42

Research Report

Comparing Estimates of Actual Evapotranspiration From Satellites, Hydrological Models, and Field Data: A Case Study from Western Turkey

Geoff Kite
and
Peter Droogers

International Water Management Institute

Research Reports

IWMI's mission is to contribute to food security and poverty eradication by fostering sustainable increases in the productivity of water through better management of irrigation and other water uses in river basins. In serving this mission, IWMI concentrates on the *integration* of policies, technologies and management systems to achieve workable solutions to real problems—practical, relevant results in the field of irrigation and water resources.

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical, and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI's own staff and Fellows, and by external reviewers. The reports are published and distributed both in hard copy and electronically (http://www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

Research Report 42

Comparing Estimates of Actual Evapotranspiration from Satellites, Hydrological Models, and Field Data: A Case Study from Western Turkey

Geoff Kite
and
Peter Droogers

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

IWMI gratefully acknowledges the financial support for its research work from the following Governments, Development Banks, Agencies, and Foundations: Australia, Brazil, Canada, China, Denmark, France, Germany, India, Iran, Japan, Netherlands, Norway, Pakistan, South Africa, Sweden, Switzerland, Taiwan, Turkey, United Kingdom, United States of America, European Union (EU), African Development Bank (AfDB), Asian Development Bank (ADB), Food and Agriculture Organization of the United Nations (FAO), Ford Foundation, International Fund for Agricultural Development (IFAD), World Bank, Taoyan Irrigation Research and Development Foundation, Tsao-Jiin Memorial Foundation for R&D for Agriculture and Irrigation, Environment Greening Foundation, Chi-Seng Water Management and Development Foundation, Council of Agriculture (COA), and Agricultural Engineering Research Center (AERC). The Governments of India, Iran, Mexico, Nepal, Pakistan, Sri Lanka, and Turkey also provided program support for IWMI-related activities in these countries.

The authors: Geoff Kite and Peter Droogers are both Hydrologists at the International Water Management Institute, Colombo, Sri Lanka.

This report is based on papers of a special issue of the Journal of Hydrology written by the scientists who participated in an experiment to compare actual evapotranspiration from satellites, hydrological models and field data. The authors express their thanks to Rick Allen, Wim Bastiaanssen, Müslüm Beyazgül, Henk de Bruin, Bhaskhar Choudhury, Francine Engelsman, Raoul Granger Yildrim Kayam, and Wouter Meijninger for their hard work and good company.

The General Directorate of Rural Services, Government of Turkey, provided local funding in Menemen. The Meteorology and Air Quality Group, Wageningen Agricultural University provided field equipment and scientific and technical staff.

G. Kite, and P. Droogers. 2000. *Comparing estimates of actual evapotranspiration from satellites, hydrological models, and field data: A case study from Western Turkey.* Research Report 42. Colombo, Sri Lanka: International Water Management Institute.

/ estimation / field tests / measurement / productivity / remote sensing / crops / water requirements / water balance / irrigation management / river basins / hydrology / models / evapotranspiration / Turkey /

ISBN 92-9090-412-7
ISSN 1026-0862

Please send inquiries and comments to: *iwmi-research-news@cgiar.org*

Contents

Summary

This research report provides an overview of an experiment in which 8 different methods of estimating actual evaporation and transpiration were compared using a common database. Methods based on field data, hydrological models, and satellite data were used and the objectives were to compare results and to assess the utility of each method for various applications. Evaporation and transpiration are important components of the hydrological cycle, which cannot be directly measured. Traditionally, actual evapotranspiration has been computed as a residual in water balance equations, from estimates of potential evapotranspiration or from field measurements at meteorological stations. Recently, however, researchers have begun using scintillometers, remotely sensed data, and hydrological models to estimate areal actual evapotranspiration. An experiment was carried out at two sites in western Turkey during the summer of 1998 to compare the newly developed methods with more conventional methods. This report introduces the different estimation techniques, the experimental sites and the data set. The results of the different methods are reviewed and compared and recommendations are made as to the suitability of the different methods for different circumstances. Particular emphasis is placed on the data requirements, the ease of use, and the constraints of each method.

Comparing Estimates of Actual Evapotranspiration from Satellites, Hydrological Models, and Field Data: A Case Study from Western Turkey

Geoff Kite and Peter Droogers

Introduction

This paper provides an overview of the results of an experiment in which 8 different methods of estimating actual evaporation (E) and transpiration (T) were compared using a common database. The purpose of the experiment was to determine the values obtained by several different approaches to estimating E and T, make a comparison of the values obtained by the different methods, and assess the utility of each method for different applications.

There have been previous land-surface-atmosphere experiments that used different evapotranspiration methods (e.g., First International Field Experiment (FIFE) in Kansas, Sellers et al. 1992, and Hydrologic and Atmospheric Pilot Experiment (HAPEX)-Sahel, Gourtorbe et al. 1997). However, these studies used individual data sets that made them difficult to compare the evapotranspiration methods.

The rationale for this experiment was to see the extent to which newly developed techniques provide data that compare with more traditional methods that rely either on field measurements or merely calculate evaporation and transpiration as a residual of a water balance. To make the comparison as rigorous as possible the methods were tested using a common data set provided from two sites in western Turkey. Most comparisons are based on data for two days of satellite overpasses, but some methods were able to provide results for longer periods and larger areas.

Three groups of estimation methods, each of which is summarized in this paper and explained in detail in papers in a special edition of the Journal of Hydrology, were used for the experiment:

- Use of methods such as the United Nations Food and Agriculture Organization (FAO) -24, FAO-56, and scintillometer, which use field measurements from meteorological equipment.

- Use of hydrological models, including Soil Water Atmosphere Plant (SWAP) field scale modeling and Semi-distributed Land-Use based Runoff Processes (SLURP) basin level modeling, in which E and T are computed as part of full hydrological cycle calculations at various space and time scales.

- Use of methods based on remotely sensed data, including satellite-derived feedback mechanisms, biophysical processes, and energy balance techniques. Remote sensing techniques infer ET values from measured reflectance signals but may also use ground-based meteorological data.

The initiative for the experiment was developed during a collaborative study of the Gediz River Basin by the International Water Management Institute (IWMI) and the General Directorate of Rural Services, Government of

Turkey (GDRS), in which models were used to investigate the role of irrigation schemes within overall basin water resources. Crop transpiration is often used to estimate irrigation productivity (Molden et al. 1998) while soil evaporation is often regarded, from an irrigated agricultural point of view, as an unproductive use of water.

Traditionally, actual evapotranspiration has been computed as a residual in water balance equations, from estimates of potential evapotranspiration using a soil moisture reduction function or from field measurements by meteorological equipment. Recently, however, researchers have begun using satellite data (e.g., Bastiaanssen et al. 1998; Choudhury 1997; Granger 1997) to estimate regional actual evapotranspiration.

In 1997, IWMI brought researchers together to discuss the progress in remote sensing techniques and to carry out a comparison between methods using field measurements. One of the difficulties with such a comparison is the difference in spatial scale between the point estimates derived by climate-station-based techniques and the areal-averages produced by the remote sensing techniques. This problem is eased by two recent developments. First, the development of the scintillometer technique, which estimates evapotranspiration over an area (e.g., de Bruin et al. 1995) and second, the development of hydrological models that produce estimates of evaporation and transpiration at many locations over large areas and for long periods of time (e.g., Droogers and Kite1999). These two techniques act as intermediate steps between the field and the satellite estimates.

IWMI convened a workshop at the Agricultural Research and Training Center (ARTC), Menemen, western Turkey, in the spring of 1998 to which experts in field techniques, hydrological modeling, and remote sensing methods were invited to present their techniques and to discuss collaboration. As a result of the workshop, it was agreed to carry out an experiment in the Gediz Basin near Menemen during the summer of 1998. Two field sites were instrumented, satellite images were obtained, and hydrological models were applied at various scales. Two CD-ROMS (Droogers and Kite 1998) containing all the acquired data and images were prepared and distributed to each research team. Each researcher computed actual evaporation and transpiration (or evapotranspiration) for a series of crop and land-cover types (or for an average land cover) at two field sites on two Landsat overpass dates. Their results are summarized in this report and are given in more detail in the Journal of Hydrology Special Issue *Comparing Actual Evapotranspiration from Satellite data, Hydrological Models and Field Data* (Kite and Droogers 2000). As a result of the comparison, it seemed logical to look into more detail at the methods not merely in terms of estimating E and T but also the way in which they can be used for other related purposes.

Field Sites

The Gediz River in western Turkey has a length of about 275 km, drains an area of 17,200 km^2 and flows from east to west into the Aegean Sea just north of Izmir (figure 1). The river network is heavily controlled by reservoirs and regulators that divert water for irrigation. The reservoirs store river flow from the predominantly winter precipitation for release during the summer. Precipitation in the basin ranges from over 1,000 mm/year in the 2,300 m high mountains at the eastern end of the basin to a low of around 500 mm near the Aegean coast. The air temperatures range from –24 ^{o}C at high elevations in winter to over 40 ^{o}C in the interior plains in summer. The natural vegetation of

FIGURE 1.
The location of Gediz Basin, western Turkey.

the basin is mainly shrubland, maki (a mix of bay, myrtle, scrub oak, and juniper trees, amongst others), and coniferous forest with large outcrops of barren limestone mountain. Crops produced in the basin include cotton, cereals, grapes, vegetables and fruits, olives, tobacco, and melons.

Two instrumented sites were established, both dominated by irrigated crops. The first, *cotton field,* was an irrigated cotton field surrounded by other cotton fields at Kessiköy within the Menemen Left Bank irrigation scheme. The second site, *valley*, was a transect across the Gediz Valley from Belen in the north to Suluklu in the south, a distance of 2,700 m (figure 2 and table 1). The crop coverage at the valley site was 60 percent raison grape, 15 percent cotton, 15 percent fruit trees, 5 percent other trees, and 5 percent pasture. The irrigation pattern varied for each farm and crop. Weather data were also available from an automatic climate station located at the Menemen Agricultural Research Center. The coordinates are given in table 1.

On the date of the first Landsat overpass, 26 June 1998, the leaf area indices of all the crops were low, the topsoil was dry, and the subsoil was wet (figure 3, top). By 29 August, the date of the second Landsat overpass, the cotton and grape crops were fully developed, and the soil condition was determined by the irrigation pattern (figure 3, bottom and figure 4).

FIGURE 2.
Landsat TM image (band 3, August 29 1998) showing the locations of the cotton field and valley field sites and the Menemen Research Centre climate station.

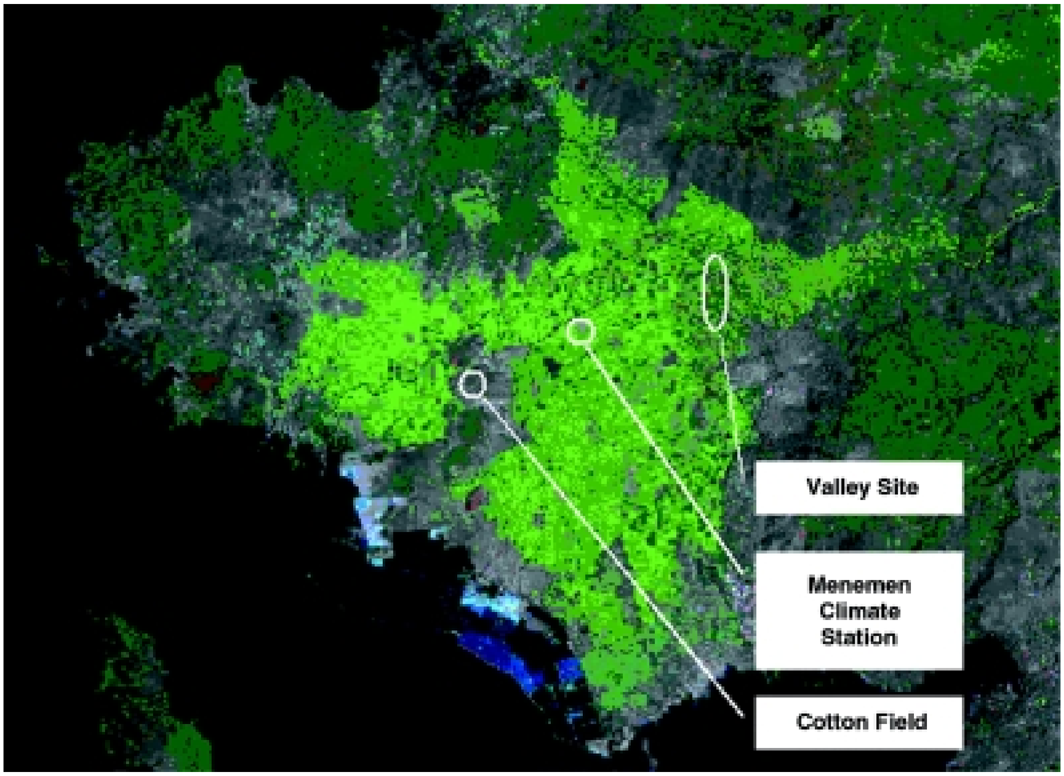


TABLE 1.
Locations of the experimental sites.

Site	Latitude degrees, minutes, seconds	Longitude degrees, minutes, seconds	Elevation mamsl (meters above mean sea level)
Cotton field	38 36 43	26 58 16	8
Valley (Suluklu)	38 36 59	27.05 56	15
Valley (Belen)	38 39 21	27.06 04	15
Menemen climate station	38 37 00	27.03 00	9

FIGURE 3.
The cotton field site as seen on 26 June 1998 (top) and 31 August 1998 (bottom).

FIGURE 4.
A view of the valley site on 31 August 1998.

Data Collection for Comparison

Instrumentation at the cotton field site consisted of a 15 cm aperture scintillometer using a 0.94 µm light-emitting diode (LED) source. The scintillometer had a path length of 670 m at an elevation of 3.2 m. A mast held a ventilated Schultze net radiometer and an automated climate station with METWAU (Meteorology and Air Quality Group, Wageningen Agricultural University) anemometer, thermocouples and soil temperature probes at 5 depths. Soil moisture was measured at 5 locations and 5 depths using a neutron-probe instrument. Phreatic water level was measured at two locations. Gravimetric soil moisture contents were measured at 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, and 100–120 cm depths. Neutron probe readings, phreatic water level measurements, and gravimetric sampling were done on a weekly basis and direct prior and two days after irrigation. Data on bulk density, soil texture and field capacity were also obtained. Data from the scintillometer were recorded on a built-in data logger and the climate mast data were recorded on a Campbell Scientific 21X data logger every ten minutes.

At the valley site, a second identical scintillometer was installed. This scintillometer had a path of 2,700 m at an effective height of 18 m above the valley floor. No other instruments were installed at this site.

The hourly meteorological data were available from the Menemen Research Center climate station for 1998, although May data were missing. Historical daily climate data from this station were available for global radiation, pan evaporation, precipitation, relative humidity, hours of bright sunshine, average air temperature, minimum air temperature, maximum air temperature and wind speed.

The National Oceanic and Atmospheric Administration-Advanced Very High Resolution

Radiometer(NOAA-AVHRR) and Landsat TM (Thematic Mapper) images were purchased for two dates, 26 June and 29 August 1998, and, in addition, NOAA images were obtained for another 15 dates during the period January–September 1998.

Methods

This section provides brief descriptions of the methods used. The reader is referred to the individual papers in the Journal of Hydrology Special Issue (Kite and Droogers 2000) for more details.

Field Measurement Method and Climate Station Methods

Three methods were selected to represent the field-based and climate-station based ET methods. Two of them represent the standard methods applied in agricultural science to estimate crop water requirements, and the third one, the scintillometer, represents an innovative method to measure sensible heat flux over an area (which can be used with other information to derive actual ET). The first two methods, FAO-24 and FAO-56, used the same input in terms of meteorological data, while the scintillometer data were derived from separate measurements.

Estimation Methods for Crop Water Requirements, FAO-24

In 1977, the report FAO-24 (Doorenbos and Pruitt 1977) proposed guidelines for using the Blaney-Criddle, Penman, radiation, and pan evaporation methods to compute a reference crop evapotranspiration. FAO-24 has been used in many countries under different climatic and soil conditions for many years and a great deal of experience in the use of these methods has been gained. An updated procedure (FAO-56) (Allen et al. 1998) is now published recommending a new standard for reference evapotranspiration. It was therefore of interest to use the methods described in FAO-24 for the Menemen experimental site (Beyazgül, Kayam, and Engelsman 2000) and to compare the results with the application of the new FAO-56 Penman-Monteith procedure (Allen 2000).

For the cotton field site, typical meteorological parameters, crop characteristics, and soil parameters were obtained. Reference evapotranspirations, $ET_{o,}$ were calculated using the four methods from FAO-24 (Blaney-Criddle, Penman, radiation, and pan evaporation) and additionally, the Hargreaves method (Hargreaves and Samani 1982) and the Penman-Monteith method (Monteith 1981). The derived reference evapotranspirations (ET_o) were multiplied by a crop factor (K_c) resulting in crop evapotranspirations (ET_c). For the six methods considered, the same K_c factor was assumed, but the factor itself varied during the different growing stages of the crop.

Finally, the actual evapotranspirations (ET_{act}) were estimated by a simple water-budget approach taking into account the limitations in soil water. The cotton field water table depths were shallow, ranging from about 50 cm at the start of the growing season down to about 120 cm at the end. With a rooting depth of 100 cm, a substantial upward flux from the groundwater into the root zone would be expected. Two cases were investigated. First, no knowledge of soil moisture was assumed. Second, weekly soil moisture contents were used to correct the simulated moisture contents to the measured ones. The differences in ET_{act} between these two methods must originate from capillary rise.

Crop Coefficient and Reference Evapotranspiration Method, FAO-56

The FAO-56 approach (Allen et al. 1998; Allen 2000) first calculates a reference evapotranspiration (ET_o) for grass or an alfalfa reference crop and then multiplies this by an empirical crop coefficient (K_c) to produce an estimate of crop potential evapotranspiration (ET_c). The ET_c calculations used the dual crop coefficient approach that includes separate calculation of transpiration and evaporation occurring after precipitation and irrigation events.

The FAO-56 Penman-Monteith method computes reference evapotranspiration from net radiation at the crop surface, soil heat flux, air temperature, wind speed and saturation vapor pressure deficit. The crop coefficient is determined from a stress reduction coefficient (K_s), a basal crop coefficient (K_{cb}) and a soil water evaporation coefficient (K_e). The K_{cb}, curve is divided into four growth stages: initial, development, midseason, and late season. Field capacity and wilting point estimates determine soil water supply for evapotranspiration. The downward drainage of the topsoil is included but no upward flow of water from a saturated water table was considered, possibly causing some overprediction of water stress between the known irrigations. Water stress in the FAO-56 procedure is accounted for by reducing the value of K_s.

The weather data from the Menemen Research Center climate station were screened and missing data for May, November, and December 1998 were estimated from adjacent periods. This did not affect the estimates of ET for the two Landsat overpass dates but did affect the growing season and the annual totals reported.

A visual rating of field appearances using a composite Landsat image of the project locations was used to reduce the potential K_c ET_c values by a constant percentage over all months and crops to account for less than pristine conditions and management.

The valley site evapotranspiration values were produced by simulating three replications with different planting dates and different initial dates of irrigation for each crop and then averaging the results. All crops at the valley study site were presumed to be fully irrigated after the first irrigation except for pasture, which was intentionally stressed to simulate typical management. The K_c values for all crops approached 1.2 during winter and spring periods following rain when the soil surface layer was fully wet. K_{cb} during nongrowing periods was assumed to be zero to reflect a very dry soil surface with little ground cover. The K_c during the midseason period was reduced by 15 percent from the values in FAO-56 to account for the low planting densities and planting gaps noted in photographs of the study areas and to account for the impacts of irrigation uniformity on field-scale ET.

Large Aperture Scintillometer

Estimation of actual evapotranspiration using the energy balance method requires knowledge of the sensible heat flux. According to the Monin-Obukhov similarity theory, the sensible heat flux, H, is related to the structure parameter of temperature, C_T^2. A large aperture scintillometer is an instrument to collect path-average values of C_T^2 (de Bruin et al. 1995). The scintillometer directs a light source between a transmitter and receiver and the receiver records and analyses fluctuations in the turbulent intensity of the refractive index of the air. These fluctuations are due to changes in temperature and humidity caused by heat and moisture eddies along the path of the light. Additional data on temperature, pressure, and humidity are necessary to compute the characteristic parameter of the refractive index. This can then be converted to sensible heat flux. An important feature of the scintillometer technique is although the measurement is along the path of the light beam, because of the effects of wind, this is actually an estimate of H over an area. The method therefore forms an intermediate level between the field scale measurements and the large area remote sensing estimates.

The installed scintillometers derived 10-minute averages and standard deviations of the refractive index structure parameter, C_n^2 for the entire growing season of 1998. Measurements of C_n^2 at the valley site were supplemented by wind speed and temperature measured at the Menemen Research Center climate station. The roughness length was derived from a standard classification using photographs of the area. The effective height of the instrument was derived from a weighting function and a topographical map. Since actual values of the Bowen ratio were not measured, the method was applied three times using Bowen ratios of 0.3, 0.5, and 1. Only daytime data were used; nighttime sensible heat fluxes were assumed to be zero. On 26 June, the wind direction was variable and both east and west upwind areas were included in the scintillometer footprint. On 29 August, the prevailing wind was easterly and a 1,500 m upwind footprint was used.

The scintillometer data from the cotton field site could not be processed using the standard procedure. The cause or source of failure could not be diagnosed by the researcher and, therefore, the data were abandoned. Instead, the data gathered from the micrometeorological station were used in the temperature variance method. An approximate analytic solution was used to determine the hourly daytime values of sensible heat for 26 June and 29 August which were then converted to daily means.

Hydrological Models

Hydrological models simulate the transformation of precipitation into streamflow taking into account all the component processes such as evapotranspiration, interception, infiltration, runoff, and groundwater flow and including all the artificial effects of dams, reservoirs, diversions, and irrigation schemes. They are therefore able to estimate evaporation and transpiration at many points and at many times. In this experiment a detailed agro-hydrological model and a basin scale model were used to bridge the gap between the field techniques and the remote sensing techniques.

Detailed Agro-Hydrological Model, SWAP

The physically based simulation model SWAP (Soil, Water, Atmosphere, Plant; van Dam et al. 1997) calculates potential evapotranspiration by using the Penman-Monteith algorithm for three different conditions (bare soil, dry crop, and wet crop) by adjusting parameters for albedo, crop height, and crop resistance. Actual crop transpiration and soil evaporation may be simulated by taking into account the crop development stage as well as limitations in soil moisture. The model may be applied for many combinations of crop and soil to simulate the overall performance of irrigation schemes (Droogers et al. 2000).

The SWAP model was applied for the cotton field and valley sites for the first nine months of 1998. For the cotton field site, detailed information on soils, water table, cropping stage and irrigation applications were used as input to SWAP. For the valley site, a period of nine months was also used, but as detailed input data were lacking, more assumptions had to be made. With a mixed cropping pattern, a lumped approach was used to estimate actual evapotranspiration. While knowledge of irrigation application days is especially critical for determining actual E and T, these were not known for the valley site and, therefore, a rotational irrigation application was assumed. This assumption resulted in a constant small amount of crop stress over the whole site.

Basin-Scale Hydrological Model, SLURP

SLURP (Semi-distributed Land Use-based Runoff Processes) is a model that conceptualizes the complete hydrological cycle and also includes features such as reservoirs, diversions and extractions, and irrigation schemes (Kite 1997). The model divides a basin into many smaller subbasins using topographic analysis. Each subbasin (known as an aggregated simulation area, ASA) is again subdivided into areas of different land use. At each time increment, a vertical water balance is applied sequentially to the matrix of ASAs and land covers. Each element of the matrix is simulated by nonlinear reservoirs representing canopy interception, snowpack, rapid runoff, and slow runoff. The model routes precipitation through the physical processes and generates outputs (evaporation, transpiration, and runoff) and changes in storage (canopy interception, snowpack, soil moisture, and groundwater). Runoffs are accumulated from each land cover within an ASA and the combined runoff is converted to streamflow and routed to the outlets of each ASA and then to the basin outlet.

In this experiment the model used the Penman-Monteith equation to compute potential evapotranspiration for a dry crop and for a bare soil and requires information on crop height, canopy resistance, and leaf area index, although Morton, Priestley-Taylor, and Granger techniques are also available in the model. The available soil moisture is calculated as a function of the field capacity and root zone depth. Canopy/soil evaporation and crop transpiration are computed separately.

Irrigation rates were assumed at 100 mm/day for each of the four cotton field applications, which compares with a maximum daily rainfall over the winter period of about 110 mm. The irrigation rate for the valley site was also assumed as 100 mm/day but the actual dates of irrigation at many farms within the cross section were not known. In this case, a series of 10 model runs were made using 4 irrigations in different patterns and the average result was used.

The SLURP model was applied on a daily basis to the 17,200 km^2 Gediz Basin, Turkey (see figure 1) using 27 ASAs and 37 land covers for the period October 1986–September 1998. The outputs from the model included streamflow at many points along the river system and daily soil evaporation, crop transpiration, and net water production distributed over the entire basin.

Remote Sensing Methods

Remote sensing methods are attractive to estimate ET as they cover large areas and can provide estimates at a very high spatial resolution. Intensive field monitoring is also not required, although some ground-truth measurements can be helpful in interpreting the satellite images. Three methods were selected varying in resolution and degree of physical realism.

Satellite-Derived Feedback Mechanism

Most methods for estimating evapotranspiration make use of net radiation as the driving parameter and vapor pressure deficit to define vapor transfer. A remote sensing approach has been developed in which surface albedo from satellite visible channels is used to estimate net radiation and, using a feedback relationship, the surface temperature from infra-red channels is used to obtain the vapor pressure deficit in the overlying air (Granger 1997). The feedback relationship states that the temperature and humidity observed in the air are a reflection of the surface partitioning of energy and vice versa. The relationship involved has been shown to be applicable above a wide range of natural surfaces ranging from bare soil to forest covers. This technique presents some advantages over the conventional approach in which the surface temperature is used as an index of the sensible heat transfer and the evapotranspiration is then inferred from a simplified inverted energy balance. The method allows for the application of remotely sensed data in conjunction with conventional evapotranspiration models. It also represents a convenient approach for the application of satellite-derived estimates of regional evapotranspiration within hydrological models without involving the need to collect supporting ground-based atmospheric data.

The raw NOAA-AVHRR images were processed for geometric conversion, calculation of albedos or reflectances from visible channels, calculation of brightness temperatures from infrared channels, and extraction of satellite position and viewing angles using a commercial software package. Channel 4 and 5 brightness temperatures, along with satellite viewing angle, were used to obtain the surface temperature for each pixel in the image. Menemen Research Center long-term mean air temperature, clear sky global radiation, and relationship between daily maximum and daily mean temperatures were used. The satellite-derived surface temperatures were converted to daily means and the vapor pressure deficit at each pixel was estimated from the air temperature and saturated vapor pressure. The channel 2 reflectance was used as albedo when estimating the net radiation at each pixel from incoming short-wave radiation. Since the basin vegetation varies considerably, the NDVI vegetation index was calculated from the raw satellite data and used to estimate the vegetation roughness and the vapor transfer coefficient. Evapotranspiration was then calculated at each pixel using the Granger (1989) model.

LANDSAT TM data were atmospherically corrected using soil temperature profiles from the Menemen Research Center climate station and a standard mid-latitude atmosphere. LANDSAT channel 3 was used to estimate the surface albedo. The vapor pressure deficit and net radiation were then calculated for each pixel as in the NOAA procedure. The LANDSAT-derived vegetation index was used to estimate the surface roughness and calculate evapotranspiration at each pixel using the Granger (1989) model.

Biophysical Processes with Remotely Sensed Data

The total evapotranspiration couples the water and energy balance equations while transpiration is strongly linked to the rate of carbon assimilation. A biophysical model (Choudhury and DiGirolamo 1998) links the water, energy, and carbon processes by using satellite and ancillary data to quantify total evaporation, transpiration, and biomass production (Choudhury 1997). Transpiration is calculated using the Penman-Monteith equation in which the minimum canopy stomatal resistance is determined by the rate of carbon assimilation. Soil evaporation is considered to occur in two stages (the energy-limited rate is calculated using the Priestley-Taylor equation, while the exfiltration limited rate uses the Philip's equation). The rate of carbon assimilation, together with estimated respiration and soil water stress provides biomass production. Satellite observations are used to obtain fractional vegetation cover, surface albedo, incident solar and photosynthetically active radiation, fractional cloud cover, air temperature, and vapor pressure. Precipitation is obtained by combining satellite and surface observations. Biophysical parameters of the model (e.g., soil hydraulic characteristics and maximum carbon assimilation rate of a leaf) are determined from published records and land cover of the area.

The model was used to analyze the daily energy and water balance equations for a 1-degree grid including the Gediz Basin for the period January 1986–December 1990. The seasonal and interannual variations of evaporation and transpiration and their relations with precipitation, net radiation, and net carbon accumulation were computed. The canopy stomatal resistance needed by Penman-Monteith was computed using a linear correlation with carbon assimilation rates derived from leaf absorptance and photosynthetically active radiation (PAR). The Matthews global distribution of land use was used. The data had spatial resolutions varying from 2.5^{o} to 0.25^{o}, all were reduced to 0.25^{o}.

SEBAL Remote Sensing Technique

The Surface Energy Balance Algorithm for Land (SEBAL) is a parameterization of the energy balance and surface fluxes based on spectral satellite measurements (Bastiaanssen et al. 1998). SEBAL requires visible, near-infrared, and thermal infrared input data, which means that applications of Landsat Thematic Mapper (TM) and NOAA Advanced Very High Resolution Radiometer (AVHRR) sensors are useable.

Instantaneous net radiation values were computed from incoming solar radiation measured at two ground stations and outgoing thermal radiation estimated from two cloud-free Landsat TM images via surface albedo, surface emissivity, and surface temperature.

Surface albedo was computed from the top of the atmosphere broadband albedo using an atmospheric correction procedure. Soil heat flux was computed from surface temperature, surface albedo, normalized difference vegetation index (NDVI) and roughness length derived from the soil adjusted vegetation index (SAVI). The sensible heat flux was determined by an iterative solution of standard heat and momentum transport equations using a pixel-based Monin-Obukhov stability correction.

Spatial interpolation techniques were applied consecutively to incorporate spatial thermal radiation variations and the effects arising from buoyancy on momentum and sensible heat fluxes. Using Landsat TM band 6, a wet and a dry pixel were selected for each of the two days considered. The sensible heat flux H was set to 0 for the wet pixel and to the difference between net radiation and soil heat flux for the dry pixel. For the dry pixel it was assumed that dT_a (the vertical difference in air temperature) is a function of the sensible heat flux while for the wet pixel, dT_a was assumed to be zero. From the dT_a and the TM band 6 radiometric surface temperature T_{TM6} for these two pixels, a linear relationship was assumed and used to compute dT_a for the remaining pixels of the image. In both images the minimum values of dT_a were about 10 ^oC. Sensible heat flux at each pixel was computed from the dT_a pixel values and the latent heat flux was found as a residual term.

The instantaneous latent heat fluxes were then converted to the required daily ET values by assuming that the instantaneous evaporative fraction is similar over 24 hours.

Results

The actual evapotranspirations estimated by the various methods for the two field sites on 26 June and 29 August 1998 are given in table 2. The last two columns show the differences between average results for each method and the average of all the methods. The following paragraphs summarize the results from each method and are followed by a more general discussion.

TABLE 2.
Actual evaporation and transpiration results, in mm, from the various methods, for the cotton field and valley sites.

	26 June 1998						29 August 1998						Difference	
	Cotton field			Valley			Cotton field			Valley			mm	percent
	E	T	ET	E	T	ET	E	T	ET	E	T	ET		
FAO-24			5.1						5.5				1.3	31
FAO-56	0	3.1	3.1	0.4	4.5	4.9	0.1	5.2	5.3	0.2	4.1	4.3	0.4	9
Scintillometer[a]			3.9			3.4			3.9			3.5	-0.4	-9
SWAP	0.2	1.6	1.8	0.3	4.7	5.0	0.2	4.7	4.9	0.1	3.2	3.3	-0.3	-7
SLURP	0	1.5	1.5	0	2.8	2.8	0.1	4.8	4.9	0.1	4.9	5.1	-0.5	-12
Feedback-NOAA			3.7			4.5			2.6			2.7	-0.7	-17
Feedback-Landsat			3.6			3.6			3.5			3.8	-0.4	-10
Biophysical[b]			6.4			5.6			6.4			5.6	2.0	48
SEBAL			2.4			3.1			4.4			3.4	-0.7	-18
Average			3.5			4.1			4.6			4.0		

[a]The scintillometer methods gave only sensible heat; this was converted to evapotranspiration using net radiation data from Bastiaanssen (2000). No scintillometer data were available for the cotton field; instead data from the temperature variance method were used.

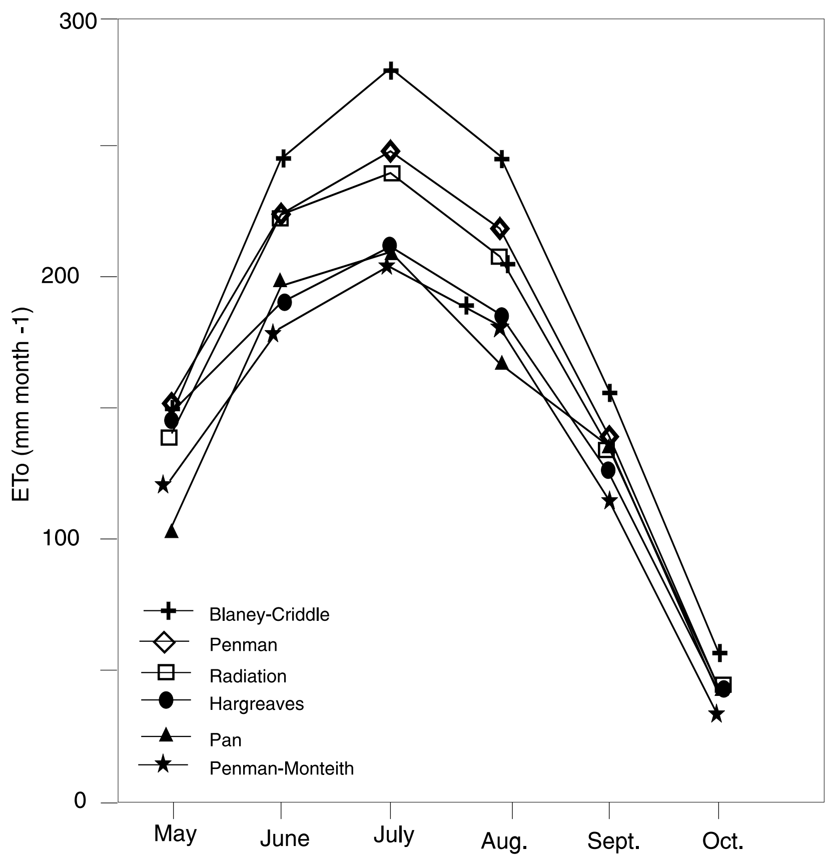
[b] Derived from 1986-1990 average June–August total ET.

Estimation Methods for Crop Water Requirements (FAO-24)

Growing season (April–October) values for reference ET were used in an initial comparison of the FAO-24, Hargreaves, and Penman-Monteith techniques in order to select representative field-scale values (Beyazgül, Kayam, and Engelsman 2000). The results ranged from a low of 831 mm for the Penman-Monteith method to 1,131 mm for the Blaney-Criddle method (figure 5). The average (excluding pan evaporation) is 1,049 mm. The ET reference values computed using the Hargreaves method and the Penman-Monteith method are 16 percent and 26 percent, respectively, lower than the average. Values of ET_c were 85 percent of ET_0 for the whole growing season, but varied between 32 percent of ET_0 in May to 113 percent in August.

For the case with the constant soil moisture contents, predicted crop stress was severe and there was not much difference in the values of ET actual amongst the different methods. However, when we included weekly measured soil moisture contents, the differences between the methods became much greater, ranging from a seasonal total of 885 mm using Blaney-Criddle

FIGURE 5.
Reference evaporation, at the cotton field site, using FAO-24 methods; Bayazgül Kayam, and Engelsman 2000.



down to 697 mm for Penman-Monteith. The differences between the two approaches, including or excluding measured soil moisture contents, are striking and vary between 121 mm and 267 mm depending on the method. The results given in table 2 are from the Penman-Monteith method, as this seemed to be the most stable and reliable.

Only evapotranspiration estimates were derived using this method; no breakdown into evaporation and transpiration was possible.

Crop Coefficient and Reference Evapotranspiration Method (FAO-56)

The ET_c values were computed for five crops and they indicate that the cotton field crop was moisture-stressed between the dates of the two satellite overpasses due to delay of the first irrigation and experienced additional water stress prior to the second irrigation (figure 6) (Allen 2000).

The results for the cotton field and valley sites are given in table 2. The confidence limits for ET_c (using the dual K_{cb} + K_e approach) for the two study days are estimated to be ± 15 percent at 95 percent confidence.

This method was also used to derive E and T estimates for the 1998 growing season and for the full 1998 year. Seasonal values of E and T for the cotton field are estimated to be 50 mm and 570 mm, and for the valley to be 100 mm and 730 mm, respectively. Confidence in Et_c predicted for the growing season is ± 25 percent.

Large Aperture Scintillometer

For the valley site, mean heat fluxes for 26 June (before irrigation) and 29 August (after irrigation) were derived as 90 Wm^{-2} and 35 Wm^{-2} respectively (figure 7). For purposes of comparison, the Meijninger and de Bruin (2000) sensible heat fluxes from the valley scintillometer were converted to estimates of actual evapotranspiration using areal net radiation estimates from Bastiaanssen (2000) and assuming zero soil heat flux. Table 3 shows the data used and the resulting ET are given in table 2.

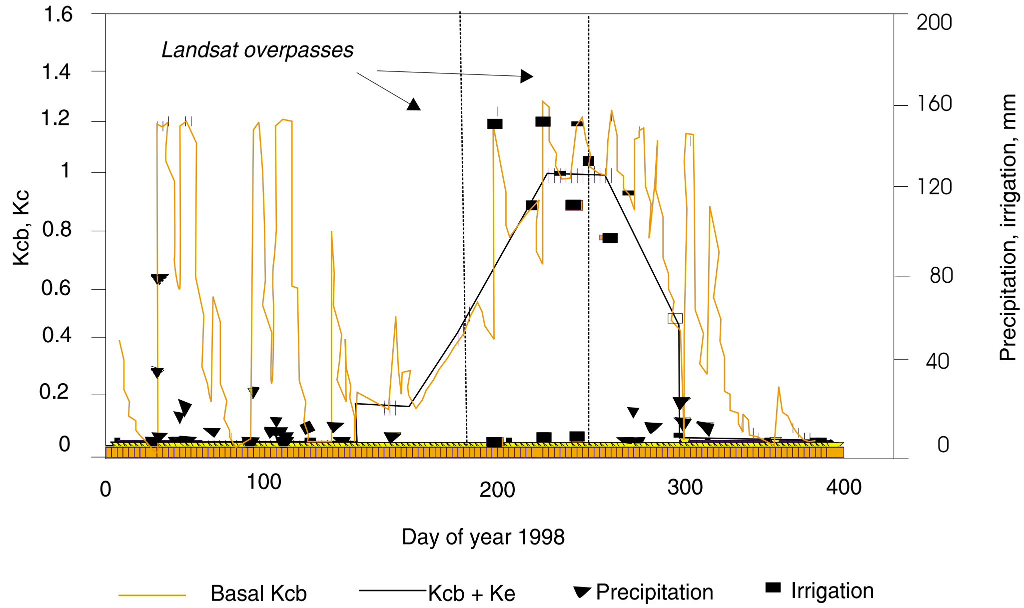
In this report, the sensible heat fluxes for the cotton field site derived from the temperature variance method (Meijninger and de Bruin 2000) were converted to estimates of actual evapotranspiration using areal net radiation data from Bastiaanssen (2000). Only ET estimates are possible from this method with no breakdown to E and T.

TABLE 3.
Conversion from scintillometer sensible heat flux to actual evapotranspiration.

	26 June		29 August	
	Cotton field	Valley	Cotton field	Valley
Sensible heat flux ($W\ m^{-2}$)	83*	90	32*	35
Net radiation ($W\ m^{-2}$)	193	186	142	134
Latent heat ($W\ m^{-2}$)	110	96	110	99
Evapotranspiration (mm)	3.9	3.4	3.9	3.5

*Data from temperature variance method.

FIGURE 6.
FAO-56 crop coefficients K_{cb} and K_e with resulting evapotranspiration for the cotton field site, 1998 (Allen 1999).



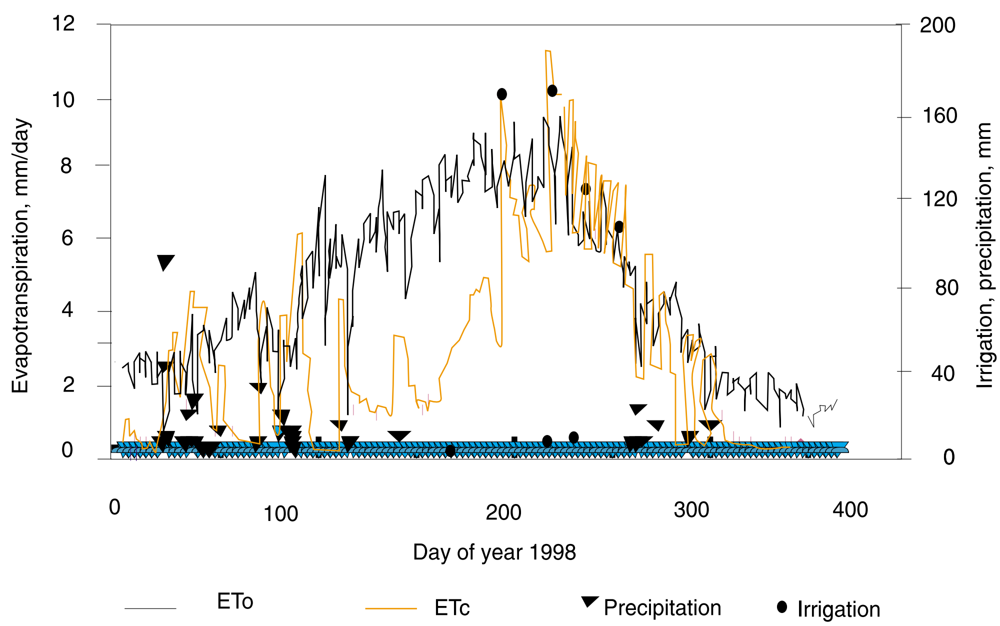
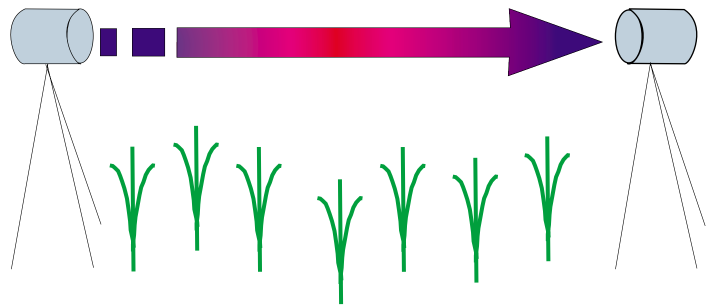


FIGURE 7.
Sketch of the scintillometer application.



$H=f(C^2_T)$; $C^2_T=f(C^2_n)$
C^2_n is the (measured) refractive index structure parameter
C^2_T is the temperature structure parameter
H is the sensible heat flux

Hydrological Models

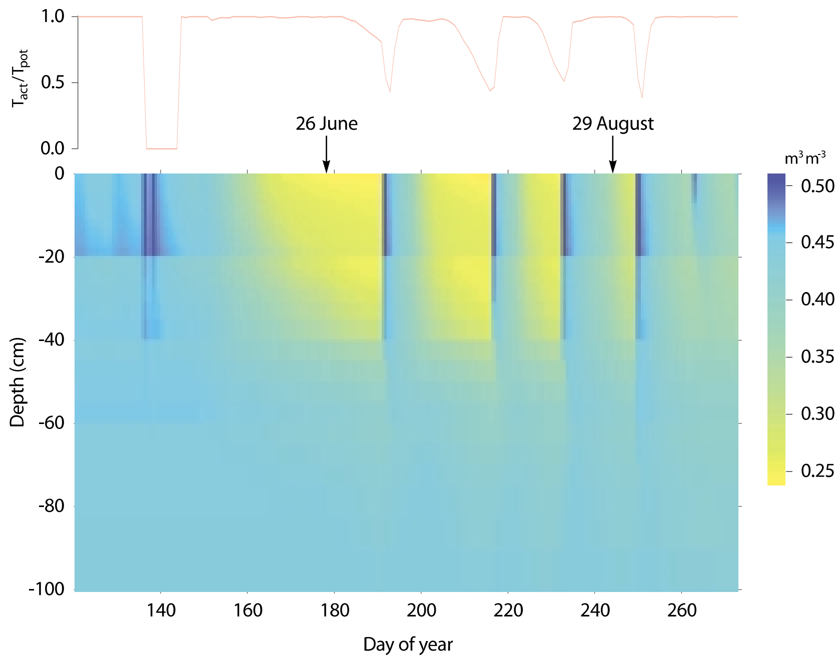
Detailed Agro-Hydrological model (SWAP)

The application of the SWAP model (van Dam et al. 1997) resulted in a detailed analysis of the soil-water-crop relationships, showing all the terms of the water balance, soil moisture contents, potential and actual transpiration, and evaporation (figure 8) (Droogers 2000). Results for the cotton field show that on 26 June, potential T was low and potential E was high, as a result of the low leaf area index of 0.5. Because the topsoil was very dry and sub-soil still wet, actual E was very low and actual T was equal to the potential. On 29 August, cotton field was fully developed, LAI was 4.0, potential T was high, and potential E was low. On this day, actual T reached the potential rate and E was small.

The model showed that T on 26 June was considerably higher for valley than for the cotton field as the cropping pattern for valley included 60 percent grapes and 15 percent orchards. On 29 August, some crop stress occurred, resulting in a lower T, as the soil water storage was depleted and was not fully compensated by the irrigation applications. The results show that a distinction between actual crop transpiration and soil evaporation can be made and that the lumped method is able to estimate areal actual evapotranspiration.

The application of the SWAP model also derived growing season values of E and T for each site. Seasonal values of E and T for cotton field are 130 mm and 493 mm, respectively, and for valley are 102 mm and 702 mm, respectively.

FIGURE 8.
The SWAP model results showing the ratio of actual transpiration to potential transpiration and the distribution of soil moisture with depth and time for the cotton field site during the 1998 irrigation season.



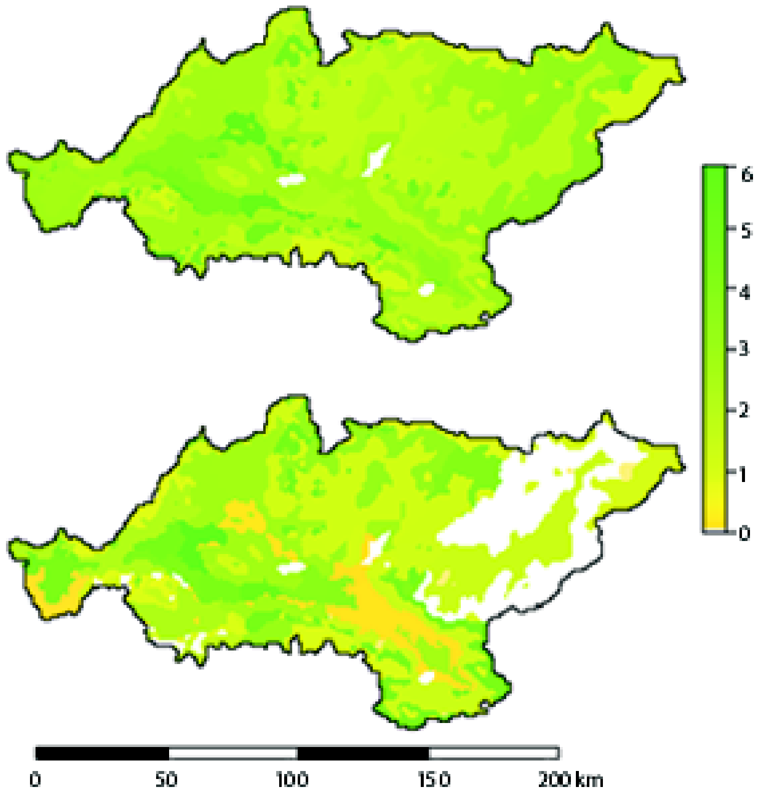
Basin-Scale Hydrological Model (SLURP)

The SLURP results for the October 1997–September 1998 hydrological year show that soil evaporation varied from 0 to 6 mm/day over the winter and spring period, falling to zero (except after irrigation) during the growing season (Kite 2000). Transpiration remained close to zero from the end of November until the start of the growing season (April) and then rose rapidly to 5–10 mm/day before tailing off at the end of October again. E and T values for the two sites and two overpass days are given in table 2.

The application of the SLURP model also derived growing season values of E and T for each site. The seasonal values of E and T for the cotton field are 20 mm and 584 mm, respectively, and for the valley are 30 mm and 722 mm, respectively.

This method also estimated E and T for each $1km^2$ of the basin for each day during the period 1988–1998. The areal distribution of T over the basin on 26 June shows much less variation than on 29 August because of the distribution of irrigated areas in the basin and the pattern of crop watering (figure 9). The basin-wide E and T on 26 June are 0.1 mm and 3.4 mm, respectively, and on 29 August are 0.2 mm and 3.7 mm, respectively. For the 1998 growing season, the basin-average E and T and are 88 mm and 455 mm, respectively, while mean annual (1988–1998) basin-wide evaporation and transpiration are 88 mm and 378 mm, respectively.

FIGURE 9.
Distributed transpiration, in mm, over the 17,200 km^2 Gediz Basin on the two Landsat overpass dates, 26 June1998 (top) and 29 August1998, (bottom) from the SLURP hydrological model (Kite 2000).

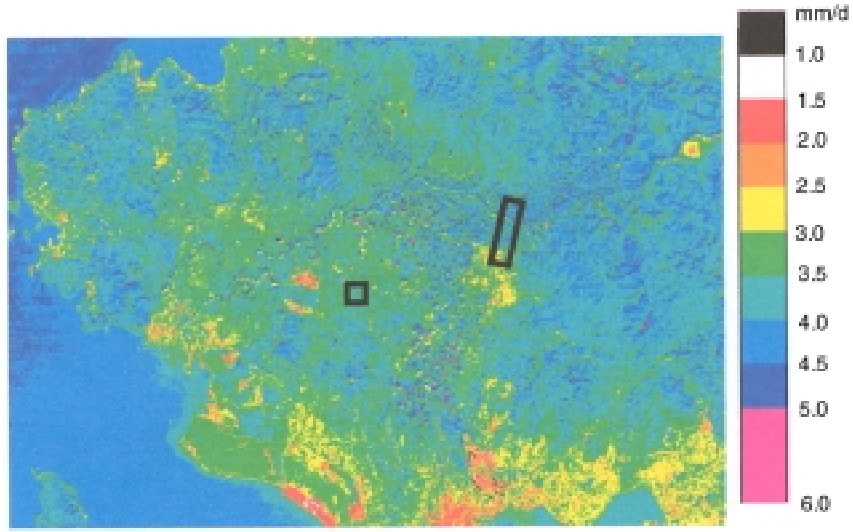


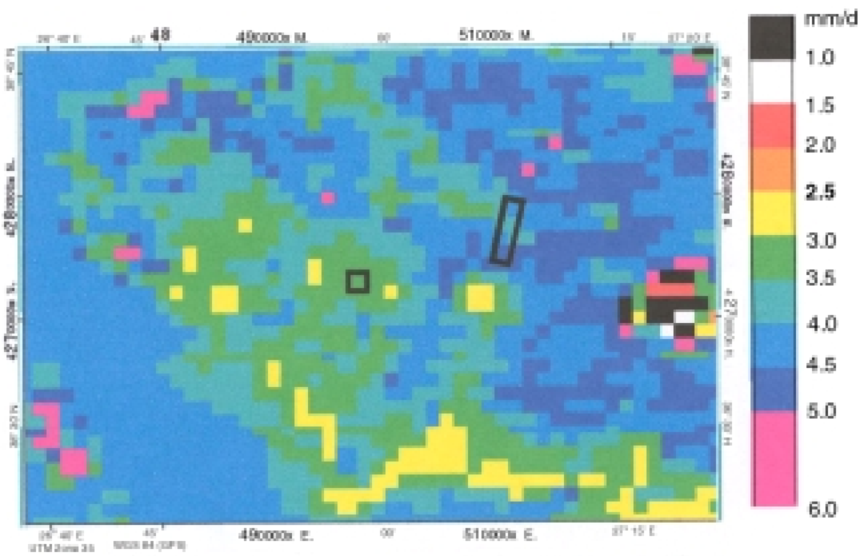
Remote Sensing Methods

Satellite-Derived Feedback Mechanism

Figures were derived showing the distribution of evapotranspiration across the target area for the two Landsat overpass days (figure 10) (Granger 2000). The numerical values for the two sites are given in table 2. The use of two satellites allows a comparison between the results at two resolutions. At cotton field, on 26 June, the two satellites produce very similar results; however, on 26 June at valley, Landsat is almost 1 mm lower than NOAA while for both sites on 29 August, Landsat is 1 mm higher than NOAA. Table 2 shows that on 26 June, the two satellite methods agree, while for 29 August, the Landsat estimate is somewhat higher than the NOAA. The standard deviations of the Landsat pixel values within the NOAA pixels representing the cotton field and valley sites on 26 June are 0.3 and 0.4, respectively, and on 29 August are 0.1 and 0.4, respectively.

FIGURE 10.
Evapotranspiration over the Menemen Left Bank irrigation scheme on the 26 June 1998 Landsat overpass using Landsat (top) and NOAA AVHRR (bottom) images (Granger 1999).





This method was also able to derive evapotranspiration estimates for the total basin area. On 26 June, 11 percent of the basin area was cloud-covered. For the cloud-free portion of the basin, the average daily evapotranspiration rate was 3.5 ± 1.2 mm. On 29 August, the basin was completely clear; the average daily evapotranspiration was 2.8 ± 0.2 mm.

Biophysical Processes with Remotely Sensed Data

The climatological data used in the model were found to agree with the local weather station data (Choudhury 2000). Comparisons with measurements at other locations showed uncertainties of about 15 percent and 20 percent for computed annual and monthly evaporation respectively. Figure 11 shows the monthly evapotranspiration and net carbon accumulation for the area of the Gediz Basin. The 1998 growing season ET at the cotton field and the valley sites were estimated at 575 and 500 mm, respectively, on the basis of crop type. The average annual (1986–1990) basin-wide evaporation and transpiration estimates are 217 mm and 178 mm, respectively. The daily values given in table 2 were derived from the 1986–1990 average seasonal totals and do not distinguish between specific dates.

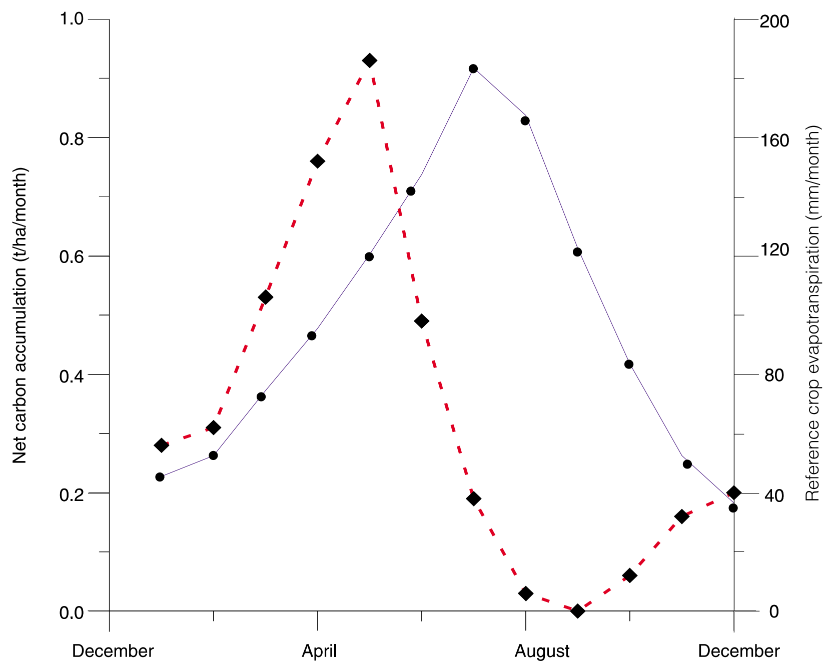
SEBAL Remote Sensing Technique

Figure 12 shows the distributed evapotranspiration values for the area of the field sites on 26 June and 29 August 1998 (Bastiaanssen 2000). The derived evaporative fraction data indicate that June is, in general, drier than August as a result of the lower crop cover in June and the commencement of the irrigation season in July. This can be clearly seen from the results for the cotton field (table 2), where values of ET for June were lower than for August. The evaporative fraction shows that for both sites and both dates the actual ET is lower than the potential. The energy balance results show that 26 June had more solar radiation and a consequent higher net available energy than 29 August. As the peak solar radiation fell outside the irrigation season, sensible heat fluxes were relatively high and latent heat fluxes low during June. The lower evaporative fraction during June reveals that soil moisture was the constraint on actual evapotranspiration; an evaporative fraction of approximately 40 percent indicates a severe reduction of potential evapotranspiration. An evaporative fraction of approximately 80 percent for crops in August suggests that they were well supplied with water but, since solar radiation was already reduced by this date, the evapotranspiration was still relatively low.

Overall Comments on Results

The actual ET estimated by the various methods for 26 June, 1998, varied from 1.5 mm to 6.4 mm for the cotton field and 2.8 mm to 5.6 mm for the valley site. On 29 August, the ET ranged from 2.6 mm to 6.4 mm for the cotton field, and 2.7 mm to 5.6 mm for the valley site (table 2). In all cases, the highest values are those estimated from seasonal results of the biophysical model. No clear trend could be observed between the field methods, the models, and the RS estimates. The FAO-24 method, the scintillometer, and the remote sensing methods could give only ET estimates while the FAO-56 and the hydrological models were able to provide

FIGURE 11.
Evapotranspiration (blue solid line, right axis) and net carbon accumulation (red dotted line, left axis) for the Gediz Basin area in 1998 (Chaudhury 1999).



both E and T results. All the methods that were able to estimate E indicate that the soil evaporation was only a small fraction of the ET.

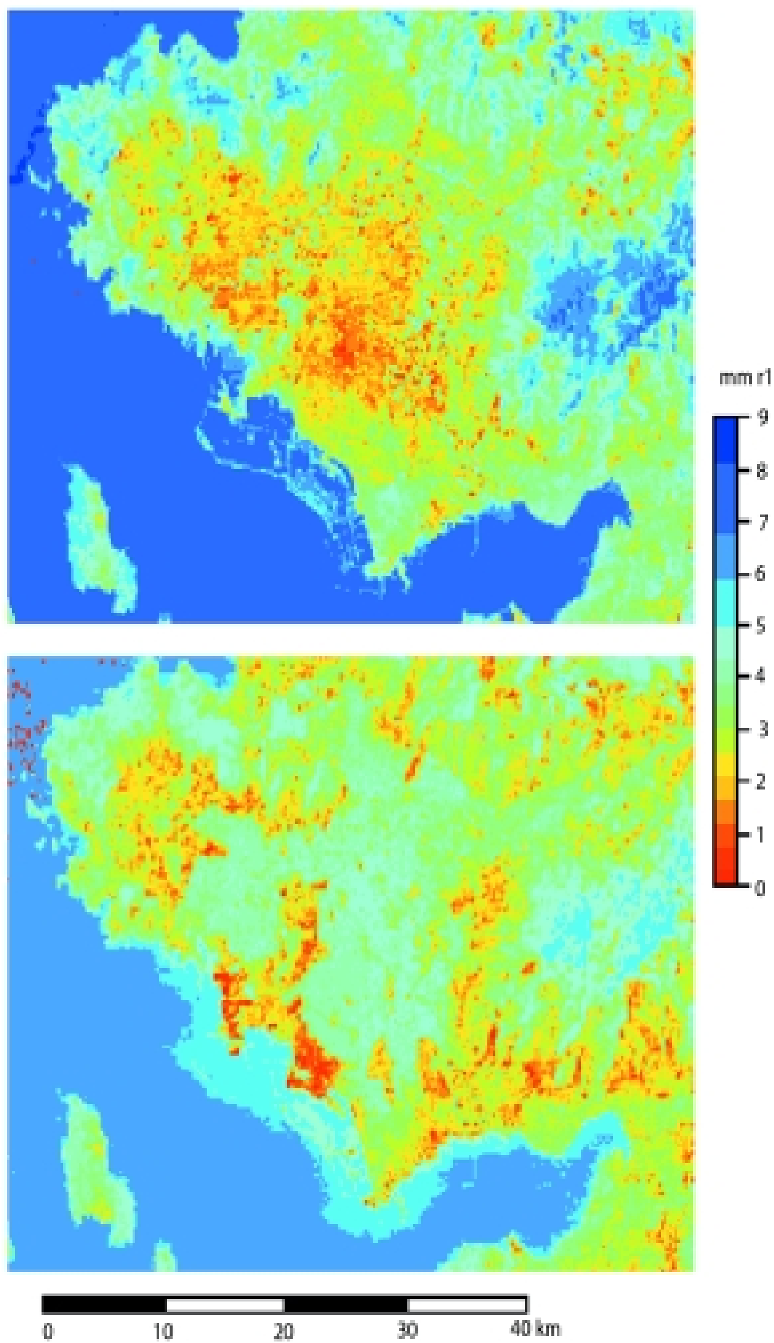
The FAO-24, FAO-56, SWAP, and SLURP methods all use Penman-Monteith to compute potential ET. These should all be comparable but data are not available to confirm this. The methods then differ in their means of computing the actual ET, which is a function of the soil moisture content.

The two hydrological models are in reasonable agreement on both dates for the cotton field but differ considerably on both dates for the valley site. This is probably due to the different assumptions of irrigation pattern for the valley site.

Amongst those remote sensing methods that used Landsat images, the estimates from the SEBAL and feedback methods are not consistent. On 26 June, SEBAL is lower than feedback at both sites but on 29 August, SEBAL is higher than feedback at the cotton field.

Several methods computed E and T or ET for longer periods or for larger areas. Amongst those methods, the ranges of actual ET estimates for the 1998 growing season were much smaller: from 604 mm to 620 mm for the cotton field and from 750 mm to 830 mm for the valley site. However, the narrow ranges of ET hide considerable differences between the estimates of E and T. For the cotton field, the FAO-56 and SLURP estimates of E and T are in reasonable agreement while SWAP has higher E and lower T. For the valley site, in contrast, FAO-56 and SWAP have comparable E while the SLURP estimate of E is much lower. This seems to

FIGURE 12.
Evapotranspiration over the Menemen Left Bank Irrigation scheme on the two Landsat overpass dates, 26 June 1998 (top) and 29 August 1998 (botton), from the SEBAL remote sensing technique (Bastiaanssen 2000).



be due to different assumptions on growing patterns and irrigation scheduling.

The sensible heat estimates from the valley scintillometer and the cotton field temperature variance method (Meijninger and de Bruin 2000) can also be compared to those from SEBAL (table 4). It is not obvious why, while the instantaneous measurements by the two methods at the overpass time are very different (e.g., 26 June, valley site), the computed daily mean values of sensible heat from the two methods are often similar. It is also noticeable that the differences are large in June, a dry month with no irrigation, and much smaller in August, a wetter month with irrigation. This may indicate a sensitivity of the scintillometer to humidity.

Differences between the various estimates of ET and the overall average are shown in the last two columns of table 2 in millimeters and in percentage. These values are included to reflect relative differences among the methods and do not indicate absolute accuracy.

TABLE 4.
Comparison of sensible heat flux data from the scintillometer and SEBAL. All data are given in W m^{-2} and the instantaneous measurements are at 0930 Landsat overpass time.

	26 June		29 August	
	Cotton field	Valley	Cotton field	Valley
Instantaneous sensible heat (SEBAL)	190	170	34	52
Instantaneous sensible heat (scintillometer)	75*	100	25*	42
Daily mean sensible heat (SEBAL)	124	98	18	37
Daily mean sensible heat (scintillometer)	83*	90	14*	35

*Data from temperature variance method.

Discussion and Conclusions

Increasing demands for water require improved allocation of a scarce resource between competing interests. Studies are required to investigate whether irrigation management and productivity can be improved and, if so, what would be the effects on other water users. Performance indicators that rely on knowledge of water supply, soil evaporation, crop transpiration, and return flows are useful tools in such studies. Soil evaporation and crop transpiration are generally computed from field data or as residuals in water balances. New methods using remotely sensed data and hydrological models needed to be evaluated and compared to more traditional techniques before they could be reliably applied. A field experiment over the summer of 1998 in western Turkey provided a data set for such an intercomparison.

The results show a wide range of estimated ET with no patterns evident amongst the various methods. A clear judgement as to which methods produce the most accurate results is difficult to make. The assumption that field methods are probably the most reliable is hard to justify as the three field methods differ considerably (table 2). Moreover, no clear conclusions can be made between the three groups of results: field measurements, models, or remote sensing.

However, if we make some assumptions on uncertainties in the three terms of the energy balance equation, we can indicate which methods fall within a reasonable confidence range. Assume that the average uncertainties for all the methods are 30 percent for sensible heat flux H, 100 percent for soil heat flux G, and 20 percent for net radiation R_n. Then, if on 26 June, the magnitude of ET is about the same as H, about 5 times G and about 0.5 R_n, the average uncertainty in ET estimated as a residual of the energy balance, and assuming independence of terms, would be about 52 percent. This results in a confidence band of 2.4–5.8 mm/day and for 29 August, when the magnitude of ET is about 3 times H, about 8 times G and about 0.8 R_n, the uncertainty in ET is 32 percent and the confidence band is 2.9–5.1 mm/day. All the methods except the biophysical in August fall within these confidence bands.

For the cotton field on 26 June, the confidence limits are 1.8–5.3 mm/day and all methods except SLURP and biophysical processes fall within these limits. On 29 August, the limits are 3.1–6.1 mm/day and only feedback-NOAA and biophysical fall outside the limits.

As noted, the ET estimates by the biophysical method are only approximate for the specific test dates due to the broad temporal nature of the method.

The methods have different spatial and temporal capabilities. Table 5 shows that there tends to be a relationship between complexity and variety of output. FAO methods are generally simpler and produce a limited set of point-based results; SLURP and SWAP are complex but produce a wide variety of results while the remotely sensed methods (because of access and processing times and the need for cloud-free images) have limited temporal applicability.

Data requirements can also be a limiting factor in the applicability of a method. Table 6 shows the types of data needed by each method.

It is clear that no single method is ideal; all have their advantages and disadvantages. It is probable that using a combination of methods will bring out the complementarity and prove better than any technique used alone. The following conclusions refer specifically to the different types of methods used and some recommendations for use of the different methods are given later.

TABLE 5.
Summary of data requirements and applicability of outputs of ET methods.

	Data requirements		Complexity	Coverage	Resolution	Temporal scale	Predictive
	Static	Dynamic					
FAO-24	-[a]	-	-	-	+[b]	-	-
FAO-56	-	+	o[c]	-	+	o	o
Scintillometer	-	o	o	o	+	+	-
SWAP	o	+	+	-	+	+	+
SLURP	+	+	+	+	-	+	+
Feedback	-	-	o	+	+	-	-
Biophysical	-	-	+	+	-	-	-
SEBAL	-	-	+	+	+	-	-

[a]low [b]high [c]average

TABLE 6.
Data requirements for the various evapotranspiration methods.

	Climate data	Satellite data	Soils data	Special data
FAO-24	√	-	√	-
FAO-56	√	-	√	-
Scintillometer	√	-	-	Needs special instrument
SWAP	√	-	√	-
SLURP	√	-	√	
Feedback	√	√	-	-
Biophysical	-	√	-	Needs many published data
SEBAL	√	√	-	-

Field Measurements

Estimation Methods for Crop Water Requirements (FAO-24)

The standard methods described in FAO-24 are relatively easy to use, as they require only regular climate data. There are large differences in results from the various methods and the Penman-Monteith appears to be the most stable and reliable. The process of transforming reference ET to crop ET and to actual ET requires additional information on crops, soils, and hydrological conditions.

For the conditions at the cotton field site, the application of the FAO-24 methods showed that it was essential to include the effect of capillary rise in the calculations of actual ET. The inclusion of a weekly measured soil moisture content in combination with a simple water balance model seems to be promising although this involves many field measurements.

Crop Coefficient and Reference Evapotranspiration Method (FAO-56)

The FAO-56 method also requires minimal data for application and is relatively quick and easy to apply. The FAO-56 method is useful for operational applications, where day-to-day estimates of ET_c are needed and may prove to be valuable for filling the gap between satellite analyses. However, the procedure is generally limited to agricultural crops since, for natural vegetation, uncertainty increases due to variation in plant density, leaf area, rooting depths, and lack of phenology-soil water feedback loops.

As with all point data methods, the spatial resolution of the results is limited by the degree to which weather data can be extrapolated. This is affected by the heterogeneity of the surrounding terrain and weather systems and is typically about 150 km.

Large Aperture Scintillometer

The large-scale scintillometer at the valley site proved to be a robust and reliable instrument from which to compute actual sensible heat fluxes. The method can be applied for long periods of time with minimal effort. The lack of wind speed data at the valley site caused uncertainty in the calculated sensible heat flux of about 5 percent.

The problems found with the cotton field scintillometer imply a lack of generality that needs to be investigated before the method can be widely applied. As the scintillometer measures an areal parameter, and also requires point meteorological data, it is not clear which area the results would apply over.

Only sensible heat is computed with this method. The net radiation must be derived elsewhere before ET can be computed. The analysis procedure also assumes a Bowen ratio value and assumes that nighttime sensible heat fluxes are negligible.

Hydrological Models

Detailed Agro-Hydrological Model (SWAP)

The physically based agro-hydrological model SWAP can be run with different levels of data. For the cotton field site, detailed information on soils, water tables, crops, and irrigation applications was used and the results were specific for the field considered. On the other hand, for the valley site, various assumptions were made; especially about the amount and timing of irrigation, and the results are more area-specific than field-specific. SWAP can be used to understand processes and to investigate alternative scenarios.

Basin-Scale Hydrological Model (SLURP)

The SLURP model was the only method that was able to estimate evaporation and transpiration for the full spatial and temporal ranges (crop to basin, day to annual average). The estimates of evapotranspiration agree well with other methods for the growing season, with the only other basin-wide estimates on overpass days (feedback method) and with the only other long-term mean annual data (biophysical model). The advantage of the hydrological model is that it can be used continuously (even on cloudy days) and also to evaluate alternative scenarios.

Remote Sensing Methods

The remote sensing methods all have the advantage that the spatial resolution is high (especially for the Landsat methods) and the spatial coverage is high (especially for the NOAA methods), and the disadvantage that only instantaneous estimates can be obtained. This last point leaves us with two problems; first to derive daily values from a split-second observation and, second, the necessity of analyzing many (maybe expensive) images for seasonal estimates of ET. For some areas, the requirement of cloud-free days can be a limitation for remote sensing methods.

Satellite-Derived Feedback Mechanism

The feedback mechanism was able to estimate evapotranspiration for the two specific sites using both NOAA-AVHRR and Landsat TM data and to estimate basin averages using the NOAA-AVHRR. The procedures used are straightforward and relatively easy to apply. Assumptions are made regarding the relationships between vapor pressure deficit and saturation vapor pressure and between single-measurement and daily mean air temperatures, but these are justified by experimental data from many sites. The relationship between net long-wave and incoming short-wave radiation uses a constant derived for dry continental locations, which may not be directly applicable for a humid maritime environment.

The NOAA images used by this method were georeferenced while the Landsat images were assumed correct from the supplier; this may introduce some bias.

The results in table 2 show that the feedback method using Landsat is closer to the mean of all the methods than the feedback using NOAA. This may indicate the difficulty in estimations for specific points from lower resolution NOAA images.

Biophysical Processes with Remotely Sensed Data

The advantage of this method is that, as transpiration is coupled to carbon assimilation, it can give results that no other method can provide such as the mean annual water use efficiency in terms of carbon production per unit of water. However, because of the dependence on published remotely sensed data it was only possible to use this method for a historical period and not for the two 1998 intercomparison dates. The 1986–1990 growing season average ET from this method is 575 mm for cotton field site and 500 mm for valley. The latter is substantially lower than for the other methods. The method also operates at a larger scale (0.25^{o} latitude and longitude) than the other methods and does not explicitly include the effects of surface or groundwater irrigation.

SEBAL Remote Sensing Technique

The SEBAL method derives the evaporative fraction from satellite data. This is a measure of energy partitioning and a good indicator of crop stress. Actual evapotranspiration can be easily obtained from the product of the evaporative fraction and the net radiation. The SEBAL remote sensing technique is not restricted to irrigated areas, but can be applied to a broad range of vegetation types. Data requirements are low and restricted to satellite information although some additional ground observations can be used to improve the reliability.

As with the feedback and other visible and infrared methods, images must be cloud-free. Additionally for SEBAL, the image must contain at least one fully wet and one fully dry pixel in order to obtain a range of sensible heat fluxes. The analysis assumes that instantaneous evaporative fraction is similar to its 24-hour counterpart.

Recommendations

The results have shown that all methods could compute evapotranspiration for the two sites on the two specified days (except that the scintillometer computed only sensible heat) and that some methods also have wider applicability. It was pointed out in the conclusions that there is a range of computed values and that no method is ideal; all have their advantages and disadvantages. Evapotranspiration is generally computed not for its own sake but for some other purpose, and each method can be assessed for its usefulness in this regard. To make some general recommendations, several important topics have been identified where knowledge of evapotranspiration is required.

Water Productivity Analyses

Water productivity or irrigation performance assessment requires knowledge of all the terms of the water balance, including evapotranspiration. It can be expressed at different scales ranging from field to basin and is normally calculated over a growing season or an entire year. Methods that rely on the collection and analysis of field data are too labor-intensive for large areas of varied crops. Remote sensing techniques are useful here for areal distribution of ET at very high resolution but cannot provide the other data required, such as return flows, drainage, percolation, and capillary rise. A promising technique might be to estimate crop yield directly by RS methods. Alternatively, hydrological models are able to provide all the terms of the water balance as well as to estimate crop yields and RS estimates of ET could be used to verify the hydrological models on cloud-free satellite overpass days.

Irrigation Management

As water becomes scarcer, the task of allocating water within irrigation areas will become more difficult. Remotely sensed techniques that can detect crop stress appear at first glance to be attractive tools; they cover large areas and the additional data requirements are low. However, the acquisition and analysis times of high-resolution images (Landsat) are too long to be of any use in irrigation management. Low-resolution images (NOAA-AVHRR) are rapidly available and analyzed, but the resolution is only suitable for areas corresponding to main canals. For lower level management (secondary canals) the scintillometer can be a useful tool, although additional field data at a point scale (net radiation, wind speed) are required. Hydrological models and the FAO methods can be set up at the beginning of the season and fed with daily standard climatic data to inform irrigation managers in advance about water requirements. The advantage of this approach is that this could be done in advance by assuming standard climatic conditions for the near future.

Constructing Irrigation Schemes

The key element of constructing and planning new irrigation schemes is the knowledge of crop water requirements. Obviously, field measurements as well as RS are impossible, as no irrigation schemes are present. Procedures such as FAO-24 were and will be used as a standard in planning irrigation schemes. As indicated by Beyazgul et al. (2000) big differences exist between the different methods and ignoring important aspects such as capillary rise can result in substantial errors. FAO-56 provides a major improvement but is still subject to limitations. Point meteorological data collected before the irrigation system is installed will not be representative of later conditions; in particular, earlier temperatures will be higher and vapor pressures will be lower. Hydrological models, taking into account all the hydrological aspects, are an attractive alternative.

Basin Planning, Water Resources Allocation

Water allocation within a basin is a matter of considering all the water users in a basin such as agriculture, industry, urban, and environmental. Remote sensing techniques are very useful as they can give ET over large areas for all the different land covers in a basin over the recent past. Field measurements are limited to smaller areas and are not realistic at basin level. Instead of only analyzing current or past water allocations, alternatives should be evaluated to distribute water in a more productive way. Clearly, this can be done only by the use of hydrological models in simulating different scenarios. As an example, water in the Gediz Basin is exported from the basin to the rapidly growing city of Izmir. The effects of present and future extractions on the basin can only be evaluated with hydrological models.

Climate Change Impact

Many scientists are concerned about the effect of possible changes in climate and changes in land use on water resources. The implications of such changes for irrigated agriculture are particularly important. Such scenarios can be effectively studied using hydrological models; RS and field techniques cannot help.

Literature Cited

Allen, R. 2000. Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *Journal of Hydrology* 229(1-2): 27-41.

Allen, R.; L. S. Pereira; D. Raes; M. Smith. 1998. *Crop evapotranspiration: Guidelines for computing crop requirements*. Irrigation and Drainage Paper No. 56. Rome, Italy : FAO.

Bastiaanssen, W. G. M.; M. Menenti; R. A. Feddes; and A. A. M. Holtslag. 1998. A remote sensing surface energy balance algorithm for land (SEBAL), 1. Formulation. *Journal of Hydrology* 212-213: 198-212.

Bastiaanssen, W. G. M. 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. *Journal of Hydrology* 229(1-2): 87-100.

Beyazgül, M.; Y. Kayam; and F. Engelsman. 2000. Estimation methods for crop water requirements in the Gediz basin of Western Turkey. *Journal of Hydrology* 229(1-2): 19-26.

Choudhury, B. J. 1997. Estimating land surfac evaporation using multispectral satellite and ancillary data. In *Applications of remote sensing in hydrology, Proc. Symp. No 17, NHRI, Saskatoon, Canada*, eds. G.W. Kite, A. Pietroniro, and T. Pultz. Canada: National Hydrology Research Institute (NHRI).

Choudhury, B. J. 2000. Seasonal and interannual variations of evaporation and their relations with precipitation, net radiation, and net carbon accumulation for the Gediz Basin area. *Journal of Hydrology* 229(1-2): 77-86.

Choudhury, B. J.; and N. E. DiGirolamo. 1998. A biophysical process-based estimate of global land surface evaporation using satellite and ancillary data. I. Model description and comparison with observations. *Journal of Hydrology* 205: 164-185.

de Bruin, H. A. R.; B. J. J. M. van der Hurk; and W. Kohsiek. 1995. The scintillation method tested over a dry vineyard area. *Boundary-layer Meteorology* 76: 25-40.

Doorenbos, J.; and W. O. Pruitt. 1977. *Crop water requirements*. Irrigation and Drainage Paper 24. Rome, Italy : FAO.

Droogers, P. 2000. Estimating actual evapotranspiration using a detailed agro-hydrological model. *Journal of Hydrology* 229(1-2): 50-58.

Droogers, P.; and G. W. Kite. 1998. Estimation of areal evapotranspiration: An international intercomparison study. 1998 Gediz Experiment, 2 CD-ROMs. Colombo, Sri Lanka: International Water Management Institute.

Droogers, P.; and G. W. Kite. 1999. Water productivity from integrated basin modeling. ASCE *Journal of Irrigation and Drainage Systems* 13: 275-290.

Droogers, P.; W. G. M. Bastiaanssen; M. Beyazgül; Y. Kayam; G. W. Kite; and H. Murray-Rust. 2000. Distributed agro-hydrological modeling of an irrigation system in western Turkey. *Agricultural Water Management* (in press).

Goutorbe, J. P.; T. Lebel; A. J. Dolman; J. H. C. Gash; P. Kabat; Y. H. Kerr; B. Monteny; S. D. Prince; J. N. M. Stricker; A. Tinga; and J. S. Wallace. 1997. An overview of HAPEX-Sahel: A study in climate and desertification. *Journal of Hydrology* 188-189, 4-17.

Granger, R. J. 1997. Comparison of surface and satellite-derived estimates of evapotranspiration using a feedback algorithm. In *Applications of Remote Sensing in Hydrology, Proc. Symp. No 17, NHRI, Saskatoon, pp. 71-81,* eds. G.W. Kite, A. Pietroniro, and T. Pultz. Canada: National Hydrology Research Institute (NHRI).

Granger, R. J. 1989. Evaporation from natural nonsaturated surfaces. *Journal of Hydrology* 111: 21-29.

Granger, R. J. 2000. Satellite-derived estimates of evapotranspiration in the Gediz Basin. *Journal of Hydrology* 229(1-2): 70-76.

Hargreaves, G. H.; and Z. A. Samani. 1982. Estimating Potential evapotranspiration. *Journal of Irrigation and Drainage Division*, ASCE, 108 (IR3): 225-230.

Kite, G.W. 1997. *SLURP hydrological model.* CD-ROM. Colombo, Sri Lanka: International Water Management Institute.

Kite, G.W. 2000. Using a basin-scale hydrological model to estimate crop transpiration and soil evaporation. *Journal of Hydrology* 229(1-2): 59-69.

Kite, G.W.; and P. Droogers. 2000. Comparing evapotranspiration estimates from satellites, hydrological models and field data. *Journal of Hydrology* 229(1-2).

Meijninger, W.; and H. A. R. de Bruin. 2000. The sensible heat fluxes over irrigated areas in western Turkey determined with a large aperture scintillometer. *Journal of Hydrology* 229(1-2): 42-49.

Molden, D. J. R.; R. Sakthivadivel; C. J. Perry; C. De Fraiture; and W. H. Kloezen. 1998. *Indicators for comparing performance of irrigated agricultural systems*. Research Report No. 20. Colombo, Sri Lanka: International Water Management Institute.

Monteith, J. L. 1981. Evaporation and surface temperature. *Quarterly J.Royal Soc*. 107:1-27.

Sellers, P.; F. G. Hall; G. Asrar; D. E. Strebel; R. E. Murphy. 1992. An overview of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE*). J. Geophys. Res*. 97(D17): 18345-18371.

van Dam, J. C.; J. Huygen; J. G. Wesseling; R. A. Feddes; P. Kabat; P. E. V. van Walsum; P. Groenendijk; C. A. van Diepen. 1997. Theory of SWAP version 2.0. Report 71. Wageningen, The Netherlands : The Department of Water Resources, Wageningen Agricultural University.

Research Reports

29. *Generic Typology for Irrigation Systems Operation.* D. Renault, and G.G.A. Godaliyadda, 1999.

30. *Mechanically Reclaiming Abandoned Saline Soils: A Numerical Evaluation.* S. A. Prathapar and Asad S. Qureshi, 1999.

31. *Gender Issues and Women's Participation in Irrigated Agriculture: The Case of Two Private Irrigation Canals in Carchi, Ecuador.* Elena P. Bastidas, 1999.

32. *Water Scarcity Variations within a Country: A Case Study of Sri Lanka.* Upali A. Amarasinghe, Lal Mutuwatta, and R. Sakthivadivel, 1999.

33. *Modernization Using the Structured System Design of the Bhadra Reservoir Project, India: An Intervention Analysis.* R. Sakthivadivel, S. Thiruvengadachari, and Upali A. Amarasinghe, 1999.

34. *Assessment of Participatory Management of Irrigation Schemes in Sri Lanka: Partial Reforms, Partial Benefits.* M. Samad and Douglas Vermillion, 1999.

35. *Modernizing Irrigation Operations: Spatially Differentiated Resource Allocations.* D. Renault and I. W. Makin, 1999.

36. *Institutional Change and Shared Management of Water Resources in Large Canal Systems: Results of an Action Research Program in Pakistan.* D. J. Bandaragoda, 1999.

37. *Farmer-Based Financing of Operations in the Niger Valley Irrigation Schemes.* Charles L. Abernethy, Hilmy Sally, Kurt Lonsway, and Chégou Maman, 2000.

38. *An Assessment of the Small-Scale Irrigation Management Turnover Program in Indonesia.* Douglas L. Vermillion, Madar Samad, Suprodjo Pusposutardjo, Sigit S. Arif, and Saiful Rochdyanto, 2000.

39. *Water Scarcity and the Role of Storage in Development.* Andrew Keller, R. Sakthivadivel, and David Seckler, 2000.

40. *Using Datasets from the Internet for Hydrological Modeling: An Example from the Küçük Menderes Basin, Turkey.* Martin Lacroix, Geoff Kite, and Peter Droogers, 2000.

41. *Urban-Wastewater Reuse for Crop Production in the Water-Short Guanajuato River Basin, Mexico.* Christopher A. Scott J. Antonio Zarazúa, and Gilbert Levine, 2000.

42. *Comparison of actual evapotranspiration from satellites, hydrological models and field data.* Geoff Kite and Peter Droogers, 2000.

Postal Address
P O Box 2075
Colombo
Sri Lanka

Mailing Address
127, Sunil Mawatha
Pelawatte
Battaramulla
Sri Lanka

Telephone
+94-1-867404

Facsimile
+94-1-866854

E-mail
iwmi@cgiar.org

Website
http://www.iwmi.org

IWMI
INTERNATIONAL WATER MANAGEMENT INSTITUTE

FUTURE HARVEST
IWMI—A Future Harvest Center
Supported by the CGIAR

CGIAR

ISSN 1026-0862
ISBN 92-9090-412-7