CHAPTER 5. APPLICATIONS OF WAVES

5.1 Modelling Hydrologic Processes Using WAVES

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Abstract

WAVES was tested using the energy flux and soil moisture measurements from the First ISLSCP Field Experiment (FIFE) and Hydrologic Atmospheric Pilot Experiment and Modélisation du Bilan Hydrique (HAPEX-MOBILHY). The simulated net radiation, evapotranspiration and soil moisture content agreed well with the observations and with previous studies of transpiration and soil evaporation. The success of the model was due to the reasonably realistic treatment of the soil and canopy processes. The utility and limitations of the model are discussed.

5.1.1 Introduction

The physical and biological processes describing the surface water, energy and solute balances of the plant–soil–atmosphere system are, in general, well understood. Models of that system can be formulated at almost any level of complexity with as many or as few processes as required. The level of model complexity is usually determined by the application.

Historically, physically based models have been developed to represent the real world with increasing detail. The place and use of such models, and the information contained in the data required to run them, have been debated in hydrology literature for over 20 years, most recently by Beven (1989, 1993), Hauhs (1990), Wheater and Jakeman (1993) and Barnes (1993). These authors argue that physically based models are most appropriately used in exploring the interactions between processes and fluxes under different management and/or climatic regimes, given clearly stated assumptions about which small scale processes are relevant.

In Australia, most environmental degradation is associated with changes in the surface water balance induced by changes in land cover. The temporal and spatial scales over which these changes evince themselves precludes field experimentation as a wholly sufficient or practical investigative tool for identifying optimal or appropriate land use. Decision-makers are therefore reliant on models, especially physical process models, for predicting expected changes in the landscape; the diversity of recent hydrological modelling tools in use in Australia (see Grayson and Chiew 1994 and Hatton *et al.* 1994 for recent reviews) is testament to this need.

The soil water balance of many Australian land systems does not have to be treated with a fully three-dimensional model (*sensu* Hatton *et al.* 1992, Vertessy *et al.* 1993), but rather may be approximated with a one-dimensional treatment. For such systems, the CSIRO Division of Water Resources developed the physically based ecohydrological model WAVES to enable the simulation of land system behaviour under alternative vegetation management and climatic variation.

The WAVES model predicts the dynamic interactions, and fluxes of mass and energy, within soil–vegetation–atmosphere systems. The model adopts a one or two layer canopy representation with a soil layer underneath. The aerodynamic resistance at the top of the canopy is determined based on Monin–Obukhov surface layer similarity theory and the within canopy aerodynamic resistances are estimated using the mixing-length approach (Raupach and Thom 1981). The boundary layer resistances are neglected for simplicity. The model formulates the physiological control on transpiration using the canopy resistance calculated as a function of the net assimilation rate, and the vapour pressure deficit and CO_2 concentration at the canopy surface. The soil hydrology is described by the Richards equation. A distinguishing feature of the model is to couple the soil–vegetation–atmosphere system by changing the value of the saturation vapour pressure deficit of air in the canopy. The model can be used to predict plant growth using a saturation rate kinetics formulation and to simulate solute transport in the soil (Hatton *et al.* 1992, Wu *et al.* 1994, Salama *et al.* 1999, Dawes and Short 1993).

There is a need to test and evaluate models against data sets from well-designed field experiments so that improvements or simplifications can be made. Over the last decade, several large-scale data sets have been collected, and are useful for this purpose (Shuttleworth 1991). In this paper, we test the energy and water balance components of WAVES with data obtained from the First ISLSCP Field Experiment (FIFE) and Hydrologic Atmospheric Pilot Experiment and Modélisation du Bilan Hydrique (HAPEX-MOBILHY). The plant growth and solute transport features of the model are not included in these tests. We also compare model performance against expected behaviour as described in the literature.

The data used in the present study were obtained from the First ISLSCP Field Experiment (FIFE) (Sellers *et al.* 1988) and Hydrologic Atmospheric Pilot Experiment and Modélisation du Bilan Hydrique (HAPEX-MOBILHY) (André *et al.* 1988). We first describe the experimental sites and the type of data that were available, followed by the assignment of model parameters based on soil and plant properties.

5.1.2 Experiments and Data

FIFE was conducted during the period of May to October 1987 over a 15 km × 15 km experimental area, situated 39° 00' N 96° 30' W in northeastern Kansas (Sellers *et al*. 1988). The vegetation of the experimental area consists primarily of native tall prairie grass, the growing season of which is from mid-March to mid-October. The modelled area is the King's Creek catchment, located in the northwestern quadrant of the FIFE experimental domain. During FIFE 1987, four intensive field campaigns (IFCS 1–4) were organized to measure surface fluxes. IFC 1 (May 26 to June 6) was targeted at capturing the vegetation 'green-up' phase of late spring, IFC 2 (June 25 to July 11) was to monitor the 'peak-greenness' stage of the vegetation, IFC 3 (August 6 – 21) was intended to capture soil moisture 'dry-down' conditions in the late summer, and IFC 4 (October 5 – 16) was targeted at characterizing the fully senescent phase of the vegetation (Sellers *et al.* 1992b).

The raw meteorological data, consisting of wet and dry bulb temperatures, wind speed, downward shortwave radiation, and precipitation, were taken every 30 minutes from Super-AMS station 5 (2123-SAM). The data were filtered manually to remove bad values and to fill in missing data. The surface fluxes of sensible and latent (evapotranspiration) heat from Bowen Ratio Station 2 (1916-BRS) located near the King's Creek gauging station were used to test the model. These flux data were also filtered and edited manually. Mean daily values were calculated for vapour pressure deficit and wind speed, maximum and minimum temperatures were selected, and daily total solar radiation calculated for input into WAVES.

The HAPEX-MOBILHY experiment took place at 43° 41' N 00° 06' W in southwestern France over an area 100 km × 100 km. The area was divided into two parts, *ie.* a forest region (40%) and a mixed agricultural region (60%). The forest region was nearly homogeneous with some large clearings of up to 10 km^2. In the agricultural region the main crops were corn, oats, and soya bean (André, *et al*. 1988). During a Special Observing Period (SOP), a number of surface networks operated in the HAPEX-MOBILHY region, including a set of 12 specially designed SAMER stations. The SAMER stations measured meteorological variables and surface energy fluxes, from which evapotranspiration was calculated. A detailed description of the surface networks can be found in André *et al*. (1988) and Goutorbe (1991). In addition, soil moisture contents were measured at the SAMER sites using the neutron scattering method (Cosby *et al*. 1984). The measurements were made at intervals of 10 cm starting from the soil surface to 1.6 m on weekly basis.

The SAMER data were recorded on a 15-minute interval at 12 sites uniformly distributed over the region. The accuracy of the data has been examined by Goutorbe (1991) using different methods. It was found that over a 15-minute interval the typical error for the sensible heat flux was 12% over short vegetation and 25% over tall crops. The error in evapotranspiration over a 15-minute interval was about 25%. In this study , the measurements made at the SAMER site 3 were used. The main crop at this site was soya bean. Daily climate data for input to WAVES were calculated as for the FIFE experiment.

5.1.3 Parameter estimation

The dominant soil in the King's Creek catchment is silty clay loam and the depth of the soil layer is 1.6 m. The soil physical properties of saturated moisture content, θ_s, air-dry moisture content, θ_d, saturated hydraulic conductivity, K_s, capillary length scale, λ_c, and a shape parameter, C, were assigned default values on the basis of the FIFE staff science soil survey work by applying Broadbridge–White model rules of thumb to the Clapp and Hornberger classification of soil types (Clapp and Hornberger1978; White and Broadbridge 1988).

Table 5.1 lists the model parameter values used for FIFE. Estimation of the soil hydraulic properties is described above. Values of soil and canopy albedo, and roughness length for bare soil were adopted from Brutsaert (1982). The canopy roughness length was determined as a fraction of the vegetation height, which was measured for each IFC. The leaf area index (LAI) was measured within the King's Creek catchment.

The main soil type at SAMER site 3 is silty clay loam. The soil hydraulic properties, albedo, and soil roughness length were estimated in a similar way as for FIFE (Table 5.1). The period for which the energy flux measurements were available corresponds to a growing season. We assume a linear relationship between leaf area index, canopy roughness and vegetation height, which was measured. The leaf area index was set to 0.5 for emerging plants and to 3.0 at the full development. This relationship is in agreement with field measurements at SAMER site 5 (Ben Mehrez *et al.* 1992). In both FIFE and HAPEX-MOBILHY simulations, vegetation parameters were set to those used by Dawes *et al.* (1997), given that in both experiments vegetation had C_3 photosynthesis pathways, and the sites were modelled without topographic slope.

As with any model which redistributes soil water *via* a continuity equation, a lower boundary condition must be specified. In WAVES, this is done by a user specified factor b varying between 0 and 1 times saturated hydraulic conductivity. No information was available in this regard for either field experiment. This boundary condition was estimated to give stable soil water profiles in the HAPEX simulations; this equated to a potential deep drainage rate of 0.1 mm day^{-1} when the lower boundary is saturated. The same value was used in the FIFE simulations.

5.1.4 Comparison with field measurements

a. Net radiation

The net radiation for ground surface and vegetation canopy was simulated by WAVES. For most applications, the downward longwave radiation is not routinely measured. As a result, it was calculated from air temperature and vapour pressure using Stefan–Boltzman's equation. The input required for estimating net radiation are the incoming solar radiation, air temperature and vapor pressure. Fig. 5.1 shows the comparison of calculated and measured net radiation for FIFE and HAPEX-MOBILHY. The correlation coefficient was 0.96 and the best fit slope through the origin was close to unity. The root mean square error (RMSE) was 20 W m^{-2} for the two experiments. It is clear that in both cases the model produced good estimates of It should be mentioned that in the calculation, the surface emissivity was set to a constant value of 0.97 and the atmospheric emissivity was calculated as a function of air temperature and vapor pressure. Brutsaert (1982) showed that equation (22) tends to yield smaller values of atmospheric emissivity compared to empirical equations when the vapor pressure is less than 12.0 hPa. As a result, by using this relationship the net radiation could be underestimated. In the calculation the atmospheric emissivity was corrected according to Brunt (1932) for vapor pressure less than 12.0 hPa.

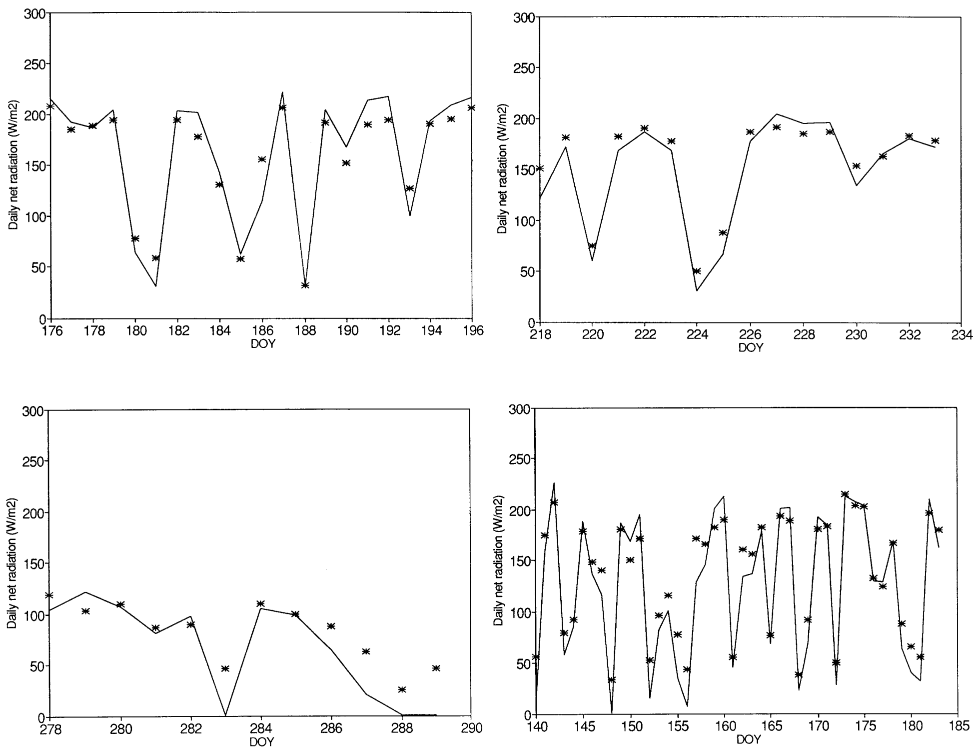

Fig. 5.1. Comparisons between simulated and observed daily net radiation during the periods of three IFCs in FIFE and SOP in HAPEX-MOBILHY. The correlation coefficient for FIFE data is 0.96 and the mean slope through the origin is 1.00. For HAPEX-MOBILHY data, the correlation coefficient is 0.96 and the mean slope through the origin is 0.97.

b. Total Evapotranspiration

Fig. 5.2 shows comparisons of the simulated and observed evapotranspiration for FIFE and HAPEX-MOBILHY for the same sites and time periods as for the net radiation in Fig. 5.1. For FIFE, the overall correlation coefficient was 0.93, the best fit slope through the origin was 1.01, and the RMSE was 0.5 mm day $^{-1}$ of average measured evapotranspiration of 3.3 mm day^{-1}. For HAPEX-MOBILHY, the correlation coefficient was 0.93, the best fit slope through the origin was 0.98, and the RMSE was 0.6 mm day^{-1} of average measured evapotranspiration of 4.0 mm day^{-1}. The total evapotranspiration estimated during the period of simulations was 159 and 172 mm for FIFE and HAPEX-MOBILHY, respectively. For the same periods, the measured total evapotranspiration was 163 and 176 mm. It is clear that the values of simulated evapotranspiration were in good agreement with the observations. It can be noted that the model performance deteriorated on day 232 and 233. Inspection of the meteorological data did not indicate why the measured evapotranspiration should be high on these two days.

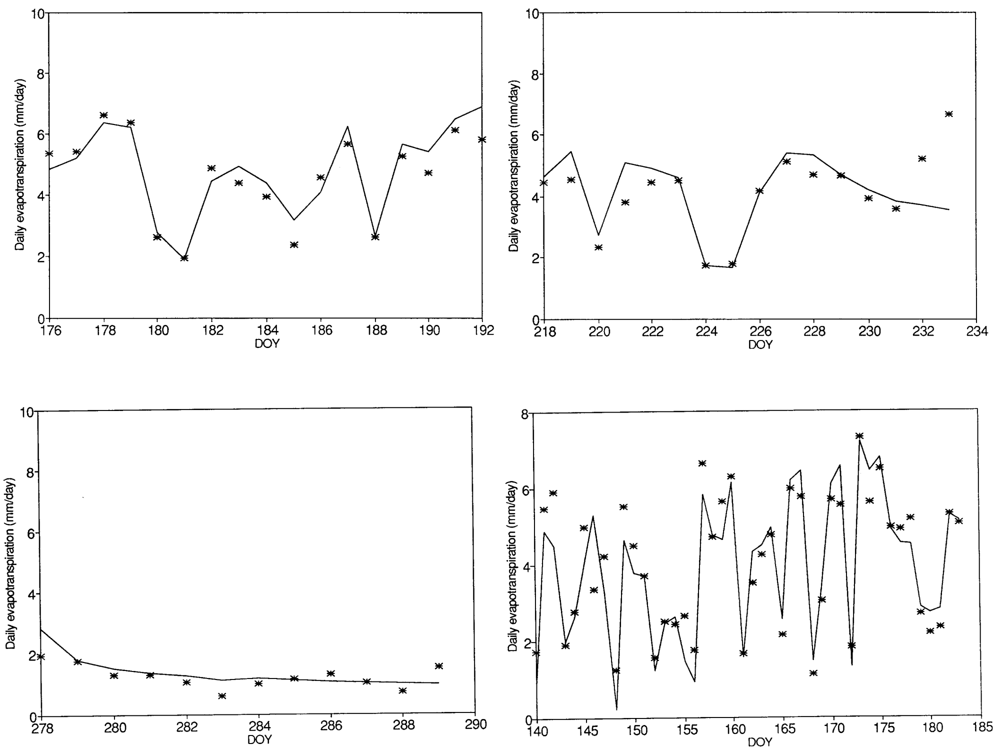

Fig. 5.2. Comparisons between simulated and observed evapotranspiration during the periods of three IFCs in FIFE and SOP in HAPEX-MOBILHY. The correlation coefficient for FIFE data is 0.93; the mean slope through the origin is 1.01. For HAPEX-MOBILHY data, the correlation coefficient is 0.93 and the mean slope through the origin is 0.98.

During the period of IFC2 and IFC3, the canopy resistance was small and the canopy was weakly coupled to the atmosphere with Ω equal to 0.7. The vapor pressure deficit of the canopy surfaces tended toward a local equilibrium value. The equilibrium value of the vapor pressure deficit depends on the net radiation and the canopy resistance in such a way that the actual evapotranspiration approaches an equilibrium evapotranspiration rate, which was independent of canopy resistance.

Energy supply was the most important regulator of evapotranspiration. On the other hand, the values of canopy resistance for IFC4 and HAPEX-MOBILHY were relatively large and the

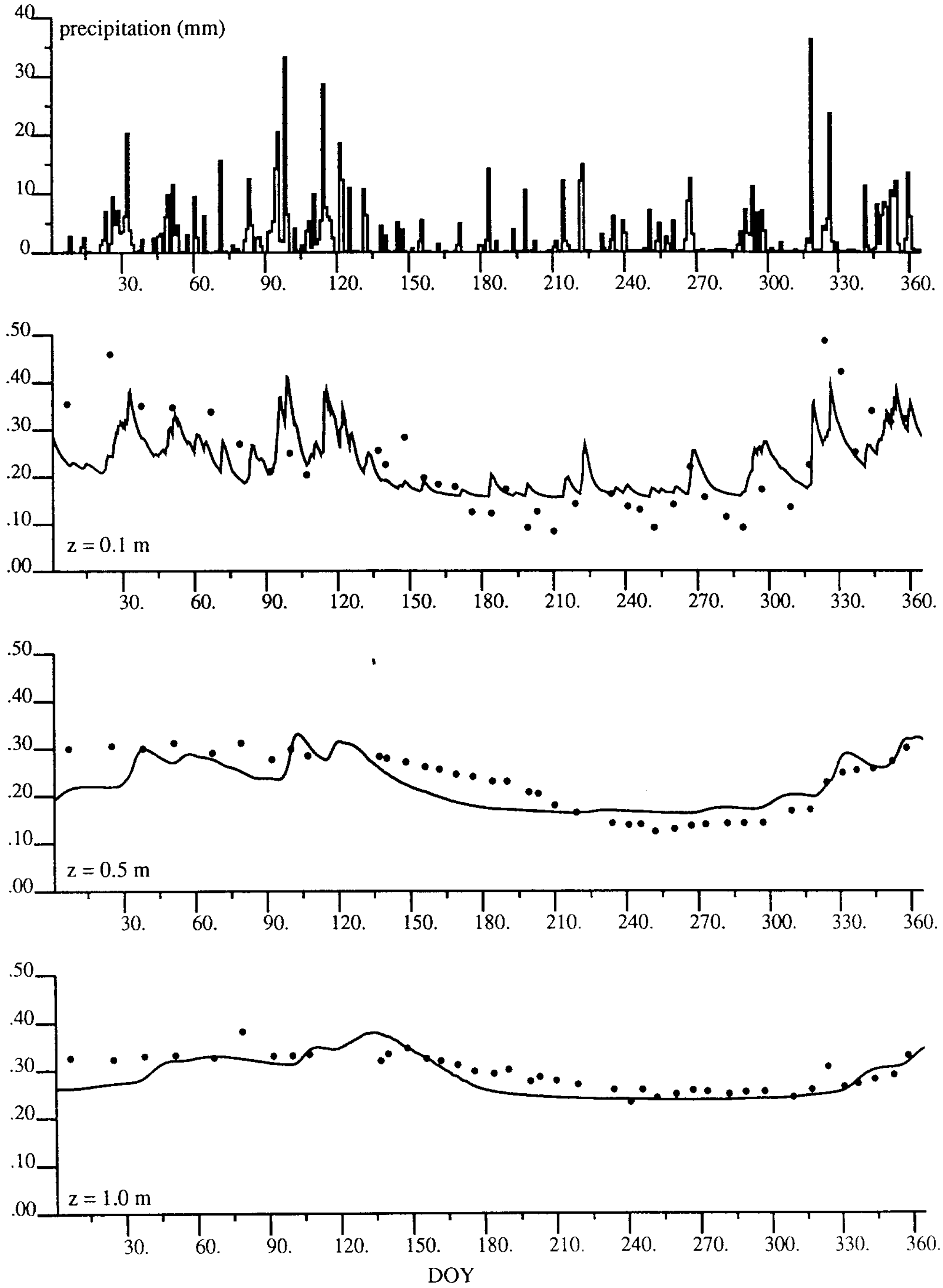

Fig. 5.3. Time course of predicted (solid line) and observed (dots) soil moisture content at SAMER site 3 for the period of January to December 1986 at three different depths.

canopies were moderately coupled to the atmosphere with W equal to 0.4. The evapotranspiration was jointly controlled by the net radiation, the vapor pressure deficit and the canopy resistance. These results showed that WAVES is capable of realistic simulation of evapotranspiration under a variety of conditions.

c. Soil moisture content

Fig. 5.3 shows the comparison between measured and simulated soil moisture content for various depths at SAMER site 3. Both the model simulations and the observations showed similar seasonal variations in the soil moisture content. In the top soil layer, the soil moisture content fluctuated strongly mainly due to precipitation. The model results showed smaller fluctuations in the soil moisture content than the measurements and the minimum soil moisture content was slightly overestimated. Model simulations of the soil moisture content at the depths of 50 cm and 100 cm were better than those near-surface simulations. In general, the calculated soil moisture agreed well with the observations considering the length of the simulation, the limited information on soil hydraulic properties, and the lack of any data regarding the lower boundary condition. The very low fitted values of b suggests that soil hydraulic properties change dramatically with depth not far below the lower boundary of the modelled region, so that there is most likely some error in assuming a homogeneous soil above this boundary.

5.1.5 Drydown process – A numerical simulation

The results in the previous sections showed that the WAVES model accurately simulated daily net radiation, evapotranspiration and soil moisture contents. Given the complexity of processes and their interactions under natural conditions, such as FIFE and HAPEX-MOBILHY, these results convey little understanding of the system behaviour and the testing of physical models, such as WAVES, *in toto* can obscure the specific behaviour associated with the processes represented. It is important to understand the roles of individual processes, and to investigate interactions between very few processes at a time. It is therefore useful to examine model performance under idealised or simplified conditions, and compare the output against expectations generalised from the literature. Specifically, it is revealing to test the model's behaviour over a period in which the soil is only drying.

The numerical simulation was designed with constant atmospheric forcing with zero precipitation. Two types of soil were considered: sandy loam and clay. The depth of the soil layer was assumed to be 1.0 m with a single C_3 vegetation layer on the top. The model was run for each soil type with initial soil moisture content set to saturation using an impermeable lower boundary condition (b = 0.0).

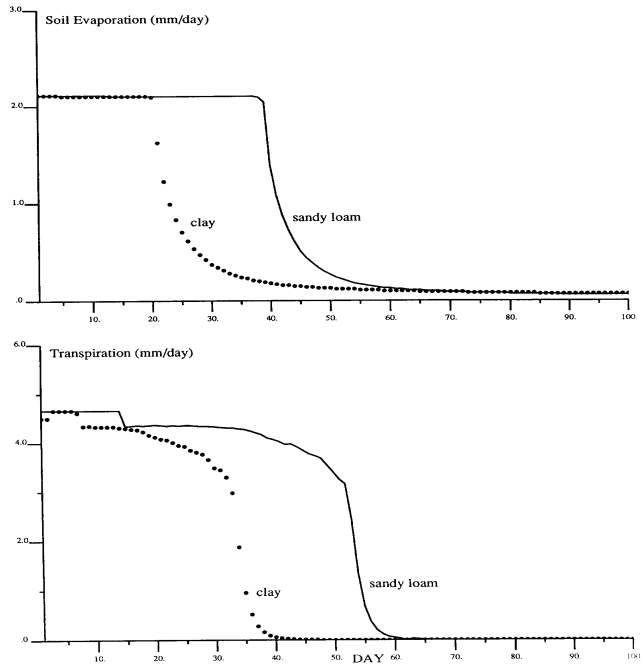

Fig. 5.4. Daily values of soil evaporation (top) and transpiration (bottom) during a 100-day simulation of the drying of initially saturated clay and sandy loam soils.

The temporal variations in the calculated soil evaporation and transpiration are shown in Fig. 5.4. It is clear that the model showed a two-stage soil evaporation process. In the first stage, the soil was wet and evaporation was controlled by the atmospheric demand. As a result, soil evaporation occurred at the potential rate (constant in this experiment). The duration of stage 1 soil evaporation depended on the hydraulic properties of the soil and lasted longer for sandy loam than for clay soils. Second-stage (soil limited) evaporation was mainly controlled by the hydraulic properties of the soil and the evaporation rate fell below the potential rate on the third day of the stage 2 drying process. The cumulative soil evaporation versus the square root of time was almost linear (Fig. 5.5).

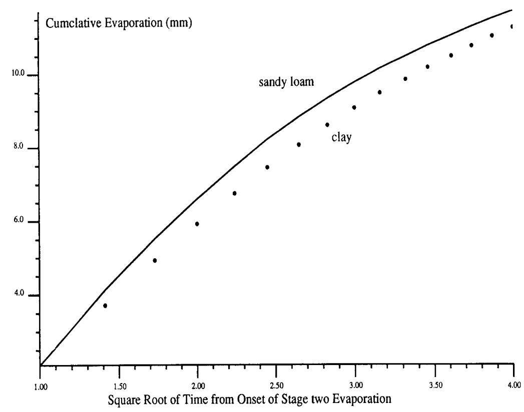

Fig. 5.5. Stage 2 cumulative soil evaporation as related the square root of time for clay and sandy loam soils.

The transpiration from WAVES showed a two-stage drying process as well: in the first stage, transpiration decreased gradually and in the second stage transpiration decreased rapidly. The stage 1 transpiration lasted longer than stage 1 soil evaporation (Fig. 5.4) since the vegetation can remove water from deeper soil. The presence of a canopy extended the period of stage 1 evaporation by several days compared with a bare soil surface and much less water was removed from the near soil surface. However, the period of the second stage of drying was significantly shortened.

As outlined in Chapter 2, the model calculates the saturation vapor pressure deficit of the canopy, which depends on degree of coupling between the canopy and the atmosphere, and the net radiation received by the canopy. For this numerical simulation, the decoupling coefficient (0.9) indicated a weak coupling between the canopy and the atmosphere. The vapor pressure deficit of the canopy was reduced by 7 hPa during the period of plant transpiration and increased to the prescribed vapor pressure deficit when the transpiration stopped.

5.1.6 Discussion

A complex, biophysically based ecohydrological model such as WAVES is a potentially useful tool for testing ideas about system behaviour as well as for generating predictions about how the surface energy and water balance might change following manipulations of the system. In Australia, the absence of field observations of landscape behaviour across the large range of physical, biological and management combinations, and the huge expense and delay in acquiring these observations, strongly argue for such a tool. While we recognise and agree with the philosophical concerns raised by ourselves (Hatton *et al*. 1994) and others (Beven 1989, Wheater and Jakeman 1993) regarding the danger of such exercises, the real and urgent need for advice on optimal land use is compelling. We also recognise the obligation to test such tools, as thoroughly as possible, against theoretical and observed behaviour. The FIFE and HAPEX-MOBILHY data offer an extraordinary opportunity to test the surface energy and water balance components of WAVES.

In general, the model closely reproduced field observations of the surface energy and water balance, and produced results consistent with theoretical expectation. Given only daily solar radiation and air temperature as climatic inputs, the model accurately predicted net radiation. This is a significant feature for models of this kind; many such treatments of the surface energy balance require net longwave as an input (e.g., Dickinson *et al*. 1986, Sellers *et al*. 1986) or use net radiation directly (Choudhury and Monteith 1988). Neither of these latter quantities is normally available across Australia.

Predicted daily total evapotranspiration compared well with observed values from the FIFE and HAPEX-MOBILHY experiments. It is significant that the daily time-step of WAVES, using mean daily values for wind speed, temperature and vapour pressure deficit, could reproduce the summed sub-hourly measured fluxes. This is a crucial feature for any physical water balance model intended for application in Australia as standard meteorological data is limited to daily resolution. Note that the model error in evaporation is well within the stated error of measurement for the HAPEX-MOBILHY data. For the FIFE experiment in particular, the model was capable of reproducing evaporation rates ranging from 1 mm d^{-1} under conditions of senescing vegetation and limiting soil moisture to 7 mm d^{-1} under high radiation, leaf area index and soil moisture. This suggests that the calculation of surface resistance by means of the modified Ball *et al*. (1987) model (Leuning 1995), using the IRM assimilation model (Wu *et al.* 1994), can account for multiple factors limiting conductance.

In the formulation of evapotranspiration, the effect of boundary layer resistance is neglected. Shuttleworth and Wallace (1985) showed that measurements of mean boundary layer resistance generally have significant scatter and the bulk boundary layer resistance is much smaller than the corresponding aerodynamic resistance; in addition the combination equation is rather insensitive to the boundary layer resistance. The good agreement between calculated and measured evapotranspiration seem to support this assumption. Another approximation made in the WAVES model is to ignore the effect of atmospheric stability on the aerodynamic resistance. This assumption leads to underestimation (overestimation) of the aerodynamic resistance when the atmosphere is in unstable (stable) conditions. Moreover, it has been found that the Penman–Monteith equation is relatively insensitive to the aerodynamic resistance when the surface roughness length is small (Zhang and Dawes, 1995). As a result, the effect of atmospheric stability correction can be neglected. For the surface conditions in FIFE sites and the agricultural part of HAPEX-MOBILHY, the results indicated that the effect of the atmospheric stability is negligible. However, for rough surfaces (e.g., forest) ignoring the atmospheric stability may cause large errors in the calculated evapotranspiration.

There was insufficient information available from either experiment to allow direct comparisons of the contribution of transpiration and soil evaporation. The numerical results from the dry-down simulations, indicating a two-stage soil evaporation process with fluxes limited initially by energy, is consistent with field measurements (Ritchie 1972). During the second stage of soil evaporation, the hydraulic properties of the soil play a more significant role than the atmospheric demand. Black *et al*. (1969) showed that cumulative evaporation is linearly related to square root of the time from the start of the second stage evaporation. The relationship has been supported by field measurements of evaporation (LaRue *et al*. 1968; Ritchie 1972). The model shows this behaviour.

In terms of plant transpiration, the WAVES model determines the relative carbon assimilation rate which is related to the canopy resistance based on the matric potential of the soil water rather than the water content. This treatment allows plant to transpire freely until all the water in root zone is extracted. The simulated transpiration also showed a two stage process. The stage 1 transpiration lasted longer than the stage 1 soil evaporation, while the stage 2 transpiration decreased more rapidly. These results indicated that transpiration is maintained by deep soil water through plant roots.

During the period of FIFE IFC2 to IFC3, simulated transpiration accounted for about 85% of the total evapotranspiration, while for IFC4 the transpiration component decreased to 60%. Fractional vegetation cover determined from LAI and canopy height using the method of Smith *et al*. (1993) was 0.94, 0.86 and 0.45 respectively for the three FIFE periods and it seems that the transpiration ratios maybe related to the fractional vegetation covers; this is consistent with the findings of Smith *et al*. (1993). For HAPEX-MOBILHY, the transpiration ratio increased from 60% to 86% as the fractional vegetation cover changed from 0.5 to 0.9.

The simulated soil moisture profiles for the HAPEX-MOBILHY experiment were consistent with observations. However, water content at the shallowest soil depth shows large temporal variation and is inherently difficult to model; the seasonal trends are reproduced, but the predicted value on any particular day may be in significant error. The two deeper times series of moisture are modelled better, but show less temporal variation to challenge the model. Therefore, we cannot consider this aspect of the model to be adequately tested in this study. It must be noted that the model results for the HAPEX-MOBILHY experiment were sensitive to the soil hydraulic properties and the lower boundary condition. This finding confirms the sensitivity analysis of the model (Hatton *et al*. 1995). These quantities are, in any practical sense, unknowable across a landscape. This is a serious limitation to wide geographic application of models requiring this information, but this is a feature common to any soil water balance model.

5.1.7 Summary

The WAVES model was tested using the data obtained from FIFE and HAPEX-MOBILHY experiments. Generally, it was found that the model is capable of accurately simulating daily total net radiation, evapotranspiration, and soil moisture content under different weather and canopy conditions with a reasonable degree of realism. A numerical experiment was carried out to investigate the model's performance under soil drying conditions. The model produced a two stage soil evaporation process as has been previously observed. Stage one soil evaporation proceeds at the potential rate. In the second stage, the soil evaporation falls below the potential rate and the cumulative evaporation versus the square root of time is almost linear. These results are consistent with theoretical expectation. For practical purposes, the model does not consider the effect of atmospheric stability on the aerodynamic resistance and an equivalence between radiative surface temperature and air temperature is assumed in the model. These simplifications do not seem to have degraded model predictions

The WAVES model can be used in its present form to identify important surface characteristics and to study hydrological responses under various land management practices. Practical applications of the model to real catchments are limited by the large number of the parameters on soil and vegetation properties, some of which are difficult to obtain in practice. Nevertheless, we assert that the model strikes a reasonable balance between generality, realism and accuracy, and provides a powerful tool for the prediction of landscape behaviour.

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