Chapter 1

AIMS AND SCOPE OF THE PROJECT

1.1 Introduction

Within the hydrological cycle the evapotranspiration process is in general second in magnitude only to the precipitation source itself. It is widely accepted that precipitation is a very important hydrological factor and therefore it has been one of the basic elements investigated in hydrology. Unfortunately, evaporation has not received so much attention. The significance of evapotranspiration in the hydrological cycle arises from the proportion of the precipitation input to a land surface which returns into the atmosphere by evapotranspiration; this proportion varies in the range from less than 50 percent in humid regions up to almost 100 percent in arid and semi arid regions; for example over the Australian continent about 90 percent of the precipitation returns to the atmosphere by evapotranspiration.

There is a considerable need for developing methods, models and procedures which are capable of accurately estimating the areal evapotranspiration under different climatic, physiographic, vegetation and other conditions. Such methods and models are required for hydrological forecasting, water resources planning, management of water supplies, irrigation and drainage of agricultural areas, as well as studies under changing conditions of land use and potential climate change. They are also very important for investigations being undertaken within several international programmes such as the WMO World Climate Programme (WCP).

The past work of WMO on the intercomparison of hydrological models had led, in 1984, to the proposal that a similar intercomparison should be undertaken of that component of hydrological models which estimates actual areal evapotranspiration. This proposal was formally presented by Canada to the seventh session of the WMO Commission for Hydrology (CHy) in 1984, which agreed that a project should be undertaken for the intercomparison of methods and sub-routines for estimating evapotranspiration in hydrological models used in the operational practice. In addition to this emphasis on routine operational use, CHy also saw the project as being of potential value to other WMO projects, including those concerning land-surface processes. Therefore, other methods and models were also considered which need more specific input information and can be applied separately or as sub-routines within compound river basin models.

The Commission and its Advisory Working Group had recommended that the project should be carefully planned and recognized from the outset that, while some of the principles and approaches used in the previous intercomparison projects could be used again, there would be many differences, particularly because the project had developed from a consideration of the evapotranspiration component of catchment models (WMO, 1992).

1.2 Historical Development of the Project

Based on the Canadian project proposal, the then CHy Rapporteur on Hydrological Models, A. Becker (Germany), prepared a draft outline of the project. Taking into account comments received from members of the CHy Advisory Working Group and a number of other experts, a draft plan for the implementation of the project was prepared. After endorsement by the CHy Advisory Working Group, it was distributed in August 1986 to the Permanent Representatives of WMO Members for their comments, with an invitation for them to indicate whether they had an interest in participating in the project. By March 1987, thirty-five replies had been received and nearly all the respondents welcomed the project proposal and expressed on interest in participating. Five replies included substantial comments and proposals for the development and implementation of the project. These were received from M. Fleming and A. Hall (Australia), J. Jaworski (Poland), R. Farnsworth (USA) and M. Trochu (France). They resulted in a number of amendments to the draft plan, which was finally completed in July 1987 (see also Becker, 1987).

Chapter 2

SCIENTIFIC REVIEW OF AREAL EVAPOTRANSPIRATION

2.1 Introduction

In reviewing the methods used for the determination of evapotranspiration, a distinction should be made between techniques related to the determination of point evapotranspiration and those concerned with areal evapotranspiration. It should be emphasized that the current WMO project is concerned solely with estimates of actual areal evapotranspiration; point estimates would only be of interest in so far as they could be used for deriving areal evapotranspiration.

In discussion of areal evapotranspiration, a reference to the concept of meteorological fields can be helpful; the spatial distribution of evapotranspiration could be termed the evapotranspiration field. Evapotranspiration is a scalar quantity; at any point of the area considered it is characterized by a single value expressed for instance in millimetres of water in a given time interval. According to Hounam (1971), the total or mean evapotranspiration in a given time period may be considered in terms of the field co-ordinates $V = V(\varphi_1, \varphi_2)$. This function describes the evapotranspiration field and the stochastic process of evapotranspiration. Field $V(\varphi_1, \varphi_2)$ may be:

- homogeneous, when the physical properties of the evapotranspiration process remain unchanged over the area under consideration;

- heterogeneous, when the physical properties of the evapotranspiration process vary with changing field co-ordinates.

In the case of homogeneous fields or those which in practice may be considered as homogeneous (quasi-homogeneous fields) evaporation or evapotranspiration from the investigated area may be determined by point estimates using different methods presented in chapter 2.2. This procedure is frequently used for the determination of areal evaporation from lakes or evapotranspiration from large flat areas with uniform crop cover and nearly uniform soil conditions. In the case of river basins, the postulate of homogeneity of the evaporation field is not usually met (Hounam, 1971). This results in general not only from the large size of catchments, but also from the spatial variability of the catchment's characteristics, namely of the roughness parameter, reflectivity, emissivity, soil moisture conditions, depth of the groundwater table and orographic features.

Estimation of evapotranspiration from heterogeneous areas is generally a difficult problem. Two major approaches can be suggested for determining the areal evapotranspiration from such an area:

- the areal water balance method which permits the determination of a single integral value of areal evapotranspiration from the catchment for a given time interval (week, month, year);

- point evapotranspiration estimations for a set of homogeneous or quasi-homogeneous fields separated within the area examined. To obtain the areal evapotranspiration, a suitable integration method is employed, which integrates the point evapotranspiration values determined for the individual homogeneous fields.

2.2 Methods for Estimating Evapotranspiration

There are three main methods for estimating or determining evapotranspiration from natural surfaces. They involve determination of:

- the evapotranspiration component of the water balance equation;

lysimeters can be very useful for the determination of point evapotranspiration or areal evapotranspiration in the case of larger, homogeneous fields. Measurement results from lysimeters are available from different hydrometeorological stations in many parts of the world, for example the Rietholzbach and Zicharec investigations mentioned in the Wageningen report (WMO, 1992). Certain types of lysimeter, especially the weighing type, can have a precision of a few tenths of a millimetre per day and so their accuracy can be very good (Oliver, 1985), particularly under summer conditions. WMO Technical Note No. 83 (WMO, 1966) gives a comprehensive survey of various lysimeters used in several countries. In addition, soil moisture measurements are frequently made for the determination of soil moisture balances or verification of soil water models. These measurements will not be discussed here but they are presented in many papers (Kutilek 1971, Saxton 1985).

2.2.2 Energy Balance Method

One of the most common and theoretically acceptable techniques used for the determination of evapotranspiration is the energy balance method which enables the calculation of the latent heat flux (λE) from a homogeneous field for 10 or 20-minute time intervals by using the energy balance equation. This equation for an active surface can be written as follows:

$$R_n + \lambda E + H + G = 0 \qquad (3)$$

where R_n is the net radiation received at the active surface, λE is the latent heat flux, λ is the latent heat of vapourization, H is the sensible heat flux and G the soil heat flux.

All the components of equation (3) may assume positive or negative values. Following the proposal made by Paszyński (1972), the positive sign was assumed to correspond to energy income to the active surface from the atmosphere or from the soil, while the negative sign will signify an energy loss from the active surface into the atmosphere or the soil.

The net radiation is generally measured by a net radiometer, the soil heat flux is measured using suitable heat flux plates, while the H term can be estimated by the aerodynamic profile method using measurement results of dry-bulb temperature and wind speed profiles, namely:

$$H = -c_p \, \rho \, K_h \frac{\delta T}{\delta z} \qquad (4)$$

where c_p is the specific heat of air at constant pressure, ρ is the density of moist air, K_h is the eddy transfer coefficient for heat and $\delta T/\delta z$ is the vertical gradient of air temperature.

The latent heat flux (λE) and after recalculation the actual evapotranspiration (E) is finally determined as the residual component of the energy budget equation. Because the sensible heat flux (H) is generally difficult to measure, the Bowen ratio

$$\beta = H/\lambda E$$

is often determined, taking into account the differences of air temperature (T) and specific humidity (q) over an active surface. Measuring these differences (ΔT) and (Δq), the ratio β can be determined, which then enables the determination of the latent heat flux (λE) or actual evapotranspiration (E) from the energy budget equation, namely:

$$E = \frac{R_n - G}{\lambda \, \rho_w \, (1+\beta)} \qquad (5)$$

In this equation, the R_n and G components are known, because they are measured in situ, and ρ_w is the density of water.

$$EP = \frac{\frac{\Delta}{\gamma} R_n + E_a}{\frac{\Delta}{\gamma} + 1} \tag{7}$$

where EP is the potential evaporation (originally the symbol E_o was used, denoting a free water surface), Δ is the slope of the saturation pressure curve at the mean air temperature, R_n is the net radiation of a water surface, γ is the psychrometric constant, E_a is a measure of the drying power of the air and was estimated by Penman as follows:

$$E_a = E_a \ (u_a) \ (e_o - e_a) \tag{8}$$

where u_a is the mean wind speed at height z_a, e_o is the saturation vapour pressure estimated for the air temperature T_a at elevation z_a and e_a is the actual vapour pressure in the air at the same elevation.

Function (7) can also be applied for the assessment of potential evapotranspiration (ETP) from an extensive area of a dense, short green crop, well supplied with water. The ETP value was originally related to potential evaporation EP or free water evaporation E_o, by an expression of the form:

$$ETP = f \ EP \tag{9}$$

where f ranges from 0.6 to 0.8 depending on the length of day and season.

The potential evaporation (EP) or the potential evapotranspiration (ETP) estimated by the combination method can be applied for the assessment of the actual evapotranspiration or the actual areal evapotranspiration. Penman (1950) was the first to propose the application of the above mentioned empirical conversion factor "f" and of calculated soil moisture deficit values "D" for the estimation of actual evapotranspiration, namely:

$$E = E(f, EP, D) \tag{10}$$

The original Penman equation (7), which contains some empiricism, was substantially refined by Monteith (1965) so that it is now one of the more physically realistic methods. The Penman-Monteith form of the combination equation is given below:

$$E = \frac{\frac{\Delta}{\gamma} \frac{R_n + G}{\lambda} + \frac{\rho \ \epsilon (e_o - e_a)}{p \ r_a}}{\frac{\Delta}{\gamma} + 1 + \frac{r_c}{r_a}} \tag{11}$$

where $\in$ is the water/air molecular ratio ($\in$ = 0.622), p is the atmospheric pressure, r_a is the aerodynamic resistance, r_c is the crop cover resistance, and the remaining symbols are the same as in equation (7).

It should be emphasized that, in the case of the combination method, three assumptions are made, namely:

- the vertical divergence of the latent and sensible heat fluxes between the surface and the elevation of the measurements is negligable;
- the eddy transfer coefficients for water vapour and sensible heat are in principle equal;
- the value Δ/γ can be estimated for air temperature T_a at elevation z_a.

These criteria are best fulfilled by physically based models and such models are probably the most appropriate for the assessment of the areal evapotranspiration. Sufficient information concerning the appropriatness of procedures for their use in simulating areal evapotranspiration with suitable accuracy, their potential for further development and their use in simulating the interactions between atmospheric and land-surface processes, could be obtained; but the investigation results presented and discussed in chapters 4, 6, 7 and 8 are not adequate for this purpose.

Some remarks should be made concerning the remote sensing methods and their increasing role in the assessment of areal evapotranspiration. There are now some models which relate the day-time surface temperature over crops to evapotranspiration. According to Oliver (1985), a great deal of research is in progress in this field. For example, more complex mathematical models have been developed which are capable of estimating evapotranspiration from various types of vegetation by incorporating remotely sensed data. It seems that in the future such techniques could have great potential in the field of the areal evapotranspiration assessment.

2.3 Previous Intercomparisons of Evapotranspiration: Methods and Procedures

It should be noted that the investigation results concerning the evaluation and the intercomparison of procedures for areal evapotranspiration assessment obtained in this project are not the first. A number of national and international studies have been undertaken in the past to compare evapotranspiration methods. The results of these studies are to be found in papers written by Bultot and Dupriez (1985), van Hylckama (1985), Jaworski (1978, 1980, 1985, 1985a, 1990), Wales-Smith and Arnott (1985), Mawdsley (1989), Petrovic (1989), Stewart (1989), Koopmans et al. (1990) and in many other publications collected in Annex 5 of the Wageningen report (WMO, 1992). It should be emphasized, however, that the current procedure for evaluation is different, particularly because it was developed from a consideration of the evapotranspiration component of catchment models (WMO, 1992 - paragraph 2.8).

It is not possible to present all the past intercomparison results concerning evapotranspiration methods and procedures, but some are discussed briefly below.

The Casebook on Operational Assessment of Areal Evapotranspiration (WMO, 1985) involves interesting evaluations of evapotranspiration procedures. There is the paper written by Wales-Smith and Arnott (1985); these authors verified, with good results, areal evapotranspiration values estimated by the MOREX procedure, comparing them with reference data determined at Cardington, UK. In the same casebook we can find the intercomparison of evapotranspiration from Saltcedar estimated by a combination procedure with measured hourly evapotranspiration data. There is also the evapotranspiration model developed by Jaworski (1985) who verified the estimated evapotranspiration values from grass cover by means of lysimeter data; the accuracy of the procedure equaled $\pm 10\%$ (± 0.5 mm/d). Mawdsley (1989) compared the areal evapotranspiration results obtained by the ABL-bulk transfer method with lysimeter estimates from Bedford, UK and concluded that the mean monthly difference between these methods equaled $\pm 13.4\%$. Stewart (1989) developed an evapotranspiration model based on the combination method and compared the data for the Thetford Forest and Konza Prairie; the results were satisfactory, the square of the correlation coefficient being in the range 0.92 to 0.98. Koopmans et al. (1990) compared two approaches in the Hupselse Beek Basin, namely the aerodynamic profile method and the Bowen ratio method; they concluded that the mean difference between these methods, evaluated by using the variation coefficient (Y), is in the range 8 to 10%. The same authors compared six different evapotranspiration models (DEMGEN, MUST, DAIR, ONZAT, SOMOF, SWATRE) and concluded that their accuracy for 10-day intervals varied between 11% and 18% on the basis of the variation coefficient Y. Jaworski (1990) compared monthly areal evapotranspiration values estimated for the Wilga Basin (area = 231.6 km^2) by means of procedures 14.1 and 14.2, with areal evapotranspiration totals determined by using the water balance technique. He stated that the root mean square error was equal ± 13.1 mm/month in the case of procedure 14.1 and ± 12.7 mm/month for procedure 14.2. There are many other interesting intercomparison results obtained in the past, which can be found in the references collected in the Annex 5 of Wageningen report (WMO, 1992).

Chapter 3

IMPLEMENTATION OF THE PROJECT

3.1 The Implementation Plan

The past work of the World Meteorological Organization on the intercomparison of hydrological models led, in 1983, to the proposal that a similar intercomparison should be undertaken of that component of hydrological models which estimated actual areal evapotranspiration.

3.1.1 The plan of action of the WMO Project was formulated on the basis of meetings, which were held as follows:

- Geneva (August/September 1984); the seventh session of the WMO Commission for Hydrology;
- Geneva (October/November 1988); the eighth session of the WMO Comission for Hydrology;
- Zũrich (October 1989); the first informal planning meeting attended by nine of the project participants; this meeting was organized by H. Lang (Switzerland);
- Wageningen (November 1990); the second informal planning meeting attended by 23 project participants; this meeting was held at the International Agricultural Centre.

3.1.2 During the informal planning meeting in Zũrich the main aspects of the project were discussed and a preliminary plan for project implementation was proposed. The plan of action commenced in 1989 with the distribution of questionnaires by the WMO Secretariat. These questionnaires are presented as Annexes 7, 8, 9 and 13 in the comprehensive report of the Wageningen meeting. The questionnaires were sent to all the prospective participants to obtain more information on the various procedures and data sets proposed.

3.1.3 Eighteen countries replied to the questionnaires and submitted more than 50 procedures. Some were later withdrawn, so that at the end of the Wageningen meeting the project encompassed 39 procedures for intercomparison. The Netherlands submitted 7 procedures, USA and France 4 procedures each, Belgium, Denmark, Germany, Morocco and Poland submitted 2 procedures each, Australia, Canada, Chile, Czechoslovakia, Malaysia, New Zealand, United Kingdom and USSR submitted one procedure each. Moreover, evapotranspiration reference data sets for 13 river basins were offered by 12 countries. The Wageningen meeting decided to use at least two reference data sets for the numerical evaluation of procedures, namely the data set for the Hupselse Beek Basin provided by H. Stricker (Netherlands), and that for the Lockyersleigh Basin, provided by J. Kalma (Australia).

3.1.4 Eight co-ordinators were nominated to oversee the implementation of the project, namely:

- J. Mawdsley (UK)	- scientific co-ordinator
- D. Jurak (Poland)	- scientific adviser
- J. Jaworski (Poland)	- co-ordinator for Group I
- H. Stricker (Netherlands)	- co-ordinator for Group II
- J. Kalma (Australia)	- co-ordinator for Group III
- A. Perrier (France)	- co-ordinator for Group IV

- the analysis and evaluation of estimation results obtained by using only routinely available data;

- the analysis and evaluation of simulation results obtained by means of calibrated procedures;

- the numerical evaluation and comparison of procedures;

- the elaboration of the final report of the WMO project.

The final report was elaborated taking into account, not only the investigation results concerning the scientific and the numerical evaluation of the analysed evapotranspiration procedures, but also the information contained in the reports of the Wageningen and Vienna meetings.

Chapter 4

SCIENTIFIC COMPARISON OF EVAPOTRANSPIRATION PROCEDURES

4.1 Introduction

4.1.1 There is a great need for methods and procedures which could be used for deriving estimates of areal evapotranspiration under different physiographic, land use and climate conditions. They are very important for hydrological forecasting, irrigation planning and control of water resources systems under given or changing climate conditions as well as for a wide range of scientific studies.

4.1.2 The original project description elaborated by A. Becker (1987) referred to methods and models used for the estimation of evapotranspiration. The participants of the Wageningen meeting proposed to use within the project the term "methods" only in the sense of a methodological approach and to use "procedure" to mean a realization of a method in terms of a particular computational procedure for use in a specific application.

4.2 Classification of Evaluated Procedures

Many of the procedures offered for evaluation in the project were seen as being similar and for this purpose the procedures were divided into four groups. The allocation of a procedure to a group depended on the particular method that provided the basis for the procedure. The titles of these groups are as follows:

Group I - Methods based on assessment of potential evaporation or potential evapotranspiration;
Group II - Combination equations with resistance expressions;
Group III - Atmospheric boundary layer methods;
Group IV - Complementary approach.

4.3 Scientific Evaluation Criteria

4.3.1 The Wageningen report elaborated in 1992 emphasized the three-fold nature of the procedure intercomparisons which should be undertaken in all the four groups, namely:

- the scientific/theoretical assessment;
- the study of data needs and operational limitations;
- the numerical evaluation.

The same approach will be taken in Sections 4.4-4.7, but without the numerical evaluation of evapotranspiration procedures.

4.3.2 Basing on the proposals of the Wageningen meeting, the scientific evaluation of the procedures should be based on the following criteria:

- the theoretical and scientific bases of the procedures;
- the general structure of the procedures;
- the input data needs and calibration requirements;
- the practical limitations of the procedures;
- the ability of the procedures to be included as components in hydrological models;
- the possibility of applying the procedures for the evaluation of climate change influence on the hydrological processes;
- the evaluation of the procedures in previous verifications.

$$E = E(f,\ EP,\ D) \tag{10}$$

More realistic models and procedures were developed later, based on soil water parameters, calculated soil moisture values and physiologic plant characteristics - for example the plant cover resistance, the plant leaf area - which can be applied for the estimation of areal evapotranspiration by means of potential evaporation and transformation factors variable in time and space.

4.4.2 Structure of Evapotranspiration Procedures in Group I

The results of the theoretical and experimental research obtained so far (Bultot and Dupriez 1985; Jaworski 1989 and 1990; Klämt, 1991; Kristensen and Jensen, 1975; Monteih, 1965; Storm, 1991; Szeicz et al. 1969) made it possible to refine the methodology discussed in Sub-section 4.4.1 because of the development of physically-based mathematical models which could be used for the simulation of the evapotranspiration process. The investigation results obtained until now have proved that the evapotranspiration process depends mainly on the following factors:

- atmospheric factors and solar radiation energy required to turn water into vapour and to transport the latter from the evaporating surface;

- soil-water factors, in the first place on the soil moisture (water storage) in the upper layer of the unsaturated zone, where the main part of the plant-root system occurs;

- plant physiologic factors, namely the plant cover resistance, the plant leaf area, the root density and depth.

Taking into consideration the above mentioned factors and first of all the interdependence of the main components of the evapotranspiration subsystem, namely the atmospheric, the plant and soil-water environment, the structure of most procedures in Group I was accepted as follows:

(a) Inputs to the procedures consist of the energy income represented by potential evaporation or potential evapotranspiration and the mass inflow in the form of real precipitation; both the potential evaporation and the precipitation are evaluated for daily time intervals.

(b) The physical laws of energy and mass conservation and the physical characteristics of the active surface and the soil are used for the estimation of areal evapotranspiration and soil moisture values.

(c) The procedures accept in principle the various quasi-homogeneous fields in the basin which are dealt with separately, taking into account the characteristics of the basin's surface and soil, and in part also the groundwater table.

In principle all the procedures in Group I consist of six components, namely:

(i) the first permits the estimation of potential evaporation or potential evapotranspiration as a function of meteorological data;

(ii) the second estimates the evaporation of rain water retained on the plant cover using an interception-throughfall subprocedure;

(iii) the third permits the estimation of transformation factors as a function of calculated soil moisture values, or soil moisture deficits and/or characteristics of the active surface (albedo, roughness parameter, type of vegetation, leaf area index);

T_a	-	the mean air temperature for daily time periods at a height of z_a;
R_n	-	the mean daily net radiation above a grass surface (or the sunshine duration s);
u_a	-	the mean daily wind speed at height z_a;
e_a	-	the mean daily actual vapour pressure at height z_a;
P	-	daily total actual precipitation.

If attainable, atmospheric pressure data are also used. Additional data are needed for procedure 2.2, also in the case of a minimum data set, namely:

R_s	-	global radiation;
T_{min}	-	daily minimum value of the air temperature;
T_{max}	-	daily maximum value of the air temperature;
Δe	-	daily mean saturation deficit in the air;
O	-	daily value of river flow.

The least number of variable input data are needed for procedures 8.1 and 8.2, namely:

P	-	daily total actual precipitation;
T_a	-	mean air temperature for daily time period at height z_a;
R_s	-	global radiation or sunshine duration;
RH	-	mean air humidity for daily time periods at height z_a.

Furthermore, for the areal evapotranspiration estimation by means of procedures contained in Group I, the following constant characteristics of the investigated area should be known:

- land use, type of vegetation, albedo;
- physiologic plant characteristics: plant leaf area, root zone depth, the development stage of vegetation;
- soil types, soil fractions, soil moisture characteristics field capacity, permanent wilting point.

Calibration is desirable for all the procedures presented in Group I, namely for procedures 2.2, 6.1, 14.2 and also for procedures 8.1, 8.2, if these are to be applied to other climates and vegetation types. However, recalling past experience with the Hupselse Beek Basin, it should be emphasized that the above mentioned procedures could be applied without prior calibration.

The following data are required for calibration purposes:

- daily or yearly values of the river runoff (procedures 2.2, 6.1, 14.2);
- elevation of the groundwater table (procedure 6.1);
- soil moisture distribution at selected sites (procedure 6.1); - measured evapotranspiration values (procedures 8.1, 8.2).

Most of the procedures presented in Group I are in principle limited to closed river basins without important irrigation or drainage (procedures 2.2, 6.1, 14.2). Model 6.1 is limited to homogeneous areas on grid squares; procedure 8.1 is restricted in principle to Central Europe, and procedures 8.1 and 8.2 are not adaptable to high mountain areas.

4.4.4 Qualitative Evaluation of Evapotranspiration Procedures - Group I

The qualitative evaluation of procedures contained in Group I was performed taking into account the proposals of the Wageningen meeting (WMO, 1992) and the evaluation criteria presented in Section 4.3 of this Report.

It should be emphasized that the consideration of the theoretical and scientific bases of the procedures presented in Sub-section 4.4.1 is of great importance for the procedure evaluation.

Summing up the qualitative evaluation of procedures included in Group I and taking into consideration the criteria referred to in Section 4.3, it would appear that the procedures in Group I which would be worth developing for operational purposes in the future, are procedure 14.2 (J.Jaworski) and procedure 2.2 (F. Meulenberghs). Taking into account the aims of the Project, procedure 8.1 seems to be of only limited value.

4.5 Scientific Evaluation of Procedures in Group II

Group II - Combination Equations with Resistance Expressions - contains five procedures, namely:

- 1.1 Penman-Monteith equation with explicit surface resistance expression (J.D. Kalma, Australia);
- 6.2 SHE.DK Option two, Penman-Monteith method (B. Storm, Denmark);
- 14.1 Jaworski ET model (J. Jaworski, Poland);
- 19.1 Meteorological Office Rainfall and Evaporation Calculation System (MORECS) (W. H. Moores, B. A. Callander, United Kingdom);
- 21.1 SPA (Soil-plant-atmosphere) (L. S. Kuchment, Russia).

A detailed description of procedure 14.1 is presented in Annex VI. These procedures, originating from the Penman-Monteith combination equation or from the modified versions of it, are characterized by making use of transport resistances. It should be mentioned that, at the beginning of the investigation period, Group II contained 12 procedures (Annex 3 of the Wageningen report), but only five procedures' owners elaborated short descriptions of procedures which provide a basis for the scientific evaluation of the groups.

4.5.1 Theoretical Basis of Procedures in Group II

The evapotranspiration procedures in Group II apply areal evapotranspiration modelling in a physically-based way, taking into account the interdependence of the main components of the evapotranspiration sub-system, i.e. the atmospheric, plant and soil-water environment. All the procedures originating from the Penman-Monteith equation transform potential evaporation (EP) or potential evapotranspiration (ETP) into actual evapotranspiration (E) by using aerodynamic resistance and crop cover resistance.

The Penman-Monteith form of the combination equation (Monteith 1965) is substantially refined in comparison with the basic Penman equation. The Penman-Monteith equation includes aerodynamic and crop cover resistances, which represent the effect of the vegetation on the evapotranspiration process. The aerodynamic resistance describes the effect of the physical roughness of different surfaces on the transfer of energy and mass from the active surface to the atmosphere. The crop cover resistance describes the physiological control over the transpiration process. The Penman-Monteith form of the combination equation (Monteith 1965) is given below:

$$E = \frac{\frac{\Delta}{\gamma}\frac{R_n+G}{\lambda} + \frac{\rho\epsilon\,(e_o-e_a)}{p\ r_a}}{\frac{\Delta}{\gamma} + 1 + \frac{r_c}{r_a}} \tag{11}$$

where G is the heat exchange between the active surface and the ground; ρ the density of air; ρ_w the density of evaporating water; λ is the latent heat of vaporization of water; $\in$ the water/air molecular ratio ($\in = 0.622$); p the atmospheric pressure; r_a the aerodynamic resistance; r_c the crop cover resistance; and the remaining symbols are the same as in equation (7).

4.5.2.5 L.S.Kuchment developed in procedure 21.1 (SPA-model) an approach which assesses the crop resistance as a function of the water potential of leaves and the soil moisture; the SPA-model was tested with success under the conditions of the Seim River Basin.

4.5.2.6 Some of the above mentioned sub-procedures developed by Kalma, Storm, Jaworski, Callander and Kuchment, included into the Penman-Monteith equation, could bring about an essential improvement of the combination approach. It should be mentioned that, independent of the differences appearing in the individual sub-procedures developed for the crop cover resistance estimation, the general structure of evapotranspiration procedures in Group II is comparable and can be characterised as follows:

(a) the input of the procedures consists of meteorological and heat balance elements, including the actual precipitation, solar radiation factors and the heat exchange between the active surface and the soil;

(b) in each of the procedures, the investigated catchment or area is divided into various homogeneous or quasi-homogeneous fields or grid squares, which are characterised by their area, the active surface (vegetation type, soil properties), soil-water conditions and the ground water table;

(c) in all the procedures the physical laws of mass and energy conservation are applied; the procedures are characterised by making use of transport resistance expressions;

(d) in principle, the procedures included in Group II consist of seven main components which are as follows:

  (i) the first component estimates the aerodynamic resistance as a function of the aerodynamic roughness of the active surface (vegetation), the wind speed and the stability of the atmosphere (only in the case of procedure 1.1);

  (ii) the second component permits the assessment of potential evaporation or potential evapotranspiration by means of meteorological data, the solar radiation or cloud cover factors and the aerodynamic resistance, r_a;

  (iii) the third estimates the evaporation of precipitation (rain or snow) retained on the active surface (crop cover) by means of an interception subprocedure;

  (iv) the fourth component assesses the crop cover resistance (and soil resistance) as a function of the calculated soil moisture availability, leaf area index, solar radiation factors and (or) surface temperature values;

  (v) the fifth transforms potential evaporation or potential evapotranspiration into actual evaporation or actual evapotranspiration of the quasi-homogeneous fields (grid squares) by means of the estimated crop cover resistance;

  (vi) the sixth calculates the soil moisture at the end of the time interval (end of the day) using the water balance equation or the Richard equation for each of the homogeneous or quasi-homogeneous fields;

  (vii) the seventh estimates the areal evapotranspiration from the investigated river basin as the weighted mean of evaporation or evapotranspiration from the individual quasi- homogeneous fields; the computational time step for estimating areal evapotranspiration being one day.

4.5.3 Data Needs, Calibration Requirements and Practical Limitations of Procedures - Group II

It should be stated that these procedures, originating as they do from the Penman-Monteith combination equation or from modified versions of it, transform potential evaporation or potential evapotranspiration into actual areal evapotranspiration by using aerodynamic and crop cover resistances. Comparing the procedures in Group II it should be emphasized that, although they have a semi-empirical form, all of them are physically based.

The general structure of the procedures is similar, but there are distinct differences in the sub-procedures elaborated for the estimation of crop cover resistance, which are crucial for the satisfactory application of the evapotranspiration procedures in this group. Analysing the different crop cover resistance expressions applied in procedures 1.1, 6.2, 14.1, 19.1 and 21.1, it appears that procedures 14.1 and 19.1 contain crop cover resistance approaches, which could be used in more general physically-based hydrological models developed for the operational practice or in investigations concerning the influence of predicted climate change on hydrological processes. These procedures have been successfully verified and there is no need for their calibration or fitting. The most ambitious crop cover resistance approach was proposed by J. Kalma (procedure 1.1), but its practical application would be complicated because of the calibration data requirement. The crop cover resistance expressions developed in procedures 6.2 and 21.1 (B. Storm, L.S. Kuchment), tested with good results, could also be used in more general hydrological models.

The aerodynamic resistance r_a included in the combination equation depends on the turbulent exchange between the active surface and the atmosphere; the expressions used in the individual procedures in Group II for the assessment of r_a-values are similar and estimate them as a function of wind speed, an aerodynamic roughness parameter and the stability of the atmosphere (stability only in the case of procedure 1.1).

Most of the evapotranspiration procedures assess the interception separately (namely procedures 6.2, 19.1, 21.1) and only in the case of procedures 1.1 and 14.1 is this component included in the estimated areal evapotranspiration value, which is a simplification of these procedures. Only three of the procedures, namely 6.2, 14.1 and 21.1, permit the simulation of the influence of a shallow groundwater table on the evapotranspiration process (capillary rise simulation). Such an approach is not included in evapotranspiration procedures 1.1 and 19.1.

The basic temporal resolution for estimating areal evapotranspiration is one day, only procedure 19.1 (MORECS) is in general valid for 7-day computational time steps, so that some problems may occur when using this procedure in more general hydrological models which mostly operate on daily or shorter computation intervals.

It should be stated that the requirement for input data is very similar in the individual evapotranspiration procedures allocated in Group II, namely they all need five or six sets of meteorological and solar radiation input data. All the procedures in Group II have some limitations which are mentioned in Sub-section 4.5.3.

There was considerable interest at the Wageningen meeting in distributing a limited set of data and requiring the modellers to attempt to estimate areal evapotranspiration without calibrating or fitting their procedures. Under these conditions, the procedures which do not need any calibration or fitting, namely procedures 14.1 (J. Jaworski) and 19.1 (B.A. Callander), would have been at a considerable advantage. For the other procedures (1.1, 6.2, 21.1), calibration is essential and requires many time reference data which are not measured in the investigated area.

Taking into account the scientific evaluation criteria proposed at the Wageningen meeting and presented in Section 4.3 of this report, it should be underlined that the areal evapotranspiration component assessed by means of four procedures (6.2, 14.1, 19.1, 21.1) has already been applied in general hydrological models. Three of the procedures, namely 6.2, 14.1 and 21.1 are already used, with good results, in investigations concerning the influence of potential climate change on hydrological processes. Most of the evapotranspiration procedures analysed in Group II (14.1, 19.1,

4.7 Scientific Evaluation of Procedures in Group IV

Group IV comprises approaches using the complementary relationship. Two proponents had originally submitted models in this categorie for evaluation: WREVAP (Canada) and the Advection-Aridity Method (Netherlands). However, only the proponent of the WREVAP model provided the required information and submitted results of computations using the reference data sets. A short description of the WREVAP Model (procedure 3.1) can be found in Annex VII.

4.7.1 Theoretical Basis of Procedures - Group IV

The complementary relationship methods are based on an approach developed by Bouchet (1963). In his analysis, based on the energy balance, Bouchet postulated that as a surface dries from initially moist conditions the potential evapotranspiration will increase while the actual evapotranspiration decreases. The relationship which he derived has come to be known as the complementary relationship between actual and potential evapotranspiration; it states that , for conditions of constant energy supply, as a surface dries the decrease in actual evapotranspiration is accompanied by an equivalent increase in potential evapotranspiration. For the condition of a saturated surface, the actual and potential evaporation rates are equal and equivalent to the wet-environment evaporation rate. The complementary relationship is thus written as:

$$E + ETP = 2ETW \qquad (12)$$

where, E, ETP and ETW are the actual, potential and wet-environment evapotranspiration rates, respectively.

The complementary relationship models make use of two potential evaporation parameters, the potential evapotranspiration, ETP, and a second parameter, ETW, the wet-environment evaporation, which Bouchet defined as the value of the potential evapotranspiration when the actual regional evapotranspiration rate is equal to the potential rate. Although the use of two potential evaporation parameters may appear to be a drawback or an unnecessary complication, there is one major benefit accruing from the use of two such parameters; the resulting relationship appears to be universally applicable, without the need for locally-optimized coefficients.

The complementary relationship concept, introduced by Bouchet (1963), takes into account the feedback relationships between the evaporating surface and the air passing over the surface; for example, a decrease in the availability of water for areal evapotranspiration causes the air above to become hotter and drier, which in turn increases the potential evapotranspiration. Thus, rather than viewing air temperature and humidity as factors causing evapotranspiration, the models using this approach estimate evapotranspiration from its effects on these parameters. One of the advantages of this approach stems from the fact that it relies on feedback relationships between the evaporating surface and the air; it thus avoids the complexities of the soil-plant system and the ensuing complexities associated with estimates of resistance terms in the vapour transfer coefficients.

The fact that complementary relationship models avoid the complexities of the soil-plant system and require little local optimization, means that the appraoch is relatively simple to apply.

Bouchet cautioned that this relationship was an approximate one. The analysis was carried out for conditions of constant energy supply; the relationship could thus be affected by advective conditions and conditions of rapidly changing energy supply to the surface. The behaviour of the complementary relationship for different scales of time and space has been analyzed (Seguin, 1975; Fortin and Seguin, 1975). There are space and time limitations to the applicability of this appraoch.

- the net radiation for soil-plant surfaces at the air temperature is produced from an estimate of the albedo of the surface and the radiation components estimated above;

- the potential evapotranspiration, ETP, is calculated from a quickly converging solution of the energy balance and vapour transfer equations;

- the wet-environment areal evapotranspiration is estimated using the net radiation for surfaces at the equilibrium surface temperature, R_{TP};

- the areal evapotranspiration, ET, is then calculated from the complementary relationship (equation 12).

4.7.3 Data Needs, Calibration Requirements and Practical Limitations of Procedures -Group IV

The program WREVAP allows a number of input options; this is designed to widen the range of data that can be accepted by the model. The program is also capable of accepting as input climatological data averaged over time periods varying from one day to one month, although Morton et al. (1985) suggest that model estimates for periods of three days or less would be less reliable.

The program requires a number of descriptors for the site under consideration, some of which may be provided in various forms: the geographical latitude of the station; the altitude of the station above sea level, or the average atmospheric pressure; the average annual precipitation.

For each calculation period the program requires the average values of the following parameters, most of which can be provided in various forms: the dewpoint temperature, or the vapour pressure, or the relative humidity; the air temperature; the ratio of observed to maximum possible sunshine duration, or the observed sunshine duration, or the observed global radiation. Note that Morton (1983) cautions that significant errors may result from the use of averaged vapour pressures or relative humidities; Morton et al. (1985) provide a procedure for the adjustment of vapour pressure values.

Morton (1983) and Morton et al. (1985) present the following limitations for the model:

(i) it requires accurate humidity data;

(ii) it is best applied to time periods greater than five days;

(iii) it cannot be used near sharp environmental discontinuities, because the advection of heat and water vapour alters the feedback relationships upon which the method is based;

(iv) it requires temperature and humidity inputs from a station whose surroundings are representative of the area of interest; and

(v) it cannot be used to predict the effects of natural or man-made changes to a surface because it neither uses nor requires knowledge of the soil-vegetation system and because post-change temperatures and humidities are not predictable.

4.7.4 Qualitative Evaluation of Evapotranspiration Procedures - Group IV

WREVAP is an operational procedure designed specifically to produce estimates of areal evapotranspiration. It can be applied with very few restrictions to any region for which the appropriate input data are available.

The CRAE model within WREVAP does not require any calibration prior to use. Morton et al. (1985) state that the complementary relationship "permits areal evapotranspiration to be estimated from its effects on the routinely observed temperatures and humidities used in computing

Chapter 5

NUMERICAL AND GRAPHICAL EVALUATION CRITERIA

The Wageningen meeting emphasized that the numerical evaluation of evapotranspiration procedures should be one of the major activities of the WMO project, as had been the case in the previous intercomparison projects. Initial proposals concerning the verification criteria which could be used for the numerical evaluation and intercomparison of tested evapotranspiration procedures were discussed at the meetings held in Wageningen (1990) and Vienna (1991). The Wageningen meeting was aware of the difficulties involved in selecting a set of evaluation criteria for use in the WMO project. It should be mentioned that the term "evaluation criteria" includes not only the numerical verification coefficients and the graphical verification plots applied during the numerical evaluation of procedures, but also the selected reference basins, the type of methods and approaches used for the determination of reference data, their temporal resolution and the selection of special verification periods. The Wageningen meeting decided to perform the numerical evaluation of procedures using reference data sets from two reference basins, namely from the Hupselse Beek basin in the Netherlands and the Lockyersleigh catchment in Australia. The description of these basins and of the reference data sets supplied can be found in Section 6. All the remaining evaluation criteria used in the WMO project for the numerical or graphical intercomparison of evapotranspiration procedures are presented and discussed below.

5.1 Type of Reference Data

At the Wageningen meeting, it was agreed that the best methods for developing independent sets of reference data, against which to compare the areal evapotranspiration estimated by the different procedures, would be the water balance technique and the Bowen ratio and related methods, for example the aerodynamic profile method. It should be emphasized that one of the reasons for selecting the two test areas (Hupselse Beek and Lockyersleigh Basin) was that the reference data for these areas were determined by means of the above methods.

5.1.1 Reference Data obtained by the Water Balance Technique

Analysis of data from well instrumented drainage basins can give a good measure of evapotranspiration. By measuring all the main water balance components in a catchment, the areal evapotranspiration can be determined as the residual of the water balance, using the general equation:

AREAL EVAPOTRANSPIRATION = precipitation minus river runoff minus
changes in the basin's water storage.

It should be emphasized that for water balance computations a good measurement of precipitation is required; an accurate measurement of actual precipitation should be available. To measure the river runoff from a catchment, gauging stations of suitable design must also have been installed. To determine the water balance over time periods of some weeks or months, water storage changes in the unsaturated and saturated zones should also be determined.

The errors in determining monthly areal evapotranspiration amounts from catchment water balances are in the range between 9 and 16 mm (Jaworski and Młynarczyk 1976). According to Konstantinov et al. (1971), the error can be about 15-20 mm.

The reference areal evapotranspiration data under Lockyersleigh conditions were determined by J. Kalma by means of the water balance method for time intervals between 27 and 55 days. More information concerning the water balance technique applied in the Lockyersleigh Basin can be found in Sub-section 6.3.2.

1/ 26 October - 15 November 1988
2/ 7 February - 19 February 1989
3/ 1 October - 25 October 1989
4/ 24 January - 2 February 1990

In this basin, wet periods with SMU ≥ 0.7 FC were as follows:

1/ 1 August - 31 August 1988
2/ 1 September - 10 September 1988
3/ 17 September - 4 October 1988
4/ 17 November - 2 December 1988
5/ 14 March - 8 September 1989

5.3 Types of Procedure Evaluation

There was a considerable interest during the Wageningen meeting in different types of numerical procedure evaluation. Taking into account the suggestions presented in paragraphs 2.8, 5.11, 6.4, 6.10 of the Wageningen report, it was decided that four types of numerical procedure evaluation should be performed, namely:

(a) Estimation of areal evapotranspiration without prior calibration or fitting of the procedures ("blind test" calculations) and numerical evaluation of the procedures by using reference data.

(b) Simulation of areal evapotranspiration by means of calibrated procedures over the calibration period and the second numerical evaluation of procedures, using once more the reference data mentioned under (a).

(c) Estimation of areal evapotranspiration without calibration or fitting of the procedures, using only routinely available data and numerical evaluation of procedures by means of the same reference data set.

(d) Simulation of areal evapotranspiration withouth prior calibration or fitting of procedures using data of the prediction period and numerical evaluation of procedures by means of the reference data set determined for that period.

It should be underlined that, during the Wageningen meeting, there was considerable interest first of all in procedure evaluations of type (a), (c) and (d). Unfortunately it was not possible to apply the four types of procedure under Lockyersleigh conditions. All four types could only be applied with the Hupselse data.

5.4 Numerical and Graphical Verification Criteria

One of the most important problems concerning the quantitative evaluation of procedures is the selection of numerical and graphical criteria for comparing the areal evapotranspiration values simulated by various procedures, with reference evapotranspiration values measured or determined in selected reference basins. The numerical and graphical verification criteria proposed and subsequently used during the quantitative evaluation consist of numerical coefficients and graphical plots applied to several areal evapotranspiration values estimated (simulated) by the various procedures tested in the project.

5.4.1 Numerical Verification Criteria

The verification coefficients (statistical coefficients or parameters) used to evaluate and compare the simulated evapotranspiration totals, and thereafter also the procedures applied for simulations, were as follows:

Chapter 6

DESCRIPTION OF CATCHMENTS AND DATA SETS USED FOR NUMERICAL EVALUATION

6.1 Introduction

During the Wageningen meeting stress was put on the desirability of using reference data sets from reference river basins which were representative of a variety of different climatic and topographic regions and of the need to ensure their completness with regard to data needs, data quality, their length and the heterogeneity and hydrological regime of the areas concerned. Emphasis was also placed on the need for standard data covering several years from well instrumented areas which could provide results of routine and non-routine measurements. The Zűrich and Wageningen meetings set out detailed guidelines for the preparation of reference data sets for the numerical evaluation of procedures.

6.2 Hupselse Beek Basin

The Hupselse Beek Basin is situated in the east of the Netherlands, in the province of Gelderland, between the villages of Groenlo, Eibergen and the Netherlands - German border. The area of the basin is 6.5 km^2; it is well above sea level with an altitude varying between 33 m and 24 m. The general slope of the basin is from east to west with an average of 0.8 percent. The upper part of the soil consists of sand deposits which are lying on a thick tertiary formation of impermeable miocene clay. There is a shallow groundwater level in the basin. Taking into account the presence of the impermeable Miocene clay layer of 40 m, groundwater interactions to the outside of the basin can be neglected. The thickness of the sand aquifer varies between 1 m and 8 m. The storage capacity of the soil is relative small. The catchment is well drained and covered by grass (78 percent), woods (6 percent) and by agricultural crops (16 percent).

The climate in the basin is humid. The mean yearly air temperature equals 12°C, the mean annual maximum and minimum temperatures are 14°C and 10°C respectfully and the mean yearly precipitation equals 760 mm.

Meteorological and hydrological measurements are made at different sites. The most important site in the Hupselse Beek Basin is the meteorological station in Assink, where the following data are collected:

- global solar radiation (Kipp solarimeter)
- short wave outgoing radiation (Kipp solarimeter)
- net radiation (CSIRO Cnl net radiometer)
- soil heat flux (flux plates T.P.D.-Delft)
- sunshine duration (Campbell-Stokes, Haenni)
- air humidity (Lambrecht, hair-hygrometer)
- air temperature (thermistors)
- precipitation (also at the ground level)(RECOVER I)
- snow water equivalent (RECOVER II)
- wind speed (cup anemometers)
- ground surface temperature (Heiman KT 16)

The wet bulb and dry bulb air temperatures are also measured by means of a modified Frankenberger psychrometer on three levels above the active surface, namely at heights of 1.5, 3.6, 7.2 m; the wind speed is measured at three levels: 1.2, 3 and 9 m. The measurements are made mostly at 20 minutes intervals.

6.2.3 Accuracy of Hupselse Beek Reference Data

In the WMO project the evapotranspiration data, determined in the Hupselse Beek basin by means of the Bowen ratio and aerodynamic profile methods, are used as reference data; these methods enable in principle the determination of actual point evapotranspiration.

Analysing the reference data collected by the Agricultural University at Wageningen, it should be stated that they are composed of actual evapotranspiration (E) determined by the above mentioned approaches in the period April-September and potential evaporation (EP) calculated by the method of Thom and Oliver (1977) for the remaining period. Moreover, in the period 9-30 September 1982, calculated potential evaporation data were used instead of actual evapotranspiration values.

Summing up, it should be stated that, when deriving these evapotranspiration reference data in the basin, three assumptions were made, namely:

Assumption 1: The actual evapotranspiration (reference data) determined by the aerodynamic profile method equals the actual evapotranspiration determined by the Bowen ratio approach.

Assumption 2: The evapotranspiration values determined by the above mentioned two methods at one point of the basin equal the areal evapotranspiration of the Hupselse Beek Basin.

Assumption 3: In the period 9-30 September 1982, reference evapotranspiration was adequately determined assuming E = EP.

Coming back to the Assumption 1, it should be stated that there are differences between the measurement results performed by the aerodynamic profile and Bowen ratio methods; these differences are, for daily time intervals, in the range between 8% and 10% (Koopmans et al. 1990). It should be also mentioned that the accuracy of these methods is evaluated to be around ±15% (Oliver, 1985). With regard to Assumption 2, it appears that the determined reference evapotranspiration does not represent exactly the Hupselse Beek areal evapotranspiration but more the actual evapotranspiration from grass cover around the meteorological station in Assink. As regards Assumption 3, it should be mentioned that such an assumption (namely E = EP) could be made in principle in September, but not under conditions prevailing in September 1982 because of the very low soil moisture values in the area at that time, as evidenced by the soil moisture values simulated procedure 14.1.

For these reasons, it was proposed to use in the numerical evaluation of procedures, only the reference evapotranspiration values determined under Hupselse Beek conditions over the periods:

1 April - 31 August 1982
1 April - 30 September 1983
1 April - 31 August 1976-81

It appears, that the accuracy of these reference data should be in the range of ±15%.

6.3 Lockyersleigh Basin

The Lockyersleigh Basin is situated in the Goulbourn - Marulan region on the Southern Tablelands of New South Wales, approximately 160 km south-west of Sydney (Alksnis et al. 1989). The field measurements are made on the catchment of the Lockyersleigh Creek, which joins the Wollondilly River to the North. The basin area from the springs to the streamflow measurement site H equals 27 km^2; the upper part of the catchment to the streamflow site G equals 14.7 km^2. In the centre of the basin lies the Lockyersleigh homestead (34°41'30''S; 149°55'00''E). Elevations in the catchment vary between 600 and 762 m above mean sea level. The terrain is undulating and largely

T_a	-	air temperature	(°C)
$T_{a\,max}$	-	maximum daily air temperature	(°C)
$T_{a\,min}$	-	minimum daily air temperature	(°C)
e_a	-	actual vapour pressure in the air	(mb)
R_s	-	the global shortwave radiation	(MJ/m^2)
R_n	-	net radiation	(MJ/m^2)
u_a	-	mean wind speed	(km/h)
P	-	precipitation at 0.5 m above the ground	(mm/d)
O_G	-	river runoff at site G	(mm/d)
O_H	-	river runoff at site H	(mm/d)

6.3.1.2 The Lockyersleigh standard data sets, the basin's descriptions and maps were sent in January 1994 to the procedure users for use in estimating the daily and monthly values of areal evapotranspiration. Here must be stated that in the case of procedures contained in Groups I and II, the areal evapotranspiration should be assessed by means of meteorological and solar radiation data measured day-by-day during a long period, so that missing or erroneous data could not be accepted. Unfortunately, only a part of the obtained climate data could be used for the simulation of the Lockyersleigh evapotranspiration. An analysis has shown that the best climate data set was completed over the period:

1 August 1988 - 29 February 1992.

This period contained only about 60 missing or erroneous data concerning the net radiation, wind speed, air temperature and actual vapour pressure. These lacking or erroneous data could be assessed on the basis of established relationships between meteorological and radiation elements.

6.3.1.3 For some of the procedures, calibration is essential using, for example, the river flow data. In the case of procedures 2.2 and 14.2, the runoff needed for calibration should be measured at least during a period of four to five years. Under the Lockyersleigh conditions, such measurements were made only during a short period, namely between July 1991 and June 1993 (site H), so that a calibration procedure could not be used and areal evapotranspiration simulations were performed without prior calibration.

6.3.2 Reference Evapotranspiration Data

6.3.2.1 The reference evapotranspiration for the Lockyersleigh Basin was determined indirectly by two methods: the Bowen ratio approach and the water balance equation.

The Bowen ratio was determined by measuring the air temperature and specific humidity differences above the active surface (ΔT, Δq) at the meteorological station. Measuring these differences and assuming that the transfer coefficients K_h and K_w are equal, the Bowen ratio β was determined, which made it possible to estimate the latent heat flux (λE) from the energy budget equation, in which the R_n and G values were known, because they were measured at sites Q and S in the Lockyersleigh Basin (Alksnis et al. 1989). The actual evapotranspiration was determined in that basin by J. Kalma during 12 day-time intervals over the period September 1988 - January 1989.

6.3.2.2 The water balance components were determined in the upper part of the Lockyersleigh Basin (river flow profile G - basin area equals 14.7 km^2) for time intervals in the range between 27 and 55 days; these intervals depended from the data of soil moisture measurements. In the case of a river basin, the areal evapotranspiration (E) can be determined from the water balance equation if the other water balance components are known, as follows:

Areal evapotranspiration = Precipitation − River runoff - Change in the basin's water storage.

(50% or 33%) is significant and, unfortunately, it is not known which of the values determined is more representative of the true areal evapotranspiration. Summing up, it seems that the error of the Bowen ratio method under Lockyersleigh conditions is somewhat larger than ±15%. Applying these reference evapotranspiration data to the numerical evaluation of procedures, it should be taken into account that they are probably not fully representative for the areal evapotranspiration from the Lockyersleigh Basin.

The reference areal evapotranspiration was determined under the conditions of the upper part of the Lockyersleigh Basin (A = 14.7 km^2) by means of the water balance method for time intervals between 27 and 55 days dependend from the data of soil moisture measurements, and using 23 soil profiles. In order to reduce the error of the water balance approach, the beginning and end of each of the water balance time intervals was selected taking into account only days without precipitation or with precipitation amounts less or equal to 1 mm/d. Taking into consideration that:

- the investigated basin area represents about 54% of the whole catchment,
- the actual precipitation of the basin's area was known,
- the river runoff was measured continuously,
- the soil-water storage changes in the balance periods were precisely determined,

it appears that the mean error of the reference areal evapotranspiration totals determined by that approach in the Lockyersleigh Basin should not be larger than ±15 mm/period.

6.3.4 It should be underlined that the standard and reference data sets from the Lockyersleigh Basin were offered to the WMO project by CSIRO, Division of Water Resources, Canberra City, Australia.

Chapter 7

NUMERICAL EVALUATION RESULTS USING
HUPSELSE BEEK DATA

7.1 Introduction

One of the very important aims of the WMO project is the quantitative evaluation of performance of the evapotranspiration procedures using numerical and graphical verification criteria. During this evaluation, particular attention should be paid to such procedure features as accuracy, effectiveness, transferability and continuity of application. Basing on the suggestions of the Wageningen and Vienna meetings, the quantitative intercomparison of procedures has been prepared, taking into account:

- the four different types of procedure evaluation discussed in Section 5.3;
- the reference evapotranspiration data determined under Hupselse Beek conditions;
- the numerical and graphical verification criteria presented in Section 5.4;
- the special verification periods selected under Hupselse Beek conditions;
- the whole verification period of 336 days (1982-83) and six 153 day period (1976-81) including wet and dry periods.

The Wageningen meeting proposed the numerical evaluation of the 39 procedures originally submitted to the project in four groups. Nevertheless, for various reasons, only six of these procedures were finally tested in the project, so there is no reason to divide them into groups. The following procedures were tested:

- procedure 2.2 (F.Bultot, F.Meulenberghs, Belgium),
- procedure 3.1 (R.Granger, Canada),
- procedure 8.1 (A.Klämt, Germany),
- procedure 8.2 (A.Klämt, Germany),
- procedure 14.1 (J.Jaworski, Poland),
- procedure 14.2 (J.Jaworski, Poland).

All these procedures were used for "blind test" calculations, but only procedures 2.2, 3.1, 14.1 and 14.2 were applied for simulation purposes (predictions) over the period 1976-1981 (procedure 2.2 only over the period 1979-81).

The numerical evaluation of procedures was undertaken using reference evapotranspiration data determined for the following periods:

1/ April - August 1982 and April - September 1983	11 months
2/ April - August 1982 and April - September 1983	336 days
3/ April - August 1976-1981	6 x 153 days
4/ dry period 18 July - 13 August 1982	27 days
5/ dry period 1 August - 31 August 1983	31 days
6/ dry period 1 September - 9 September 1983	9 days
7/ wet period 1 May - 31 May 1982	31 days
8/ wet period 17 June - 8 July 1982	22 days
9/ wet period 1 April - 30 April 1983	30 days

The results of the numerical evaluation are presented in the next section.

These equations compute values in mm/month and are in principle valid under Hupselse Beek conditions for the growing periods of the years 1982-83.

As one can see, the best results could be obtained using evapotranspiration values (monthly totals) simulated by procedures 14.1, 14.2 and 3.1, with correlation coefficients "r" in the range between 0.97 and 0.96; acceptable also are the results of procedure 2.2 with an r-value of 0.9.

7.2.2 Numerical Evaluation by means of Daily: Evapotranspiration Reference Data

The basic time step in the implemented WMO project is one day and the basic numerical evaluation of evapotranspiration procedures was performed for this time interval, not only for the special periods selected in Chapter 5, but also for the whole reference period, namely the seasons April - August 1982 and April - September 1983, taking into consideration all the 336 independent daily reference data (actual evapotranspiration values) obtained from measurements made at one site in the Hupselse Beek Basin using the Bowen ratio and aerodynamic profile approaches.

Results of the numerical comparison of estimated daily areal evapotranspiration totals (E) and determined (measured) daily reference evapotranspiration amounts (ER) in terms of the root mean square error (RM) are presented in Table 3, Annex II for the before mentioned reference seasons (336 daily values). Analysing these comparison results, it could be easily stated that, except for procedure 8.2 with a relatively large root mean square error of 1.07 mm/d, all the other procedures attained quite good results with RM values in the range 0.53 mm/d (procedures 14.1 and 14.2) to 0.6 mm/d and 0.62 mm/d (procedures 2.2 and 3.1, respectively) (Table 3).

Comparison was also made between estimated and reference evapotranspiration data over the periods April-August in the years 1982 and 1983. Table 4 of Annex II provides the statistical results of these comparisons; listed are growing season totals (April - August) and mean daily values of the reference and estimated evapotranspiration, the ratio of the relative error to the mean R, as well as the root mean square error RM. A negative value of the R coefficient indicates that the procedure tended to produce evapotranspiration values lesser than the reference values. Table 4 shows that, for the procedures tested, the R-values varied from -13.3 to 7.9% and the RM-values from 0.53 mm/d (procedures 14.1, 14.2) to 1.12 mm/d (procedure 8.2).

It was emphasized during the Wageningen meeting that reference data sets should contain dry as well as wet periods (special verification periods). After analysing the Hupselse Beek reference data, it was possible to select in the basin three dry and three wet periods as described in Section 5.2. The results of the numerical comparison of simulated (E) and reference values (ER) determined in the Hupselse Beek Basin during dry and wet periods can be found in tables 5 and 6 of Annex II. The analysis of the results presented in these tables shows that the values of the calculated verification coefficients are generally larger under dry than under wet or normal conditions.

Comparing the evaluation results obtained for the first two dry periods (July - August 1982 and August 1983), the root mean square errors which range between 0.61 and 1.9 mm/d, which demonstrates a rather poor agreement between simulated and reference data. While, over the first period, procedure 3.1 performed best (RM = 0.61 mm/d), in the second period procedures 14.2 and 14.1 gave the best results (RM = 0.74 and 0.75 mm/d accordingly). Among the remaining procedures, the worse comparison results were demonstrated twice by procedure 8.2 with RM values equal 1.9 mm/d and 1.65 mm/d (Table 5). On the contrary, very good agreement between simulated and measured evapotranspiration values appeared in the third dry period (September 1983) in the case of procedures 14.2 (RM = 0.37 mm/d) and 14.1 (RM = 0.38 mm/d); the remaining three demonstrating rather poor verification results, namely RM = 0.82 mm/d (procedure 2.2), RM = 0.95 mm/d (procedure 3.1) and RM = 1.23 mm/d (procedure 8.2).

- in the case of procedure 2.2 - 3 events;
- in the case of procedure 3.1 - 2 events;
- in the case of procedure 8.2 - 1 event;
- in the case of procedure 14.1 - 3 events;
- in the case of procedure 14.2 - 3 events.

In addition to the evapotranspiration estimations for the period 1982-83, the predictions (simulations) of daily areal evapotranspiration from Hupselse Beek Basin were also performed. The simulation results from procedures 3.1, 14.1 and 14.2 are presented in Table 7 of Annex II for the growing season 1 April -31 August over the years 1976-1981. Table 7 provides the statistical results of the comparisons for these three procedures.

Summing up the numerical evaluation results of the evapotranspiration procedures, it should be emphasized that under dry conditions the simulation was relatively successful for procedures 14.2, 14.1 and 3.1. Very good simulation results were obtained under wet conditions, above all in the case of procedures 14.2, 14.1 and 2.2. It should be underlined that all the numerical comparison results were obtained by using simulation procedures without any prior calibration or fitting ("blind test" calculations).

7.2.3 Numerical Evaluation of Procedures which use only Routinely Available Data

During the Wageningen meeting there was also a particular emphasis on procedures which could be applied on an on-going basis with routinely available data. Taking this into account, two additional procedures were proposed, namely 14.1 var.2 and 14.2 var.2. The structure of these procedures was the same as of procedures 14.1 and 14.2 but it was assumed that the net radiation (R_n) and the soil heat flux (G) were not known. Based on the parameters estimated for the Hupselse Beek Basin and on existing routinely available meteorological data, namely mean daily values of air temperature (T_a) wind speed (u_a), actual vapour pressure in the air (e_a), daily totals of actual precipitation (P) and actual sunshine duration (s), the potential evaporation values were calculated for each of the quasi-homogeneous fields in the basin. In the calculations, it was assumed that G = 0. For estimating net radiation (R_n), the components R_s and R_L were calculated by means of Black's and Brunt's equations, using parameter values proposed by Page (1964) and Penman (after Mc Culloch, 1965), namely:

$$R_s = R_E(0.18 + 0.55\frac{s}{s_o}) \tag{18}$$

$$R_L = \sigma T_a^4(0.56 - 0.08\sqrt{e_a})(0.1 + 0.9\frac{s}{s_o}) \tag{19}$$

where R_E is the solar radiation reaching the top of the atmosphere, s is the actual duration of sunshine, s_o is the maximum possible duration of sunshine during the same period, R_L is the net long wave radiation, σ is the Stefan-Boltzman constant, and other symbols are the same as in the equations presented earlier in this report. The albedo values needed for the assessment of the net radiation R_n were estimated according to the suggestions of Miara and Paszyński (1982).

None of other calculations made by means of procedures 14.1 var.2, 14.2 var.2 did differed from those performed by procedures 14.1 and 14.2. The daily areal evapotranspiration values obtained by means of procedures 14.1 var.2 and 14.2 var.2 were compared with independent reference data determined in the Hupselse Beek Basin and with evaluation results received by procedures 14.1 and 14.2 respectively.

procedures 14.1 and 14.2, they provided results which compared favourably with some of the other tested procedures.

7.2.4 Numerical Evaluation of Calibrated Procedures

After the "blind test" calculations had been performed, it was possible to calibrate the procedure. As mentioned in Chapter 4, calibration is essential for procedures 2.2, 8.2 and 14.2, but only procedures 2.2 and 14.2 were calibrated. In the case of procedure 14.2 the calibration results have shown that the parameter values used under "blind test" conditions are very close to those estimated during the calibration, so that parameter values were not changed after calibration. Procedure 2.2 was calibrated by the user (F. Meulenberghs) who was not fully satisfied from the results obtained and made the following statement: "Even with the additional calibration data, the simulation has only been performed for the 1979-81 period as the full set of data necessary to run our model was not available for the 1976-78 period. Our model is appropriate for medium-size catchments; the period of calibration must be sufficiently long to avoid possible bias (at least four to five years). These two requirements were not met in the case of the Hupselse Beek. Therefore, it is understandable that our calibrated evapotranspiration could be hardly improved on the blind test".

Nevertheless, a comparison of procedure 2.2 before and after calibration was performed, based on the statistical parameters RM, Y, R, A and the daily estimates of areal evapotranspiration under dry and wet conditions (Tables 10 and 11, Annex II). Analysing the results obtained, it could be easily stated that a real improvement in the procedure was apparent after the calibration, but in principle only under dry conditions; the verification coefficients (statistical parameters) were all reduced after the calibration (Table 10). As regards the wet periods, it should be noted that an improvement in the procedure only occured during the first wet period (1-31 May). Over the remaining wet periods, no improvement was found (Table 11). It should be emphasized, however, that procedure 2.2 after calibration successfully simulated the daily values of areal evapotranspiration over the prediction period (1979-81) - see Figure 16 (Annex III).

7.3 Graphical Evaluation of Procedures

Besides the numerical evaluation, a graphical evaluation of procedures was performed using the criteria described in Section 5.4. The graphical procedure comparison was implemented under Hupselse Beek conditions for the period 1982-83 ("blind test" calculations) basing on daily values of the areal evapotranspiration estimated by procedures 2.2, 3.1, 8.2, 14.1, 14.2 and on suitable reference evapotranspiration data. Included for each of the above mentioned procedures and for each growing season (1 April - 31 August) are:

- a scatter diagram of estimated versus determined (measured) evapotranspiration values (Figure 1.2, Annex III);

- a comparison of two mass curves representing estimated and determined evapotranspiration values (Figure 3,4, Annex III);

- a scatter diagram of estimated versus determined evapotranspiration values over wet periods (Figure 5, Annex III);

- a scatter diagram of estimated versus determined evapotranspiration values over dry periods (Figure 6, Annex III).

Moreover, for procedures 2.2, 3.1, 14.1, 14.2, a graphical comparison over the prediction period 1976-81 was prepared (for procedure 2.2 only over the period 1979-81) using simulated and reference evapotranspiration data at daily time intervals. For procedures 3.1, 14.1, 14.2 and for each growing period (1976-81), a scatter diagram is included presenting simulated versus determined evapotranspiration values.

mm/d and 0.64 mm/d were obtained for both the procedures over a period of 336 days. These values are only larger by 0.1 mm/d than those for procedures 14.1 and 14.2. Therefore, the accuracy of procedures 14.1 var.2 and 14.2 var.2 is less than that of procedures 14.1, 14.2, they provided results which compared favourably with some of the other tested procedures.

Summing up the results presented in this chapter: under dry conditions the simulation was relative successful for procedures 14.2, 14.1 and 3.1; very good simulation results, probably within the range of the error of the determined reference data, were obtained under wet conditions and also over the whole investigated period in the case of procedures 14.2, 14.1, 3.1 and 2.2.

It should be emphasized that all the numerical comparison results were obtained by using simulation procedures without any prior calibration or fitting, with the exception of the results presented in Tables 10 and 11 and Figures 9 and 16.

Chapter 8

NUMERICAL EVALUATION RESULTS USING LOCKYERSLEIGH DATA

8.1 Introduction

The numerical and graphical evaluation of the performance of the evapotranspiration procedures has also been prepared under Lockyersleigh basin conditions, taking into account:

- the two different types of evaluation presented in Section 5.3 (types a, d);
- the reference evapotranspiration data determined in the Lockyersleigh Basin by means of the water balance technique and the Bowen ratio approach;
- the numerical and graphical verification criteria proposed in Section 5.4;
- the whole verification period of 12 days (1988-89) and 10 water balance periods (1988-90).

Unfortunately, only three of the 39 procedures originally submitted to the project were finally tested using the Lockyersleigh data, namely:

- procedure 3.1 (R.Granger, Canada),
- procedure 14.1 (J.Jaworski, Poland),
- procedure 14.2 (J.Jaworski, Poland).

These procedures were used for "blind test" calculations, because river runoff measurements that are indispensable for the calibration of procedure 14.2 under Lockyersleigh conditions were only made at measurement profile "H" during a period of two years. Therefore areal evapotranspiration estimations without prior calibration were performed, given that procedures 3.1 and 14.1 do not need any calibration.

The numerical evaluation was carried out using reference evapotranspiration data determined for:

(a) 5 August 1988 to 17 July 1990 over water balance periods with time intervals between 27 and 55 days: 10 periods;

(b) 7 September 1988 to 19 January 1989: 12 daytime periods.

The reference areal evapotranspiration data referred to under (a) above were determined by means of the water balance approach, while the reference evapotranspiration data for 12 daytime periods needed for (b) were obtained by the Bowen ratio method. The results of this numerical evaluation of the procedures are presented in Section 8.2.

8.2 Numerical Evaluation of Procedures

8.2.1 Numerical Evaluation by means of the Water Balance Technique

According to Becker (1987), the water balance technique is considered as important for defining "reference estimates" of areal evapotranspiration against which the estimates derived by other approaches can be compared. Applying the water balance method to a river basin, one can obtain a good measure of the areal evapotranspiration for a heterogeneous area and time intervals of some weeks to years and areas of a few to hundreds of square kilometres. By determining all the

8.2.2 Numerical Evaluation by means of Daytime Reference: Evapotranspiration Data

Under Lockyersleigh conditions, the reference evapotranspiration data were also determined by means of the Bowen ratio method for 12 daytime periods between September 1988 and January 1989. These reference data were used as well for the numerical evaluation. The results of the numerical comparison between daily areal evapotranspiration values estimated by the tested procedures and these independent reference evapotranspiration data using the four verification coefficients RM, Y, R, A are presented in Table 15, Annex II. It may be noted that the Bowen ratio approach enables, in principle, the determination of actual point evapotranspiration, but it may not represent exactly the actual evapotranspiration from the whole catchment area. In addition, the evapotranspiration determined by this approach was not for the whole day (24 hours), but for daytime intervals (12 hours) only, so that some underestimation of the reference evapotranspiration could be expected. Making the numerical comparison of procedures, this possible underestimation of reference data should be taken into account, because the areal evapotranspiration values were assessed by the three tested procedures over daily time intervals (24 hours).

Analysing the numerical evaluation results given in Table 15 and keeping in mind the critical remarks concerning the daytime reference data, quite good agreement was obtained between estimated E-values and reference evapotranspiration data (ER), above all in the case of procedures 14.1 (RM = 1.07 mm/d, R = 8%) and 14.2 (RM = 1.14 mm/d, R = 6%). Procedure 3.1 was characterised by larger verification coefficients (RM = 1.53 mm/d, R = 30%) which indicates a poorer agreement between "measured" and estimated evapotranspiration values (Table 15). The comparison results presented in Table 15 were also obtained by using procedures without prior calibration.

8.3 Graphical Evaluation of Procedures

Under Lockyersleigh conditions the graphical evaluation of the procedures was carried out as described in Section 7.3, using the graphical criteria presented in Section 5.4. The graphical comparison was performed making use of 10 water balance periods (1988-90) and 12 daytime periods (1988-89) for the areal evapotranspiration values simulated by procedures 3.1, 14.1 and 14.2 with the relevant reference evapotranspiration data.

For each of the procedures and for each of the test periods a scatter diagram of estimated versus determined (measured) evapotranspiration values has been prepared. The resulting graphs (Figures 17, 18, Annex II) are very instructive, so a discussion concerning these graphical plots would be redundent. However a discussion concerning the results of the numerical evaluation of procedures is presented in Section 8.4.

8.4 Discussion

During the numerical evaluation, the simulation results obtained by the analysed procedures were compared with reference evapotranspiration data determined in the Lockyersleigh Basin using the water balance technique and the Bowen ratio approach. In the case of the first reference data set (evapotranspiration totals estimated by the water balance technique), the assumption was made that evapotranspiration determined for an area of 54 percent of the catchment equals the areal evapotranspiration from the whole basin. For the second reference data set, two assumptions were made, namely:

- the reference evapotranspiration determined by the Bowen ratio approach at one point of the basin equals the areal evapotranspiration from the whole catchment;
- the reference evapotranspiration determined over daytime intervals (12 daytime hours) do not differ from the evapotranspiration amounts determined over 24 hours.

Making these two assumptions may have resulted in an underestimation of the reference values. Nevertheless, the reference data sets from the Lockyersleigh Basin - above all the reference

Chapter 9

DISCUSSION OF RESULTS AND CONCLUSIONS

9.1 Discussion of Results

9.1.1 The results of the scientific evaluation and numerical comparison of evapotranspiration procedures are discussed in relation to the declared aims and objective of the WMO Project on Estimation of Areal Evapotranspiration.

9.1.2 The aims of the WMO project were as follows:

- to review and evaluate current methods and procedures for estimating actual areal evapotranspiration as a basis for offering guidance on their applicability and on their potential for further development;
- to assess their accuracy in simulating areal evapotranspiration, their potential for incorporation into hydrological models and their use in simulating the interactions between atmospheric and land-surface processes.

9.1.3 The objective of the project was a scientific (theoretical) as well as a numerical and graphical evaluation of evapotranspiration procedures. It was suggested that in the project only procedures capable of providing short-term estimates of actual areal evapotranspiration over identifiable areas greater than 1 km^2. The preferred time interval of procedures evaluated in the project was in principle one day, with a maximum of one month.

9.1.4 Many of the 39 procedures offered for evaluation in the project were seen as being similar and therefore the procedures were divided into four groups, namely:

Group I	-	Methods based on assessment of potential evaporation or potential evapotranspiration;
Group II	-	Combination equations with resistance expressions;
Group III	-	Atmospheric boundary layer methods;
Group IV	-	Complementary approach.

The allocation of a procedure to a group depended on the particular method that provided its theortetical basis. These groups originally included 17, 12, 7 and 2 procedures respectively, as specified in Annex 3 of the Wageningen report (WMO, 1992), but the scientific evaluation was finally performed taking into consideration only five procedures in Group I, five procedures in Group II and one procedure in Group IV.

9.1.5 The scientific evaluation of evapotranspiration procedures in these groups was based on the following criteria:

- the theoretical and scientific basis of the procedures;
- the general structure of the procedures;
- the input data needs and calibration requirements;
- the practical limitations of the procedures;
- the possibility of including the procedures as components in hydrological models;
- the possibility of using the procedures in evaluating the influence of climate change on hydrological processes;
- the evaluation of the procedures in previous verification and intercomparison studies.

9.1.6 Taking into consideration these criteria, it was found that the most valuable procedures which would be worth developing for operational purposes in the future are:

9.1.10.1 The comparison of estimated areal evapotranspiration over two growing seasons (1982 and 1983) with adequate reference data has shown quite good agreement of determined (ER) and estimated evapotranspiration (E) in the case of all the tested procedures. While procedure 14.1 performed best, the other procedures also achieved good results.

9.1.10.2 The evaluation of procedures by using monthly reference evapotranspiration totals has shown that the best agreement between simulated and determined evapotranspiration values occurred in the case of procedure 14.1 (RM = 6.1 mm/month); very good results were obtained also by procedures 14.2 (RM = 6.6 mm/month) and 3.1 (RM = 8 mm/month).

9.1.10.3 The success of the evaluated procedures was tested as well by forcing linear regressions between estimated and reference monthly evapotranspiration totals. The best results were obtained using areal evapotranspiration values simulated by procedures 14.1, 14.2 (correlation coefficients r = 0.97) and 3.1 (r = 0.96).

9.1.10.4 Analysing the comparison results between estimated daily evapotranspiration values and adequate daily reference data, it was shown that, except for procedure 8.2 with a relatively large root mean square error RM = 1.07 mm/d, all the other procedures obtained good results with RM values in the range 0.53 mm/d (procedures 14.1, 14.2) to RM = 0.6 mm/d and RM = 0.62 mm/d (procedures 2.2 and 3.1, respectively).

9.1.10.5 Comparing numerical verification values calculated under wet and dry conditions, it should be noted that the procedures performed better under wet than under dry conditions. While for the first dry period procedure 3.1 performed best (RM = 0.61 mm/d), in the second dry period procedures 14.1 and 14.2 gave the best results (RM = 0.75 and 0.74 mm/d). For the third dry period procedures 14.1 (RM = 0.38 mm/d) and 14.2 (RM = 0.37 mm/d) showed a very good agreement between simulated and determined evapotranspiration values. Procedure 8.2 with RM values of 1.9 and 1.65 mm/d generally provided the least favourable results.

9.1.10.6 Analysing the evaluation results obtained in the first wet period, a very good agreement between estimated and "measured" values was noted; while procedure 14.1 (RM = 0.36 mm/d) and 14.2 (RM = 0.35 mm/d) performed best, most of the other procedures achieved very good results as well. During the second wet period the evaluation results were better, procedures 14.1 and 14.2 again performing best with RM-values of 0.25 and 0.23 mm/d, respectively. Procedures 2.2 and 3.1 also obtained good results. During the third wet period the best agreement was obtained by procedures 2.2 (RM = 0.3 mm/d) and 14.2 (RM = 0.31 mm/d), but all the other procedures also performed well.

9.1.10.7 Two additional procedures were proposed and evaluated, namely 14.1 var.2 and 14.2 var.2. The structure of these procedures is the same as for procedures 14.1 and 14.2, but it was assumed that the net radiation and the soil heat flux are not known, so that areal evapotranspiration was estimated using only routinely available meteorological data. The numerical evaluation of procedures 14.1 var.2 and 14.2 var.2 has shown that the calculated RM-values are only by 0.1 mm/d larger than in the case of procedures 14.1 and 14.2.

9.1.10.8 A comparison of procedure 2.2 before and after calibration showed that calibrationprovided an improvement, but in principle only under dry conditions. Nevertheless, the owner who calibrated the procedure was not fully satisfied with the results obtained because the calibration period was shorter than required.

9.1.10.9 The evaluation of procedures using daily reference evapotranspiration values from the prediction period (April - August) for the years 1976-81 has shown that the best agreement between simulated (predicted) and determined reference evapotranspiration values occurred in the case of procedures 14.1 (RM = 0.52 mm/d) and 14.2 (RM = 0.55 mm/d); good results were also obtained by procedure 3.1 (RM = 0.73 mm/d). In this evaluation the results of "blind test" calculations were used.

9.2.3 Based on the results of procedure evaluation obtained under Lockyersleigh conditions, it should be mentioned that the simulation of areal evapotranspiration was really successful only for procedures 14.1 and 14.2. These procedures are capable of accurately simulating the daily and periodical areal evapotranspiration amounts also under conditions which differ essentially from those in the Hupselse Beek Basin. The accuracy of this evapotranspiration simulation is probably within the range of the error of reference data determined in the Lockyersleigh Basin.

9.2.4 Although the climate conditions of the Lockyersleigh basin are of a sub-humid type, the runoff from this catchment is very similar to river flow under semi-arid conditions where long periods without any base flow occur. According to Becker (1987) ..."evapotranspiration models which provide satisfactory results under such conditions can be considered as suitable also for arid and semi-arid areas."

9.2.5 Summing up the numerical evaluation results and taking into account the good and very good simulation results obtained with procedures 14.1 and 14.2 under Hupselse Beek as well as under Lockyersleigh conditions, one can conclude, that these evapotranspiration procedures are capable of accurately simulating the real course of areal evapotranspiration under different climate conditions (humid, sub-humid and probably semi-arid as well). They also have valuable features such as effectiveness and transferability and they can be applied on an on going basis with routinely available data.

9.2.6 The main reason for the effectiveness of procedures 14.1 and 14.2 would appear to be the advanced crop cover resistance expression of procedure 14.1 and the comprehensive conversion sub-procedure of procedure 14.2. The former could be applied in more general hydrological models developed for operational practice or in investigations concerning the influences of predicted climate changes. The structure of procedure 14.1, with the involved crop cover resistance sub-procedure, can be seen as a valuable improvement of the Penman-Monteith approach which is very often used in meteorological and hydrological investigations.

9.2.7 Taking into consideration the investigation results obtained in the WMO project, it can be stated that further progress in the development of areal evapotranspiration models, based on combination equations or on methods using potential evaporation or potential evapotranspiration, will depend above all on the improvement of transformation factors and sub-procedures for the crop cover resistance estimation.

9.2.8 It is recommended tha the reference data sets used in the WMO project be retained by the World Meteorological Organization for use upon request by other model owners, on the understanding that the numerical evaluation results are communicated to the international community through WMO.

9.2.9 On the recommendations of the Wageningen meeting, this final report on the project should be distributed as widely as possible to the scientific community at large.

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No. 56

ESTIMATION OF AREAL EVAPOTRANSPIRATION

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CONTENTS

FOREWORD

Evapotranspiration is one of the most important processes in the land phase of the hydrological cycle. This cycle consists of the transfer of water - by precipitation - from the atmosphere to the earth's surface whence it runs off as surface, sub-surface or groundwater flow to rivers, lakes and seas. The cycle is closed when the water evaporates back into the atmosphere where it becomes unavailable and cannot be recovered for further use. Unfortunately, unlike most of the other components of the hydrological cycle, areal evapotranspiration has defied attempts to measure it directly with suitable accuracy, so that various indirect methods are applied to assess this process. One of the most important is the use of mathematical models for the simulation of the evapotranspiration process. Such models are required for hydrological forecasting, water resources planning, management for water supply and irrigation of agricultural areas; they should be included in any modern hydrological system as well. Evapotranspiration models are also important for investigations being undertaken within the World Climate Programme on interactions between the atmosphere and the land surface.

Therefore, and taking into consideration the past work of WMO on the intercomparison of hydrological models, the WMO Commission for Hydrology (CHy) at its seventh session in 1984 recommended that a project be undertaken for the intercomparison of methods and models for estimating areal evapotranspiration, with primary emphasis on those which can be used operationally with routinely available data. This emphasis was later dropped to permit the inclusion of other methods and models, recognizing that a number of these may be candidates for future operational use. The project commenced in 1989 and was completed in 1995 by the WMO Secretariat in co-operation with national institutions involved in hydrological and meteorological services and research. The present publication contains the final report on this project.

As with the previous intercomparisons, the detailed implementation plans for the project were drawn up and approved by the participants themselves. The successful implementation of this project was made possible by the close co-operation of various national institutions and individual experts who participated in it. The researchers who took part in the three sessions and planning meetings (Zürich 1989, Wageningen 1990, Vienna 1991) helped in the formulation of the plan of action with a schedule of activities and proposed guidelines for the qualitative and quantitative evaluation of evapotranspiration procedures. Very important was the effective participation of the national institutions which had developed models and provided the standard and reference data sets for the numerical intercomparison of procedures tested in the project. Here must be mentioned H.Stricker of the Department of Hydrology, Soil Physics and Hydraulics, Agricultural University at Wageningen Netherlands, who prepared and transmitted the standard and reference data sets for Hupselse Beek and J.Kalma, then of the Commonwealth Scientific and Industrial Research Organization, Division of Water Resources, Canberra, Australia, who was responsible for the preparation and transmission of the standard and reference data sets concerning the Lockyersleigh Basin. These data sets were indispensable for the quantitative evaluation of the procedures.

Particular reference should also be made to the Institute of Meteorology and Water Management, Warsaw, Poland for performing the statistical computations for the numerical evaluation of the evapotranspiration procedures and to the National Hydrology Research Institute Saskatoon (Canada) for the performance of the graphical evaluation of the procedures tested in the project.

The final report was drafted by J.Jaworski with the exception of sub-chapters 4.6 and 4.7 which were written by J.Granger - Saskatoon. The short descriptions of procedures included as annexes in this report were written by F.Meulenberghs and D.Gellens (procedure 2.2), R.J.Granger (procedure 3.1) and J.Jaworski (procedure 14.1).

S U M M A R Y

This report presents the historical development, design, implementation and investigation results of the WMO project on estimation of areal evapotranspiration. The project commenced in 1989 with the distribution of various questionnaires concerning areal evapotranspiration procedures and data requirements, as well as characteristics of test river basins and reference data sets. The reporting phase of the project was completed in June 1995 with the elaboration of the final report.

The aims of the project were:

- to review and evaluate current methods and procedures for estimating actual areal evapotranspiration as a basis for offering guidance on their applicability and on their potential for further development;

- to assess their accuracy in simulating areal evapotranspiration, their potential for incorporation into hydrological models and their use in simulating the interactions between atmospheric and land surface processes.

The objective of the project was a scientific evaluation, taking into account the theoretical basis and methodological approach of the procedures, an assessment of data needs, computational demands and the practical or theoretical limitations of the procedures, as well as their quantitative evaluation using numerical and graphical verification criteria.

The plan of action of the WMO project was formulated on the basis of three meetings which were held in Geneva (1984, 1988) and Zürich (1989). The description and implementation plan of the project were presented in a comprehensive report entitled: "Project on Estimation of Areal Evapotranspiration" which was issued in 1992 as WMO Technical Report in Hydrology and Water Resources, No. 32 WMO/TD - No.464. The intercomparison phase of the project began at the Wageningen meeting (November 1990) and at the end of that meeting the project encompassed 39 procedures for estimating evapotranspiration. The Netherlands submitted 7 procedures, USA and France 4 procedures each, Belgium, Denmark, Germany, Morocco and Poland submitted 2 procedures each, Australia, Canada, Chile, Czechoslovakia, Malaysia, New Zealand, United Kingdom and USSR submitted 1 procedure each.

The Wageningen meeting decided to divide these 39 procedures into four groups. The allocation of a procedure to a group depended on the particular method that provided the basis for the procedure. A description and scientific comparison of the procedures in each Group are presented in chapter 4. It should be noted that, for various reasons, the scientific evaluation was performed on only 11 procedures from Groups I, II and IV.

The numerical and graphical evaluation phase of the project was completed in 1994 with the simulation of areal evapotranspiration and testing of 6 procedures on the reference data set from Hupselse Beek (Netherlands) and of 3 procedures on the reference data set from the Lockyersleigh catchment (Australia). Under Hupselse Beek conditions, procedures 2.2 (F. Bultot, F.Meulenberghs, Belgium), 3.1 (R.Granger, Canada), 8.1, 8.2 (A.Klämt, Germany) and procedures 14.1, 14.2 (J.Jaworski, Poland) were tested; under Lockyersleigh conditions, only procedures 3.1 (Canada), 14.1 and 14.2 (Poland) were numerically evaluated. Descriptions of the test basins, the standard meteorological and hydrological data, as well as of the reference data sets, are provided in chapter 6.

Taking into consideration the scientific evaluation criteria as spelt out in section 4.3, it has been found that the evapotranspiration procedures which would most be worth developing for operational purposes in the future are procedures 14.2 (Poland) and 2.2 (Belgium) in Group I, procedures 14.1 (Poland) and 6.2 (Denmark) in Group II and procedure 3.1 (Canada) in Group IV.

ANNEX I

SYMBOLS AND ABBREVIATIONS

MINU Minimum value of the soil moisture in the upper layer of the unsaturated zone

n Total number of measurements

O Total runoff (surface water and groundwater runoff) from the investigated catchment

O_G Stream flow at station G (Lockyersleigh Basin)

O_H Stream flow at station H (Lockyersleigh Basin)

p Mean atmospheric pressure

P Real (corrected) precipitation occurring on the investigated catchment area (in most cases refers to daily totals)

q Specific humidity of the air

r Correlation coefficient

R Ratio of relative error to the mean

r_a Aerodynamic resistance

r_o Crop cover, or canopy resistance

R_E Solar radiation reaching the top of the atmosphere

RH Relative humidity of the air at height z_a

R_L Net longwave radiation received at the active surface

RM Root-mean-square error

R_n Net all-wave radiation received at the active surface

R_s Global solar radiation received at the earth's surface on a horizontal surface

R_T Calculated net radiation corresponding to a plant surface whose temperature is equal to the air temperature

R_{TP} Net radiation calculated for a surface at the equilibrium surface temperature

s Actual observed sunshine duration

S Ratio of observed to maximum possible sunshine duration

SMU Soil moisture value in the upper layer of the unsaturated zone

s_o Maximum possible sunshine duration

T_a Mean air temperature at height z_a

T_D Dewpoint temperature

ρ_o	Proportional increase in atmospheric radiation due to clouds
ρ_w	Density of water
σ	Stefan-Boltzman constant
τ	Transmissivity of clear skies to direct beam solar radiation
τ_a	That part of τ that is the result of absorption
φ_1, φ_2	Co-ordinates of the evapotranspiration field

ANNEX II

RESULTS OF THE NUMERICAL EVALUATION OF EVAPOTRANSPIRATION PROCEDURES,

TABLES 1 to 15

Table 2

Numerical comparison between monthly areal evapotranspiration totals (E) estimated by the various procedures and monthly evapotranspiration reference data (ER) using the verification coefficients RM, Y, R, A - Hupselse Beek Basin, Netherlands ["blind test" calculations]

Test periods	Number of tested E-values	Numerical verification coefficients	Values of the verification coefficients RM, Y, R, A estimated for the below six procedures					
			2,2	3,1	8,1	8,2	14,1	14,2
April-August 1982 and April-September 1983	11	RM	12,5	8,0	17,1	20,1	6,1	6,6
	11	Y	0,17	0,11	0,23	0,28	0,08	0,09
	11	R	-0,10	0,04	-0,05	-0,05	0,03	0,04
	11	A	0,14	0,09	0,20	0,19	0,07	0,06

Table 4

Numerical comparison of the daily and period totals of the areal evapotranspiration amounts estimated by the various procedures with the reference evapotranspiration determined using the data from the Hupselse Beek Basin (Netherlands) for the growing periods 1 April to 31 August 1982 and 1983 ["blind test" calculations]

PROCEDURE	Year	Reference E		Estimated E		Verification Coefficients	
		Total [mm]	Mean [mm/d]	Total [mm]	Mean [mm/d]	R [%]	RM [mm/d]
2.2	1982	367.6	2.40	318.9	2.08	-13.3	0.67
	1983	353.0	2.31	327.4	2.14	-7.5	0.56
3.1	1982			392.0	2.56	6.6	0.58
	1983			374.2	2.45	6.0	0.67
8.2	1982			339.9	2.22	-7.5	1.12
	1983			340.0	2.23	-3.7	1.06
14.1	1982			361.0	2.36	-1.8	0.53
	1983			376.9	2.46	6.9	0.54
14.2	1982			365.4	2.39	-0.6	0.53
	1983			381.5	2.49	7.9	0.57

Table 6

Numerical comparison - during wet periods - between daily areal evapotranspiration amounts (E) estimated by the various procedures and independent daily evapotranspiration reference data (ER) using the verification coefficients RM, Y, R, A - Hupselse Beek Basin, Netherlands ["blind test" calculations]

Number of wet period	Test periods	Number of tested E-values	Numerical verification coefficients	Values of the verification coefficients RM, Y, R, A estimated for the five procedures				
				2,2	3,1	8,2	14,1	14,2
1.	1 May to 31 May 1982	31	RM	0,57	0,50	0,62	0,36	0,35
			Y	0,21	0,18	0,23	0,13	0,13
			R	-0,14	0,03	0,09	-0,05	0,01
			A	0,16	0,14	0,17	0,11	0,10
2.	17 June to 8 July 1982	22	RM	0,41	0,56	0,79	0,25	0,23
			Y	0,15	0,21	0,29	0,09	0,09
			R	-0,05	0,09	0,17	0,00	-0,01
			A	0,12	0,17	0,24	0,06	0,06
3.	1 April to 30 April 1983	30	RM	0,30	0,59	0,46	0,36	0,31
			Y	0,20	0,39	0,31	0,24	0,21
			R	0,13	-0,02	0,19	0,10	0,07
			A	0,18	0,25	0,24	0,19	0,18

Table 8

Numerical comparison - during dry periods - between daily areal evapotranspiration values estimated by the procedures 14.1, 14.2, 14.1 var.2, 14.2 var.2*/ and independent reference data using the verification coefficients RM, Y, R, A - Hupselse Beek Basin, Netherlands ["blind test" calculations]

Number of dry period	Test periods	Number of tested E-values	Numerical verification coefficients	Values of the verification coefficients RM, Y, R, A estimated for the four procedures			
				14,1	14,1 var.2	14,2	14,2 var.2
1.	18 July to 13 August 1982	27	RM	0,90	0,98	0,91	0,99
			Y	0,38	0,41	0,38	0,41
			R	0,05	0,08	0,06	0,09
			A	0,24	0,27	0,24	0,27
2.	1 August to 31 August 1983	31	RM	0,75	0,78	0,74	0,80
			Y	0,36	0,37	0,35	0,38
			R	-0,05	-0,02	-0,06	-0,01
			A	0,31	0,33	0,31	0,33
3.	1 September to 9 September 1983	9	RM	0,38	0,44	0,37	0,46
			Y	0,23	0,26	0,22	0,28
			R	-0,01	-0,01	-0,06	-0,06
			A	0,18	0,20	0,15	0,19

*/ Procedures 14.1 var.2, 14.2 var.2 estimated areal evapotranspiration using only routinely available data.

Table 10

Numerical comparison - during dry periods - between daily areal evapotranspiration amounts estimated by the procedure 2.2 without calibration and after calibration and independent reference data using the verification coefficients RM, Y, R, A - Hupselse Beek Basin, Netherlands

Number of dry period	Test periods	Number of tested E-values	Numerical verification coefficients	Values of the verification coefficients RM, Y, R, A	
				Procedure 2.2, not calibrated	Procedure 2.2, after calibration
1.	18 July to 13 August 1982	27	RM Y R A	0.96 0.40 -0.34 0.37	0.88 0.37 -0.31 0.34
2.	1 August to 31 August 1983	31	RM Y R A	0.93 0.44 -0.26 0.32	0.86 0.41 -0.22 0.31
3.	1 September to 9 September 1983	9	RM Y R A	0.82 0.49 -0.27 0.45	0.75 0.45 -0.22 0.42

Table 12

Areal evapotranspiration from the Lockyersleigh Basin determined by the water balance technique

No. of period	Investigation period	Number of days in the periods	P [mm/period]	S_B [mm]	S_E [mm]	O_G [mm/period]	E (E = ER) [mm/period]
1	5 to 31 August 1988	27	44.9	290.7	294.9	3.3	37.4
2	1 September to 11 October 1988	41	77.0	294.9	261.2	7.6	103.1
3	12 October to 28 November 1988	48	107.7	261.2	268.9	1.8	98.2
4	29 November 1988 to 6 January 1989	39	107.7	268.9	250.8	0.2	125.6
5	7 January to 1 March 1989	54	93.8	250.8	210.3	0.1	134.2
6	23 November 1989 to 16 January 1990	55	104.2	238.4	239.7	0.1	102.8
7	17 January to 7 March 1990	50	158.2	239.7	248.6	0.6	148.7
8	8 March to 16 April 1990	40	83.2	248.6	257.5	0.5	73.8
9	17 April to 5 June 1990	50	198.9	257.5	306.2	50.0	100.2
10	6 June to 17 July 1990	42	38.8	306.2	299.3	3.6	42.1

Remarks: Each of the S_B and S_E - values is the mean of 23 soil moisture values determined in the basin in 23 measurement profiles (sites A, B)

$$P = (P_A + P_B)/2$$

$$S_B + P = E + O_G + S_E$$

$$E = P - O_G + S_B - S_E$$

where: E - the areal evapotranspiration, P - the real precipitation, O_G - the river runoff measured in profile "G", S_B - the basin's water storage at the beginning of the time interval, S_E - the basin's water storage at the end of the time interval - all components in mm over the investigated time interval in the Lockyersleigh Basin (A = 14.7 km^2)

Table 14

Numerical comparison between the areal evapotranspiration totals (E) estimated by procedures 3.1, 14.1 and 14.2 and the independent reference areal evapotranspiration amounts (ER) using the verification coefficients RM, Y, R, A, Lockyersleigh Basin, Australia ["blind test" calculations]

Test periods	Number of tested E-values	Numerical verification coefficients	Values of the verification coefficients RM, Y, R, A estimated for the three procedures:		
			3,1	14,1	14,2
5 August 1988 to 1 March 1989 and 23 November 1989 to 17 July 1990	10	RM	66,9	13,1	13,0
	10	Y	0,66	0,13	0,13
	10	R	0,32	0,04	0,04
	10	A	0,51	0,11	0,11

* E - areal evapotranspiration totals were computed from daily evapotranspiration values estimated by procedures 3.1, 14.1, 14.2

** ER - areal evapotranspiration amounts were determined by means of the water balance technique

ANNEX III

RESULTS OF THE GRAPHICAL EVALUATION OF EVAPOTRANSPIRATION PROCEDURES

FIGURES 1 TO 18

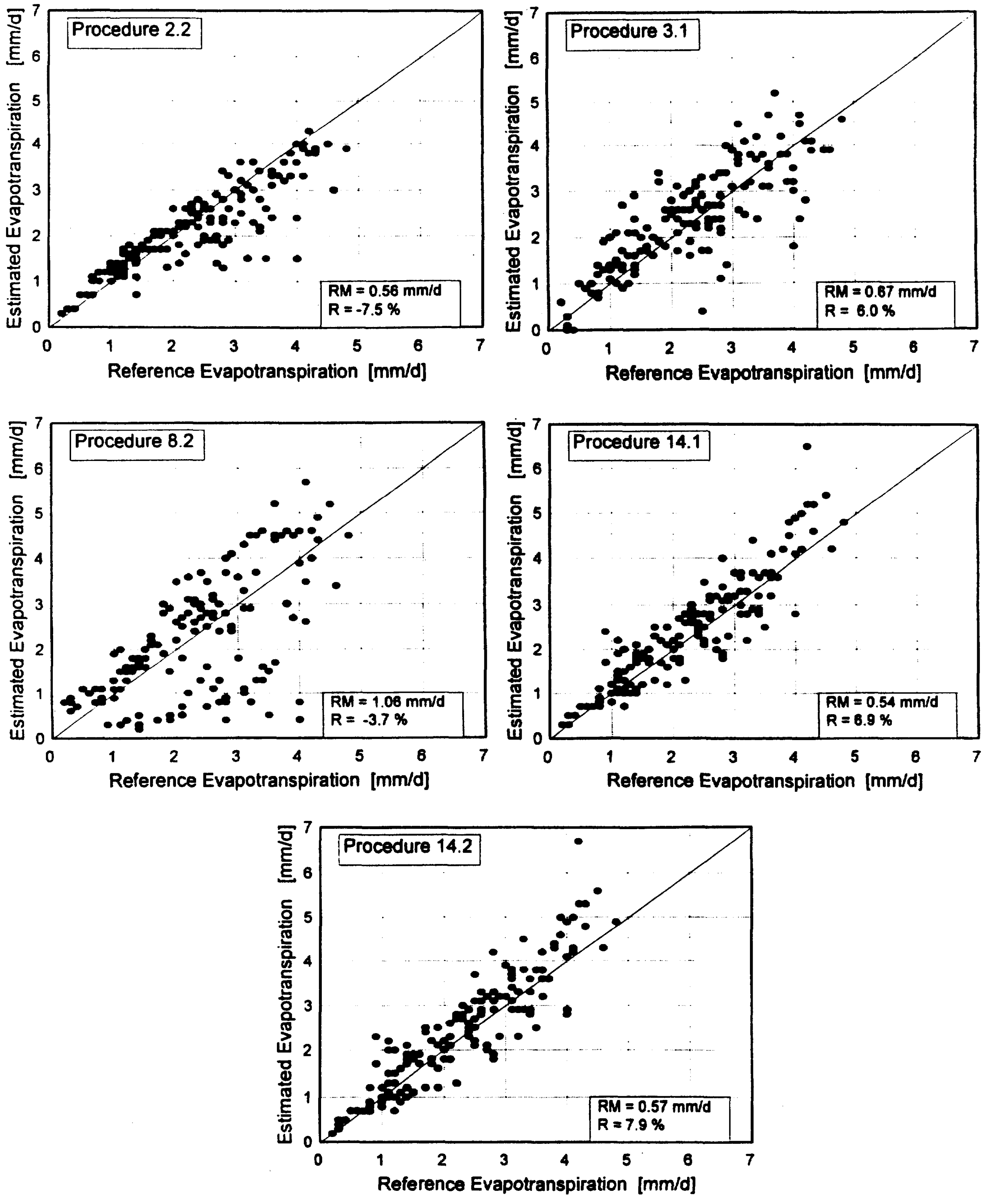

Figure 2. Comparison of daily areal evapotranspiration values estimated by the various procedures (without prior calibration) with the reference evapotranspiration values from the Hupselse Beek Basin for the period 1 April to 31 August 1983.

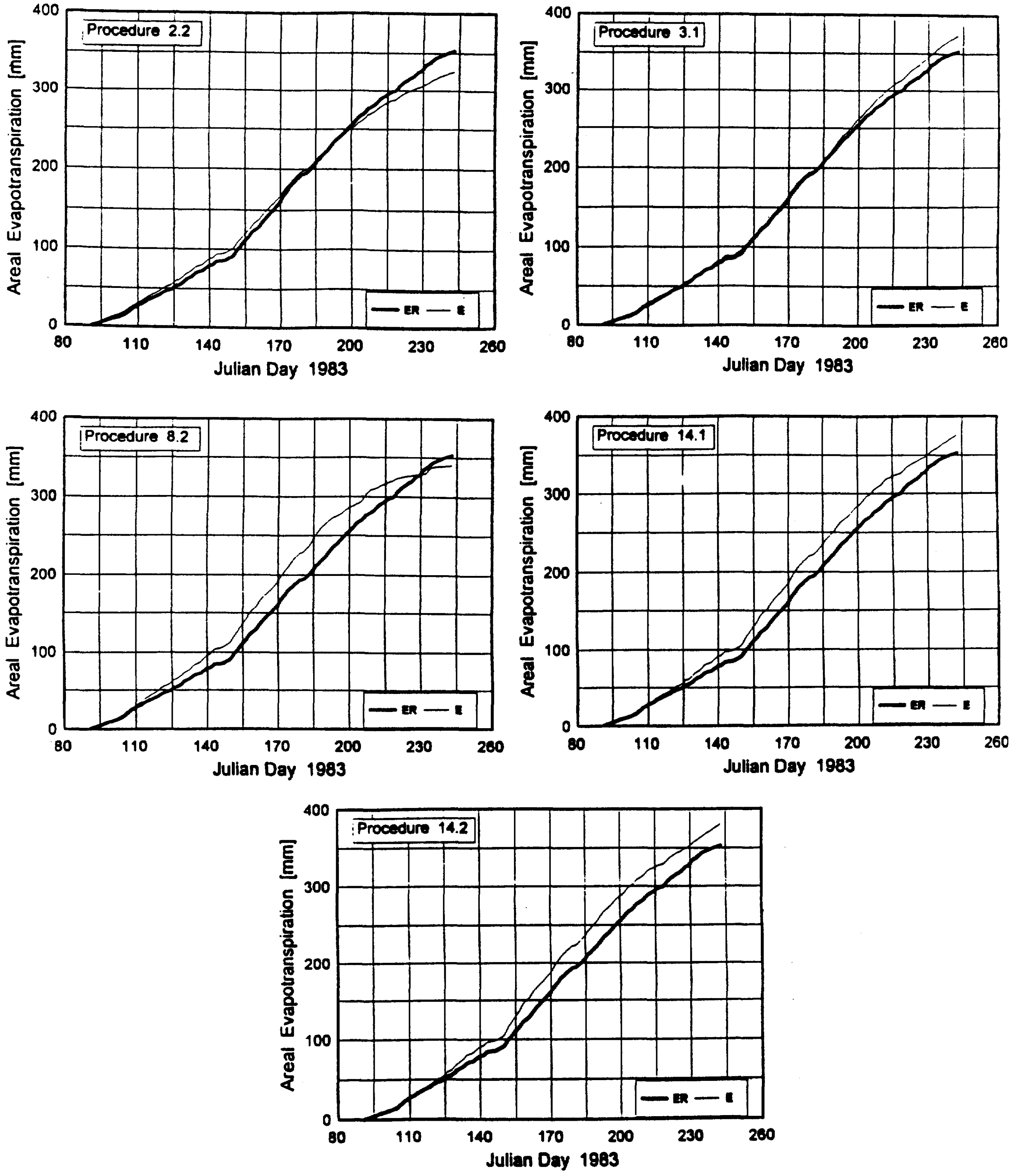

Figure 4. Comparison of mass curves of areal evapotranspiration estimated by the various procedures (without prior calibration) with the reference evapotranspiration from the Hupselse Beek Basin for the period 1 April to 31 August 1983.

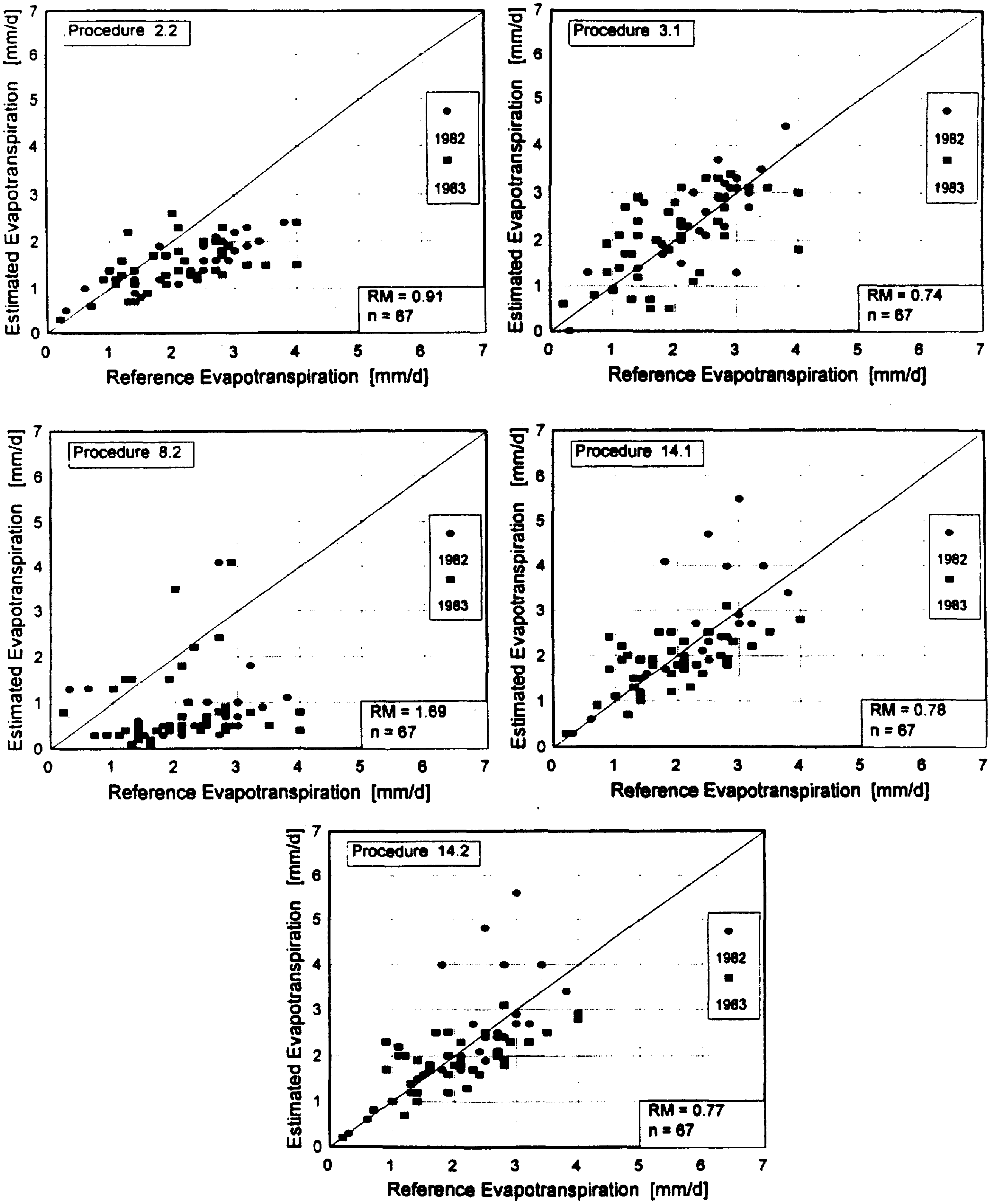

Figure 6. Comparison of daily areal evapotranspiration values estimated by the various procedures (without prior calibration) with the reference evapotranspiration values from the Hupselse Beek Basin for dry periods (SMU ≈ MINU).

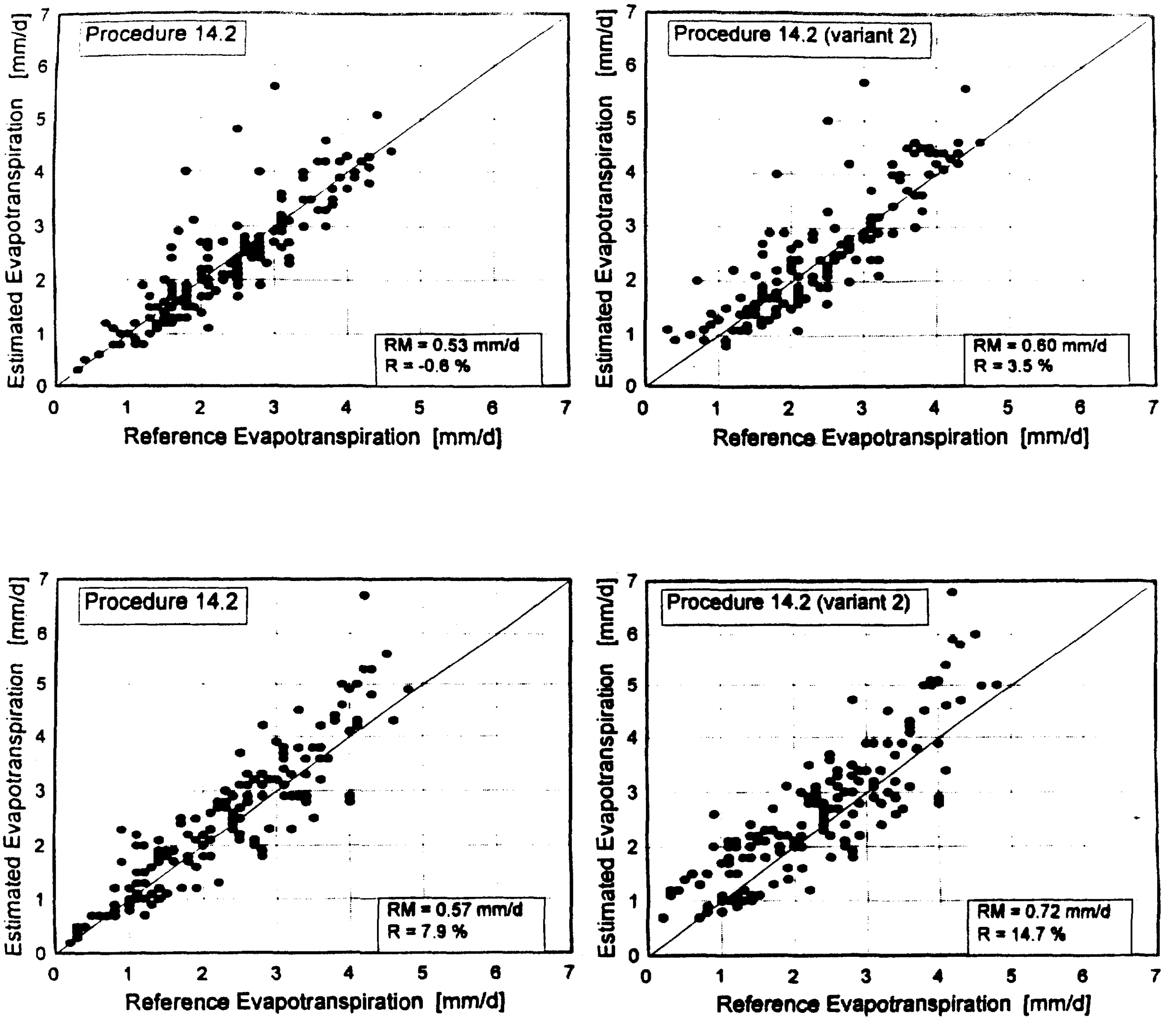

Figure 8. Comparison of daily areal evapotranspiration values estimated by procedures 14.2 and 14.2 - variant 2 (using only routinely-available data) with the reference evapotranspiration values from the Hupselse Beek Basin for the periods 1 April to 31 August 1982 and 1983 ("blind test" calculations).

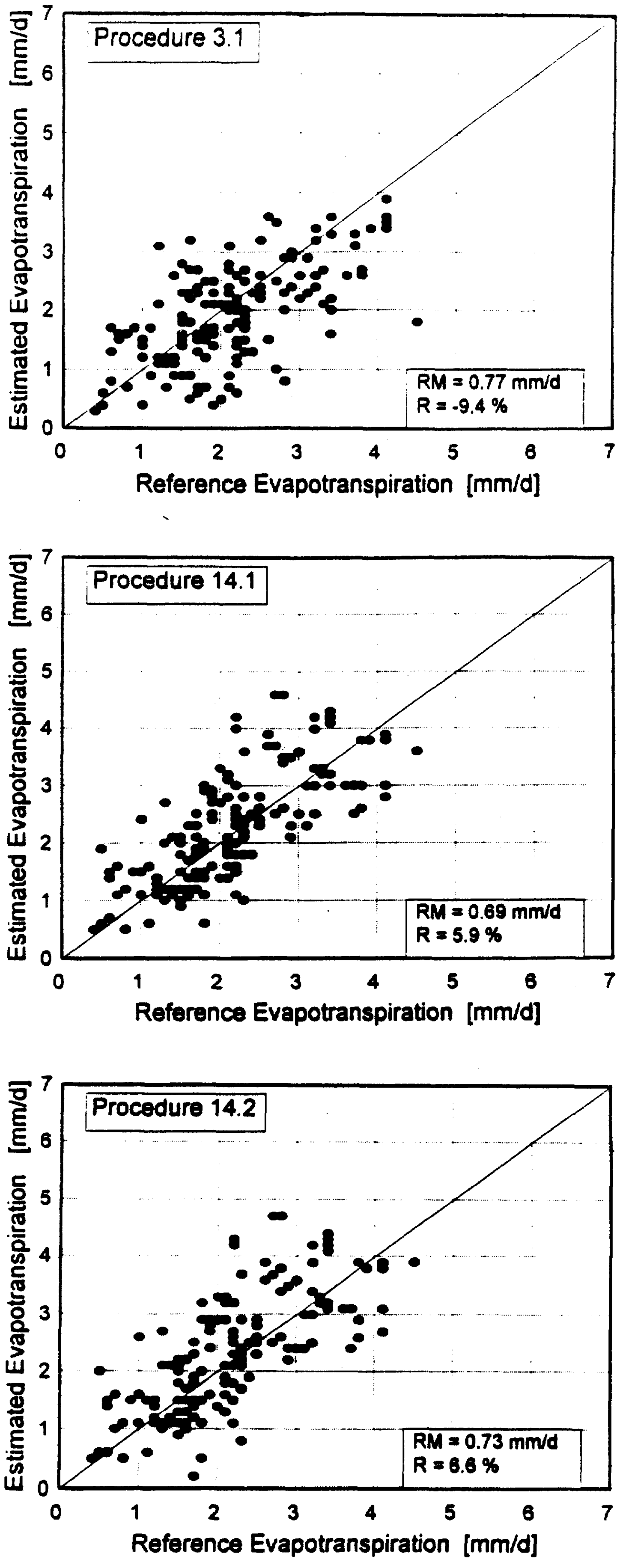

Figure 10. Comparison of daily areal evapotranspiration values estimated by the various procedures with the reference evapotranspiration values from the Hupselse Beek Basin for the prediction period 1 April to 31 August 1976.

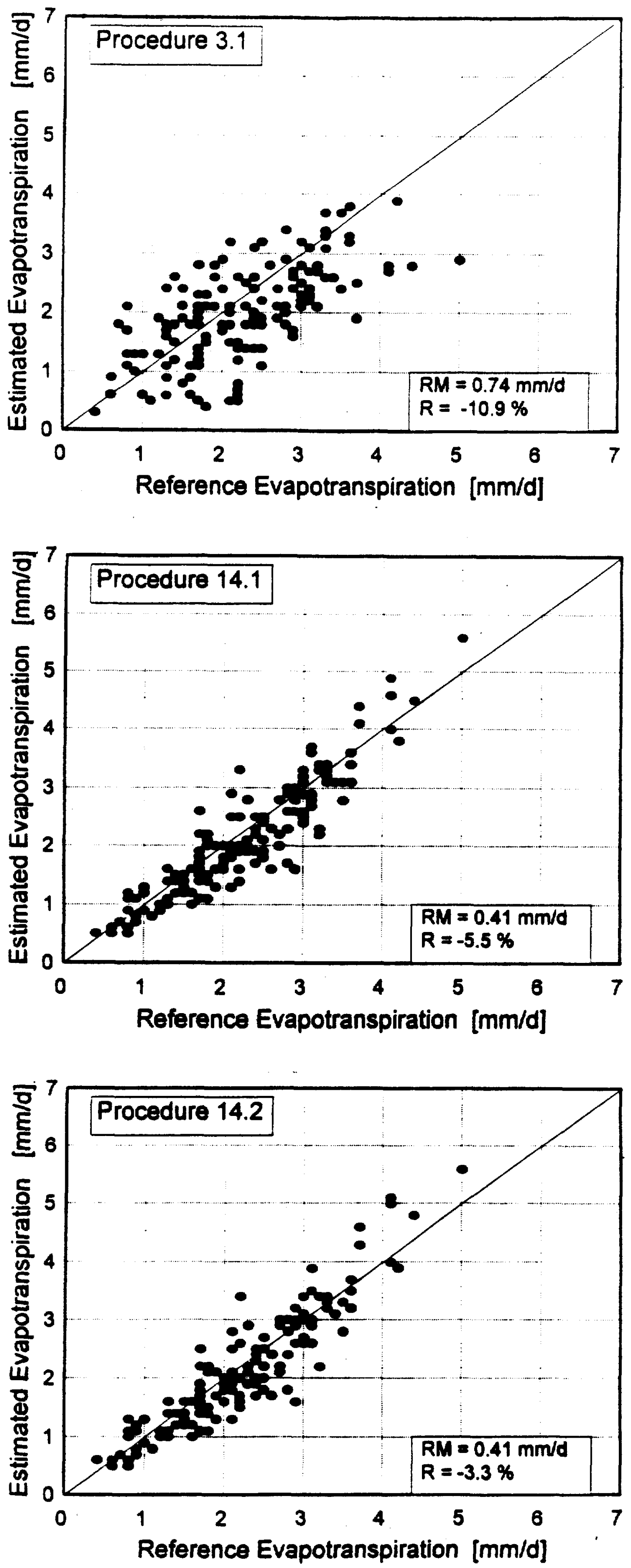

Figure 12. Comparison of daily areal evapotranspiration values estimated by the various procedures with the reference evapotranspiration values from the Hupselse Beek Basin for the prediction period 1 April to 31 August 1978.

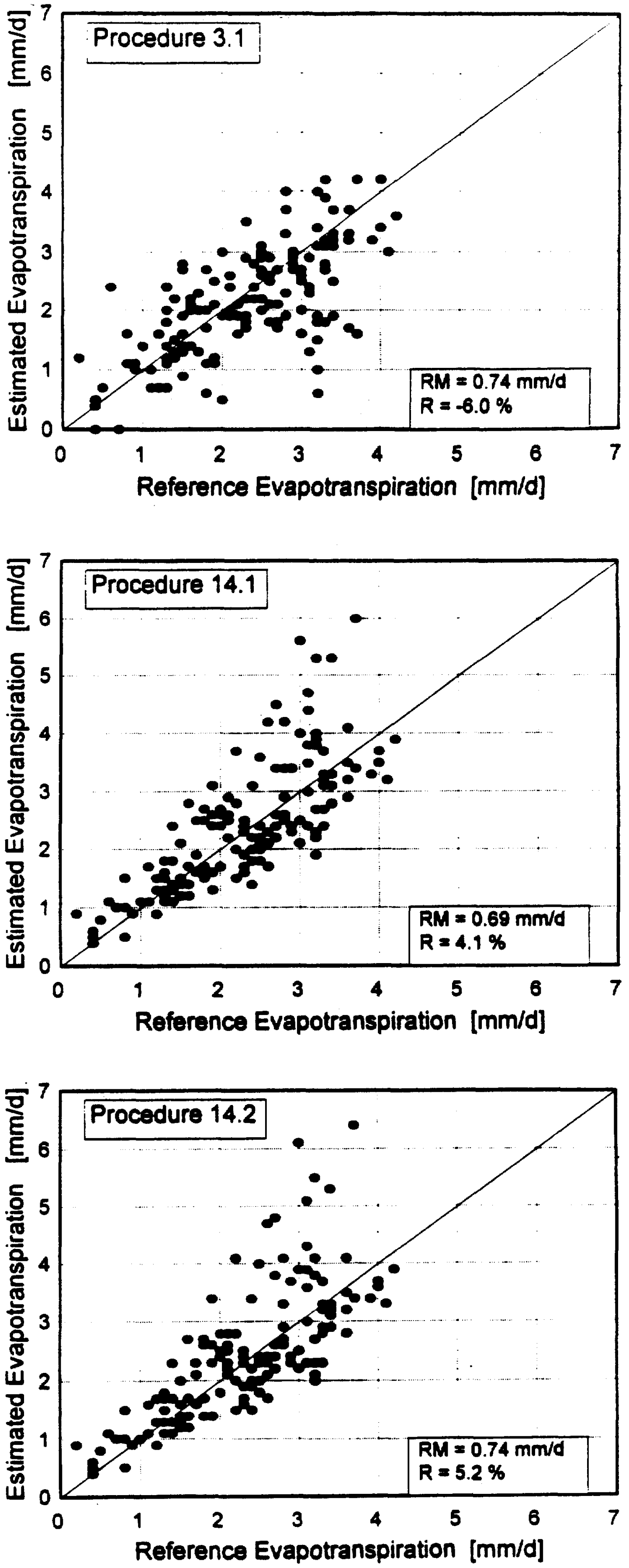

Figure 14. Comparison of daily areal evapotranspiration values estimated by the various procedures with the reference evapotranspiration values from the Hupselse Beek Basin for the prediction period 1 April to 31 August 1980.

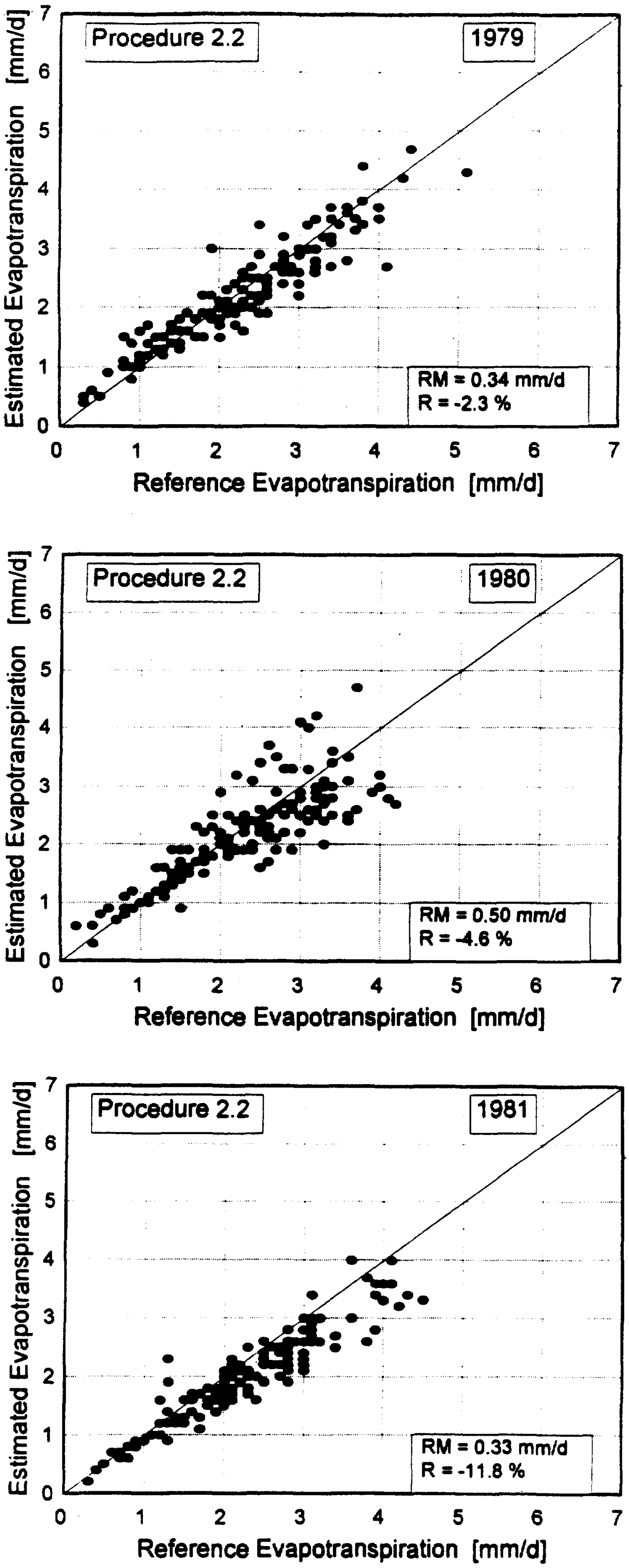

Figure 16. Comparison of daily areal evapotranspiration values estimated by procedure 2.2 (after calibration) with the reference evapotranspiration values from the Hupselse Beek Basin for the prediction periods 1 April to 31 August, 1979 to 1981.

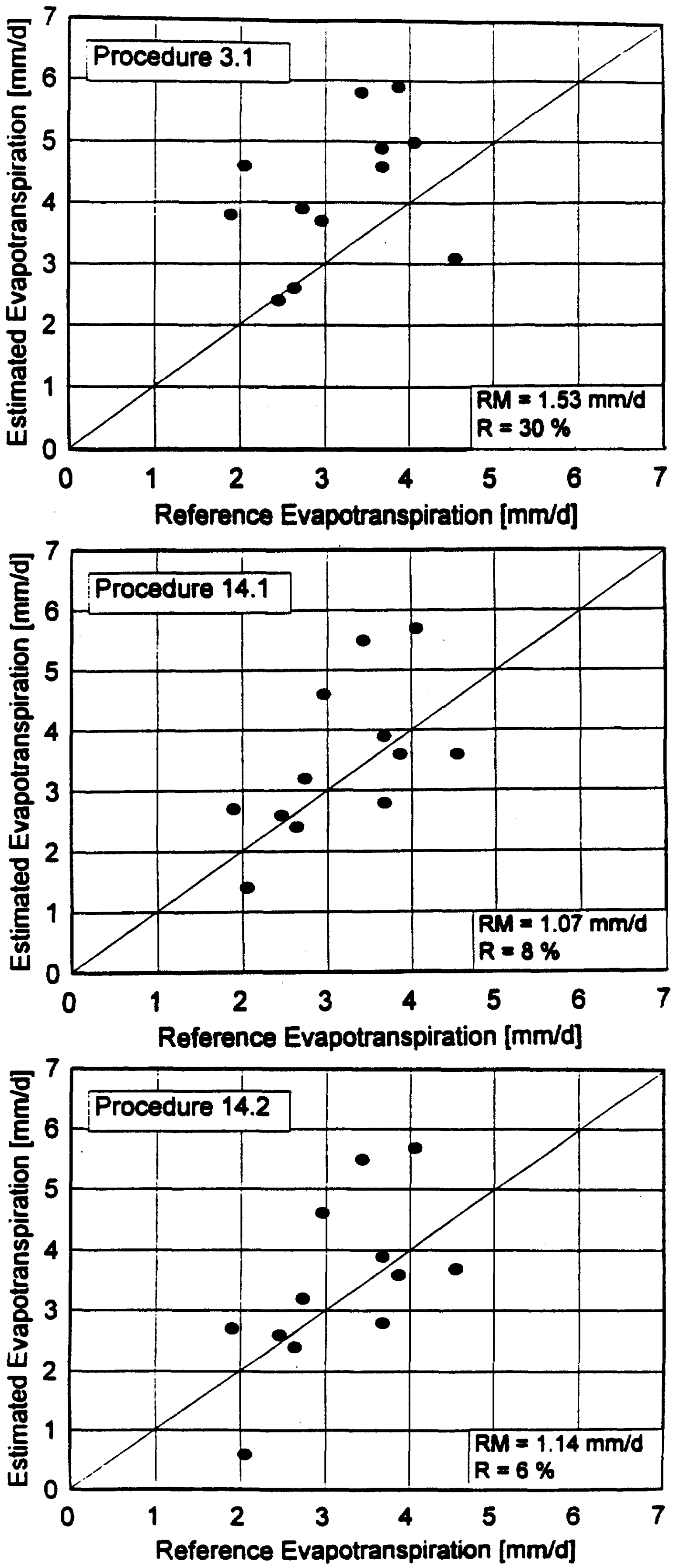

Figure 18. Comparison of daily areal evapotranspiration amounts estimated by the various procedures ("blind test" calculations) with the reference evapotranspiration values determined from the Lockyersleith daytime Bowen Ratio data for the selected test days.

A N N E X IV

DAILY AREAL EVAPOTRANSPIRATION AMOUNTS ESTIMATED BY THE VARIOUS PROCEDURES AND REFERENCE EVAPOTRANSPIRATION VALUES DETERMINED FOR THE HUPSELSE BEEK BASIN FOR THE PERIODS APRIL TO AUGUST 1982 AND APRIL TO SEPTEMBER 1983

("blind test" calculations)

Daily areal evapotranspiration amounts estimated by the various procedures and reference evapotranspiration values determined for the Hupselse Beek Basin for May 1982.

Date	Areal Evapotranspiration [mm/d]					
	Reference	Estimated by Procedures:				
		2.2	3.1	8.2	14.1	14.2
1	0.9	1.0	0.8	0.9	1.0	1.0
2	2.6	2.1	1.5	1.8	2.6	2.6
3	1.2	1.4	0.6	0.9	1.8	1.9
4	2.6	2.4	2.0	2.2	2.5	2.5
5	0.8	1.0	1.1	1.0	0.8	0.8
6	1.4	1.4	1.7	1.4	1.2	1.2
7	1.5	1.5	1.7	1.5	1.3	1.3
8	2.0	2.0	2.2	2.1	2.1	2.1
9	3.1	3.0	3.3	3.4	3.1	3.2
10	2.5	2.6	2.9	3.4	2.9	3.0
11	2.3	2.4	2.7	3.2	2.6	2.7
12	3.1	2.9	3.5	4.0	3.2	3.5
13	3.4	3.1	3.4	4.5	3.6	3.9
14	3.7	3.4	3.4	4.8	4.1	4.6
15	3.6	3.1	3.2	5.1	3.8	4.2
16	3.9	3.0	3.4	4.8	3.8	4.2
17	1.8	1.8	3.1	2.7	1.6	1.7
18	3.2	2.9	3.5	3.6	2.5	2.7
19	3.4	2.5	3.5	3.8	2.8	3.0
20	1.8	1.6	2.5	2.2	1.4	1.5
21	1.7	1.2	2.5	2.1	1.5	1.6
22	1.5	1.3	1.8	1.8	1.1	1.2
23	2.8	2.5	2.9	2.9	2.2	2.4
24	2.3	1.7	2.4	2.1	1.8	2.0
25	2.8	2.2	2.8	2.9	2.6	2.8
26	4.6	3.3	4.4	4.5	4.1	4.4
27	4.1	3.7	3.6	4.2	3.7	3.9
28	2.5	1.8	2.1	2.1	2.2	2.3
29	3.1	2.3	3.1	3.1	2.8	3.0
30	4.2	3.1	4.8	3.6	3.9	4.2
31	4.3	2.9	4.9	3.6	3.8	4.1
Total [mm]	82.7	71.1	85.3	90.2	78.4	83.5

Daily areal evapotranspiration amounts estimated by the various procedures and reference evapotranspiration values determined for the Hupselse Beek Basin for July 1982

Date	Areal Evapotranspiration [mm/d]					
	Reference	Estimated by Procedures:				
		2.2	3.1	8.2	14.1	14.2
1	2.7	2.4	2.8	3.2	2.7	2.6
2	3.9	3.4	4.4	4.9	4.0	3.9
3	0.7	1.0	1.3	1.3	1.3	1.2
4	3.1	2.4	2.4	3.1	3.1	3.0
5	3.8	3.0	3.2	3.8	3.5	3.5
6	2.1	1.7	2.2	2.4	2.2	2.2
7	3.4	3.0	4.2	4.7	3.4	3.5
8	4.1	3.2	4.7	2.0	3.9	4.0
9	4.4	3.6	5.1	2.1	5.2	5.1
10	2.6	2.0	2.2	1.2	2.8	2.8
11	3.5	2.6	5.1	1.6	3.5	3.5
12	4.0	3.0	5.0	1.7	4.3	4.3
13	3.9	2.8	4.8	1.5	4.2	4.2
14	3.7	2.6	3.9	1.2	4.2	4.2
15	3.7	3.2	4.0	2.8	3.0	3.0
16	3.1	1.9	3.1	1.0	2.6	2.6
17	3.2	2.2	4.0	1.2	3.1	3.1
18	3.8	2.4	4.4	1.1	3.4	3.4
19	2.8	1.7	3.2	0.7	2.4	2.4
20	3.0	1.8	3.3	0.7	2.9	2.9
21	3.2	1.9	2.7	0.8	2.7	2.7
22	2.4	1.3	2.2	0.5	2.1	2.1
23	2.5	1.4	2.6	0.5	2.3	2.4
24	2.1	1.1	2.3	0.3	1.9	1.9
25	2.1	1.1	2.0	0.4	2.0	2.0
26	2.1	1.1	1.5	0.4	1.7	1.7
27	2.5	1.6	2.6	1.0	1.9	1.9
28	3.0	1.8	3.1	1.0	2.7	2.7
29	3.4	2.0	3.5	0.9	4.0	4.0
30	2.5	1.9	2.1	0.6	4.7	4.8
31	3.0	2.2	1.3	0.5	5.5	5.6
Total [mm]	94.3	67.3	99.2	49.1	97.2	97.2

Daily areal evapotranspiration amounts estimated by the various procedures and reference evapotranspiration values determined for the Hupselse Beek Basin for April 1983

Date	Areal Evapotranspiration [mm/d]					
	Reference	Estimated by Procedures:				
		2.2	3.1	8.2	14.1	14.2
1	1.3	1.6	1.0	1.6	1.2	1.1
2	1.0	1.3	1.3	1.1	1.0	1.0
3	0.8	1.2	1.4	0.9	0.7	0.7
4	1.0	1.4	1.4	0.9	0.8	0.8
5	0.7	1.0	1.0	0.8	0.7	0.7
6	1.2	1.7	1.3	1.3	1.1	1.0
7	1.3	1.8	1.6	1.5	1.0	0.9
8	0.8	1.0	0.8	0.9	0.9	0.9
9	1.2	1.4	1.3	1.6	1.0	1.0
10	0.8	1.0	1.2	1.1	0.8	0.8
11	1.0	1.0	1.1	1.3	1.0	0.9
12	0.7	1.1	0.8	0.8	0.7	0.7
13	1.5	1.8	1.7	1.6	1.2	1.1
14	1.1	1.3	1.0	1.1	1.0	1.0
15	1.7	2.0	1.6	2.1	1.3	1.2
16	2.3	2.6	2.3	3.1	2.9	2.7
17	2.5	1.9	0.4	1.6	3.5	3.1
18	2.8	2.4	1.1	2.8	3.4	3.3
19	1.2	1.1	0.9	1.3	1.5	1.5
20	2.3	2.3	1.6	2.6	2.7	2.7
21	1.4	1.5	1.3	1.7	1.8	1.8
22	1.6	1.9	1.8	2.1	2.0	1.9
23	2.1	2.2	1.7	2.7	2.7	2.6
24	1.9	2.1	2.4	2.9	2.1	2.1
25	1.4	1.6	1.6	1.8	1.7	1.7
26	1.6	1.7	1.7	2.3	1.7	1.7
27	1.1	1.4	1.5	1.5	1.5	1.5
28	1.5	1.7	1.7	1.8	1.9	1.9
29	1.5	1.8	2.0	2.0	1.8	1.8
30	2.5	2.7	2.6	3.5	2.8	2.7
Total [mm]	43.8	49.5	43.1	52.3	48.4	46.8

Daily areal evapotranspiration amounts estimated by the various procedures and reference evapotranspiration values determined for the Hupselse Beek Basin for June 1983

Date	Areal Evapotranspiration [mm/d]					
	Reference	Estimated by Procedures:				
		2.2	3.1	8.2	14.1	14.2
1	4.2	4.3	2.8	4.6	6.5	6.7
2	3.0	3.0	3.1	3.6	3.7	3.9
3	3.8	3.6	3.8	4.6	4.2	4.4
4	3.9	3.8	3.2	4.5	4.8	5.0
5	3.1	3.2	3.6	4.3	3.6	3.8
6	3.3	3.6	3.8	4.5	4.4	4.5
7	4.5	4.0	3.9	5.2	5.4	5.6
8	2.8	3.4	2.2	4.0	4.0	4.2
9	2.3	2.5	3.0	3.1	2.6	2.7
10	2.6	2.4	2.4	3.1	2.8	2.9
11	4.3	3.9	3.9	4.9	4.6	4.8
12	3.6	3.3	3.1	4.4	4.1	4.2
13	4.1	3.9	2.4	3.5	4.2	4.3
14	2.9	2.6	1.4	2.4	3.2	3.2
15	3.2	3.1	2.5	2.9	2.8	2.9
16	2.6	2.3	2.2	2.8	2.7	2.8
17	4.0	3.6	3.5	3.9	4.1	4.1
18	3.3	3.0	3.2	3.7	3.7	3.8
19	3.7	3.3	5.2	4.5	3.6	3.6
20	4.8	3.9	4.6	4.5	4.8	4.9
21	4.3	3.8	4.1	4.4	5.2	5.3
22	4.2	3.8	4.1	4.0	5.2	5.3
23	4.6	3.0	3.9	3.4	4.2	4.3
24	2.9	3.3	3.4	4.1	3.1	3.2
25	2.4	2.8	3.1	3.7	2.8	2.9
26	3.4	3.4	3.7	4.6	3.6	3.6
27	2.4	2.4	2.7	2.7	2.3	2.3
28	2.6	2.4	1.7	2.7	2.8	2.9
29	0.7	0.7	1.0	1.1	0.7	0.7
30	1.0	1.2	2.0	1.9	1.2	1.2
Total [mm]	98.5	93.5	93.5	111.6	110.9	114.0

Daily areal evapotranspiration amounts estimated by the various procedures and reference evapotranspiration values determined for the Hupselse Beek Basin for August 1983.

Date	Areal Evapotranspiration [mm/d]					
	Reference	Estimated by Procedures:				
		2.2	3.1	8.2	14.1	14.2
1	2.1	2.3	2.4	1.8	1.8	1.8
2	1.9	1.7	2.6	1.5	1.2	1.2
3	2.8	1.8	2.7	0.9	1.9	1.9
4	1.2	1.3	1.7	1.5	0.7	0.7
5	2.2	1.6	2.3	1.0	1.3	1.3
6	0.2	0.3	0.6	0.8	0.3	0.2
7	2.7	2.0	3.3	2.4	2.0	2.1
8	4.0	2.4	3.0	0.8	2.8	2.9
9	2.8	2.3	2.9	0.8	3.1	3.1
10	2.5	2.0	3.3	0.7	2.5	2.5
11	2.1	1.8	3.1	0.7	2.3	2.3
12	2.1	1.4	2.1	0.5	1.7	1.8
13	1.9	1.3	1.8	0.4	1.6	1.6
14	1.4	1.1	2.1	0.5	1.1	1.2
15	3.2	1.5	3.1	0.8	2.2	2.3
16	2.8	1.3	2.1	0.4	1.8	1.8
17	1.4	0.7	2.4	0.2	1.0	1.0
18	3.5	1.5	3.1	0.5	2.5	2.5
19	4.0	1.5	1.8	0.4	2.8	2.8
20	1.9	1.3	2.6	0.5	2.5	2.5
21	2.0	2.6	2.8	3.5	1.8	1.8
22	2.9	1.9	3.4	4.1	2.3	2.3
23	2.7	1.4	2.4	0.8	2.0	2.0
24	1.2	1.6	2.7	0.4	2.0	2.0
25	1.7	1.7	2.0	0.4	2.5	2.5
26	0.9	1.2	1.9	0.3	1.7	1.7
27	1.4	1.4	2.9	0.3	1.9	1.9
28	1.4	1.1	1.2	0.2	1.9	1.9
29	1.1	1.2	1.4	0.3	2.2	2.2
30	1.1	1.1	2.1	0.3	1.9	2.0
31	0.9	1.2	1.3	0.3	2.4	2.3
Total [mm]	64.0	47.5	73.1	28.0	59.7	60.1

ANNEX V

SHORT DESCRIPTION OF PROCEDURE 2.2

- REPRESENTATIVE OF GROUP I

Françoise Meulenberghs and Daniel Gellens

Bruxelles, August 1991

The transformation factor differs according to the vegetative cover and also depends on the daily weather conditions; it is given by

$$f_v = \frac{(1 - \alpha_v)\ R_s - R_L - G}{(1 - \alpha_w)\ R_s - R_L - G}$$

where α_v is the albedo of the vegetative cover.

2.2 Submodel: interception-throughfall

The object of this first part of the model is to simulate the daily water balance in the vegetative canopy.

The first task consists of calculating the potential interception, IP, i.e. the amount of rainfall that can be caught by a completely dry vegetative canopy. In this respect, two major types of plant grouping are considered: pastures and crops on the one hand, forests on the other.

For pastures and crops, the potential interception is a function of the amount of rainfall, P, and of the leaf area index, LAI; it is expressed as

$$IP_p = -0.0111P^2 + 0.245P - 0.0109(LAI)^2 + 0.20(LAI) + 0.0271(LAI)P - 0.420$$

and limited to a maximum value defined by

$$IX_p = 0.935 + 0.498\ (LAI) + 0.00575\ (LAI)^2$$

with

$$P_x = 11.05 + 1.223\ (LAI)$$

In forest canopies, the potential interception is a function of the rainfall amount, P, the rainfall intensity (i = P/DU, in mm per ten minutes), and the evaporative power of the atmosphere.

In order to use only a small number of input data, the potential evapotranspiration is used as an index of that evaporative power. Thus, for deciduous forests:

$$IP_d = (-0.0131P^2 + 0.2491P)\left(\frac{2.750}{i + 1.2363}\right)(0.04ETP + 0.9279)$$

which is limited to a maximum value

$$IX_d = 1.2\left(\frac{2.750}{i + 1.2363}\right)(0.04ETP + 0.9279)$$

with P_x = 10 mm.

For coniferous forests:

$$IP_C = (-0.0216P^2 + 0.4915P)\left(\frac{4.0422}{i + 2.7872}\right)(0.0694ETP + 0.9486)$$

which is limited to a maximum value

$$IX_C = 2.8\left(\frac{4.0422}{i + 2.7872}\right)(0.0694ETP + 0.9486)$$

with P_x = 12 mm.

- The moisture content, $WD1_d$, at the end of the day.

It is known that the quantity of moisture lost by evapotranspiration from the soil decreases gradually as the soil dries up. In particular, in the absence of throughfall:

$$E1 = WD1_{d-1} - WD1_d = ETP_g \frac{WD1_{d-1}}{WD1X}$$

2.4 Submodel: percolation

This final submodel computes the water balance of the lower layer of the zone of aeration.

Only one parameter is needed to characterize the catchment from the point of view of this submodel, namely the amount WD2X of moisture available, at field capacity, from the lower layer of the zone of aeration.

The input variables are: the quantity of water, RECH, that infiltrates through the upper layer; the moisture content, $WD2_{d-1}$, of the lower layer at the end of the previous day.

The input variables are:

- the moisture losses, E2, by evapotranspiration from the lower layer;
- the amount of percolation water, PER, feeding the aquifer;
- the moisture content, $WD2_d$, at the end of the day.

Note that the expression used for calculating the effective evapotranspiration from this layer is the same that used in the preceding submodel.

2.5 Effective evapotranspiration

Effective evapotranspiration is the sum of the amounts of water released in the form of vapour by the vegetative canopy and from the two layers of the zone of aeration of the soil.

The full description of the procedure can be found in Bultot and Dupriez (1976, a and b), Bultot et al. (1983) and Bultot and Dupriez (1985).

2.6 Vegetation cover and precipitation

The model used is applied separately to the different types of vegetation. The effective evapotranspiration over the catchment is computed by means of a weighted mean. Seven vegetative covers and the impervious surfaces may be considered.

For medium sized catchments, rainfall data are areal rainfall over the whole catchment computed, for example, by the Thiessen method.

3. Input Data Needs

Preferred input data are:

R_s - daily mean global solar radiation, W m^{-2};

S - daily percentage of possible sunshine;

4. Application of the Procedure

4.1 Source of data

a, b — in the formula for E_a in 2.1 above are experimental values estimated for Belgian climatological conditions (Bultot et al., 1983);

R_L — if not available, this is estimated by the Brunt formula with parameters assessed for Belgian climatological conditions (Bultot et al., 1983);

G — if not available, this is estimated by a semi-empirical relation with parameters assessed for Belgian climatological conditions (Bultot and Dupriez, 1974);

The coefficients in the interception formulae are experimental values estimated in Germany for low vegetation cover (von Hoyningen-Huene, 1981) and in Belgium for forests (Bultot et al., 1972);

WD1X — is estimated by calibration;

WD2X = WDX - WD1X;

O_{sr} — is estimated by calibration for each season.

4.2 Limitations

(a) The catchment has to be closed and without important irrigation or drainage. The river discharge may not be re-distributed in time by water storages and may not include exportation through canals.

(b) The quality of the calibration depends on the length of the available observation period: this should be long enough so that the variation of groundwater storage is negligible in the water balance in comparison with accumulated precipitation and outflow at the outlet.

(c) Missing data must first be estimated before running the model.

5. Calibration of Procedures

5.1 Determination of initial surface runoff rates, O_{sr}

For a period of surface runoff, and provided that continuous observations of the discharge at the outlet of the catchment are available:

$$\overline{O}_{sr} = \frac{\sum O_s}{\sum SS}$$

On the observed hydrograph, the total flow is split up into two components, according to a conventional method, in order to evaluate the amount contributed by surface runoff.

In addition, in order to estimate the submersion surplus, it is necessary to apply the "interception-throughfall" submodel over the entire reference period, as it yields the daily values of both the throughfall and the residual potential evapotranspiration. Further, a submersion surplus can occur only on condition that the througfall is more than the residual potential evapotranspiration. It is thus sufficient merely to add up the positive values of the difference between these terms to get an approximate value of the sum of the submersion surpluses:

i	-	rainfall intensity, mm/10 min;
EGT	-	throughfall, mm;
ETP_g	-	residual potential evapotranspiration at the soil level, mm;
WD1	-	available water in the upper layer of the aeration zone of the soil, mm;
WD2	-	available water in the lower layer of the aeration zone of the soil, mm;
WD1X	-	maximum available water in the upper layer of the aeration zone of the soil, mm;
WD2X	-	maximum available water in the lower layer of the aeration zone of the soil, mm;
SS	-	submersion surplus, mm;
O_s	-	surface runoff, mm;
O_{sr}	-	surface runoff rate,
E1	-	evapotranspiration from the upper layer of the aeration zone of the soil, mm;
E2	-	evapotranspiration from the lower layer of the aeration zone of the soil, mm;
ETR	-	effective evapotranspiration, mm;
E_v	-	evaporation of water retained on the vegetative canopy;
WV_d	-	quantity of water retained on the vegetative canopy at the end of the day;
IR	-	actual interception
DU	-	duration of the daily precipitation

6.2 Definitions of terms

Potential evaporation:

"The maximum quantity of water capable of being lost as water vapour in the atmospheric direction under given meteorological conditions from a continuously wetted surface (crop, soil or other surfaces) with physical characteristics identical to the surface parameters of the investigated area, for example identical values of reflectivity, emmissivity, roughness parameter etc.".

Evapotranspiration (actual evapotranspiration):

"The quantity of water evaporated as water vapour by the soil and transpirated by plants in the atmospheric direction under existing meteorological and soil moisture conditions".

Areal evapotranspiration:

"Mean areal value of the evapotranspiration from a clearly identified area greater than 1 km^2, for instance a river catchment".

ANNEX VI

SHORT DESCRIPTION OF PROCEDURE 14.1

- REPRESENTATIVE OF GROUP II

Jerzy Jaworski

Warsaw, July 1991

means of equation (3) at the end of time interval "i" equals SMU at the beginning of time step "i+1". The first of the two fictitious reservoirs mentioned above represents the upper layer of the unsaturated zone where most of the crop-root system occurs. The root system supplies the evapotranspiration of plants with water from this reservoir until the whole available soil moisture is taken up and the storage becomes a minimum (SMU = MINU). When the first reservoir is empty, the root system penetrates deeper and draws the water from the second reservoir (lower layer of the unsaturated zone). If precipitation occurs, the first reservoir is filled up by infiltration until the soil moisture equals the maximum storage, MAXU. When this storage is exceeded, filtration, Hu, to the lower layer occurs. If the storage of the second reservoir exceeds MAXL, percolation, H, occurs in the direction of groundwater.

In this way, the reservoirs are limited by soil water characteristics, MAXU, MINU, MAXL and MINL, which can be easily estimated knowing the content of floatable soil particles (Jaworski, 1980).

Finally the procedure is applied for the calculation of mean values of potential evaporation, areal evapotranspiration and soil moisture of the whole basin. These values are estimated as weighted means; the weights are the F_{NP} parameters which represent the particular areas of the quasi-homogeneous fields.

The detailed form of eguation (1) applied to the period May-October for the estimation of the r_c-value is as follows:

$$r_c = a_1 \, (SMU + 0.5P)^{a_2} - 100 \; [s/m] \tag{1a}$$

In April, when plants are not yet fully developed, the plant cover resistance is estimated by means of equation (1b):

$$r_c = 684\left[\frac{10 \; SMUP}{2.064 \; R_n + 200}\right]^{-1.038} - 100 \qquad [s/m] \tag{1b}$$

In the cold period, namely in the period from November to March, the r_c-value is estimated using equation (1c):

$$r_c = 1739\left[\frac{10 \; SMUP}{2.064 \; R_n + 200}\right]^{-1.548} - 100 \qquad [s/m] \tag{1c}$$

Under soil drought conditions, when

SMU = MINU and SML $\leq$ 72,5%

the diffusive plant cover resistance is calculated by equation (1d), which is valid in the range 40% $\leq$ SMLP $\leq$ 72,5%, namely:

$$r_c = 3791.7 \; 10^6 \; SMLP^{-3.811} - 100 \qquad [s/m] \tag{1d}$$

The above mentioned SMUP and SMLP terms are estimated by means of equations (4) and (5) of section 4.1 of the main report. All the symbols are defined below under "Symbols and definitions".

It should be stated that evaporation from intercepted precipitation is not estimated separately, because the term is already included in the estimated areal evapotranspiration, E. If a shallow water table occurs, soil moisture, SMU_o, is calculated also by means of equation (3), but under these conditions the equation is valid only in the range

$$0,9 \; MAXU \leq SMU_o \leq MAXU$$

- for daily time periods, the assumption $G \approx 0$ can be made (Jaworski and Paszynski, 1978);

- the net radiation (R_{ng}) is estimated empirically, so that only the information concerning sunshine duration "s" (hours day^{-1}) is needed (De Jong, 1973)

- the net radiation above bare soil, R_{ns}, is estimated as a function of R_{ng};

- daily values of real precipitation are estimated knowing daily amounts of precipitation measured by a standard Hellmann gauge at a height of 1 m; this estimation method is presented in (Jaworski, 1988).

Taking into account the above, the following minimum input data can be used: T_a, s, u_a, e_a, p, P_1, P, ds where: s is sunshine duration, in hours day^{-1}; P_1 is daily amount of precipitation measured in one station at the height of 1 m in mm day^{-1}.

Using only the minimum input data, a loss of accuracy in estimated E can be expected because of the less exact measure of radiation assessment.

In the proposed procedure, the following constant characteristics of the investigated area should be known:

(a) - longitude and latitude of its centroid;

(b) - area of the investigated basin, km^2;

(c) - mean content of floatable particles fraction of the soil $\varnothing < 0{,}02$ mm (in the soil layers 0-0.4 m and 0.4-1 m), percent;

(d) - field capacity of the soil (soil layers 0-0.4 and 0-1 m), mm;

(e) - approximate depth of the groundwater table, cm;

(f) - height of meteorological measurements above the active surface, z_a, m;

(g) - land use in percent:
- bare soil
- grass
- agricultural crops
- forest
- free water surface
- irrigated areas

(h)
- area of grass (meadows and pastures) with a shallow groundwater table, km^2
- area of grass (meadows and pastures) with a deep groundwater table, km^2
- area of forests with a shallow ground water table, km^2
- area of forests with a deep ground water table, km^2

(i) - type of agricultural crops, percent;

(j) - mean height of the main agricultural crops in March, April, May, June, July, August, September, October, m or cm;

(k) - mean height of grass in the above mentioned months, m or cm;

(l) - mean height of forest trees m;

z_o - is calculated by means of the method proposed in (Szeicz, Endrödi and Tajchman, 1969);

SMUP - is estimated by means of:

$$SMUP = 100 - [(MAXU - \overline{SMU}) \frac{100 - 40}{MAXU - MINU}] \quad [\%] \qquad (4)$$

where $\overline{SMU}$ = SMU + 0.5 P

SMLP - is calculated by:

$$SMLP = 100 - [(MAXL - SML) \frac{100 - 40}{MAXL - MINL}] \quad [\%] \qquad (5)$$

The above mentioned symbols are defined below under "Symbols and Definitions".

4.2 Limitations of procedure

The developed procedure is in principle limited to humid and subhumid areas, and should be used above all in well described, closed basins.

5. Calibration of Procedure

No calibration is required.

6. Symbols and Definitions

6.1 Symbols

a_1, a_2 - numerical parameters depending on mechanical soil composition

a_i, a_k - numerical parameters used in equation (1)

ds - snow cover depth, cm

E - areal evapotranspiration (including interception) estimated by the procedure, mm d^{-1}

$\overline{E}$ - mean yearly areal evapotranspiration (including interception) estimated by the procedure, mm $year^{-1}$

EP - potential evaporation estimated by means of the equation proposed by Penman-Monteith (10), mm d^{-1}

e_a - actual vapour pressure at height z_a, kPa

F_{NP} - parameter representing the particular areas of the quasi-homogeneous fields

G - heat exchange below the interface, W m^{-2}

H - filtration (percolation) from the lower layer of the unsaturated zone in the groundwater direction, mm d^{-1}

Δ - slope of the saturation vapour pressure temperature curve at air temperature, kPa K^{-1}

6.2 Definitions

- Evapotranspiration (actual evapotranspiration):

The quantity of water evaporated as water vapour by the soil and transpirated by plants in the atmospheric direction under existing meteorological and soil moisture conditions.

- Areal evapotranspiration:

The quantity of water evaporated as water vapour by the soil and transpirated by plants in the atmpspheric direction under existing meteorological and soil moisture conditions from a clearly identified area greather than 1 km^2.

- Potential evaporation:

The maximum quantity of water capable of being lost as water vapour in the atmospheric direction under given meteorological conditions from a continiuonsly wetted surface (crop, soil or other surfaces) with physical characteristics identical to the surface parameters of the investigated area, for example identical values of reflectivity, emmissivity, roughness parameter etc.

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ANNEX VII

SHORT DESCRIPTION OF PROCEDURE 3.1

- REPRESENTATIVE OF GROUP IV

Raoul J.Granger

Saskatoon, July 1991

The calculation procedures used and the equations describing the various components have been given in detail by Morton (1983), therefore only a general presentation of the model structure and flow is presented, and only the equations describing the major components are reproduced here.

For the station or area under consideration:

- the model requires values for the latitude, the altitude or average atmospheric pressure and the average annual precipitation. The ratio of the atmospheric pressure to that at sea level is used in the calculation of albedo, atmospheric turbidity and long-wave radiation loss.

For each calculation period:

- the model requires data for the average air temperature, T, the average dew-point temperature, T_D, the ratio of observed to maximum possible sunshine duration, S, and the date. Alternative forms of humidity and radiation index data could also be used; and the model can be applied to a range of period lengths;

- the saturation vapour pressures at the dew-point temperature, υ_D, and at the air temperature, υ, and the slope of the saturation vapour pressure curve at the air temperature, Δ, are calculated;

- the model calculates the extra-atmospheric global radiation, G_E, based on various angles and functions related to the latitude and the earth's position in its orbit around the sun;

- an estimate of the global radiation at the surface, R, is produced based on an estimate of its clear-sky value, R_o, using:

$$R_o = R_E\tau[1 + (1 - \tau/\tau_a)(1 + a_o\tau)]$$

$$R = SR_o + (0.08 + 0.30S)(1 - S)R_E$$

where τ is the transmittancy of clear skies to direct beam solar radiation, τ_a the part of τ that is the result of absorption, and a_o is the clear-sky albedo;

- the net long-wave radiation loss for soil-plant surfaces at the air temperature is calculated from:

$$R_L = \epsilon_o\sigma(T + 273)^4[1 - (0.71 + 0.007\upsilon_D p/p_s)(1 + \rho)]$$

where ϵ_o is the emissivity, σ is the Stefan-Boltzmann constant, and ρ is the proportional increase in atmospheric radiation due to clouds;

- the net radiation for soil-plant surfaces at the air temperature is produced from an estimate of the albedo of the surface and the radiation components estimated above, using:

$$R_T = (1 - a)R_s - R_L;$$

- the air temperature;

- the ratio of observed to maximum possible sunshine duration, or the observed sunshine duration, or the observed global radiation.

4. Application of procedure

WREVAP is an operational procedure designed specifically to produce estimates of areal evapotranspiration. It can be applied with very few restrictions to any region for which the appropriate input data are available. However, Morton (1983) and Morton et al. (1985) present the following limitations for the model:

(i) it requires accurate humidity data;

(ii) it is best applied to time periods greater than five days;

(iii) it cannot be used near sharp environmental discontinuities, because the advection of heat and water vapour alters the feedback relationships upon which the method is based;

(iv) it requires temperature and humidity inputs from a station whose surroundings are representative of the area of interest, and

(v) it cannot be used to predict the effects of natural or man-made changes to a surface because it neither uses nor requires knowledge of the soil-vegetation system and because post-change temperatures and humidities are not predictable.

The CRAE model (within WREVAP) can be applied to a number of hydrological situations. With independent estimates of each of its terms (including evapotranspiration), the water balance for a drainage basin becomes a much more useful tool. Morton (1983) provides examples of the analysis of the changes in basin storage and the seasonal water balance for a number of basins, with operational estimates of evapotranspiration provided by this model.

Morton (1983) also demonstrates the usefulness of independent estimates of evapotranspiration, along with knowledge of basin storage, to runoff prediction and flow forecasting.

Whereas constraint (v) above indicates that the model cannot be used to predict the effects of changes, it can, however, detect and monitor the hydrometeorological effects of climatic or land-use changes once temperature, humidity and insolation data become available.

5. Calibration of procedure

The CRAE model within WREVAP does not require any calibration prior to use. Morton et al. (1985) state that the complementary relationship "permits areal evapotranspiration to be estimated from its effects on the routinely observed temperatures and humidities used in computing potential evapotranspiration, thereby avoiding the complexities of the soil-plant system and the need for locally callibrated coefficients. This means that the results are independent and falsifiable, so that errors in the associated assumptions can be detected and corrected by progressive testing against long-term water balance estimates of river basin evapotranspiration from an ever-widening range of environments". Data from river basins in Canada, Ireland, USA, Australia, New zealand, Brazil and a number of countries in Africa were

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