4.3 Simulation of field water use and crop yield

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4.3.1 Introduction

This contribution differs in two respects from the preceding sections on the simulation model ARID CROP. The model ARID CROP, written in CSMP, simulates transpiration and dry matter production of vegetations growing on homogeneous soil profiles and in absence of a soil water table. As a result of the long integration interval of one day, the description of the soil physical processes had to be simplified and treated somewhat differently than is usual in soil physics. The approach to simulation of the soil water balance presented in this section describes a field situation in a temperate climate with a heterogeneous soil profile and a high groundwater table. The program of the water balance section in this model is executed with fairly small time steps, so that the description of its processes can follow more closely the classical soil physics approach to water in soils.

Figure 57 depicts a typical situation that can be simulated with the model described below. It shows how flow takes place under cropped field conditions in a layered soil, the boundaries of which include two ditches on the side and a pumped aquifer at the bottom. In addition to the effect of these boundaries, fluctuations of the water-table are caused by water uptake by the crop (the roots

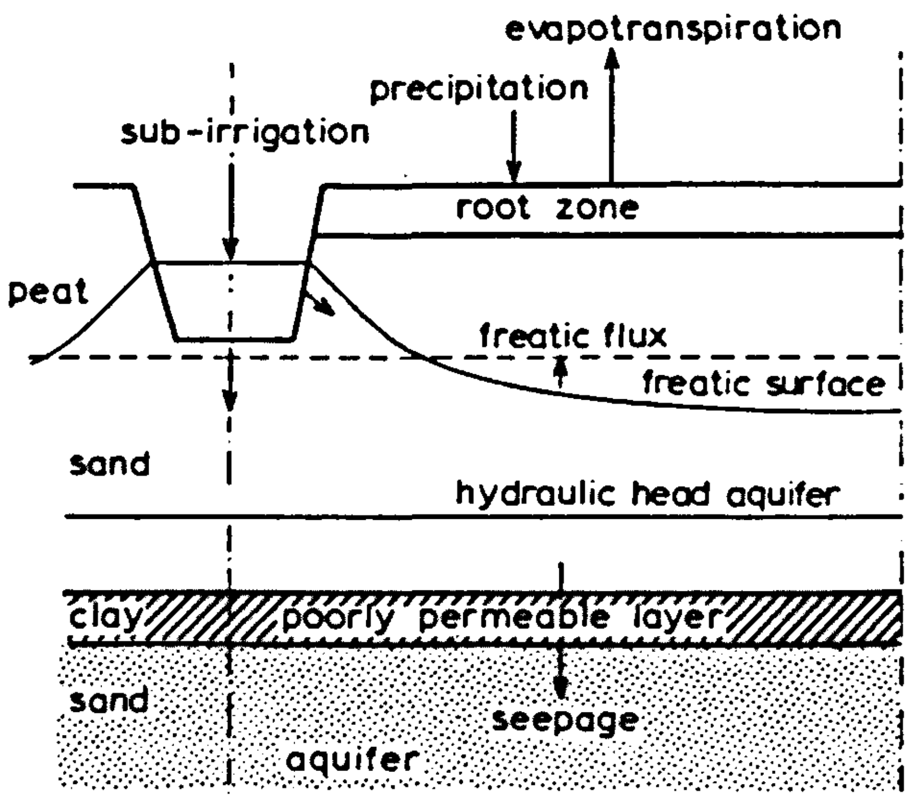

Figure 57. Scheme of the water balance for the case of sub-irrigation from open water courses, upward flow from the water-table to the root zone, and leakage into a pumped aquifer. Because of the symmetry, only half of the vertical cross-section between two ditches is given.

of which grow with time) and evaporation at the soil surface. The total of influences constitutes the so-called water balance. To be able to handle such a system, a rather detailed knowledge of the factors concerned is needed.

Originally, effects of water management, of groundwater recharge, of soil improvement and of other measures were often measured by establishing representative experimental fields, collecting as much data as possible, making various changes in the prevailing circumstances and analyzing the results. With the introduction of the computer it became possible to simulate the effects with the aid of physical-mathematical models, which ideally should react in the same manner to any changes made as the actual system. In the following, two models of Feddes, Kowalik & Zaradny (1978) will be presented that can be used either separately or conjointly. The first model, program SWATR, calculates the actual transpiration of a crop (Subsection 4.3.2). The second model, program CROPR, calculates the actual growth rate of a crop (Subsection 4.3.3). Finally, a discussion of strong and weak points of these models is presented (Subsection 4.3.4).

A diagram illustrating the approach is given in Figure 58. It shows the flow patterns and the action of various factors in the soil – plant – atmosphere system. The water balance of the soil – root system is shown on the left hand side of Figure 58. Irrigation or rain water that is not intercepted by the crop will

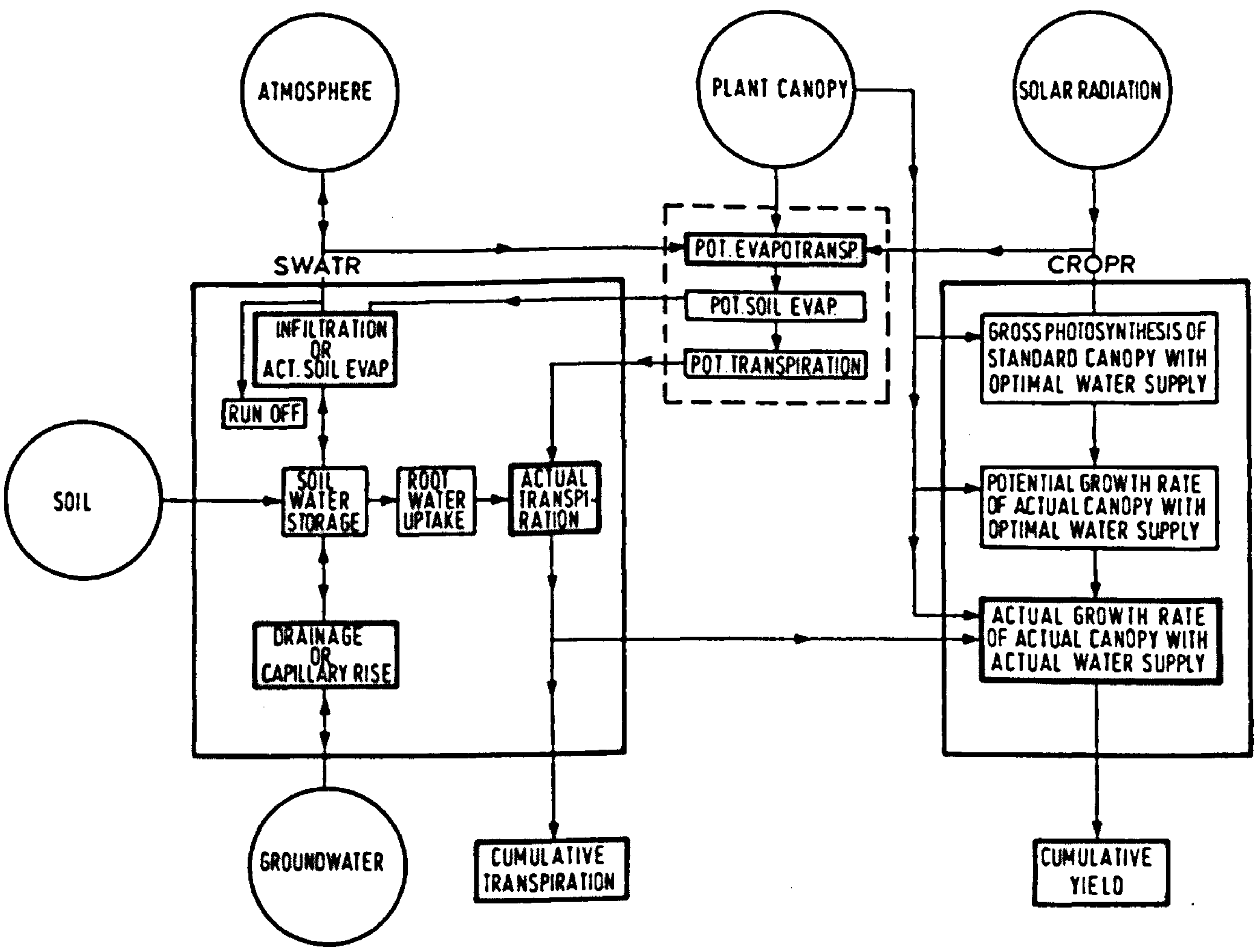

Figure 58. Flow chart of the integrated model approach to assess effects of changes of environmental conditions upon crop water use and crop yield (Feddes et al., 1978).

reach the soil. Part of it will become soil moisture, only to be lost by soil evaporation or transpiration. The part of rainfall that does not infiltrate will be lost as surface runoff. The excess of soil moisture will percolate downward to the groundwater table and recharge the groundwater storage.

The transformation of solar radiation into actual crop yield is schematically shown in the right hand side of Figure 58. Gross potential photosynthesis of a 'standard crop canopy' can be calculated according to a model of de Wit (1965) taking into account the height of the sun, the condition of the sky, the canopy architecture and the photosynthesis function of the individual leaves (cf. Subsection 3.2.4). A 'standard canopy' is defined as a canopy with a leaf area index 5 (5 m^2 of leaves per square metre of soil surface) that is fully supplied with nutrients and water. Under actual field conditions these maximum photosynthesis rates will never be reached and corrections have to be made for actual conditions of light energy flux, for air temperature, for fraction of soil covered and for amounts of roots. Moreover, the growth rate is lower than the rate of photosynthesis as a result of respiration losses and investment of dry matter in roots. Accounting for these effects yields the potential growth rate of an actual canopy with optimal water supply. Finally, the actual dry matter yield can be calculated by introducing the actual water uptake of the root system.

4.3.2 The model for field water use, SWATR

To describe one-dimensional water flow in a heterogeneous soil-root system we start with the continuity equation (see also Section 4.2):

$$\frac{\delta\theta}{\delta t} = -\frac{\delta q}{\delta z} - S \qquad (61)$$

where θ is the volumetric water content ($cm^3\ cm^{-3}$), t the time (d), S the volume of water taken up by the roots per unit bulk volume of soil in unit time ($cm^3\ cm^{-3}\ d^{-1}$) and z the vertical coordinate (cm), with origin at the soil surface and directed positive upwards.

The integral of the sink term over the rooting depth z_r (cm, using positive values) yields the actual rate of transpiration T ($cm\ d^{-1}$):

$$T = \int_0^{z_r} S\,dz \qquad (62)$$

A major difficulty in solving Equation 61 stems from S being unknown. In the field the root system will vary with the type of soil and usually changes with depth and time. Thus root properties, such as root density, root distribution, root length, etc., will also change with depth and time. Experimental and accurate evaluation of such root functions is both time consuming and costly. For these reasons Feddes et al. (1978) propose to use a root extraction term, S, that only depends on the soil-moisture pressure head, h, and the maximum extraction rate, S_{max}, as:

$$S = \alpha(h) S_{max} \quad (63)$$

with:

$$S_{max} = \frac{T_m}{z_r} \quad (64)$$

where T_m is the maximum possible, i.e. the potential transpiration rate (cm d^{-1}).

It is assumed (see Figure 59) that under conditions wetter than a certain 'anaerobiosis point' (h_1) water uptake by roots is zero. Under conditions drier than wilting point (h_4) water uptake by roots is also zero. Water uptake by the roots is assumed to be maximal when the pressure head in the soil is between h_2 and h_3. When h is below h_3 but larger than h_4, it is assumed that the water uptake decreases linearly with h to zero. Although it is recognized that h_3 depends on the transpiration demand of the atmosphere (reduction in water uptake occurs at higher (wetter) h_3-values under conditions of higher demand), the limiting point is taken to be a constant.

Equations 63 and 64 can be combined to:

$$S = \alpha(h) \frac{T_m}{z_r} \quad (65)$$

which means that potential transpiration rate, T_m, is distributed equally over the rooting depth, z_r, and reduced for prevailing water shortages by the factor $\alpha(h)$. It is emphasized that Equation 65 is also a drastic simplification, made in the interest of practicality. One of the advantages of this model is that the root system is characterized by the rooting depth, z_r, only (as in ARID CROP, Subsection 4.2.3). In practice this parameter is easily measured. Also the proportionality factor α is a simple function of soil-water pressure head h.

An alternative formulation for S_{max} has recently been made by Hoogland et al. (1981). To account for effects of soil temperature, soil aeration, rooting intensity and xylem resistance upon S_{max}, these authors assumed a linear reduction of S_{max} with soil depth according to:

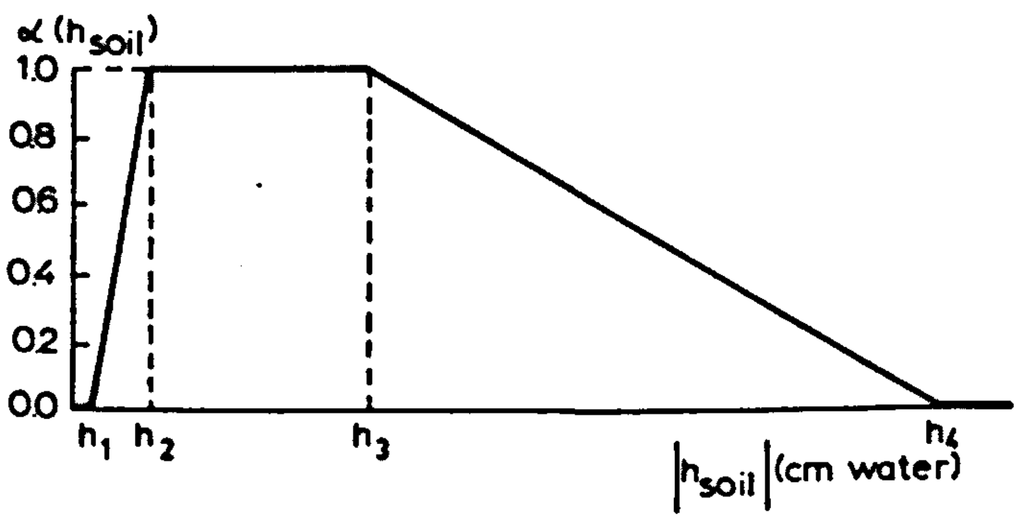

Figure 59. General shape of the dimensionless sink term variable, $\alpha(h)$, as a function of the absolute soil water pressure head, h (Feddes et al., 1978).

$$S_{max} = a - b|z| \qquad \text{for} \qquad |z| \leq z_r \tag{66}$$

where a and b are constants, in principle to be determined from measured root water uptake data. As a first estimation we assume that $0.01 \leq a \leq 0.03$ cm^3 cm^{-3} d^{-1}, with a mean value of about 0.02, as often found in the literature. The value of b is even more difficult to assess. (If no information about b is available, one may as a first approximation set b equal to zero, giving S_{max} a constant value.) The formulation for the modified sink term now becomes:

$$S = \alpha(h) \cdot S_{max}(z) \tag{67}$$

The water uptake summed over all layers cannot exceed the potential transpiration rate, thus:

$$\int_z^0 S\,dz \leq T_m \qquad \text{for} \qquad |z| \leq z_r \tag{68}$$

And because water extraction is calculated in the program from the top layer downwards, this formulation permits the simulation that water is extracted preferentially from the upper, relatively wet soil layers. The potential transpiration demand can be met as long as the plant does not extract water from all soil layers of the root zone.

By combination of Equations 61, Darcy's law and 63 and introduction of the differential moisture capacity $C = d\theta/dh$, one arrives at the partial differential flow equation that describes flow of water in the soil – root system as:

$$\frac{\delta h}{\delta t} = \frac{1}{C(h)} \frac{\delta}{\delta z} [K(h)(\frac{\delta h}{\delta z} + 1)] - \frac{S(h)}{C(h)} \tag{69}$$

with $S(h)$ defined according to Equation 65. To obtain a solution, Equation 69 must be supplemented by appropriate initial and boundary conditions. As initial conditions (at $t = 0$) the pressure head is specified as function of z:

$$h(z,t = 0) = h_0(z) \tag{70}$$

At the lower boundary (−L) the pressure head is specified as:

$$h(z = -L, t) = h_{-L}(t) \tag{71}$$

The soil-water (Darcian) flux, q, at the upper boundary is governed by the meteorological conditions. The soil can lose water to the atmosphere by evaporation or gain water by infiltration. While the maximum possible (potential) rate of evaporation from a given soil depends only on atmospheric conditions, the actual flux across the soil surface is limited by the ability of the porous medium to transmit water from below. Similarly if the potential rate of infiltration (e.g. the rain or irrigation intensity) exceeds the absorption capacity of the soil, part of the water will be lost by surface runoff. Here, again, the potential rate of infiltration is controlled by atmospheric (or other) external conditions, whereas the actual infiltration depends on antecedent moisture conditions in the soil.

Thus, the exact boundary condition to be assigned at the soil surface is not known *a priori,* but a solution must be sought by maximizing the absolute value of the evaporation flux (Hanks et al., 1969a).

If one takes $q^*(z = 0,t)$ as the maximum possible rate of evaporation from the surface, the following expressions must always be satisfied:

$$|q^*(z = 0,t)| \geq |q(z = 0,t)| = |-K(h)(\frac{\delta h}{\delta z} + 1)| \quad (72)$$

$$\text{with } h_l \leq h \leq 0 \quad (73)$$

where h_l is the minimum pressure head to be allowed under air-dry conditions. Assuming that the pressure head at the soil surface is at equilibrium with the atmosphere, then h_l can be derived from the well-known relationship:

$$h_l = \frac{RT}{Mg} \ln(F) \quad (74)$$

where R is the universal gas constant (J mole^{-1} K^{-1}), T is the absolute temperature (K), g is acceleration due to gravity (m s^{-2}), M is the molecular weight of water (kg mole^{-1}) and F is the relative humidity of the air (fraction). T and F can be taken from the Stevenson screen.

The maximum possible soil evaporation flux (q^*, Equation 72) as well as the maximum possible transpiration rate (T_m, which determines the maximum possible water uptake by roots per unit area of soil, see Equation 65) can be determined in a number of alternative ways. Potential evapotranspiration ET^* is the sum of potential transpiration T_m and potential soil evaporation E^*:

$$ET^* = T_m + E^* \quad (75)$$

The value of ET^* can be calculated for example from the combination-energy balance equation of Monteith-Rijtema, from the Priestley and Taylor equation or as a multiplication of the Penman open water evaporation with a crop coefficient. The values of E^* can be computed from a simplified combination-energy balance equation by neglecting the aerodynamic term and taking into account only that fraction of R_n that reaches the surface (Ritchie-approach). Hence, T_m can be determined as the remaining unknown in Equation 75. For full details, see Feddes et al. (1978).

Knowing now the initial and other boundary conditions, Equation 69 could be solved by approximating it by an implicit finite difference scheme, laying a grid over the depth-time region as occupied by the independent variables z and t, respectively. The program SWATR (written in FORTRAN IV) has been designed for a two-layered soil profile and is able to handle maximally 25 nodal points, with constant depth increments. The time step Δt is variable and calculated according to:

$$\Delta t^{i+1} < \frac{\zeta \Delta z}{|q|^i} \quad (76)$$

where q is the actual flux at the top or bottom boundary of the system for the previous stage of computation and ζ is a factor where $0.015 < \zeta < 0.035$.

Input data in model SWATR are: $h(\theta)$ and $K(h)$ relationships for upper and lower soil layer, depth of the root zone z_r, critical values of the sink term as denoted in Figure 59, initial condition $h(z,t = 0)$, boundary conditions at the soil surface of $T_m(t)$ and of the maximum possible evaporation or infiltration flux through the soil surface ($q^*(0,t)$), boundary condition at the bottom of a water table with $h(z,t) = 0$. Values of $T_m(t)$ and $q^*(0,t)$ can be determined from meteorological and crop data.

Output data of the model include cumulative values of $T(t)$, of integrated water content over the soil profile, of upward/downward flows, of runoff, of $\theta(z,t)$, and $S(z,t)$.

The SWATR model was subjected to field tests. It was found that although computed soil water content profiles did not agree completely with measured profiles, cumulative (evapo)transpiration was simulated fairly well. One example of the results is shown in Figure 60, where curves of cumulative flow are

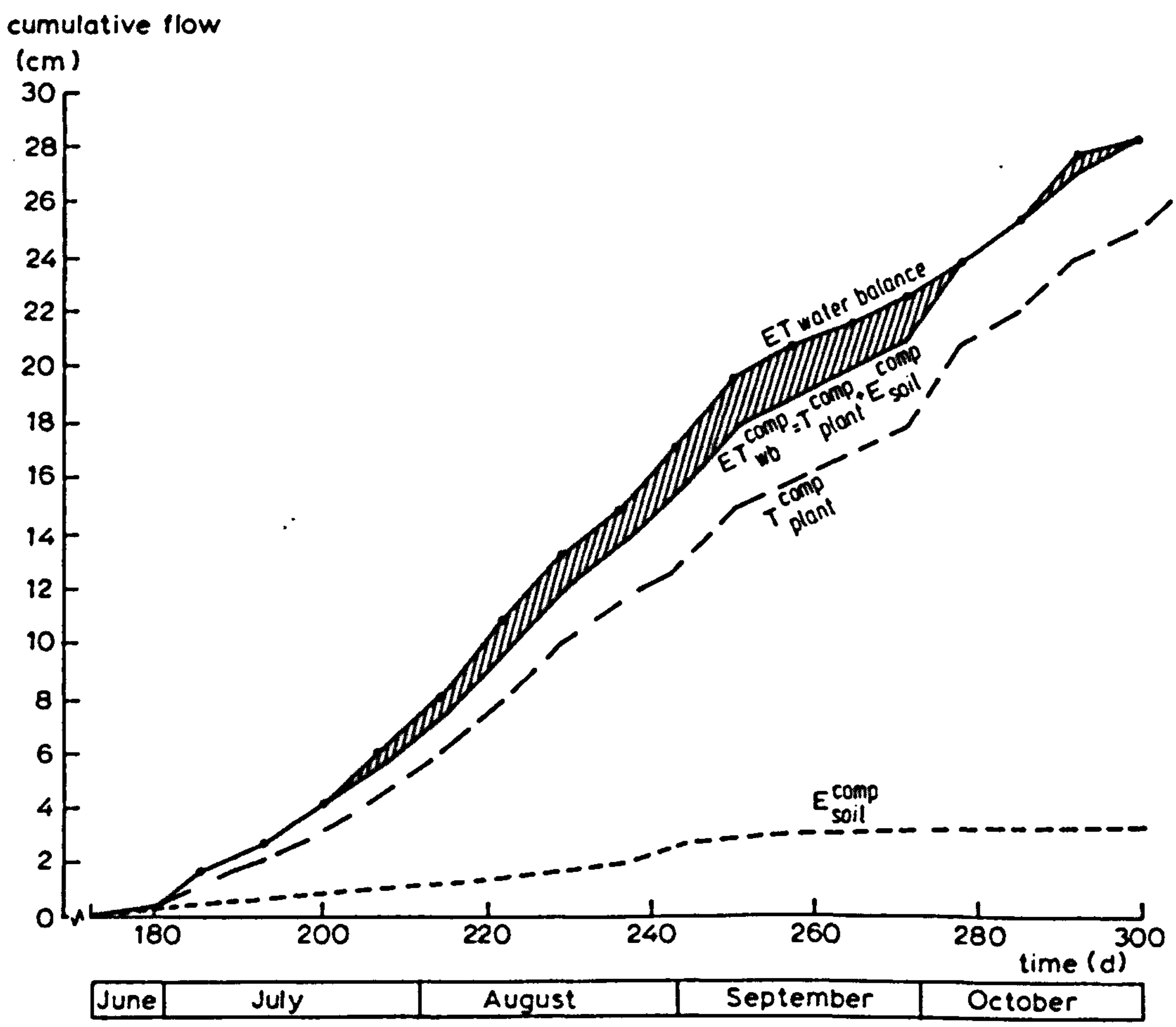

Figure 60. Comparison of the sum of cumulative transpiration and soil evaporation as simulated with model SWATR with lysimetrically measured data for a red cabbage crop, growing on clay in the presence of a watertable (Feddes et al., 1978).

given for a red cabbage crop growing on a clay soil: first the measured cumulative evapotranspiration ($ET_{\text{water balance}}$) as obtained from a lysimeter; secondly the cumulative transpiration $T_{\text{plant}}^{\text{comp}}$ as computed with the model by integration of the sink term over depth; thirdly the cumulative computed soil evaporation $E_{\text{soil}}^{\text{comp}}$; fourthly the sum of $T_{\text{plant}}^{\text{comp}}$ and $E_{\text{soil}}^{\text{comp}}$. From Figure 60 it is seen that there is rather good agreement between computed and measured evapotranspiration, especially at the beginning and end of the period considered.

It is to be noted that a proper estimation of potential transpiration, T_m, is necessary to obtain proper values of actual transpiration. Too high values of T_m will result in a too fast drying-out of the soil. However, there is some feedback in the model as a too-dry water content in one time step will result in a stronger reduction in transpiration during the next time step. Thus, although the distribution of cumulative transpiration with time may not be simulated well, final computed cumulative transpiration may still be quite good.

To extend the flexability of this model and approach, some modifications were introduced recently. Belmans et al. (1981) have developed a new version of SWATR, named SWATRE(extended). As compared with the previous program, the following modifications were made:

- application of another finite difference scheme, chosen according to Haverkamp et al. (1977) and Vauclin et al. (1979), that allows for lower computing cost and that still yields an acceptable accuracy of the soil water balance;
- extension to maximally five soil layers having different properties;
- maximally 40 compartments of equal size in which the entire soil profile is divided;
- the possibility of using the alternative sink term model, Equation 67;
- extension to the use of different types of boundary conditions. Options now include the use of one of the following boundary conditions at the bottom layer: a groundwater level; a flux from the saturated zone (prescribed) while the groundwater level is computed; a flux from the saturated zone (calculated as the sum of the flux towards ditches and the flux of deep percolation) and the groundwater level is computed; a flux from the saturated zone (calculated with a flux – groundwater level relationship) and the groundwater level is computed; a pressure head of the bottom compartment; zero flux at the bottom (of an unsaturated soil profile), i.e. when an impermeable layer is present; free drainage at the bottom (unit hydraulic gradient, unsaturated soil profile)

4.3.3 The model for crop production CROPR

The growth rate of a crop $\dot{q}$ (kg ha^{-1} d^{-1}) is influenced by such growth factors as solar radiation, temperature, water, nutrients and carbon dioxide. Only when all these factors are adequately available, both growth rate and yield will be potential ($\dot{q}_{pot}$ and Q_{pot}). Then potential growth depends on the biological growth capacity of the plant. When one of the growth factors is limiting, growth

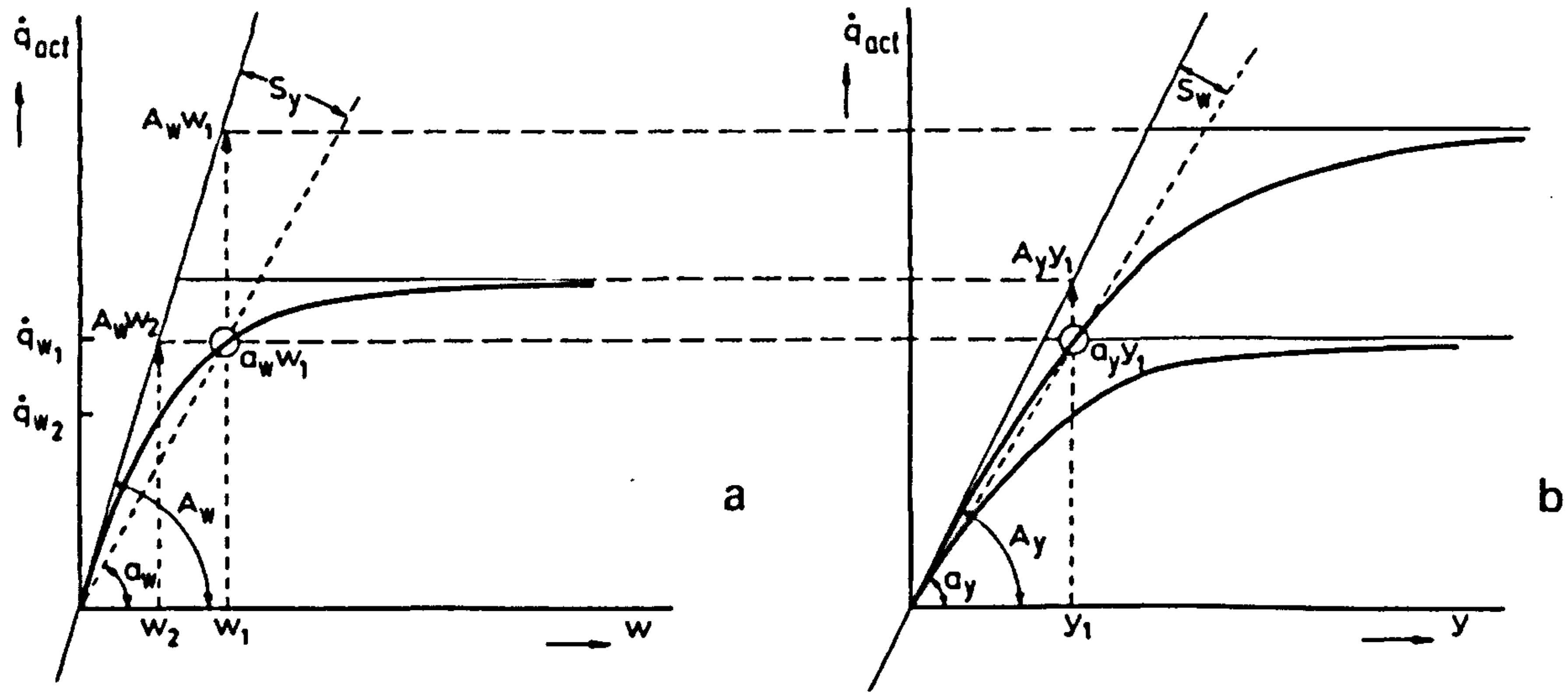

Figure 61a. The response curve of the actual rate of growth ($\dot{q}_{act}$) to the growth factor w at the value y_1 of the growth factor y. The growth rates $\dot{q}_{w_1}$ and $\dot{q}_{w_2}$ at the values w_1 and w_2 of w are shown. The upper asymptotes $A_w w_1$ and $A_w w_2$ of Figure 61b are determined in this graph (dotted lines). The slopes A_w, a_w and their difference S_y are discussed in the text.

Figure 61b. The response curves of the actual rate of growth to the growth factor y at the values w_1 and w_2 of the growth factor w. The upper asymptote $A_y y_1$ of Figure 61a is determined with this graph.

rate and yield are limited ($\dot{q}_{act}$ and Q_{act}). Although other growth factors may still be optimal, potential growth cannot be reached.

The growth rate of a crop as a function of a single growth factor may be represented by a hyperbolic function, with the potential growth rate as the upper limit and the efficiency of utilization of this factor as initial slope of the hyperbola. This is analogous to Figure 25 in Section 3.2 for leaf photosynthesis. Figure 61a shows such a relationship for the growth factor water, represented by the symbol w. A similar function may be drawn for other growth factors. In this section we consider a crop well supplied with nutrients, so that weather conditions, in particular the growth factor solar radiation, determine the potential growth rate. This growth factor is represented by the symbol y.

The question arises how to weight the combined effect of the growth factors water and radiation if both are below their optimum level. The approach of multiplication of relative effects of internal and environmental factors has been shown (Subsection 3.3.3), and the minimum value concept has been discussed briefly (Subsection 1.2.3). An alternative approach was adopted in CROPR, and is explained here in principle. More detail can be found in Feddes et al. (1978), where slightly different symbols are used.

Figure 61a presents a response of the growth rate, $\dot{q}$ (kg ha^{-1} d^{-1}) to the growth factor water (w), defined (Bierhuizen & Slatyer, 1965) as the rate of transpiration of the canopy (T, mm d^{-1}) divided by the water vapour deficit of the air (Δe, mbar):

$$w = \frac{T}{\Delta e} \qquad (77)$$

T is obtained from SWATR or otherwise. The initial slope of the response curve (A_w, kg mbar mm^{-1} ha^{-1}) is a water-use efficiency factor. The upper level of the response curve is the potential growth rate $\dot{q}_{pot}$ (kg ha^{-1} d^{-1}).

With a high level of radiation (i.e.: a high level of $\dot{q}_{pot}$) and a relatively low value of w, the growth rate $\dot{q}$ is almost proportional to w. When w increases, the increase in $\dot{q}$ becomes smaller because its maximum value is approached. The slope of the line connecting a point from the hyperbola (encircled in Figures 61a and 61b) and the origin, may be called a_w. The difference between the slope A_w and a_w is small when w is small and large when w is large. This is an indication of the degree of insufficiency (S) of the other growth factor: radiation. Thus:

$$S_y = A_w - a_w \qquad (78)$$

The response curve of growth rate $\dot{q}$ versus radiation y can be described similarly (Figure 61b), where the variables A_y, a_y and S_w have corresponding meanings. Hence:

$$S_w = A_y - a_y \qquad (79)$$

(Please note that the measuring of the symbol S in the model SWATR is completely different.)

The upper asymptotes in both graphs are different from day to day, reflecting changes in crop and environmental conditions. Both response curves are mutually dependent. The upper asymptote of the response curve of growth to radiation y (Figure 61b) is the one under the actual availability of water: at the value w_1, this asymptote is $A_w w_1$. The asymptote for the response curve to water is the one determined by the radiation regime: $A_y y_1$. When the value of the growth factor w decreases from w_1 to w_2 (Figure 61a), the upper asymptote of the response curve to radiation decreases from $A_w w_1$ to $A_w w_2$ (Figure 61b). One observes that the result of such a decrease in transpiration is that, following the hyperbolic curve of Figure 61a, the actual rate of growth decreases from $\dot{q}_{w_1}$ to $\dot{q}_{w_2}$, S_y decreases as a consequence. Simultaneously, S_w in the new response curve to radiation will increase. This interdependence is precipitated in the following central supposition of this approach to crop growth rates: the decrease in insufficiency of one growth factor is accompanied by an increase in insufficiency of the other growth factor to such an extent that the product of both remains constant:

$$S_y \cdot S_w = C \qquad (80)$$

(for the mathematical derivation of this supposition: see Feddes et al. (1978)). This supposition implies that a dynamic equilibrium exists of the degree in which the plant experiences the sum of the stresses imposed by insufficiences of the various growth factors, and that the resulting total stress is as small as possible.

The next question is a mathematical one: how to compute the actual growth rate $\dot{q}_{act}$ from this network of interrelated variables. In Equation 78, a_w can be replaced by $\dot{q}_{act}/w$, and in Equation 79 a_y can be replaced by $\dot{q}_{act}/y$ (Figure 61). Substitutions of Equations 78 and 79 into 80 yields:

$$(A_w - \dot{q}_{act}/w)(A_y - \dot{q}_{act}/y) = C \quad (81)$$

Dividing the terms of Equation 81 by $A_w A_y$, and replacing $C/A_w A_y$ by the mathematical parameter ζ, gives:

$$(1 - \frac{\dot{q}_{act}}{A_w\, w})(1 - \frac{\dot{q}_{act}}{A_y\, y}) = \zeta \quad (82)$$

Multiplication of both terms results in a quadratic expression of the actual growth rate:

$$\dot{q}^2_{act} - \dot{q}_{act}(A_w w + A_y y) + A_w w A_y y(1 - \zeta) = 0 \quad (83)$$

Only the smallest of the two mathematical roots of this expression has a real meaning, so that the final expression of the growth rate becomes:

$$\dot{q}_{act} = \tfrac{1}{2}(A_w w + A_y y) - \tfrac{1}{2}[(A_y y + A_w w)^2 - 4\, A_y y A_w w(1 - \zeta)]^{0.5} \quad (84)$$

The product $A_y y$ represents the potential rate of growth of the crop, $\dot{q}_{pot}$. This product might give the impression that the potential growth rate increases proportionally with the level of radiation without any maximum set to it. Obviously, this is not correct. Therefore, $\dot{q}_{pot}$ is not computed in CROPR as a simple product, but according to:

$$\dot{q}_{pot} = P_{st} \cdot \phi_r \cdot \alpha_T \cdot S_c \cdot \beta_h \quad (85)$$

where P_{st} is gross photosynthesis rate of a 'standard canopy' according to de Wit (1965), ϕ_r is a factor to account for the total respiration of the crop, α_T is a parameter accounting for effect of temperature on growth, S_c is fraction of soil covered and β_h is ratio of harvested part to total plant. The values of ϕ_r, α_T, β_h and the development of crop cover with time S_c are inputs into the model. So there is not yet a feedback with computed actual production rates.

Having calculated actual growth rates, $\dot{q}^i_{act}$ day by day, final yield Q_{act} is calculated as the sum of the daily growth over the growing period:

$$Q_{act} = \sum_{i=1}^{n} \dot{q}^i_{act}\,\Delta t \quad (86)$$

In a similar way one can calculate the potential yield:

$$Q_{pot} = \sum_{i=1}^{n} \dot{q}^i_{pot}\,\Delta t \quad (87)$$

where Δt in both equations represents a period of one day.

Equation 82 is the expression of a non-rectangular hyperbola of the form presented in Figure 61a. To present the completely correct interpretation of Equation 82, Figure 62 is given. It shows that the response curve is bounded by the asymptotes:

$$\dot{q}_{act} = A_w w + \dot{q}_{pot} \zeta \tag{88}$$

and:

$$\dot{q}_{act} = \dot{q}_{pot}(1 - \zeta) \tag{89}$$

where $\dot{q}_{pot}$ represents $A_y y$. That its asymptotes are not exactly identical to $A_y y$ and $A_w w$, as was suggested in the beginning of this subsection and in the Figures 61a and 61b, is the result of the assumption (Equation 80) that the product of the insufficiencies in growth factors is a constant: the degree of insufficiency of any growth factor can never be completely zero, but always keeps a small value. This small value is represented by the constant ζ, to which the value of 0.01 has usually been attributed. It makes that both the initial slope and the maximum value of $\dot{q}_{act}$ of the response curves are 1% smaller than the values $A_w w$ and $A_y y$, and A_w and A_y, respectively. In principle ζ should be calculated from experimentally determined response curves.

The parameter ζ has an important effect on the shape of the response curves: it reflects their degree of curvature. A very small value of ζ results in hyperbolas close to their asymptotes (the hyperbolas transform into their asymptotes when ζ approaches zero).

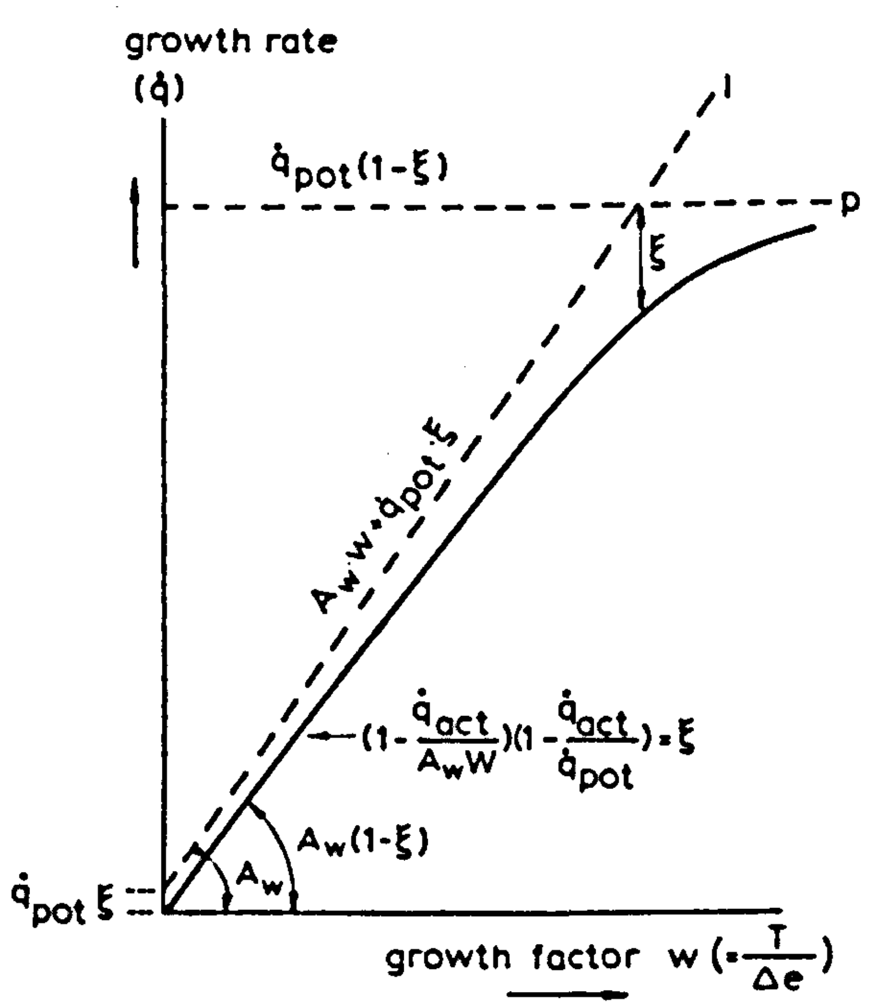

Figure 62. Actual growth rate $\dot{q}$ versus the growth factor water w described as a non rectangular hyperbola, Equation 81, bounded by the asymptotes l and p. Line l indicates the productivity of the crop for growth factor w. Line p represents the production level under conditions of adequate supply of growth factor w and limited supply of some other growth factor y (Feddes et al., 1978).

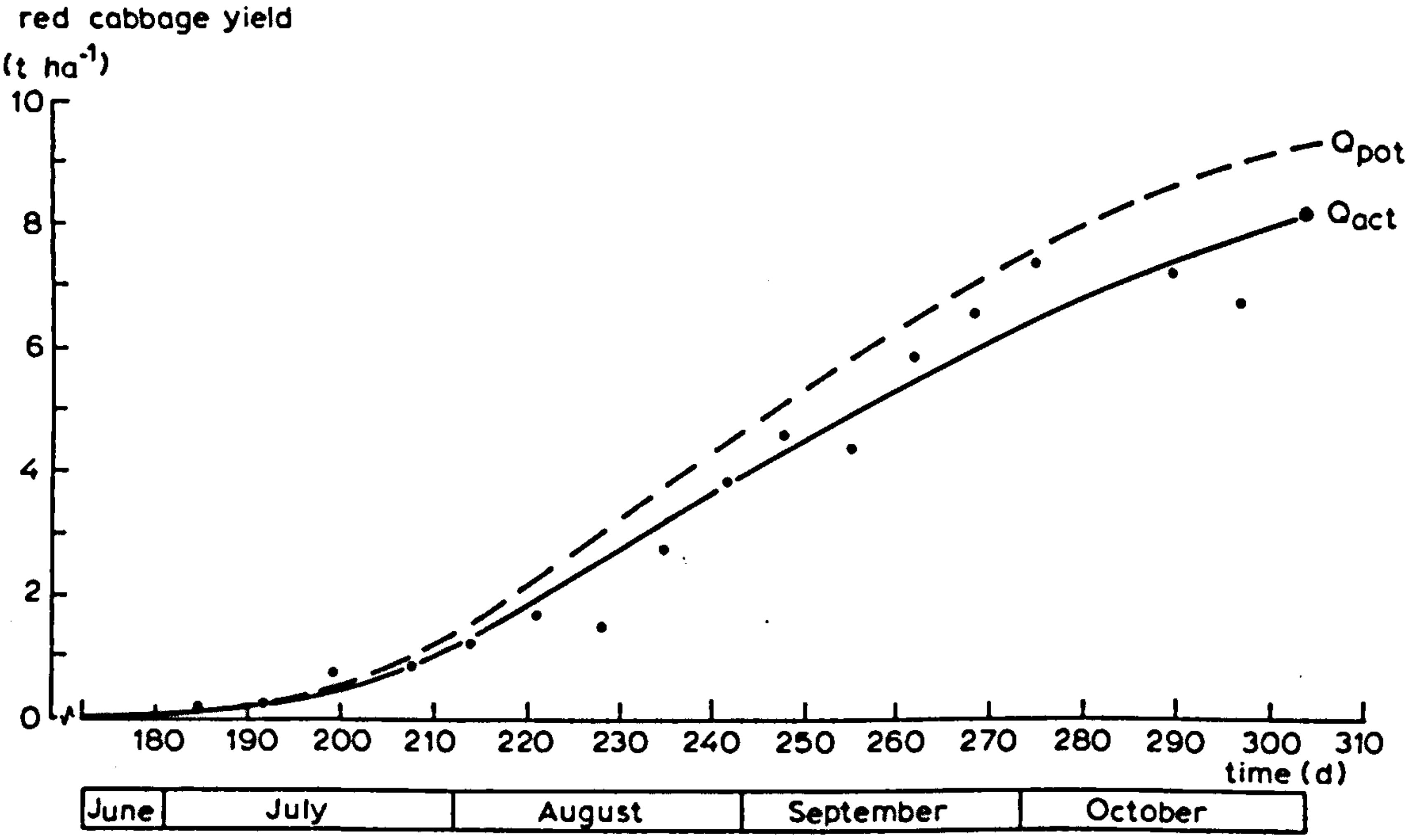

Figure 63. Comparison of measured yield data with computed actual (Q_{act}) and potential (Q_{pot}) cumulative dry matter yields of red cabbage crop derived with the production model CROPR, using as input the simulated transpiration data of Figure 60 (Feddes et al., 1978). Measured growth rates of individual plots (•); the result of the final harvest (●).

Using the transpiration data of Figure 60 as an input for CROPR, computed actual dry matter yields can be compared with measured data. Figure 63 shows that the calculations compare well with the measurements. The measured data represent weekly harvests of one plant. With a heterogeneous crop like cabbage, a relatively large variation in dry matter production then is to be expected. The points show a random scatter around the calculated curve, but the final yield was predicted quite well. The difference between actual yield and computed potential (maximum) yields appeared to be 12%.

The model CROPR was also used for calculating crop yields of grassland. Figure 64 presents computed growth rates and cumulative yields of grassland on two soil profiles in 1972. Measured cumulative yields also are given. The computed cumulative yields agree fairly well with the measured ones.

4.3.4 *Discussion*

About the approach to the effect of water shortage on the growth rate of the crop, some additional remarks can be made:

– the shape of the response curve of growth to water, as presented in Figure 61a, is not in agreement with the concept of a constant water-use efficiency, as discussed in Subsection 4.1.2. In practice, however, this difference might be small as the maximum value of transpiration is never such, that values of w at the far right hand side of the curve of Figure 61a are used;

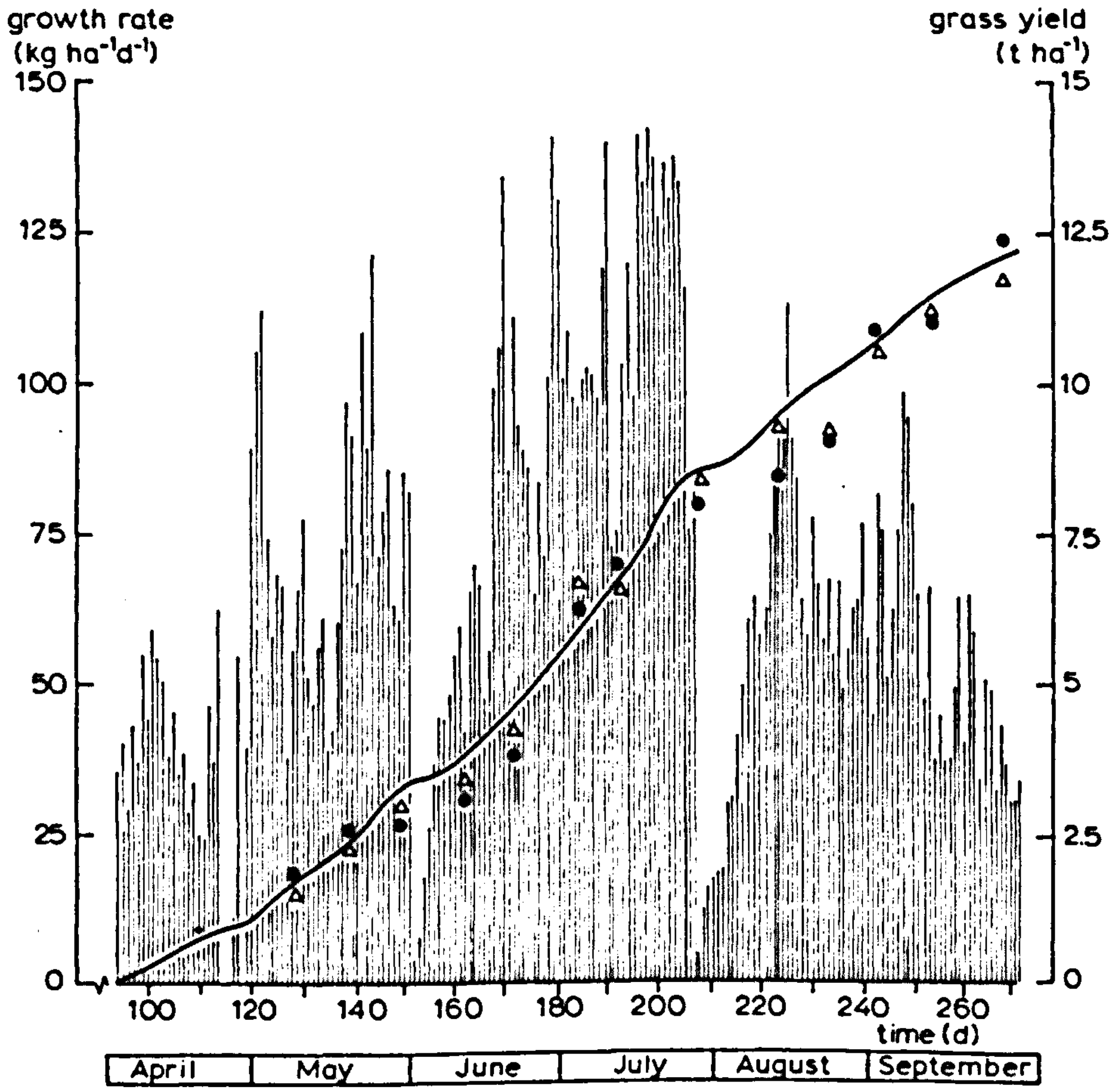

Figure 64. Comparison of computed actual growth rate ($\dot{q}_{act}$) and yield (Q_{act}) with measured maximum yield data on a silty clay over sand (●) and on a silty clay (Δ) of a grass crop in a wet year (Feddes et al., 1978).

– the parameter ζ usually has a value of 0.01. Sensitivity analysis showed that when changing ζ from 0.01 to 0.04 substantial reductions in final yield may occur. It seems therefore worthwhile to give proper attention to the estimation of ζ based on experimental data. The same holds for the value A_w.

– Feddes et al. (1978) present a generalized formulation of crop production that describes the combined effect of n different growth factors w, y, z, etc., as:

$$(1 - \frac{\dot{q}_{act}}{A_w\, w})(1 - \frac{\dot{q}_{act}}{A_y\, y})(1 - \frac{\dot{q}_{act}}{A_z\, z}) \ldots = \zeta \qquad (90)$$

An advantage of this method is the relatively low number of parameters that are required to describe the effect of different growth factors: per factor, only the initial efficiencies $A_w, A_y, A_z, \ldots$ have to be specified, plus the parameter ζ for all curves together, ζ having a relatively low value. This implies that the effect of shortage of a growth factor is generally proportional to the use of this factor up to the potential growth rate (for those conditions) and that luxury consumption of this factor may occur at still higher utilization rates. A disadvantage is that different kinds of responses cannot be distinguished. This might be a handicap at the level of production where nitrogen availability limits growth, because there is no direct relation between the rate of uptake of nitrogen and the rate of growth of the crop (Subsection 5.1.2). However, for all other factors for which a response curve might be drawn as indicated in Figure 62, the approach of Feddes et al. (1978) can be followed.

Figure 60 showed that the model SWATR simulates water use quite well in a temperate and humid climate, as in the Netherlands, and the Figures 63 and 64 show that the model CROPR, using output of a corresponding simulation run of SWATR, simulates crop growth in these conditions fairly well. To improve further on the quality of the model, both models will be integrated more intensively some time in the near future. This is possible as more and more information becomes available about partitioning of dry matter production over leaf and non-leaf material as a function of the development stage of the crop and of moisture stress (e.g. Subsections 3.3.6 and 4.1.4), hence the actual development of soil cover or leaf area with time can be predicted more accurately. The submodel SWATR will then continue to be used with small time steps, and the submodel CROPR with one day time steps. The interaction between both submodels will occur at the frequency of the one day time step.

I will close with a few remarks about some other models on crop growth and water use that have been published. Compared to these models, in the combination of SWATR and CROPR more emphasis is given to soil physical as well as to soil hydrological aspects, i.e. different boundary conditions at the bottom of the soil system are considered. Furthermore, there is a different approach to handle the boundary conditions at the soil surface, while micrometeorological data are considered on a daily basis. It is recalled that the model is designed to simulate for conditions where moisture stress (shortage or excess) occurs, but where nutrients are sufficiently available and pests do not interfere.

The SWATR model requires a very limited amount of information about roots. Most water uptake models need detailed information about root distribution, root densities, conductivities of the soil-root system, soil and plant resistances. Often these parameters vary with soil type and, also, with depth and time. Their experimental evaluation is sometimes impossible, and always time consuming and costly. Moreover, investigations have shown that the parameters mentioned do not always adequately describe the complex root water uptake processes. Therefore, less detailed models have been proposed that are easier to handle and, despite the rough approximation of the problem, might serve the practical needs of the agronomist and engineer. The decision of which root water uptake model to use will largely depend on the amount and extent of input data available and on the specific goal.

Effects of soil aeration, soil temperature and soil fertility upon root growth and water uptake by roots have been dealt with in many separate laboratory and field experiments. Although some relationships have been found, the understanding of the entire complex system is still rather poor. Therefore in root growth and water uptake models corrections for temperature and aeration are made according to very simple relationships. Generally one speaks in terms of 'minimum', 'optimum' and 'maximum' conditions for growth and uptake, with linear effects assumed between these points.

Root water uptake models can only be used if we are well informed about the physical properties of the soil. It is emphasized that the soil moisture retention and hydraulic conductivity curve should be determined from undisturbed soil samples. This is usually done for measurements in the relatively wet range. For the dry range however, one often uses disturbed samples. The application of the so-called hot-air method for determination of the hydraulic conductivity curve from undisturbed samples is recommended. This method was developed by Arya (1973) in the USA and it is now used in Europe. The method is simple, fast and covers a large soil moisture range. The use of undisturbed samples is important, because small differences in the soil profile may have large influences on both water flow in the soil and water uptake by the roots. Even when taking undisturbed samples, the variation of soil properties within a small 'homogeneous' region may be such that interpretation of the data becomes difficult. This problem of spatial variability has been addressed by e.g. Warrick et al. (1977).

For the reasons mentioned above one has to consider present root water uptake models as primitive tools in predicting water use of a crop. Strict meteorological methods to estimate (evapo)transpiration such as the energy balance approach, the aerodynamic or profile method, or the so-called combination method, however, seem no more accurate or useful.

Crop production models are often relatively simple and generally apply to crops without water sensitive growth stages, i.e. the effects of water stress on growth during all growth stages are similar. For crops showing different effects of water stress during various physiological stages of growth, rather complicated expressions have been developed. However, those models often do not show better results than the simple models (e.g. Stewart et al., 1977). For a literature review of existing simulation models of various crops, the reader is referred to e.g. Arkin et al. (1979). The adaptation of plants to water and temperature stress usually is not included in crop production models (cf. Subsection 4.1.6). For more information about morphological and physiological adaptations of plants to these types of stresses, and their influence on crop production, see, for example Turner & Kramer (1980).