730, 0.,
    2.1, 0.
 FSOTB  =
    0.000, 0.000,
    0.720, 0.000,
    0.895, 0.430,
    1.230, 1.000,
    1.730, 1.0,
    2.1, 1.

* table of initial light use efficiency as function of temperature
EFFTB  = 10.,0.54, 40.,0.36

* table of factor accounting for effect of temperature on AMAX
REDFTT = -10.,0., 10.,0., 20., 1., 37.,1., 43.,0.

* table of specific green stem area as function of development stage
SSGATB = 0.,0.0003, 0.9,0.0003, 2.1,0.

* table of nitrogen fraction in the leaves as function of
* development stage
 NFLVTB =
    0.00, 0.54,
    0.16, 0.54,
    0.33, 1.53,
    0.65, 1.22,
    0.79, 1.56,
    1.00, 1.29,
    1.46, 1.37,
    2.04, 0.83,
    2.10, 0.83

MAINLV = 0.02   ! maintenance respiration coefficient of leaves
MAINST = 0.015  ! maintenace respiration coefficient of stems
MAINSO = 0.003  ! maintenace respiration coefficient of storage organs
MAINRT = 0.01   ! maintenace respiration coefficient of roots

CRGLV  = 1.326  ! carbohydrate requirement for leaf dry matter production
CRGST  = 1.326  ! carbohydrate requirement for stem dry matter production
CRGSO  = 1.462  ! carbohydrate requirement for storage organ "    "
CRGRT  = 1.326  ! carbohydrate requirement for root          "    "
CRGSTR = 1.11   ! carbohydrate requirement for stem reserves production

FCSTR  = 0.444  ! mass fraction carbon in the stem reserves
FCLV   = 0.419  ! mass fraction carbon in the leaves
FCST   = 0.431  ! mass fraction carbon in the stems
FCRT   = 0.431  ! mass fraction carbon in the roots
FCSO   = 0.487  ! mass fraction carbon in the storage organs

LRSTR  = 0.947  ! fraction of allocated stem reserves that is
                ! available for growth
TCLSTR = 10.    ! time coefficient for loss of stem reserves

* table for leaf death coefficient as function of development stage
DRLVT  = 0.,0., 0.6,0.,  1.,0.015, 1.6,0.025, 2.1,0.05
```

```
* Water-limited production data
ZRTI   = 0.0001
ZRTMC = 0.4  ! maximum rooting depth of crop
GZRT = 0.01  ! growth rate roots

ZRTMCW = 0.2 ! For PADDY subroutine, maximum depth roots if
             ! no drought stress
ZRTMCD = 0.4 ! For PADDY subroutine, maximum depth roots if
             ! drought

STLG = 2.80
ULLS = 2.87
LLLS = 3.90
ULDL = 3.80
LLDL = 4.20
ULRT = 2.87
LLRT = 4.20


***************************************************************
* 3. Switch parameters                                        *
***************************************************************
SWINLV = -1. ! switch to use NFLV as function of DVS or daynumber
             ! -1: versus DVS; 1: versus DOY
SWITMP = -1.  ! switch to use GCM temperature correction
             ! -1: do not use; 1: do use
SWILAI =  1.  ! switch to use measured or simulated LAI (LAI leaves)
             ! -1: measured LAI; 1: simulated LAI
SWICOV = -1. ! switch to use plastic cover over seed-bed
              ! -1: do not use; 1: do use

***************************************************************
* 4. Measured data                                            *
***************************************************************
* Switches that indicate whether variables have been measured
* or not: 'Y' means measured and given; 'N' means not measured.
* Note: 'Y' and 'N' should be given in capital letters!

MLAI   = 'N' ! measured leaf area index LAIL
MNFLV  = 'N' ! measured N-content leaves NFLV
MWTDM  = 'N' ! measured weigth total dry matter WTDM
MWST   = 'N' ! measured weight stems WST
MWLVG  = 'N' ! measured weight green leaves WLVG
MWLVD  = 'N' ! measured weigth dead leaves WLVD
MWPA   = 'N' ! measured weigth panicle WPA

* Measured data values: No data for zonation
```

A1.7 List of variables

This list only contains variables that are not included in ORYZA1 Version 1.3 as documented in the SARP Research Proceedings (Kropff et al., 1994).

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	-
ANGA	Parameter in Angstrom formula	-
ANGB	Parameter in Angstrom formula	-
AOB	Intermediate variable	-
ASIN	Arcsine function (intrinsic FORTRAN function)	-
BBRAD	Black body radiation	$J\ m^{-2}\ s^{-1}$
BOLTZM	Stefan-Boltzman constant	$J\ m^{-2}\ d^{-10}K^{-4}$
CLEAR	Penman's original clearness factor	-
CLUSTF	Cluster factor	-
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	-
DROUT	Control variable indicating drought/no drought	-
DS	Stress factor for death of leaves caused by drought	-
DERT	Effect of drought stress on water uptake	-
DSO	Daily extraterrestrial radiation	$J\ m^{-2}\ d^{-1}$
DSTRS	Stress factor for death of leaves caused by drought	-
DVEW	Effect of water stress on development rate in vegetative phase	-
EES	Extinction coefficiemt for evaporation in bare soil	m^{-1}
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	-
FVAP	Vapour pressure effect on RLWN (Brunt equation)	-
ICNT	Control variable for drought stress	-
IDATE	Integer value of day of year	d

Name	Description	Units
IDOYTR	Integer value of day of year at transplanting	d
INSD	Counter for non-drought stress days	-
ISTD	Counter for consecutive drought stress days	-
ITIM	Time of simulation	d
ITRT	Time of transplanting	d
LHVAP	Latent heat of evaporation of water	J kg^{-1} H_2O
LLDL	Lower limit dead leaves	pF value
LLLS	Lower limit leaf rolling	pF value
LLRT	Lower limit relative transpiration	pF value
LLDLWR	Lower limit dead leaves averaged over root zone	m^3 m^{-3}
LLLSWR	Lower limit leaf rolling averaged over root zone	m^3 m^{-3}
LLRTWR	Lower limit relative transpiration averaged over root zone	m^3 m^{-3}
LS	Stress factor for leaf rolling (varies from 0 to 1)	-
LSTRS	Stress factor for leaf rolling (varies from 0.5 to 1)	-
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	-
PSYCH	Psychrometic instrument constant mbar	$^oC^{-1}$
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}
RLWN	Net long-wave radiation	J m^{-1} d^{-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	-
SLOPE	Tangent of the relation between saturated vapour pressure and temperature	mbar $^oC^{-1}$
SQV	Intermediate variable in calculation of reflection coefficient	-
STLG	Limit for leaf expansion	pF value
STLGWR	Limit for leaf expansion avearged over root zone	m^3 m^{-3}
SVP	Saturated vapour pressure	mbar
SWIWLP	Switch to select irrigated lowland (0), rainfed lowland (1), or rainfed upland (2)	-
TKL	Array fof thicknesses of soils compartments	m
TKLT	Thickness of combined soil compartments	m
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}
TRRM	Potential transpiration rate canopy per united rooted length	mm d^{-1} m^{-1}
TRW	Actual transpiration rate canopy	mm d^{-1}

Name	Description	Units
TRWCU	Cumulative actual transpiration (after transplanting)	mm
TRWL	Array of TRW per soil compartment	mm d^{-1}
TSLVTR	Temperature sum for leaf area development at tranplanting	^oC d
ULDL	Upper limit dead leaves	pF value
ULLS	Upper limit leaf rolling score	pF value
ULRT	Upper limit relative transpiration rate	pF
ULDLWR	Upper limit dead leaves averaged over root zone	m^3 m^{-3}
ULLSWR	Upper limit leaf rolling averaged over root zone	m^3 m^{-3}
ULRTWR	Upper limit relative transpiration averaged over root zone	m^3 m^{-3}
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}
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}
WCST	Array of volumetric water content per soil compartment, at saturation	m^{-3} m^{-3}
WCSTUP	Saturated volumetric water content of first soil compartment	m^{-3} m^{-3}
WCUP	Actual volumetric water content first soil compartment	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}
WL0	Amount of ponded water	mm
WLVGIT	Dry weight of green leaves	kg ha^{-1}
ZLL	Depth upper boundary compartment	m
ZR	Rooted depth	m
ZRT(I)	Rooted depth (initial)	m
ZRT	Array of ZRT differentiated per soil compartment	m
ZRTL	Rooted depth in specific soil compartment	m
ZRTM	Maximum for ZRT	m
ZRTMC	Maximum rooting depth of crop (LOWBAL, SAHEL)	m

Name	Description	Units
ZRTMCD	Maximum rooting depth of crop in case of drought (PADDY)	m
ZRTMCW	Maximum rooting depth of crop under well-watered conditions (PADDY)	m
ZRTMS	Maximum rooting depth of soil	m

Appendix 2 Soil-water balance module SAHEL

A2.1 Listing SAHEL

```
*----------------------------------------------------------------------*
*  SUBROUTINE SAHEL                                                    *
*                                                                      *
*  Version: 1.2                                                        *
*  Date   : November 1993                                              *
*  Purpose: This subroutine is a simple soil water balance for freely  *
*           draining upland soils. Especially adapted for combination  *
*           with ORYZA model (into ORYZA_W)                            *
*                                                                      *
*  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 (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* ITASK   I4  Task that subroutine should perform (-)              C   *
* IUNITD  I4  Unit that can be used for input files (-)          C/IN *
* IUNITO  I4  Unit number of output file (-)                     C/IN *
* IUNITL  I4  Unit number for log file messages (-)              C/IN *
* FILEI2  C*  Name of input file no. 2 (-)                       C/IN *
* OUTPUT  R4  Flag to indicate if output should be done (-)       C/I *
* TERMNL  R4  Flag to indicate if simulation is to stop (-)     C,I,O *
* TIME    R4  Time of simulation (d)                               T   *
* DELT    R4  Time step of integration (d)                         T   *
* SWIWLP  I4  Switch to select production environment (-)          I   *
* RAIN    R4  Daily amount of rainfall (mm d-1)                    I   *
* RAINN   R4  Rainfall rate next day (mm d-1)                      I   *
* EVSC    R4  Potential soil evaporation rate (mm d-1)             I   *
* TRWL    R4  Array of actual transpiration rate/layer (mm d-1)    I   *
* INL     I4  Number of soil compartments (-)                      I   *
* NL      I4  Number of soil layers (-)                            O   *
* TKL     R4  Array of thicknesses 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 content at wilting point/layer (cm3       *
*             cm-3)                                                O   *
* WCFC    R4  Array of water content field capacity/layer (cm3         *
*             cm-3)                                                O   *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) O   *
* WCLQT   R4  Array of actual soil water contents/layer (cm3 cm-3) O   *
* WL0     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,INL,NL,TKL,
     &                 TKLT,ZRTMS,WCWP,WCFC,WCST,WCLQT,WL0)

      IMPLICIT REAL(A-Z)

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

*     Standard local variables
      INTEGER ITOLD

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


      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 nl. if integration is required immediately
*     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) CALL OUTCOM(
     &                 'SAHEL, water balance SAHEL for free drainage'
     &                 )

*     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)

      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
      IF (NL.GT.INL) CALL ERROR('SAHEL','too many layers')

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

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

   ITOLD = ITASK

   RETURN
   END
```

A2.2 Soil data file

```
Example of soil data for SAHEL water balance module
*******************************************************************
* LOAM.DAT; Soil characteristics for a standard loam soil.
*******************************************************************
TKL1      = 0.2;      TKL2      = 0.3;    TKL3      = 0.5
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
FWCLI1  = 1.0;    FWCLI2  = 1.0;  FWCLI3  = 1.0
FRNOF     = 0.0
ZRTMS   = 0.9
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 modules SAHEL or PADDY:

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

A2.3 List of variables

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 application (= 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 3 Soil-water balance module LOWBAL

A3.1 Listing LOWBAL

```
*----------------------------------------------------------------------*
*  SUBROUTINE LOWBAL                                                   *
*                                                                      *
*  Version: 2.0                                                        *
*  Date   : November 1993                                              *
*                                                                      *
*  Purpose: simple water balance for puddled rice soils in irrigated   *
*  and rainfed lowland environments.                                   *
*                                                                      *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     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 number of output file (-)                      C/IN *
* IUNITL  I4  Unit number for log file messages (-)               C/IN *
* FILEI2  C*  Name of input file no. 2 (-)                        C/IN *
* OUTPUT  R4  Flag to indicate if output should be done (-)       C/IN *
* TERMNL  R4  Flag to indicate if simulation is to stop (-)       I/O  *
* DELT    R4  Time step of integration (d)                         T   *
* SWIWLP  I4  Switch to select production environment (-)          C   *
* ITIM    I4  Time of simulation (d)                               T   *
* ITRT    I4  Time of transplanting (d)                            T   *
* DVS     R4  Development stage of the crop (-)                    I   *
* TRWL    R4  Array of actual transpiration rate/layer (mm d-1)    I   *
* EVSC    R4  Potential soil evaporation rate (mm d-1)             I   *
* RAIN    R4  Daily amount of rainfall (mm d-1)                    I   *
* RAINN   R4  Rainfall rate next day (mm d-1)                      I   *
* INL     I4  Number of soil compartments (-)                      I   *
* NL      I4  Number of soil layers (-)                            O   *
* TKL     R4  Array of thicknesses 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 content at wilting point/layer (cm3       *
*             cm-3)                                                O   *
* WCFC    R4  Array of water content field capacity/layer (cm3         *
*             cm-3)                                                O   *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) O   *
* WCLQT   R4  Array of actual soil water contents/layer (cm3 cm-3) O   *
* WL0     R4  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 file CONTROL.DAT)                        *
*----------------------------------------------------------------------*
      SUBROUTINE LOWBAL(ITASK,IUNITD,IUNITO,IUNITL,FILEI2,OUTPUT,TERMNL,
     &                  DELT,SWIWLP,ITIM,ITRT,DVS,TRWL,EVSC,RAIN,RAINN,
     &                  INL,NL,TKL,TKLT,ZRTMS,WCWP,WCFC,WCST,WCLQT,WL0)

      IMPLICIT REAL(A-Z)

      INTEGER ITASK,IUNITD,IUNITO,IUNITL,SWIWLP
      INTEGER INL,NL,ITIM,ITRT
      REAL WCAD(1),WCWP(INL),WCFC(INL),WCST(INL),WCLQT(INL)
      REAL TKL(INL),TRWL(INL)
      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)

*------Initializing state variables
      WL0 = WL0I
      WL0MX = WL0MXI
      TKLP = TKLPI
      TKLPM = TKLPI*SHRINK
      WLP = (WCSTP*TKLPM)+(TKLPI-TKLPM)
      WCLP = WLP/TKLP
      DSLR = 1.
      RII = 0.
      RIDUM = 0.
      RUNOF = 0.
      RNOFCU = 0.
      SP = SPSOIL
      RAINCU = 0.
      RIICU = 0.
      EVSWCU = 0.
      SPCU = 0.

*------For communication with ORYZA subroutine
      NL = 1
      IF (NL.GT.INL) CALL ERROR('LOWBAL','too many layers')

      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 (WL0.LE.0) THEN
          SP = 0.
        ELSE
          IF ((WL0/DELT).GE.SPSOIL) THEN
            SP = SPSOIL
          ELSE
            SP = WL0/DELT
          END IF
        END IF
      END IF

*------Reduction of EVSC when no more ponded water
      IF (WL0.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

*------Seed-bed, it is assumed that the seed-bed is continuously
*      (daily) irrigated: a dummy gift RIDUM is used to keep
*      the water level in the seed-bed to WL0I.
*------Main field: a constant irrigation gift is supplied
*      when the water level drops below WL0MIN, and when the crop
*      is not yet in ripening phase.
      IF (SWIWLP.EQ.0) THEN
        IF (ITIM.LT.ITRT) THEN
          RIDUM = SP+TRWP+EVSW-RAIN
          RII = 0.
        ELSE IF (ITIM.EQ.ITRT) THEN
          RIDUM = 0.
          RII = 0.
        ELSE IF (ITIM.GT.ITRT) THEN
          IF (WL0.LE.WL0MIN.AND.DVS.LT.DVSIE) THEN
            RIDUM = 0.
            RII = RIGIFT
          ELSE
            RII = 0.
            RIDUM = 0.
          END IF
        END IF
      ELSE IF (SWIWLP.EQ.1) THEN
        IF (ITIM.LT.ITRT) THEN
          RIDUM = SP+TRWP+EVSW-RAIN
          RII = 0.
        ELSE IF (ITIM.GE.ITRT) THEN
          RIDUM = 0.
          RII = 0.
        END IF
      END IF

*------Cracked situation
      IF (CRACK) THEN
```

```
         IF ((RAIN+WL0).LE.DDR) THEN
            IF (WL0.LE.0..AND.RAIN.EQ.0.) THEN
               SP = 0.
            ELSE IF (WL0.LE.0..AND.RAIN.GT.0.) THEN
               SP = MAX(RAIN-EVSW,0.)
            ELSE
               SP = WL0+RAIN
            END IF
         ELSE
            SP = DDR
         END IF
      END IF

      IF (OUTPUT) THEN
         CALL OUTDAT(2,0,'EVSW',EVSW)
         CALL OUTDAT(2,0,'WL0',WL0)
         CALL OUTDAT(2,0,'RII',RII)
         CALL OUTDAT(2,0,'RIDUM',RIDUM)
         CALL OUTDAT(2,0,'TKLP',TKLP)
         CALL OUTDAT(2,0,'WCLP',WCLP)
         CALL OUTDAT(2,0,'RAINCU',RAINCU)
         CALL OUTDAT(2,0,'RIICU',RIICU)
      END IF

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

      ELSE IF (ITASK.EQ.3) THEN

*-----Surface drainage is standard zero
         RUNOF = 0.

*-----1. Situation with ponded water
         IF (WL0.GT.0) THEN
            WL0 = INTGRL(WL0,(RAIN+RII+RIDUM-EVSW-TRWP-SP),DELT)
*--------1.1 bund overflow
            IF (WL0.GT.WL0MX) THEN
               RUNOF = WL0-WL0MX
               WL0 = WL0MX
*--------1.2 no more ponded water; soil not yet completely shrunken
            ELSE IF (WL0.LT.0.AND.TKLP.GT.TKLPM) THEN
*----------1.2.1 further shrinkage of puddled layer
               IF (WL0.GE.(TKLPM-TKLP)) THEN
                  WL0MX = WL0MX-WL0
                  TKLP = TKLP+WL0
                  WLP = (WCSTP*TKLPM)+(TKLP-TKLPM)
                  WCLP = WLP/TKLP
                  WL0 = 0.
*----------1.2.2 complete shrinkage of puddled layer
               ELSE IF (WL0.LT.(TKLPM-TKLP)) THEN
                  WL0MX = (WL0MXI+TKLPI)-TKLPM
                  TKLP = TKLPM
                  WLP = (WCSTP*TKLP)+(WL0-(TKLPM-TKLP))
                  WCLP = WLP/TKLP
                  WL0 = 0.
               END IF
*--------1.3 no more ponded water; soil already completely shrunken
            ELSE IF (WL0.LT.0..AND.TKLP.EQ.TKLPM) THEN
               WLP = WLP+WL0
               WCLP = WLP/TKLP
               WL0 = 0.
            END IF

*------2. Situation with no ponded water
         ELSE IF (WL0.LE.0) THEN
            WLP = INTGRL(WLP,(RAIN+RII+RIDUM-EVSW-TRWP-SP),DELT)
*--------2.1 completely shrunken puddled layer
            IF (WLP.LE.(TKLPM*WCSTP)) THEN
               TKLP = TKLPM
               WL0MX = (WL0MXI+TKLPI)-TKLP
               WCLP = WLP/TKLP
               WL0 = 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
                  WL0D = WLP-((TKLPM*WCSTP)+(TKLP-TKLPM))
                  IF (WL0D.GT.WL0MX) THEN
                     WL0 = WL0MX
                     RUNOF = WL0D-WL0MX
                  ELSE
                     WL0 = WL0D
                  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
                  WL0MX = (WL0MXI+TKLPI)-TKLP
                  WCLP = WLP/TKLP
                  WL0 = 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.
            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 = INTGRL(RNOFCU,RUNOF,DELT)
            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
      END IF

      ITOLD = ITASK

      RETURN

      END
```

A3.2 Soil data file

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
WL0MXI = 100.00
TKLPI    = 200.00
SP SOIL  = 5.00
DDR      = 2000.00
WL0I     = 50.00
WL0MIN = 10.00
SHRINK = 0.7
WCCRAC = 0.00
WCSTP  = 0.52
WCWPP  = 0.01
WCFCP  = 0.01
WCADP  = 0.01
RIGIFT   = 50.00
RIPUD    = 200.
DVSIE    = 1.85
SOILOW = 'Lowland, puddled soil type'
```

A3.3 List of variables

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

Appendix 4 Soil-water balance module PADDY

A4.1 Listing PADDY

```
*----------------------------------------------------------------------*
*     SUBROUTINE PADDY                                                 *
*     VERSION 1.0                                                      *
*     October 1994                                                     *
*     Documented in SARP Research Proceedings (1994)                   *
*     ORYZA_W: Rice growth model for fully irrigated and               *
*     water -limited conditions                                        *
*     MCS Wopereis, BAM Bouman, TP Tuong, HFM ten Berge, MJ Kropff     *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* ITASK   I4  Task that subroutine should perform (-)               C  *
* IUNITD  I4  Unit that can be used for input files (-)          C/IN *
* IUNITO  I4  Unit number of output file (-)                     C/IN *
* IUNITL  I4  Unit number for log file messages (-)              C/IN *
* FILEI2  C*  Name of input file no. 2 (-)                       C/IN *
* OUTPUT  R4  Flag to indicate if output should be done (-)       C/I *
* TERMNL  R4  Flag to indicate if simulation is to stop (-)     C/I/O *
* WSTAT   C*  Status code from weather system (-)                   C  *
* WTRTER  L4  Flag whether weather can be used by model (-)         C  *
* DOY     R4  Daynumber (January 1 = 1) (-)                         I  *
* DELT    R4  Time step of integration (d)                          T  *
* TIME    R4  Time of simulation (d)                                T  *
* ITIM    I4  Time of simulation (d)                                T  *
* ITRT    I4  Time of transplanting (d)                             T  *
* RAIN    R4  Daily amount of rainfall (mm d-1)                     I  *
* EVSC    R4  Potential soil evaporation rate (mm d-1)              I  *
* TRWL    R4  Array of actual transpiration rate/layer (mm d-1)     I  *
* INL     ??  Number of soil compartments (-)                       I  *
* NL      I4  Number of soil layers (-)                             I  *
* ZRTMS   R4  Maximum rooting depth of soil (m)                     O  *
* TKLP    R4  Array of layer thicknesses (m)                        O  *
* TKLT    R4  Depth of simulated soil (m)                           O  *
* WCWP    R4  Array of water content at wilting point/layer (cm3       *
*             cm-3)                                                 O  *
* WCFC    R4  Array of water content field capacity/layer (cm3         *
*             cm-3)                                                 O  *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3)  O  *
* WCL     R4  Array of actual water content / layer (cm3 cm-3)      O  *
* TOTPOR  R4  Array of total porosity / layer (cm3 cm-3)            O  *
* WL0     R4  Amount of ponded water (mm)                           O  *
* SWITPF  R4  Switch for pF data (-)                                O  *
*----------------------------------------------------------------------*
      SUBROUTINE PADDY(ITASK,IUNITD,IUNITO,IUNITL,FILEI2,OUTPUT,TERMNL,
     &                 WSTAT,WTRTER,DOY,DELT,TIME,ITIM,ITRT,RAIN,EVSC,
     &                 TRWL,INL,NL,ZRTMS,TKLP,TKLT,WCWP,WCFC,WCST,WCL,
     &                 TOTPOR,WL0,SWITPF)

      IMPLICIT REAL(A-Z)

*---- formal parameters
      INTEGER ITASK,IUNITD,IUNITO,IUNITL,INL,NL,ITIM,ITRT
      INTEGER SWITPF
      LOGICAL OUTPUT,TERMNL,WTRTER
      CHARACTER FILEI2*80,WSTAT*6
      REAL DOY,DELT,TIME,RAIN,EVSC,ZRTMS,TKLT,WL0
      REAL TRWL(INL),TKLP(INL),WCWP(INL),WCFC(INL),WCST(INL),WCL(INL)
      REAL TOTPOR(INL)

*     Local variables

*---- water balance parameters
      INTEGER SWITIR,SWITVP,SWITKH,SWITGW
      INTEGER SWITPD,SWITFD
      INTEGER NLPUD
      INTEGER MNL
      PARAMETER (MNL=10)
      REAL WCLI(MNL),TKL(MNL),WLFL(MNL+1),CAPRI(MNL),GWFILL(MNL)
      REAL WLAD(MNL),WLFC(MNL),WLST(MNL),WL(MNL),ZL(MNL)
      REAL WLCH(MNL)
      REAL FLOW

* For SHRINK subroutine
      REAL VL(MNL)
      REAL WCCR
* End for SHRINK subroutines

* For calculation groundwater level
      REAL ZWA,ZWB,MAXGW,MINGW,ZWTBI

      LOGICAL CRACKS,PUDDLD,FREEDR,GRWAT
      INTEGER ILZMAX,I,IGW
      INTEGER IZWTB,IRIRR
      REAL RIRRIT(100)

      COMMON /NUCHT / VGN(10),VGA(10),VGR(10),VGL(10)
      COMMON /HYDCON/ KST(10),WCAD(10),WCSTRP(10)
      COMMON /POWER / PN(10)
      COMMON /SWIT  / SWITKH
      REAL KSAT(10)

      REAL ZWTB
      PARAMETER (ILZMAX=400)
      DIMENSION ZWTB(ILZMAX)
      COMMON /GWT   / ZWA,ZWB,MAXGW,MINGW,ZWTBI,ZWTB,IZWTB

      SAVE
*---- standard local variables
      INTEGER ITOLD

      TINY = 1.0E-5
```

```
      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.

      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

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

         CRACKS = .FALSE.
         PUDDLD = .FALSE.
         FREEDR = .FALSE.
         GRWAT = .FALSE.
         ZW = 0.
         PERC = 0.
         IR = 0.

*---- read input from soil data file
         CALL RDINIT(IUNITD,IUNITL,FILEI2)
*---- puddled / non-puddled switch
         CALL RDSINT('SWITPD',SWITPD)
         IF (SWITPD.EQ.1) THEN
            PUDDLD = .TRUE.
         ELSE IF (SWITPD.EQ.0) THEN
            PUDDLD = .FALSE.
         END IF
         IF ((SWITPD.NE.0).AND.(SWITPD.NE.1))
     &        STOP 'PLEASE CHECK VALUE SWITPD IN SOIL DATA FILE'

*---- free draining / impeded drainage switch
         CALL RDSINT('SWITFD',SWITFD)
         IF (SWITFD.EQ.1) THEN
            FREEDR = .TRUE.
         ELSE IF (SWITFD.EQ.0) THEN
            FREEDR = .FALSE.
         END IF
         IF ((SWITFD.NE.0).AND.(SWITFD.NE.1))
     &        STOP 'PLEASE CHECK VALUE SWITFD IN SOIL DATA FILE'

         IF ((SWITPD.EQ.1).AND.(SWITFD.EQ.1)) STOP
     &       'PLEASE CHECK VALUES SWITFD AND SWITPD IN SOIL DATA FILE'

*---- groundwater present / not present switch
         CALL RDSINT('SWITGW',SWITGW)
         IF (SWITGW.EQ.1.OR.SWITGW.EQ.2) THEN
            GRWAT = .TRUE.
         ELSE IF (SWITGW.EQ.0) THEN
            GRWAT = .FALSE.
         END IF
         IF ((SWITGW.NE.0).AND.(SWITGW.NE.1).AND.(SWITGW.NE.2))
     &        STOP 'PLEASE CHECK VALUE SWITGW IN SOIL DATA FILE'

*------- pf switch
         CALL RDSINT('SWITPF',SWITPF)
         IF (SWITPF.NE.0.AND.SWITPF.NE.1)
     &        STOP 'PLEASE CHECK VALUE SWITPF IN SOIL DATA FILE'

*------- variable percolation rate switch
         IF (PUDDLD) THEN
            CALL RDSINT('SWITVP',SWITVP)
            IF (SWITVP.NE.0.AND.SWITVP.NE.1)
     &           STOP 'PLEASE CHECK VALUE SWITVP IN SOIL DATA FILE'
         END IF

*------- irrigation switch
         CALL RDSINT('SWITIR',SWITIR)
         IF (SWITIR.NE.0.AND.SWITIR.NE.1.AND.SWITIR.NE.2)
     &        STOP 'PLEASE CHECK VALUE SWITIR IN SOIL DATA FILE'

         IF (SWITIR.EQ.1) CALL RDAREA('RIRRIT',RIRRIT,100,IRIRR)
         IF (SWITIR.EQ.2) CALL RDSREA('IRRI',IRRI)

         CALL RDSINT('NL',NL)
         IF (NL.GT.INL) CALL ERROR('PADDY','too many layers')

         CALL RDFREA('TKL',TKL,MNL,NL)
         CALL RDFREA('WCLI',WCLI,MNL,NL)

*------- pf defined in terms of Van Genuchten
         IF (SWITPF.EQ.1) THEN
            CALL RDFREA('VGA',VGA,MNL,NL)
            CALL RDFREA('VGL',VGL,MNL,NL)
            CALL RDFREA('VGN',VGN,MNL,NL)
            CALL RDFREA('VGR',VGR,MNL,NL)
```

```
         CALL RDFREA('WCST',WCST,INL,NL)
      ELSE
*------- only moisture contents at sat., fc, wp, and air dry given
         CALL RDFREA('WCST',WCST,INL,NL)
         CALL RDFREA('WCFC',WCFC,INL,NL)
         CALL RDFREA('WCWP',WCWP,INL,NL)
         CALL RDFREA('WCAD',WCAD,10,NL)
      END IF

*---- bund height
      IF (.NOT.FREEDR) THEN
         CALL RDSREA('WL0MX',WL0MX)
      ELSE
         WL0MX = 0.
      END IF
*---- minimum ponded water depth if fully irrigated
      IF (.NOT.FREEDR) THEN
         CALL RDSREA('WL0MIN',WL0MIN)
      ELSE
         WL0MIN = 0.
      END IF
*---- initial ponded water depth
      IF (.NOT.FREEDR) THEN
         CALL RDSREA('WL0I',WL0I)
      ELSE
         WL0I = 0.
      END IF
*---- percolation rate
      IF (.NOT.FREEDR) THEN
         CALL RDSREA('PERCOL',PERCOL)
      ELSE
         PERCOL = 1000.
      END IF
*---- saturated hyraulic conductivity
      IF (.NOT.FREEDR) CALL RDFREA('KST',KST,10,NL)

*---- number of puddled soil compartments
      IF (PUDDLD) THEN
         CALL RDSINT('NLPUD',NLPUD)
         IF (NLPUD.GT.NL) STOP 'NLPUD CANNOT BE GREATER THAN NL'
         IF (NLPUD.LE.0) STOP 'NLPUD MUST BE GREATER THAN 0'
      END IF
*---- volumetric water contents of ripened previously puddled
*---- compartments
      IF (PUDDLD) CALL RDFREA('WCSTRP',WCSTRP,MNL,NL)

*---- critical pF value for cracking
      IF (PUDDLD) CALL RDSREA('PFCR',PFCR)

*------- kh switch
      CALL RDSINT('SWITKH',SWITKH)
      IF (SWITKH.NE.0.AND.SWITKH.NE.1.AND.SWITKH.NE.2)
     &      STOP 'PLEASE CHECK VALUE SWITKH IN SOIL DATA FILE'

      IF (SWITKH.EQ.0) THEN
         IF (SWITVP.EQ.1) STOP
     &    'PLEASE CHECK VALUES OF SWITKH AND SWITVP IN SOIL DATA FILE'
      END IF
      IF (SWITKH.EQ.1) THEN
*---- kh defined in terms of van genuchten parameters
         CALL RDFREA('KST',KST,10,NL)
         CALL RDFREA('VGA',VGA,10,NL)
         CALL RDFREA('VGL',VGL,10,NL)
         CALL RDFREA('VGN',VGN,10,NL)
         CALL RDFREA('VGR',VGR,10,NL)
      ELSE IF (SWITKH.EQ.2) THEN
*---- kh defined in terms of power function
         CALL RDFREA('KST',KST,10,NL)
         CALL RDFREA('PN',PN,10,NL)
      END IF

      IF (GRWAT) THEN
         IF (SWITGW.EQ.1) THEN
            CALL RDAREA('ZWTB',ZWTB,ILZMAX,IZWTB)
         ELSE IF (SWITGW.EQ.2) THEN
            CALL RDSREA('MAXGW',MAXGW)
            CALL RDSREA('MINGW',MINGW)
            CALL RDSREA('ZWA',ZWA)
            CALL RDSREA('ZWB',ZWB)
            CALL RDSREA('ZWTBI',ZWTBI)
            IF (MINGW.GT.MAXGW) STOP
     &                'PLEASE CHECK MINGW OR MAXGW IN SOIL DATA FILE'
         END IF
      END IF
*---- maximum rooting depth soil
      CALL RDSREA('ZRTMS',ZRTMS)

*------- reading of soil data completed
      CLOSE (IUNITD)

      I = 1
      DO WHILE (I.LE.NL)
         IF (FREEDR) KST(I) = 1000.
         KSAT(I) = KST(I)
         IF (.NOT.PUDDLD) WCSTRP(I) = WCST(I)
         I = I+1
      END DO

      IF (SWITPF.EQ.1) THEN
         I = 1
         DO WHILE (I.LE.NL)
            CALL SUWCMS2(I,2,WCST(I),WCFC(I),100.)
            CALL SUWCMS2(I,2,WCST(I),WCWP(I),1.6E4)
            CALL SUWCMS2(I,2,WCST(I),WCAD(I),1.0E7)
            I = I+1
         END DO
      END IF
```

```
         I = 1
         DO WHILE (I.LE.NL)
            IF (WCLI(I).LT.WCAD(I).OR.WCLI(I).GT.WCST(I))
     &           CALL SUERR(3,WCLI(I),WCAD(I),WCST(I))
            IF (WCSTRP(I).GT.WCST(I))
     &           STOP 'PLEASE CHECK VALUES WCSTRP AND WCST'
            I = I+1
         END DO

         TKLT = 0.

*---- convert TKL from m into mm; calculate water contents in mm
         I = 1
         DO WHILE (I.LE.NL)
* For ORYWAT subroutine   (dimension: m)
            TKLP(I) = TKL(I)
            TKLT = TKLT+TKL(I)
* End for ORYWAT subroutine
            TKL(I) = 1000*TKL(I)
            WLFC(I) = WCFC(I)*TKL(I)
            WLAD(I) = WCAD(I)*TKL(I)
            WLST(I) = WCST(I)*TKL(I)
            WL(I) = WCLI(I)*TKL(I)
            I = I+1
         END DO

         IF (PUDDLD) THEN
*------- Initialize SHRINK subroutine

*------- Calculate water content when cracks penetrate through a
*------- soil compartment
            IF (SWITPF.EQ.1) THEN
               CALL SUWCMS2(NLPUD,2,WCST(NLPUD),WCCR,10**PFCR)
            ELSE
               IF (PFCR.LE.4.2.AND.PFCR.GE.0.) THEN
                  WCCR = WCWP(NLPUD)+((WCFC(NLPUD)-WCWP(NLPUD))/2.2)
     &                   *(4.2-PFCR)
               ELSE IF (PFCR.GT.4.2.AND.PFCR.LE.7.) THEN
                  WCCR = WCAD(NLPUD)+((WCWP(NLPUD)-WCAD(NLPUD))/2.8)
     &                   *(7.0-PFCR)
               ELSE
                  STOP 'PLEASE CHECK VALUE PFCR IN SOIL DATA FILE'
               END IF
            END IF

            I = 1
            DO WHILE (I.LE.NL.AND.I.LE.NLPUD)
               CALL SHRINK(ITASK,I,WL(I),TKL(I),WCST(I),WCSTRP(I),WCL(I)
     &                     ,TOTPOR(I),VL(I))
               I = I+1
            END DO
         END IF

*----- depth of top of compartments
         I = 1
         DO WHILE (I.LE.NL)
            IF (I.EQ.1) THEN
               ZL(I) = 0.
            ELSE
               ZL(I) = ZL(I-1)+TKL(I-1)/10.
            END IF
            I = I+1
         END DO

*------- check groundwater table depth
         IF (GRWAT) CALL GWTAB(ITASK,SWITGW,NL,DOY,DELT,WLFL,TKL,ZWPREV,
     &                         IGW,ZW)

*---- initialization of state variables

*------- initial ponded water depth (mm)
         WL0 = WL0I

*------- initial (total) water content in soil profile (mm)
         I = 1
         DO WHILE (I.LE.NL)
            WCL(I) = WCLI(I)
            WCUMI = WCUMI+WL(I)
            I = I+1
         END DO

         WCUM = WCUMI

*----- reset days since last ponded water
         DSPW = 1.

*------- reset cumulative amounts
         DRAICU = 0.
         UPRICU = 0.
         GWCU = 0.
         EVSWCU = 0.
         RAINCU = 0.
         RNOFCU = 0.
         TRWCU = 0.
         WCUMCO = 0.
         WL0CO = 0.

      ELSE IF (ITASK.EQ.2) THEN

         WL0CH = 0.
         WCUMCH = 0.
         RUNOF = 0.
         EVSW = 0.
         EVSWS = 0.
```

```
      CAPTOT = 0.
      GWTOT = 0.
      IR = 0.
      DRAIN = 0.


*------- reset rates to 0
      I = 1
      DO WHILE (I.LE.NL)
         WLFL(I) = 0.
         WLCH(I) = 0.
         CAPRI(I) = 0.
         GWFILL(I) = 0.
         I = I+1
      END DO
      WLFL(I) = 0.
*------- transpiration summed over all layers (mm/d)

      TRW = 0
      I = 1
      DO WHILE (I.LE.NL)
         TRW = TRW+TRWL(I)
         I = I+1
      END DO

*------Seed-bed:it is assumed that the seed-bed is continuously
*      (daily) irrigated: a dummy gift IR is used to keep
*      the water level in the seed-bed to WL0I.
*------Main field: a constant irrigation gift is supplied
*      when the water level drops below WL0MIN, and when the crop
*      is not yet in ripening phase, if SWITIR equal to 2 and IRRI
*      in the value is given a large enough value.

      IF (ITIM.LT.ITRT) IR = PERC+EVSC+TRW

*------- if irrigated, supply constant irrigation (mm/d) if ponded water
*------- level is below minimum

      IF (SWITIR.EQ.1.AND.ITIM.GE.ITRT) IR = LINT(RIRRIT,IRIRR,DOY)

      IF (WL0.LE.WL0MIN.AND.SWITIR.EQ.2.AND.ITIM.GE.ITRT) IR = IRRI

      IF (SWITIR.EQ.0.AND.ITIM.GE.ITRT) IR = 0.

*---- reset percolation to zero:
      PERC = 0.


*------- 1. Ponded water on field
      IF (WL0.GE.TINY) THEN

*---------- reset number of days after ponded water
         DSPW = 1.

*---------- 1.1 Ponded water can sustain evaporation and transpiration
         IF (WL0/DELT+RAIN+IR.GE.EVSC+TRW) THEN

*------------- calculate change in ponded water depth (mm/d)
            WL0CH = RAIN+IR-EVSC-TRW

*------------- reset transpiration losses per soil compartment to zero
*------------- as transpiration is taken from ponded water
            I = 1
            DO WHILE (I.LE.NL)
               TRWL(I) = 0
               I = I+1
            END DO

*------------- for water balance check
            EVSW = EVSC
            EVSWS = 0.

            IF ((.NOT.FREEDR).AND.(.NOT.CRACKS)) THEN
*------------- calculate percolation rate (mm/d)
               IF (SWITVP.EQ.0) THEN
                  IF (WL0/DELT+WL0CH.GE.PERCOL) THEN
                     PERC = PERCOL
                  ELSE
                     PERC = WL0/DELT+WL0CH
                  END IF
               ELSE
                  IF (.NOT.PUDDLD)
     &                STOP 'SWITVP MUST BE 0 FOR NON-PUDDLED SOIL'
                  IF (NLPUD.LT.NL) THEN
                     CALL SATFLX(TKL,NLPUD,WL0,PERC)
                  ELSE
                     STOP 'SWITVP MUST BE 0 IF NL = NLPUD'
                  END IF
                  IF (WL0/DELT+WL0CH.LE.PERC) PERC = WL0/DELT+WL0CH
               END IF

*---------- recalculate change in ponded water depth (mm/d)
               WL0CH = WL0CH-PERC

*---------- calculate runoff (mm/d) if ponded water depth
*---------- exceeds bund height
               IF (WL0+WL0CH*DELT.GE.WL0MX) THEN
                  RUNOF = (WL0+WL0CH*DELT-WL0MX)/DELT
                  WL0CH = WL0CH-RUNOF
               END IF

               I = 1
               DO WHILE (I.LE.NL+1)
                  WLFL(I) = PERC
                  I = I+1
               END DO
```

```
            ELSE

*---------- calculate flow through boundaries of soil compartments
               WLFL(1) = RAIN+IR-EVSC-TRW

               I = 1
               DO WHILE (I.LE.NL)
                  CALL DOWNFL(I,KSAT(I),WLFL(I),TRWL(I),EVSWS,WL(I),
     &                        WLFC(I),DELT,WLFL(I+1))
                  I = I+1
               END DO

               IF (.NOT.FREEDR) THEN
                  I = NL
                  DO WHILE (I.GE.1)
                     CALL BACKFL(I,WL(I),WLFL(I),WLFL(I+1),EVSWS,
     &                           TRWL(I),WLST(I),DELT,FLNEW,REST)
                     WLFL(I) = FLNEW
                     I = I-1
                  END DO

                  WLOCH = MAX(0.,(REST-WLST(1))/DELT)

                  IF (WL0+WLOCH*DELT.GE.WLOMX) THEN
                     RUNOF = (WL0+WLOCH*DELT-WLOMX)/DELT
                     WLOCH = WLOCH-RUNOF
                  END IF
               END IF

            END IF

*---------- 1.2 Ponded water depth can sustain evaporation but
*----------     only part of transpiration

         ELSE IF ((WL0/DELT+RAIN+IR.GE.EVSC).AND.
     &            (WL0/DELT+RAIN+IR.LT.EVSC+TRW)) THEN

*------------- calculate change in ponded water depth (mm/d)
               WLOCH = -WL0/DELT

*------------- percolation is zero because no ponded water left
               PERC = 0.
               I = 1
               DO WHILE (I.LE.NL+1)
                  WLFL(I) = PERC
                  I = I+1
               END DO

*------------- correct transpiration losses per soil compartment as
*------------- transpiration losses are partly covered by ponded water
               I = 1
               DO WHILE (I.LE.NL)
                  TRWL(I) = ((TRW+EVSC-RAIN-IR-WL0/DELT)/TRW)*TRWL(I)
     &                      *DELT
                  I = I+1
               END DO

*------------- for water balance check
               EVSW = EVSC
               EVSWS = 0.

*---------- 1.3 Ponded water can sustain part of evaporation only
            ELSE IF (WL0/DELT+RAIN+IR.LT.EVSC) THEN

*------------- calculate change in ponded water depth (mm/d)
               WLOCH = -WL0/DELT
               PERC = 0.
               WLFL(1) = RAIN+IR
               I = 2
               DO WHILE (I.LE.NL+1)
                  WLFL(I) = PERC
                  I = I+1
               END DO

*------------- calculate contribution of first soil compartment to
*------------- evaporation
               EVSW = MIN(EVSC+WLOCH,WL(1)/DELT-WLAD(1)/DELT+RAIN+IR)

               EVSWS = EVSW
*------------- for water balance check
               EVSW = WL0/DELT+EVSWS

            END IF

         ELSE

*---------- 2. No ponded water on surface
*---------- calculate evaporation rate from soil surface (mm/d)
            EVSH = MIN(EVSC,MAX(0.,(WL(1)-WLAD(1))/DELT+RAIN+IR))
            EVSD = MIN(EVSC,0.6*EVSC*(SQRT(DSPW)-SQRT(DSPW-1.))+RAIN+IR)
            EVSW = INSW(DSPW-1.1,EVSH,EVSD)
            EVSW = MIN(EVSW,MAX(0.,RAIN+IR+(WL(1)-WLAD(1))/DELT))

            EVSWS = EVSW

            DSPW = DSPW+1.

            WLFL(1) = RAIN+IR


            I = 1
            DO WHILE (I.LE.NL)
               CALL DOWNFL(I,KSAT(I),WLFL(I),TRWL(I),EVSWS,WL(I),WLFC(I)
```

```
     &                   ,DELT,WLFL(I+1))
            I = I+1
         END DO

         IF (.NOT.FREEDR) THEN
            I = NL
            DO WHILE (I.GE.1)
               CALL BACKFL(I,WL(I),WLFL(I),WLFL(I+1),EVSWS,TRWL(I),
     &                     WLST(I),DELT,FLNEW,REST)
               WLFL(I) = FLNEW
               I = I-1
            END DO

            WLOCH = MAX(0.,(REST-WLST(1))/DELT)

            IF (WL0+WLOCH*DELT.GE.WL0MX) THEN
               RUNOF = (WL0+WLOCH*DELT-WL0MX)/DELT
               WLOCH = WLOCH-RUNOF
            END IF
         END IF
      END IF

      IF (GRWAT) THEN
*------- drain compartments in groundwater
         I = IGW
         DO WHILE (I.LE.NL)
            IF (WL(I).GE.WLFC(I)) THEN
               DRAIN = (WL(I)-WLFC(I))/DELT
               WLFL(I+1) = DRAIN+MAX(0.,WLFL(I)-TRWL(I))
            ELSE
               WLFL(I+1) = MAX(0.,WLFL(I)-TRWL(I)+(WL(I)-WLFC(I))
     &                     /DELT)
            END IF
            I = I+1
         END DO

         I = NL
         GWTOT = 0.
         DO WHILE (I.GE.1)
            GWFILL(I) = 0.
*---------- check if groundwater in soil compartment
*---------- if groundwater table is negative it is assumed that
*---------- this represents water on the soil surface

            GWCHK = MAX(0.,ZW-ZL(I)-0.5*TKL(I)/10.)
            IF (GWCHK.EQ.0.) THEN
               WRITE (*,*) 'Groundwater in compartment ',I
               IF (I.EQ.1) THEN
                  GWFILL(I) = MAX(0.,(WLST(I)-WL(I))/DELT+TRWL(I)+
     &                        WLFL(I+1)+EVSWS-WLFL(I))
               ELSE
                  GWFILL(I) = MAX(0.,(WLST(I)-WL(I))/DELT+TRWL(I)+
     &                        WLFL(I+1)-WLFL(I))
               END IF
               GWTOT = GWTOT+GWFILL(I)
            END IF

*------ Capillary rise
            MS = 0.
            FLOW = 0.
            IF (WL(I).GT.WLAD(I).AND.WL(I).LT.WLFC(I).AND.ZW.GT.ZL(I)
     &         +TKL(I)/10.) THEN
               IF ((SWITKH.NE.0).AND.(SWITPF.EQ.0)) THEN
                  IF (WCL(I).GE.WCWP(I).AND.WCL(I).LT.WCFC(I)) THEN
                     FACT = MAX(0.,
     &                      MIN(1.,(WCL(I)-WCWP(I))/(WCFC(I)-WCWP(I))
     &                      ))
                     MS = 10**(4.2-FACT*2.2)
                  ELSE IF (WCL(I).LT.WCWP(I)) THEN
                     FACT = MAX(0.,
     &                      MIN(1.,(WCL(I)-WCAD(I))/(WCWP(I)-WCAD(I))
     &                      ))
                     MS = 10**(7.0-FACT*2.8)
                  END IF
               END IF
               IF ((SWITKH.NE.0).AND.(SWITPF.EQ.1))
     &             CALL SUWCMS2(I,1,WCST(I),WCL(I),MS)
               IF (MS.GT.100.)
     &             CALL SUBSL2(LOG10(MS),ZW-ZL(I)+0.5*TKL(I)/10.,I,
     &            WCST(I),FLOW)

               IF (FLOW.LT.0) FLOW = 0.
               IF (I.EQ.1) THEN
                  CAPRI(I) = MIN(FLOW,(WLST(I)-WL(I))/DELT+EVSWS+TRWL
     &                       (I)+WLFL(I+1)-WLFL(I))
               ELSE
                  CAPRI(I) = MIN(FLOW,(WLST(I)-WL(I))/DELT+TRWL(I)+
     &                       WLFL(I+1)-WLFL(I))
               END IF

            END IF
            CAPTOT = CAPTOT+CAPRI(I)
            I = I-1
         END DO

      END IF

      I = 1
      DO WHILE (I.LE.NL)
         IF (I.EQ.1) THEN
            WLCH(I) = WLFL(I)-WLFL(I+1)-TRWL(I)-EVSWS+CAPRI(I)
     &                +GWFILL(I)
         ELSE
            WLCH(I) = WLFL(I)-WLFL(I+1)-TRWL(I)+CAPRI(I)+GWFILL(I)
         END IF
         WCUMCH = WCUMCH+WLCH(I)
```

```
         I = I+1
      END DO
      IF (OUTPUT) THEN
         CALL OUTDAT(2,0,'WL0',WL0)
         CALL OUTDAT(2,0,'RAIN',RAIN)
         CALL OUTDAT(2,0,'IR',IR)
         CALL OUTDAT(2,0,'PERC',PERC)
         CALL OUTARR('TRWL',TRWL,1,6)
         CALL OUTARR('WCL',WCL,1,10)
         CALL OUTARR('WLFL',WLFL,1,11)
         CALL OUTARR('CAPRI',CAPRI,1,10)
         CALL OUTDAT(2,0,'ZW',ZW)
         CALL OUTDAT(2,0,'EVSC',EVSC)

         CALL OUTDAT(2,0,'EVSW',EVSW)
         CALL OUTDAT(2,0,'EVSWS',EVSWS)
         CALL OUTDAT(2,0,'DRAICU',DRAICU)
         CALL OUTDAT(2,0,'UPRICU',UPRICU)
         CALL OUTDAT(2,0,'EVSWCU',EVSWCU)
         CALL OUTDAT(2,0,'RAINCU',RAINCU)
         CALL OUTDAT(2,0,'RNOFCU',RNOFCU)
         CALL OUTDAT(2,0,'TRWCU',TRWCU)
         CALL OUTDAT(2,0,'WCUMCO',WCUMCO)
         CALL OUTDAT(2,0,'WL0CO',WL0CO)
         CALL OUTARR('TOTPOR',TOTPOR,1,3)

      END IF


   ELSE IF (ITASK.EQ.3) THEN

      IF (GRWAT) THEN
*-------- new groundwater table depth
         ZWPREV = ZW
         CALL GWTAB(ITASK,SWITGW,NL,DOY,DELT,WLFL,TKL,ZWPREV,IGW,ZW)
      END IF
*---- integration of state variables
      WL0 = INTGRL(WL0,WL0CH,DELT)
      I = 1
      DO WHILE (I.LE.NL)
         WL(I) = INTGRL(WL(I),WLCH(I),DELT)
         I = I+1
      END DO

      I = 1
      DO WHILE (I.LE.NL)
         WCL(I) = WL(I)/TKL(I)
         I = I+1
      END DO

      IF (PUDDLD) THEN
         I = 1
         DO WHILE (I.LE.NL.AND.I.LE.NLPUD)
            CALL SHRINK(ITASK,I,WL(I),TKL(I),WCST(I),WCSTRP(I),WCL(I)
     &                 ,TOTPOR(I),VL(I))
            IF (WCL(I).LT.WCCR) THEN
               KSAT(I) = 1000.
               WRITE (*,*) 'CRACKS REACHED BOTTOM COMPARTMENT ',I
            END IF
            IF (WCL(NLPUD).LT.WCCR) CRACKS = .TRUE.
            WLST(I) = VL(I)*TOTPOR(I)
            WLFC(I) = WLST(I)
            I = I+1
         END DO

      END IF
*---- cumulative amounts
      DRAICU = DRAICU-WLFL(NL+1)*DELT
      UPRICU = UPRICU+CAPTOT*DELT
      GWCU = GWCU+GWTOT*DELT
      EVSWCU = EVSWCU-EVSW*DELT
      RAINCU = RAINCU+(RAIN+IR)*DELT
      RNOFCU = RNOFCU-RUNOF*DELT
      TRWCU = TRWCU-TRW*DELT

*----- water balance check
      WCUM = WCUM+WCUMCH*DELT

*----- contribution of profile to water balance, since start
      PROREL = WCUMCH
      WCUMCO = WCUMCO+PROREL*DELT
*----- contribution of surface water to water balance, since start
      SURREL = WL0CH
      WL0CO = WL0CO+SURREL*DELT

*----- total change in system water content
      CKWIN = WCUMCO+WL0CO
*----- total of external contributions to system water content
      CKWFL = RAINCU+RNOFCU+EVSWCU+TRWCU+UPRICU+DRAICU+GWCU
*----- check this
      CALL SUWCHK(CKWFL,CKWIN,TIME)

   ELSE IF (ITASK.EQ.4) THEN
   END IF
   ITOLD = ITASK
   RETURN

   END
```

A4.2 Listing subroutines used in PADDY

```
*----------------------------------------------------------------------*
* SUBROUTINE SATFLX                                                    *
*                                                                      *
```

```
* Date      : March 1993, Version: 1.0                               *
* Purpose   : SATFLX determines percolation rate as a                *
*             function of ponded water depth, hydraulic conductivity *
*             compacted layer and hydraulic conductivity subsoil     *
*                                                                    *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)    *
* name    type meaning (unit)                                  class *
* ----    ---- ---------------                                 ----- *
* TKL      R4  Array of thicknesses soil layers (m)              I   *
* NLPUD    I4  Number of puddled soil compartments including plow    *
*              sole (-)                                          I   *
* WL0      R4  Amount of ponded water (mm)                       I   *
* PERC     R4  Percolation rate (cm d-1)                         O   *
*--------------------------------------------------------------------*

      SUBROUTINE SATFLX(TKL,NLPUD,WL0,PERC)

      IMPLICIT REAL(A-Z)
      INTEGER SWITKH,I,NLPUD
      DIMENSION TKL(10)
      COMMON /SWIT  / SWITKH
      COMMON /NUCHT / VGN(10),VGA(10),VGR(10),VGL(10)
      COMMON /HYDCON/ KST(10),WCAD(10),WCSTRP(10)
      COMMON /POWER / PN(10)

      SAVE

      TKLTOT = 0.
      TINY = 1.E-5
*-------- arbitrary initial value for pressure head subsoil
      HS = -10.0
*---- pressure head top compartments (WL0 and TKL are in mm!)

      I = 1
      DO WHILE (I.LE.NLPUD-1)
         TKLTOT = TKLTOT+TKL(I)/10.
         I = I+1
      END DO
      HT = WL0/10.+TKLTOT

*-------- thickness plow sole in cm
      DZL = TKL(NLPUD)/10.

      IF (SWITKH.EQ.1) THEN
*-------- van genuchten parameters of unsaturated compartment 3
         N = VGN(NLPUD+1)
         A = VGA(NLPUD+1)
         L = VGL(NLPUD+1)
         M = 1.-1./N

*-------- assign arbitrary value to F, the difference function
         F = 10*TINY

         I = 1
         DO WHILE ((ABS(F).GT.TINY).AND.(I.LE.50))

            IF (HS.GT.0) THEN
*--------- estimated pressure head out of range, reset to previous
*--------- value, divided by 2
               WRITE (*,*) ' HS > 0, RESET'
               HS = (HSPREV/2)
            END IF

*--------- calculate van genuchten parameters
            HLP1 = (1.+(A*ABS(HS))**N)**M-(A*ABS(HS))**(N-1.)

            HLP2 = 1.+(A*ABS(HS))**N

            FX = HLP1**2
            GX = HLP2**(M*(L+2.))

*---------- estimated flux through unsaturated compartment
            F2 = KST(NLPUD+1)*(FX/GX)

*---------- calculate derivative of van genuchten equation
            DFX = 2.*HLP1*(M*(HLP2**(M-1.))*(-N)*A*((A*ABS(HS))**(N-1.))
     &            -A*(-N+1.)*((A*ABS(HS))**(N-2.)))
            DGX = M*(L+2.)*(HLP2**(M*(L+2.)-1.))*A*(-N)
     &            *((A*ABS(HS))**(N-1.))

*---------- estimated flux through saturated compartment
            F1 = KST(NLPUD)*((HT-HS)/DZL+1.)

*---------- continue iteration until difference f is approximately zero
            F = F2-F1


            DF = KST(NLPUD+1)*((GX*DFX-FX*DGX)/GX**2)+KST(NLPUD)/DZL

*-------------- keep current value of HS in case next is positive
            HSPREV = HS

*---------- estimate new value for pressure head unsaturated compartment
            HS = HS-F/DF

            I = I+1
         END DO
      ELSE IF (SWITKH.EQ.2) THEN
*-------- power function for hydraulic conductivity

         N = PN(NLPUD+1)
         F = 10.*TINY

         I = 1
         DO WHILE ((ABS(F).GT.TINY).AND.(I.LE.50))
```

```
            IF (HS.GT.0) HS = HSPREV/2
*------------- estimated flux through saturated compartment
            F1 = KST(NLPUD)*((HT-HS)/DZL+1.)

*------------- estimated flux through unsaturated compartment
            F2 = KST(NLPUD+1)*(ABS(HS)**N)

*------- continue iteration until difference f is approximately zero
            F = F2-F1

            DF = -N*((ABS(HS))**(N-1.))*KST(NLPUD+1)+KST(NLPUD)/DZL

*------- keep current value of HS in case next is positive
            HSPREV = HS

*------- estimated new value for pressure head unsaturated compartment
            HS = HS-F/DF
            I = I+1

         END DO
      END IF
*------- save flux (mm/d)
      PERC = 10.*(F1+F2)/2.
      RETURN
      END


*----------------------------------------------------------------------*
* SUBROUTINE SUBSL2                                                    *
*                                                                      *
* Author   : C. Rappoldt                                               *
*            M. Wopereis (revision March 1993)                         *
* Date     : January 1986, revised June 1990                           *
*            Slightly changed to work with VG parameters, March 1993   *
* Purpose  :                                                           *
* Chapter 15 in documentation WOFOST Version 4.1 (1988) This routine   *
* calculates the rate of capillary flow or percolation between         *
* groundwater table and root zone. The stationary flow is found by     *
* integration of dZL = K.d(MH)/(K + FLW), where Z= height above        *
* groundwater, MH= matric head, K= conductivity and FLW= chosen flow.  *
* In an iteration loop the correct flow is found.  The integration     *
* goes at most over four intervals: [0,45],[45,170], [170,330] and     *
* [330,MH-rootzone] (last one on logarithmic scale).                   *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* PF      R4  pF value of soil compartment I (-)                   I   *
* D       R4  Distance of soil compartment I to groundwater            *
*             table, subroutine SUBSL2 (cm)                        I   *
* I       I4  Compartment index (-)                                I   *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) I   *
* FLOW    R4  Capillary rise calculated by subroutine SUBSL2 (mm       *
*             d-1)                                                 O   *
*                                                                      *
* Subroutines and functions called: AFGEN.                             *
* Called by routine WATGW.                                             *
*----------------------------------------------------------------------*

      SUBROUTINE SUBSL2(PF,D,I,WCST,FLOW)

*15.1 declarations and constants
      IMPLICIT REAL(A-Z)
      INTEGER I1,I2,I3,IINT,IMAX,I
      REAL START(4),PFSTAN(9),PGAU(3),WGAU(3)
      REAL DEL(4),PFGAU(12),HULP(12),CONDUC(12)

      COMMON /NUCHT / VGN(10),VGA(10),VGR(10),VGL(10)
      COMMON /HYDCON/ KST(10),WCAD(10),WCSTRP(10)
      COMMON /POWER / PN(10)

      SAVE

      DATA ELOG10/2.302585/,PGAU/.1127016654,.5,.8872983346/
      DATA WGAU/.2777778,.4444444,.2777778/
      DATA START/0.,45.,170.,330./,LOGST4/2.518514/
      DATA PFSTAN/.705143,1.352183,1.601282,1.771497,2.031409,2.192880,
     &     2.274233,2.397940,2.494110/

*15.2 calculation of matric head and check on small pF
      PF1 = PF
      D1 = D
      MH = EXP(ELOG10*PF1)
      IF (PF1.LE.0.) GOTO 90
      IINT = 0

*15.3 number and width of integration intervals
      DO I1 = 1,4
         IF (I1.LE.3) DEL(I1) = MIN(START(I1+1),MH)-START(I1)
         IF (I1.EQ.4) DEL(I1) = PF1-LOGST4
         IF (DEL(I1).LE.0.) GOTO 20
         IINT = IINT+1
10    END DO

*15.4 preparation of three-point Gaussian integration
20    DO I1 = 1,IINT
         DO I2 = 1,3
            I3 = 3*(I1-1)+I2
            IF (I1.EQ.IINT) GOTO 30
*        the three points in the full-width intervals are standard
            PFGAU(I3) = PFSTAN(I3)
            GOTO 40
30          CONTINUE
*        the three points in the last interval are calculated
            IF (IINT.LE.3) PFGAU(I3) = LOG10(START(IINT)+PGAU(I2)*DEL(
     &                                 IINT))
```

```
            IF (IINT.EQ.4) PFGAU(I3) = LOGST4+PGAU(I2)*DEL(IINT)
40          CONTINUE
*        variables needed in the loop below
* NEXT LINE CHANGED
*          CONDUC(I3) = EXP (ELOG10*AFGEN (CONTAB,ILCON,PFGAU(I3)))
* START CHANGES
            CALL SUMSKM2(I,EXP(ELOG10*PFGAU(I3)),WCST,KMS)
            CONDUC(I3) = KMS
* END CHANGES
            HULP(I3) = DEL(I1)*WGAU(I2)*CONDUC(I3)
            IF (I3.GT.9) HULP(I3) = HULP(I3)
     &                        *ELOG10*EXP(ELOG10*PFGAU(I3))
51       END DO
50    END DO

*15.5 setting upper and lower limit
      FU = 1.27
* NEXT LINE CHANGED
*      FL = -1.*EXP (ELOG10*AFGEN (CONTAB, ILCON, PF1))
* START CHANGES
      CALL SUMSKM2(I,EXP(ELOG10*PF1),WCST,KMS)
      FL = -1.*KMS
* END CHANGES
      IF (MH.LE.D1) FU = 0.
      IF (MH.GE.D1) FL = 0.
      IF (MH.EQ.D1) GOTO 80

*15.6 Iteration loop
      IMAX = 3*IINT
      DO I1 = 1,15
         FLW = (FU+FL)/2.
         DF = (FU-FL)/2.
         IF ((DF.LT.0.01).AND.((DF/ABS(FLW)).LT.0.1)) GOTO 80
         Z = 0.
         DO I2 = 1,IMAX
            Z = Z+HULP(I2)/(CONDUC(I2)+FLW)
60       END DO
         IF (Z.GE.D1) FL = FLW
         IF (Z.LE.D1) FU = FLW
70    END DO

*15.7 output IN MM/D
80    FLOW = 10*(FU+FL)/2.
      RETURN

*15.8 in case of small matric head

* NEXT LINE CHANGED
* START CHANGES
90    K0 = KST(I)
* END CHANGES
* FLOW IN MM/D
      FLOW = 10*K0*(MH/D-1.)

      RETURN
      END

*----------------------------------------------------------------------*
* SUBROUTINE SUMSKM2                                                   *
*                                                                      *
* Purpose: SUMSKM2 calculates the hydraulic conductivity at            *
*          given suction for compartment I on the basis of chosen      *
*          option                                                      *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* I       I4  Compartment index (-)                                I   *
* MS      R4  Soil water suction (cm)                              I   *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) O   *
* KMS     R4  Hydraulic conductivity (cm d-1)                      O   *
*                                                                      *
* SUBROUTINES called :                                                 *
*                                                                      *
*     - SUERR, SUWCMS2                                                 *
*                                                                      *
* FUNCTIONS called :  none                                             *
*                                                                      *
* FILE usage : none                                                    *
*----------------------------------------------------------------------*

      SUBROUTINE SUMSKM2(I,MS,WCST,KMS)

      IMPLICIT REAL(A-Z)
      INTEGER I

*-----common blocks
      INTEGER SWITKH
      COMMON /NUCHT / VGN(10),VGA(10),VGR(10),VGL(10)
      COMMON /HYDCON/ KST(10),WCAD(10),WCSTRP(10)
      COMMON /POWER / PN(10)
      COMMON /SWIT  / SWITKH
*-----variables retain their values between subsequent calls
*     of this subroutine
      SAVE

      DATA TINY/1.E-10/
      DATA MSAD/1.E7/

*-----check input value MS
      IF (MS.LT.-TINY.OR.MS.GT.1.E8) CALL SUERR(1,MS,0.,1.E8)

      IF (MS.GE.MSAD-TINY) THEN
*-----   air dry
         KMS = 0.
      ELSE
```

```
*-----   calculate conductivity
         IF (SWITKH.EQ.1) THEN
*-----      Van Genuchten conductivity
            WCL = 0.
*           dummy value; wcl is returned by suwcms2!
            CALL SUWCMS2(I,2,WCST,WCL,MS)
            VGM = 1.0-1.0/VGN(I)
            WREL = (WCL-VGR(I))/(WCSTRP(I)-VGR(I))
            HLP1 = WREL**VGL(I)
            HLP2 = 1.0-WREL**(1./VGM)
            HLP3 = 1.0-HLP2**VGM
            KMS = KST(I)*HLP1*HLP3*HLP3
         ELSE IF (SWITKH.EQ.2) THEN
*-----      power function conductivity
            IF (MS.LE.1.) KMS = KST(I)
            IF (MS.GT.1.) KMS = KST(I)*(MS**PN(I))
         ELSE IF (SWITKH.EQ.5) THEN
*           user can here specify preferred conductivity function;
*           the following two lines should be removed:
            WRITE (*,10)
            STOP
         END IF
         IF (KMS.LT.TINY) KMS = 0.
      END IF
10    FORMAT (///,' *** fatal error; option SWIT3=5 requires ',/,
     &         ' specification of conductivity function')
      RETURN
      END
*----------------------------------------------------------------------*
*  SUBROUTINE SUWCMS2                                                  *
*                                                                      *
*  Purpose: SUWCMS2 calculates volumetric soil water content from      *
*           soil water suction, and vice versa. Various options are    *
*           offered. See SWIT8 in input file or SAWAH manual.          *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                    class *
* ----   ---- ---------------                                   ----- *
* I       I4  Compartment index (-)                                I  *
* SWIT4   I4  Switch to set request MS(WCL) or WCL(MS) (-)         I  *
* WCST    R4  Array of water content saturation / layer (cm3 cm-3) I  *
* WCL     R4  Array of actual water content / layer (cm3 cm-3)   I/O *
* MS      R4  Soil water suction (cm)                             I/O *
*                                                                      *
*  SUBROUTINES called:                                                 *
*   -    SUERR                                                         *
*                                                                      *
*  FUNCTION called:                                                    *
*   -    none                                                          *
*                                                                      *
*  FILE usage:                                                         *
*   -    none                                                          *
*                                                                      *
***********************************************************************

      SUBROUTINE SUWCMS2(I,SWIT4,WCST,WCL,MS)

      IMPLICIT REAL(A-Z)
      INTEGER I,SWIT4

*-----common blocks
      COMMON /NUCHT / VGN(10),VGA(10),VGR(10),VGL(10)
      COMMON /HYDCON/ KST(10),WCAD(10),WCSTRP(10)
*-----variables retain their values between subsequent calls
*     of this subroutine
      SAVE

      DATA TINY/0.001/

      IF (SWIT4.EQ.1) THEN
*        suction calculated from water content
         IF (WCL.LT.WCAD(I).OR.WCL.GT.WCST)
     &        CALL SUERR(3,WCL,WCAD(I),WCST)
         IF (WCL.GT.WCSTRP(I)) THEN
*           it is assumed that MS remains zero during shrinkage
            MS = 0.
         ELSE
*           Van Genuchten option
            HLP1 = AMAX1(WCAD(I),WCL)
            WREL = (WCL-VGR(I))/(WCSTRP(I)-VGR(I))
            VGM = 1.-1./VGN(I)
            HLP2 = 1./VGA(I)
            HLP3 = -1./VGM
            HLP4 = 1./VGN(I)
            MS = HLP2*(WREL**HLP3-1.)**HLP4
         END IF
      ELSE IF (SWIT4.EQ.2) THEN
*        water content calculated from suction
         IF (MS.LT.-TINY.OR.MS.GT.1.E8) CALL SUERR(4,MS,0.,1.E8)
*        van Genuchten option
         VGM = 1.-1./VGN(I)
         HLP1 = (MS*VGA(I))**VGN(I)
         WREL = (1.+HLP1)**(-VGM)
         WCL = WREL*(WCSTRP(I)-VGR(I))+VGR(I)
      END IF

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SHRINK                                                   *
*                                                                      *
*  Version: 1.0                                                        *
*  Date:    April 1994                                                 *
*  Purpose: SHRINK calculates volumetric water content of              *
*           puddled soil compartments                                  *
```

```
*          using a shrinkage factor equal to WCSTRP/WCST                  *
*                                                                         *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)         *
* name    type meaning (unit)                                       class *
* ----    ---- ---------------                                      ----- *
* ITASK    I4  Task that subroutine should perform (-)                I   *
* I        I4  Compartment index (-)                                  I   *
* WL       R4  Water content (mm)                                     I   *
* TKL      R4  Array of thicknesses soil layers (m)                   I   *
* WCST     R4  Array of water content saturation / layer (cm3 cm-3)   I   *
* WCSTRP   ??  Array saturated volumetric water content ripened           *
*              soil per soil compartment (cm3 cm-3)                   I   *
* WCL      R4  Array of actual water content / layer (cm3 cm-3)       O   *
* TOTPOR   R4  Array of total porosity / layer (cm3 cm-3)             O   *
* VL       R4  Array thickness soil compartment after shrinkage (mm)  O   *
*-------------------------------------------------------------------------*

      SUBROUTINE SHRINK(ITASK,I,WL,TKL,WCST,WCSTRP,WCL,TOTPOR,VL)

      IMPLICIT REAL(A-Z)

      INTEGER I,ITASK
      REAL WLLOW(3)

      SAVE

      TKLMIN = (WCSTRP/WCST)*TKL
      WLST = WCST*TKL

      IF (ITASK.EQ.1) THEN
         WLLOW(I) = WL
         IF (WL.GE.WCSTRP*TKLMIN) THEN
            VL = MIN(TKL,TKLMIN+(WL-WCSTRP*TKLMIN))
            WCL = WL/VL
            TOTPOR = WCL
         ELSE
            WCL = WL/TKLMIN
            TOTPOR = WCSTRP
            VL = TKLMIN
         END IF
      ELSE
         IF (WL.LT.WLLOW(I)) THEN
            IF (WL.GE.WCSTRP*TKLMIN) THEN
               VL = MIN(TKL,TKLMIN+(WL-WCSTRP*TKLMIN))
               WCL = WL/VL
               TOTPOR = WCL
            ELSE
               WCL = WL/TKLMIN
               TOTPOR = WCSTRP
               VL = TKLMIN
            END IF
         ELSE
            WCL = WL/VL
            END IF
         END IF

         RETURN
         END

*-------------------------------------------------------------------------*
* SUBROUTINE SUERR                                                        *
*                                                                         *
* Purpose: SUERR checks whether value of variable X is within             *
*          pre-specified domain                                           *
*                                                                         *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)         *
* name    type meaning (unit)                                       class *
* ----    ---- ---------------                                      ----- *
* IMNR     I4  Help variable for subroutine SUERR (-)                 I   *
* X        R4  Value of variable to be checked (variable)             I   *
* XMIN     R4  Minimum allowable value of X (variable)                I   *
* XMAX     R4  Maximum allowable value of X (variable)                I   *
*                                                                         *
* WARNINGS:                                                               *
*                                                                         *
*   X < XMIN * 0.99 and XMIN .NE. -99 then expert message is produced     *
*   X > XMAX * 1.01 and XMAX .NE. -99 then expert message is produced     *
*                                                                         *
* SUBROUTINES called : none                                               *
*                                                                         *
* FUNCTIONS called :                                                      *
*                                                                         *
* FILE usage : none                                                       *
*-------------------------------------------------------------------------*

      SUBROUTINE SUERR(IMNR,X,XMIN,XMAX)


*(JJ) IUNLOG is a obsolete variable: it is NEVER assigned a value, and
*     stillit is 'used' in determining whether to write something to
*     the logfile it is supposed to be defined by (or something like
*     that). Note that this variable is used in various subroutines
*     throughout WBAL8.


      IMPLICIT REAL(A-Z)
      INTEGER IUNLOG,IMNR
      CHARACTER*1 DUMMY
      CHARACTER*38 ERRM(5)

*-----common block
      COMMON /UNITNR/ IUNLOG

*-----variables retain their values between subsequent calls
*     of this subroutine
      SAVE
```

```
      DATA ERRM/'MATRIC SUCTION OUT OF RANGE IN SUMSKM2',
     &     'WATER CNT OUT OF RANGE IN SUSLIN      ',
     &     'WATER CNT OUT OF RANGE IN SUWCMS2     ',
     &     'MATRIC SUCTION OUT OF RANGE IN SUWCMS2',
     &     'ONE OR MORE TRWL(I) OUT OF RANGE      '/

      IF ((X.LT.XMIN*0.99).AND.(XMIN.NE.-99.)) GOTO 10
      IF ((X.GT.XMAX*1.01).AND.(XMAX.NE.-99.)) GOTO 10
      RETURN

10    CONTINUE
      WRITE (*,20) IMNR,X,XMIN,XMAX
      WRITE (*,30) ERRM(IMNR)
      IF (IUNLOG.GT.0) THEN
         WRITE (IUNLOG,20) IMNR,X,XMIN,XMAX
         WRITE (IUNLOG,30) ERRM(IMNR)
      END IF
      READ (*,'(A)') DUMMY
      STOP
20    FORMAT (//,' ***fatal error in variable or parameter value ***',/,
     &        '    message number, value, minimum and maximum: ',/,10X,
     &        I2,3(3X,E10.3))
30    FORMAT (A)
      END

*----------------------------------------------------------------------*
* SUBROUTINE SUWCHK                                                    *
*                                                                      *
* Purpose: SUWCHK checks the soil water balance by comparing           *
*          time-integrated boundary fluxes versus change in            *
*          total amount of water contained in the system.              *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* CKWFL   R4  Sum of time-integrated boundary fluxes (mm)          I   *
* CKWIN   R4  Change in water storage since start (mm)             I   *
* TIME    R4  Time of simulation (d)                               I   *
*                                                                      *
* SUBROUTINES called : none                                            *
* FUNCTIONS called : none                                              *
*                                                                      *
* FILE usage :                                                         *
*    - * (screen), unit IUNLOG                                         *
*----------------------------------------------------------------------*

      SUBROUTINE SUWCHK(CKWFL,CKWIN,TIME)

      IMPLICIT REAL(A-Z)
      INTEGER IUNLOG

*-----common
      COMMON /UNITNR/ IUNLOG

*-----variables retain their values between subsequent calls
*     of this subroutine
      SAVE

      FUWCHK = 2.0*(CKWIN-CKWFL)/(CKWIN+CKWFL+1.E-10)
      XDIF = ABS(CKWIN-CKWFL)
      IF (ABS(FUWCHK).GT.0.01.AND.XDIF.GT.1.0) THEN
*-----   absolute error in water balance exceeds 1 mm
*        and relative error exceeds 1%.
         WRITE (*,10) FUWCHK,CKWIN,CKWFL,TIME
         IF (IUNLOG.GT.0) WRITE (IUNLOG,10) FUWCHK,CKWIN,CKWFL,TIME
      END IF
10    FORMAT (/'* * * error in water balance, please check * * *',/,
     &        ' CKWRD  =',F6.3,' CKWIN=',F8.2,' CKWFL=',F8.2,
     &        ' AT TIME = ',F6.1)
      RETURN
      END

*----------------------------------------------------------------------*
* SUBROUTINE GWTAB                                                     *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* ITASK   I4  Task that subroutine should perform (-)             C,I  *
* SWITGW  I4  Groundwater switch (-)                               C   *
* NL      I4  Number of soil layers (-)                            I   *
* DOY     R4  Daynumber (January 1 = 1) (-)                        I   *
* DELT    R4  Time step of integration (d)                         I   *
* WLFL    R4  Array flux at boundaries of soil compartment (mm d-1) I  *
* TKL     R4  Array of thicknesses soil layers (m)                 I   *
* ZWPREV  R4  Groundwater tabel depth of previous day (cm)         O   *
* IGW     I4  Number of shallowest soil compartment in groundwater     *
*             (-)                                                  O   *
* ZW      R4  Depth of groundwater table below soil surface (cm)   O   *
*----------------------------------------------------------------------*
      SUBROUTINE GWTAB(ITASK,SWITGW,NL,DOY,DELT,WLFL,TKL,ZWPREV,IGW,ZW)

      IMPLICIT REAL(A-Z)

*     Formal parameters
      INTEGER ITASK,SWITGW,NL,IGW
      REAL WLFL(NL+1),TKL(NL)

*     Local variables
      INTEGER IZWTB,ILZMAX
      PARAMETER (ILZMAX=400)
      COMMON /GWT   / ZWA,ZWB,MAXGW,MINGW,ZWTBI,ZWTB(ILZMAX),IZWTB
      SAVE
```

```
      IF (ITASK.EQ.1) THEN
         IF (SWITGW.EQ.1) THEN
            ZW = LINT(ZWTB,IZWTB,DOY)
         ELSE
            ZW = ZWTBI
         END IF
         ZWPREV = ZW
      END IF
      IGW = 1
      ZLL = 0.
      ZWL = 0.
      DO WHILE ((IGW.LE.NL).AND.(ZWL.LE.0.))
         ZLL = ZLL+TKL(IGW)/10.
         ZWL = ZLL-ZWPREV
         IGW = IGW+1
      END DO
      IF (ZWL.GT.0.) IGW = IGW-1
      IF (ITASK.EQ.3) THEN
         IF (SWITGW.EQ.1) THEN
            ZW = LINT(ZWTB,IZWTB,DOY)
         ELSE
            ZW = ZW+ZWA*DELT-ZWB*10.*WLFL(IGW)*DELT
            IF (ZW.LT.MINGW) ZW = MINGW
            IF (ZW.GT.MAXGW) ZW = MAXGW
         END IF
      END IF
      RETURN
      END

*----------------------------------------------------------------------*
* SUBROUTINE DOWNFL                                                    *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* I       I4  Compartment index (-)                                I   *
* KSAT    R4  Saturated hydraulic conductivity (cm d-1)            I   *
* FLIN    R4  Flux into compartment (mm d-1)                       I   *
* TRWL    R4  Array of actual transpiration rate/layer (mm d-1)    I   *
* EVSWS   R4  Actual evaporation rate soil compartment 1 (m d-1)   I   *
* WL      R4  Water content (mm)                                   I   *
* WLFC    R4  Array amount of water per soil compartment at 'field     *
*             capacity' (mm)                                       I   *
* DELT    R4  Time step of integration (d)                         T   *
* FLOUT   R4  Flow out of compartment (mm d-1)                     O   *
*----------------------------------------------------------------------*

      SUBROUTINE DOWNFL(I,KSAT,FLIN,TRWL,EVSWS,WL,WLFC,DELT,FLOUT)

      IMPLICIT REAL(A-Z)
      INTEGER I
      SAVE

      IF (I.EQ.1) THEN
         FLOUT = MIN(10.*KSAT,MAX(0.,FLIN-EVSWS-TRWL+(WL-WLFC)/DELT))
      ELSE
         FLOUT = MIN(10.*KSAT,MAX(0.,FLIN-TRWL+(WL-WLFC)/DELT))
      END IF

      RETURN
      END

*----------------------------------------------------------------------*
* SUBROUTINE BACKFL                                                    *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                                     class *
* ----   ---- ---------------                                    ----- *
* I       I4  Compartment index (-)                                I   *
* WL      R4  Water content (mm)                                   I   *
* FLIN    R4  Flux into compartment (mm d-1)                       I   *
* FLOUT   R4  Flux out of compartment (mm d-1)                     I   *
* EVSWS   R4  Actual evaporation rate soil compartment 1 (m d-1)   I   *
* TRWL    R4  Array of actual transpiration rate/layer (mm d-1)    I   *
* WLST    R4  Array amount of water per soil compartment at            *
*             saturation (mm)                                      I   *
* DELT    R4  Time step of integration (d)                         T   *
* FLNEW   R4  Boundary flow between soil compartments recalculated     *
*             via subroutine BACKFL (mm d-1)                       O   *
* HLP     R4  Help variable for subroutine BACKFL (mm)             O   *
*----------------------------------------------------------------------*

      SUBROUTINE BACKFL(I,WL,FLIN,FLOUT,EVSWS,TRWL,WLST,DELT,FLNEW,HLP)

      IMPLICIT REAL(A-Z)
      INTEGER I
      SAVE

      HLP = 0.

      IF (I.EQ.1) THEN
         HLP = WL+(FLIN-FLOUT-EVSWS-TRWL)*DELT
      ELSE
         HLP = WL+(FLIN-FLOUT-TRWL)*DELT
      END IF

      IF (HLP.GT.WLST) THEN
         FLNEW = FLIN-(HLP-WLST)/DELT
      ELSE
         FLNEW = FLIN
      END IF
      RETURN
      END
```

A4.3 Soil data file

```
********************************************************************
* EXAMPLE INPUT FILE, CONTAINS MAXIMUM NUMBER OF
* PARAMETERS NEEDED
********************************************************************

* Switches:
* Puddling switch: puddled (1); non-puddled (0)
SWITPD = 1
* Drainage switch: free draining (1); impeded drainage (0)
SWITFD = 0
* Irrigation switch: no irrigation (0); irrigation read from table (1);
* irrigation if ponded water depth drops below minimum value (2)
SWITIR = 0
* Conductivity switch: no data (0); Van Genuchten parameters (1);
* Power function (2)
SWITKH = 0
* Water retention switch: data given for saturation, field capacity,
* wilting point and when air dry (0); via Van Genuchten parameters (1)
SWITPF = 0
* Groundwater switch: not in profile (0); read from this file (1);
* calculated (2)
SWITGW = 1
* Percolation switch: read from this file (0); calculated (1)
* Value for SWITVP can only be 1 if puddled soil
SWITVP = 0

* Number of soil layers (maximum is 10)
NL = 9

* Thickness of soil compartments (m)
TKL = 3*0.05, 3*0.05, 0.10, 0.20, 0.20

* Percolation rate (if SWITVP = 0)
PERCOL = 10.0

* Maximum rooting depth in soil (m)
ZRTMS = 1.0

* Irrigation table, amount of irrigation (y in mm) for a given calendar
* day (x), used if SWITIR = 1
RIRRIT = 23., 0.,
60., 0., 79., 0., 111.,0.,112.,100.,
113.,0.,117.,0.,118.,100.,119.,0.,123.,0.,124.,100.,300.,100.

* Irrigation parameter, used if SWITIR = 2, i.e. amount of irrigation
* if ponded water depth drops below WL0MIN (mm)
IRRI = 50.

* Saturated hydraulic conductivity (needed if SWITFD = 0,
* and if SWITKH is 1 or 2)
KST = 2*127.0, 3.0, 3*35.0, 2*103.0, 42.0
* Van Genuchten parameters (needed if SWITKH = 1 and/or SWITPF = 1)
VGA = 3*0.127, 3*0.047, 2*0.078, 0.032
VGL = 3*-6.2, 3*-0.6, 2*-4.9, -11.1
VGN = 3*1.119, 3*1.095, 2*1.076, 1.073
VGR= 9*0.01
* Power function parameter (needed if SWITKH = 2)
PN = 3*-2.5, 3*-2.5, 2*-2.5, -2.5

* Saturated volumetric water content
WCST = 3*0.52, 3*0.55, 2*0.61, 0.64
* Volumetric water content at field capacity (needed if SWITPF = 0)
WCFC = 3*0.48, 3*0.47, 2*0.52, 0.58
* Volumetric water content at wilting point (needed if SWITPF = 0)
WCWP = 9*0.21
* Volumetric water content when air dry (needed if SWITPF = 0)
WCAD = 9*0.01
* Initial volumetric water content
WCLI = 3*0.52, 3*0.47, 2*0.52, 0.58

* Ponded water depth (mm)
WL0MX = 150.
* Minimum ponded water depth (mm)
WL0MIN = 50.
* Initial ponded water depth (mm)
```

```
WLOI = 100.

* Groundwater table depths (y in cm) as a function of calendar day (x)
* needed if SWITGW = 1
ZWTB = 1., 150., 300., 150.
* Groundwater parameters, needed if SWITGW = 2
* Initial groundwater depth (cm)
ZWTBI = 100.
* Minimum groundwater depth (cm)
MINGW = 100.
* Maximum groundwater depth (cm)
MAXGW = 100.
* Sensitivity factor of recharge (-)
ZWA = 1.0
* Depth groundwater table is receding in case of no recharge (cm/d)
ZWB = 0.5

* FOLLOWING PARAMETERS ONLY NEEDED IF SOIL IS PUDDLED
* i.e. if SWITPD = 1
* Number of puddled compartments, including plow sole (cannot exceed NL)
NLPUD = 3
* Volumetric water content of ripened soil (previously puddled)
WCSTRP = 3*0.52, 3*0.55, 2*0.61, 0.64
* pF value of puddled root zone at which cracks reach the non-puddled
* subsoil, i.e. break through the plow sole
PFCR = 3.0
```

A4.4 List of variables used in PADDY

Name	Description	Units
CAPRI	array capillary rise per soil compartment	mm d^{-1}
CAPTOT	total capillary rise	mm d^{-1}
CKWFL	total of external contribution to system water content	mm
CKWIN	total change in system water content	mm
CRACKS	logical indicating if cracks penetrate through puddled topsoil	-
DELT	time step	d
DOY	calendar day	d
DRAICU	cumulative outflow from deepest soil compartment	mm
DRAIN	variable used to drain soil compartment to field capacity	mm d^{-1}
DSPW	days passed without ponded water on soil surface	d
EVSC	potential evaporation rate	mm d^{-1}
EVSD	actual evaporation rate soil if DSPW > 1	mm d^{-1}
EVSH	actual evaporation rate soil if DSPW = 1	mm d^{-1}
EVSW	actual evaporation rate	mm d^{-1}
EVSWCU	cumulative actual evaporation rate	mm
EVSWS	actual evaporation rate soil compartment 1	m d^{-1}
FILEI2	name of soil data input file	-
FLNEW	boundary flow between soil compartments recalculated via subroutine BACKFL	mm d^{-1}
FLOW	capillary rise calculated by subroutine SUBSL2	mm d^{-1}
FREEDR	logical indicating free drainage or impeded drainage	-
GWCU	cumulative contribution groundwater table	mm
GWFILL	array used to 'fill-up' soil compartment if in groundwater	mm d^{-1}
GWTOT	total contribution groundwater table	mm d^{-1}
GRWAT	logical indicating if groundwater table is in soil profile	-
HYDCON	common block needed to communicate with subr. SUMSKM2	-
I	counter, usually used to indicate soil compartment number	-
IGW	number of shallowest soil compartment in groundwater	-
ILZMAX	maximum number of groundwater table measurements	-
INL	number of soil compartments	-
IR	irrigation	mm d^{-1}
IRIRR	number of days with additional irrigation	-
IRRI	additional irrigation if ponded water declines below minimum	mm d^{-1}
ITIM	time of simulation	d
ITASK	determines action of PADDY	-
ITOLD	previous action of PADDY	-
ITRT	time of transplanting	d
IUNITD	unit number soil data file	-
IUNITL	unit number log file	-
IUNITO	unit number output file	-
IZWTB	number of days with groundwater table measurements	-
KSAT	saturated hydraulic conductivity	cm d^{-1}
KST	saturated hydraulic conductivity	cm d^{-1}
MAXGW	maximum groundwater table depth	cm

Name	Description	Units
MINGW	minimum groundwater table depth	cm
MS	moisture suction (pressure head)	cm
NL	number of soil compartments	-
NLPUD	number of puddled soil compartments including plow sole	-
NUCHT	common block with Van Genuchten parameters	-
OUTPUT	flag indicating if output to file is required	-
PERC	actual percolation rate	mm d^{-1}
PERCOL	percolation rate from soil data input file (constant)	mm d^{-1}
PFCR	critical pF value where cracks break through soil compartment	-
PN	parameter n in power function for hydraulic conductivity	-
POWER	common block containing PN	-
PROREL	contribution of profile storage to water balance	mm d^{-1}
PUDDLD	logical indicating if profile is puddled / non-puddled	-
RAIN	rainfall	mm d^{-1}
RAINCU	cumulative rainfall	mm
REST	rest water component in top soil compartment calculated by subroutine BACKFL	mm
RIRRIT	irrigation table	-
RNOFCU	cumulative runoff	mm
RUNOF	runoff	mm d^{-1}
SURREL	contribution of stored surface water to water balance	mm d^{-1}
SWITFD	free draining / impeded drainage switch	-
SWITGW	groundwater switch	-
SWITIR	irrigation switch	-
SWITKH	hydraulic conductivity switch	-
SWITPD	puddled / non-puddled switch	-
SWITPF	water retention curve switch	-
SWITVP	switch for calculation of percolation rate	-
TERMNL	flag indicating if simulation should terminate	-
TIME	time	d
TKL	array thickness of soil compartments	mm
TKLP	array thickness of soil compartments	m
TKLT	total thickness of soil profile	m
TOTPOR	array total porosity of soil compartments	cm^3 cm^{-3}
TRW	total transpiration rate	mm d^{-1}
TRWCU	cumulative transpiration	mm
TRWL	array water uptake per soil compartment due to transpiration	mm d^{-1}
UPRICU	cumulative capillary rise	mm
VGA	van Genuchten alpha parameter	cm^{-1}
VGL	van Genuchten lambda parameter	-
VGN	van Genuchten n parameter	-
VGR	van Genuchten residual water content	-
VL	array thickness soil compartment after shrinkage	mm
WBINIT	flag indicating if water balance needs initialization for crop rotations, not yet in use in this version of PADDY	-
WCAD	array volumetric water content per soil compartment when 'air dry'	cm^3 cm^{-3}

Name	Description	Units
WCCR	critical volumetric water content where cracks break through soil compartment	$cm^3\ cm^{-3}$
WCFC	array volumetric water content per soil compartment at 'field capacity'	$cm^3\ cm^{-3}$
WCL	array actual volumetric water content of soil compartment	$cm^3\ cm^{-3}$
WCLI	array initial volumetric water content of soil compartment	$cm^3\ cm^{-3}$
WCST	array saturated volumetric water content per soil compartment	$cm^3\ cm^{-3}$
WCSTRP	array saturated volumetric water content ripened soil per soil compartment	$cm^3\ cm^{-3}$
WCUM	amount of stored soil water in soil profile	mm
WCUMCH	rate of change in amount of stored soil water	mm d^{-1}
WCUMCO	contribution of soil storage term to overall water balance	mm
WCUMI	initial amount of stored soil water in soil profile	mm
WCWP	array volumetric water content per soil compartment at 'wilting point'	-
WL	array amount of water in soil compartment	mm
WL0	amount of ponded water	mm
WL0CH	rate of change of amount of ponded water	mm d^{-1}
WL0CO	contribution of surface storage term (ponded water) to overall water balance	mm
WL0I	amount of initial ponded water	mm
WL0MIN	minimum amount of ponded water before start of irrigation	mm
WL0MX	maximum amount of ponded water (=bund height)	mm
WLAD	array amount of water per soil compartment when 'air dry'	mm
WLCH	array change in amount of water per soil compartment	mm d^{-1}
WLFC	array amount of water per soil compartment at 'field capacity'	mm
WLFL	array flux at boundaries of soil compartment	mm d^{-1}
WLST	array amount of water per soil compartment at saturation	mm
WLWP	array amount of water per soil compartment at 'wilting point'	mm
WSTAT	flag for weather system	-
WTRTER	flag for weather system	-
ZL	array depth of top of soil compartments	cm
ZRTMS	maximum rooting depth soil profile	m
ZW	depth of groundwater table below soil surface	cm
ZWA	depth groundwater table is receding in case of no recharge	cm
ZWB	sensitivity factor of recharge groundwater table	-
ZWPREV	groundwater table depth of previous day	cm
ZWTB	table with groundwater table data	-
ZWTBI	initial depth of groundwater table below soil surface	-

Appendix 5 Other input files

A5.1 Control data

```
*******************************************************************
* CONTROL.DAT; to control input and output file names
*******************************************************************
   FILEON = 'RESULTS.OUT'   ! Normal output file
   FILEOL = 'MODEL.LOG'     ! Log file
   FILEIR = 'RERUNS.DAT'    ! Reruns file
   FILEIT = 'TIMER.DAT'     ! File with timer data
   FILEI1 = 'ORYZA_Wz.DAT'  ! First input data file (crop)
   FILEI2 = 'SOIL.DAT '   ! Second input data file (soil)

 * FILEI3 = ' '             ! Third input data file (not used)
 * FILEI4 = ' '             ! Fourth input data file (not used)
 * FILEI5 = ' '             ! Fifth input data file (not used)
```

A5.2 Timer data

```
 * Timer file generated by FST translator version 1.15
 *
 * contains:
 * - The used DRIVER and TRACE in case of GENERAL translation
 * - The TIMER variables used in both translation modes
 * - Additional TIMER variables in case of GENERAL translation
 * - The WEATHER control variables if weather data are used
 * - Miscellaneous FSE variables in case of FSE translation
 *
 * File: ORYZA1.FST
 * Date: 16-05-94
 * Time: 14:17:38
 * TIMER variables used in GENERAL and FSE translation modes
 * -----------------------------------------------------------
 STTIME = 23.          ! start time
 FINTIM = 100.         ! finish time
 DELT   = 1.           ! time step (for Runge-Kutta first guess)
 PRDEL  = 1.           ! output time step
 IPFORM = 4            ! code for output table format:
                       ! 4 = spaces between columns
                       ! 5 = TAB's between columns (spreadsheet output)
                       ! 6 = two column output
```

```
 MULTIP = 1.
 ANGA = 0.29
 ANGB = 0.42

! The string array PRSEL contains the output variables for which
! formatted tables have to be made. One or more times there is a
! series of variable names terminated by the word <TABLE>.
! The translator writes the variables in each PRINT statement to
* PRSEL =   ! a separate table

 COPINF = 'N'   ! Switch variable whether to copy the input files
                ! to the output file ('N' = do not copy,
                ! 'Y' = copy)
 DELTMP = 'N'   ! Switch variable what should be done with the
                ! temporary output file ('N' = do not delete,
                ! 'Y' = delete)
 IFLAG  = 1100  ! Indicates where weather error and warnings
                ! go (1101 means errors and warnings to log
                ! file, errors to screen, see FSE manual)
 *IOBSD = 1991,182  ! List of observation data for which output is
                    ! required. The list should consist of pairs
                    ! <year>,<day> combination


 * WEATHER control variables
 * -------------------------
 WTRDIR = ' '
 CNTR   = 'PHIL'             ! Country code
 ISTN   = 2                  ! Station code
 IYEAR  = 1988               ! Year

 SWIWLP = 3
```

A5.3 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              (kJ m-2 d-1) or (mJ m-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
```

A5.4 Rerun data

```
* Example of reruns file for PADDY

* Set 1
SWITIR = 0
WL0I = 50.
* Set 2
SWITIR = 1
WL0I = 20.
* Set 3
SWITIR = 2
WL0I = 100.
```