Remote Sensing and Hydrology 2000 (Proceedings of a symposium held at Santa Fe, New Mexico, USA, April 2000). IAHS Publ. no. 267, 2001.

Combining remote sensing and hydrological models to enhance spatial and temporal variability

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Abstract The development of water saving measures requires a thorough understanding of the water balance at a high spatial and temporal resolution. Remote sensing is strong in producing information at a high spatial scale, while simulation models are strong in producing water balance estimates at a high temporal resolution. Actual evapotranspiration for an irrigated area in western Turkey was calculated using the SEBAL remote sensing land algorithm using two Landsat images. The hydrological model SWAP was set up to simulate the water balance for the same area, assuming a certain distribution in soil properties, planting dates, and irrigation practices. A comparison between evapotranspiration determined from SEBAL and from SWAP was made, and differences were minimized by adapting the stochastic input in planting date and irrigation practice. The optimized stochastic input data for SWAP was used to simulate all terms of the water balance for the entire irrigation scheme.
Key words evapotranspiration; SEBAL; simulation models; SWAP; Turkey

INTRODUCTION

The increasing scarcity of water is a real threat for sustainable development of large areas in the world. A thorough knowledge of all the terms of the water balance is, therefore, essential to explore possible water saving measures. While evapotranspiration (ET) is one of the most important components of the water balance, it is also one of the most difficult to measure. Two important developments to estimate ET are hydrological models and remotely sensed techniques (Kite & Droogers, 2000).

The advantage of hydrological models is that all the terms of the water balance can be estimated, including actual ET, over an unlimited time frame. Remote sensing (RS) provides only a snapshot—for Landsat images minimally at a re-visit period of 16 days if the atmosphere is free of clouds—but the spatial resolution is high. A combined use of hydrological models and RS can overcome the shortcomings of a low spatial coverage of point or field-scale models and the low temporal resolution of high spatial resolution RS images.

In summary, the objectives of this study are to: (a) estimate ET using the hydrological model SWAP in a stochastic mode; (b) estimate ET using the SEBAL RS land algorithm for two specific days; (c) update the stochastic model input using RS ET estimates; and finally, (d) estimate all the terms of the water balance using the SWAP model.

MATERIALS AND METHODS

Study area

The Menemen Left Bank (MLB) in the Gediz Basin, western Turkey, was selected for the current study. The area of MLB is about 16 500 ha and the main crops are cotton (70%), grapes (24%), and others such as orchards, wheat, maize and vegetables. Annual average rainfall over the last 30 years was 510 mm, and ranged from 334 mm in 1992 to 731 mm in 1981, of which 50% precipitates during winter, and the remainder in spring and autumn. Average annual temperature is 17°C and shows little year-to-year variation. Average temperatures in January and July are 8°C and 26°C, respectively.

Remote sensing algorithm SEBAL

The Surface Energy Balance Algorithm for Land (SEBAL) calculates both the instantaneous and 24-h integrated surface heat fluxes (Bastiaanssen, 2000). The method is based on calculating all the terms of the energy balance using RS data, which leads to the evaporative fraction, defined as the latent heat flux over net available energy. The latter is expressed as the difference between the net radiation and soil heat flux. This instantaneous evaporative fraction is shown in the literature to be similar to the 24-h evaporative fraction (e.g. Shuttleworth *et al.*, 1989; Brutsaert & Chen, 1996), and this allows estimation of the latent heat flux on a 24-h basis. A detailed description of the SEBAL algorithm is beyond the scope of this paper, but it can be found in Bastiaanssen *et al.* (1998).

Agro-hydrological model SWAP

The hydrological analyses were performed using the SWAP 2.0 model (Van Dam *et al.*, 1997). SWAP is a one-dimensional physically based model for water, heat and solute transport in the saturated and unsaturated zones, and includes modules for simulating irrigation practices and crop growth. The SWAP model was applied in a stochastic mode to represent the hydrological conditions for cotton and grapes for the entire MLB area. Such a calculation procedure aims to describe the variability in space and time without specifying where in the area such a combination of input data and water balance outputs actually occurs. Three input parameters were used to represent the variation in the conditions for MLB: soils data, planting date and irrigation management. Detailed information on this approach can be found in Droogers & Bastiaanssen (2000).

RESULTS

SWAP was applied first in a deterministic mode: all input data were fixed at the mean values of soil, crop and irrigation inputs (Droogers, 2000). Table 1 shows the results of this deterministic mode for the two Landsat overpass days. Cotton ET was low on 26 June, as the crop was still in the development stage with a Leaf Area Index (LAI) of 0.5.

Table 1 Areal evapotranspiration (mm day^{-1}) for the two Landsat overpass days, using SWAP in a deterministic mode, a stochastic mode (original and fitted), and using the RS-SEBAL technique.

	26 June: Cotton	Grapes	Area	29 August: Cotton	Grapes	Area
SWAP deterministic	1.6	2.8	1.9	3.7	3.5	3.6
SWAP stochastic	2.0	2.7	2.2	4.6	3.8	4.4
SWAP stochastic fitted	2.3	2.7	2.4	4.1	3.6	4.0
SEBAL	2.2	2.8	2.4	3.9	3.6	3.9

The determination and validation of the actual ET maps produced by SEBAL are described by Bastiaanssen (2000). Overlaying the actual ET maps with the crop maps created the opportunity to evaluate the crop specific ET rates at the onset and end of the irrigation season. Figure 1 shows the spatial patterns of ET over the Menemen Left Bank command area. Cotton is less developed on 26 June and thus produces less ET, while on 29 August the crop is fully developed and transpires at a higher rate than the grapes.

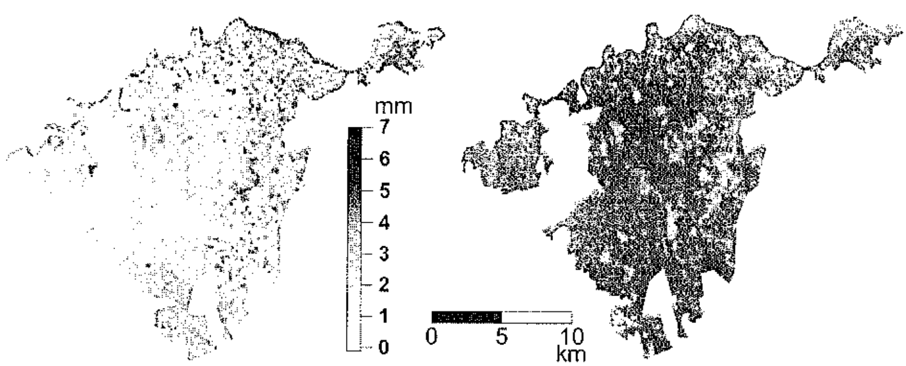

Fig. 1 Actual evapotranspiration estimated with the SEBAL algorithm for MLB on 26 June and 29 August.

Figure 2 shows the distribution in ET values for the two crops as determined by SWAP and SEBAL at the two Landsat overpass days. The overall trend shows a reasonable agreement between SWAP and SEBAL for the cotton, with somewhat lower values for SWAP on 26 June and somewhat higher values on 29 August. For the grapes, a substantial deviation between SWAP and SEBAL can be observed. As we again consider SEBAL as the reference, the distribution in ET is far too low for SWAP, though average values were very close (Table 1).

By adjusting the SWAP stochastic input data (irrigation scheduling, planting date for cotton, emergence date of grapes) a similar pattern in ET as estimated by SEBAL was obtained (Fig. 3). However, the original estimated value of LAI for the cotton (4.0) also had to be reduced to values from SEBAL (3.0).

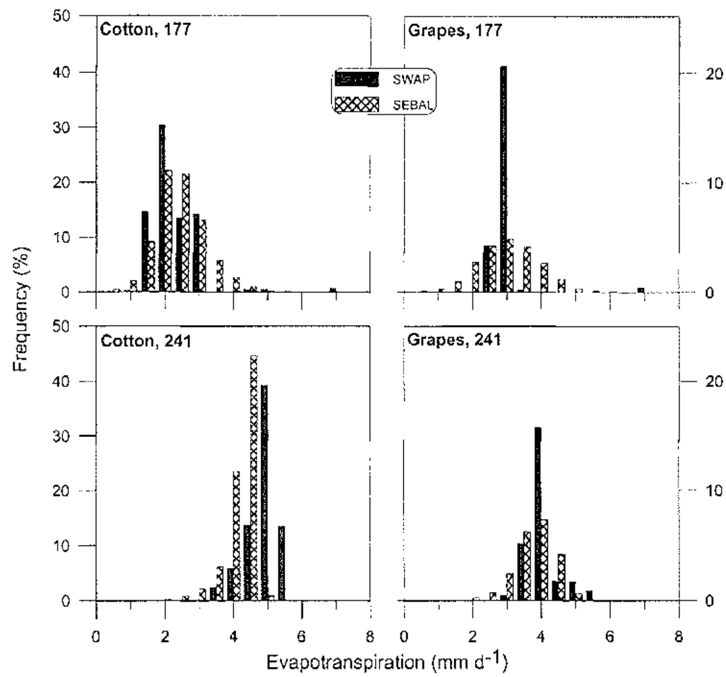

Fig. 2 Areal and crop-wise frequency distribution of actual evapotranspiration for the two Landsat overpass-days calculated with SEBAL, superimposed with the results of the SWAP hydrological model.

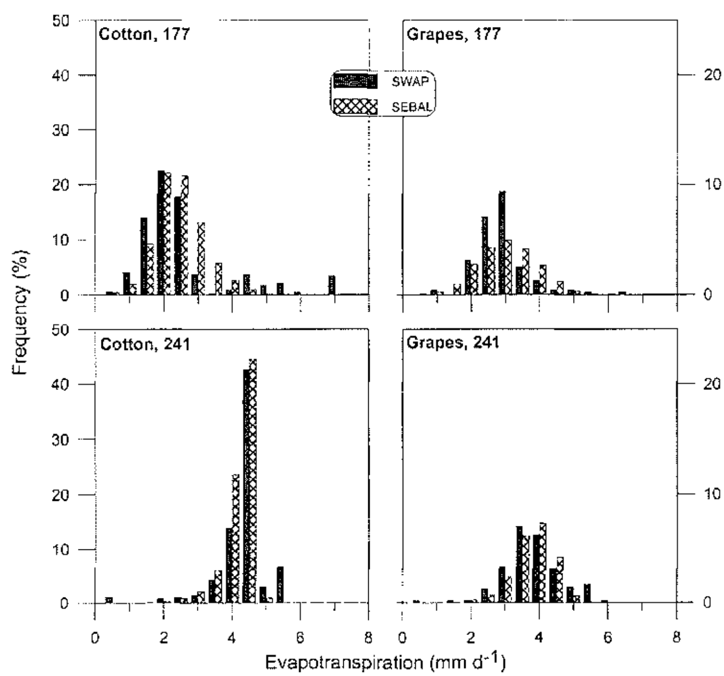

Fig. 3 SWAP and SEBAL evapotranspiration frequency distribution, as Fig. 2, but with fitted stochastic input data for SWAP.

The SWAP model is able to simulate all the terms of the water balance at a high temporal resolution, i.e. daily, over an unlimited time frame. Using the updated stochastic input from the comparison with SEBAL, this high temporal resolution is provided at a high spatial resolution too (Fig. 4). In terms of actual ET, the model enables us to make a distinction between the crop transpiration and soil evaporation. This distinction is important as soil evaporation is considered to be a loss from a food production point of view, while only crop transpiration is considered as a beneficial use of water. Variation in soil evaporation is low. The dual-distribution in ET clearly reflects the two crops: lower values for cotton and higher values for grapes.

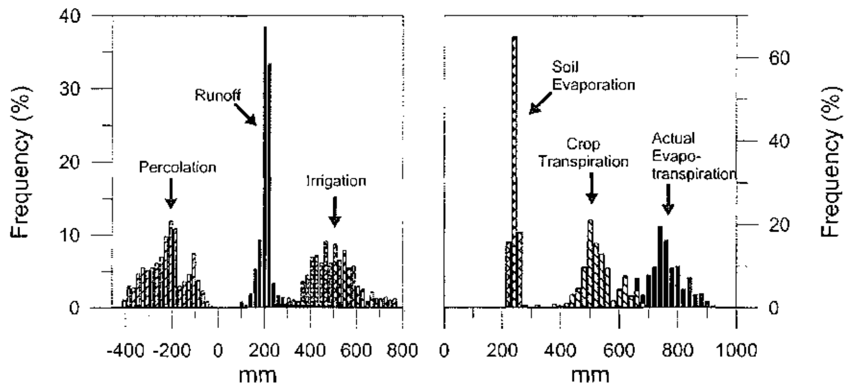

Fig. 4 Frequency distribution of terms of the water balance for the entire MLB using the SWAP model with the fitted stochastic input data.

CONCLUSIONS

The methodology described here uses RS data to evaluate current water management practices, expressed as actual ET, at a high degree of spatial detail (30 m). The agro-hydrological model is able to fill the temporal gaps between successive satellite overpasses, as well as to quantify all the other terms of the water balance that are not obtainable from satellite images, including the separation of soil evaporation (non-beneficial depletion) and crop transpiration (beneficial depletion).

The use of the actual ET to fit the stochastic input data from SWAP is a legitimate choice as this factor can be considered as the component of the water balance that integrates all the processes in the soil–water–plant–atmosphere continuum. Processes such as runoff, percolation, soil water storage and plant growth affect this actual ET.

The SWAP model only requires standard day-to-day meteorological data from the field. Other soil- and crop-related model parameters can be estimated from the literature. The distribution functions of the soil, crop and irrigation input parameters can be determined from RS data. The input requirements of the SEBAL model are restricted to the solar and infrared radiation for the day and moment of image acquisition. As both models have a strong physical basis, i.e. the Richards equation for SWAP, and the Monin-Obukhov similarity hypothesis for SEBAL, we feel that they can be applied in a wide variety of irrigation conditions without the need for extensive field surveys.

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