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MODEL FOR SIMULATING SURFACE EVAPORATION AND BIOMASS PRODUCTION UTILIZING ROUTINE METEOROLOGICAL AND REMOTE SENSING DATA

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ABSTRACT

A model is described that uses routinely available meteorological and remotely sensed observations to simulate regional evapotranspiration and biomass production. The model contains a soil water balance submodel that is calibrated during the growing season using remotely sensed observations of surface temperature. It also contains a vegetation growth submodel that is similarly calibrated using remotely sensed observations of plant canopy light absorption. The model is demonstrated using data from the Walnut Gulch Watershed, a semiarid rangeland in southeastern Arizona.

INTRODUCTION

Remote sensing can be an effective method for estimating evapotranspiration and plant canopy density over a geographical region (Moran et al., 1992). While satellites can easily survey large areas of the earth's surface, a drawback to their use in operational monitoring programs is the relative infrequency of their observations of a given location as a result of their overpass schedule and the occurrence of cloud cover. Thus, satellite observations represent discrete time events which may indicate little about how the biosystem got to its observed state or what its condition will be in the future.

Mathematical models of the vegetation-soil-atmosphere system can provide a continuous description of vegetation growth and evapotranspiration. They can also be used to project the future condition of the biosystem. To be consistently accurate, most models require detailed micrometeorological and edaphic information. The difficulty and expense of collecting this information on a regional scale often makes the use of mathematical models impractical for regional monitoring.

Mathematical models that can incorporate infrequent remotely sensed problem (Haas et al., 1989, 1992). These models use routinely available meteorological observations (daily air temperature, humidity, rainfall, wind speed, and solar irradiance) along with remotely sensed surface reflectance and temperature to simulate both the growth and water status of agricultural crops and natural vegetation communities.

This paper describes the results of modeling the evapotranspiration and biomass production of a semiarid rangeland using infrequent remotely sensed information and routinely available meteorological observations.

THE MODEL

The model consists of two submodels-- a soil water balance submodel and a vegetation growth submodel. These submodels operate in sequence to produce simulations of evapotranspiration, soil moisture, leaf canopy density, and biomass production. A numerical procedure called within-season calibration is used in the model to manipulate the values of certain parameters and initial conditions so that model simulations are brought into agreement with remotely sensed observations.

Soil Water Balance Submodel

The formulation of the soil water balance submodel assumes the following:

1) For vegetated surfaces in arid and semi-arid environments, the contribution of soil surface evaporation to evapotranspiration (ET) is negligibly small compared to the contribution from plant transpiration, except immediately after a rainfall.
2) When soil water is abundant, ET approaches potential ET (PET) for the vegetation canopy.

Based on these assumptions, ET is determined on any given day by the degree to which the ET of the vegetation canopy approaches PET and the degree to which the vegetation canopy covers the surface.

Studies involving agricultural crops (cf. Meyer and Green, 1980; Rosenthal et al., 1987) indicate that the ratio ET/PET appears to be a relatively consistent function of the available soil water fraction in the rooting zone,

$$\begin{aligned} ET/PET &= ASWF/0.3 \quad \text{for } ASWF < 0.3 \\ ET/PET &= 1 \quad \text{for } ASWF > 0.3 \end{aligned} \qquad (1)$$

Available soil water fraction (ASWF) is defined as the amount of soil water between the wilting point for the vegetation and the maximum drained capacity for the field, normalized by the maximum drained capacity. Maximum drained capacity is often called "field capacity".

Ritchie and Burnett (1971) showed that, when soil water was abundant, the ratio of vegetation transpiration to PET could be expressed as a consistent function of LAI for dissimilar agricultural crops (cotton and grain sorghum),

$$ET/PET = 0.7\sqrt{LAI} - 0.21 \qquad (2)$$

Based on this information, ET was computed in the soil water balance submodel using the following relationship,

$$ET = PET \cdot SWFACTOR \cdot GCFACTOR \qquad (3)$$

in which SWFACTOR is the ratio ET/PET from Eqn. 1 and GCFACTOR is the ratio ET/PET from Eqn. 2. PET was computed from routinely-available meteorological observations (average daily air temperature, average daily dew point temperature, average daily wind speed, and total daily solar irradiance) using the combination equation described by Van Bavel (1966).

Changes in soil water and ET were simulated with a daily time step using the stepwise process depicted in Fig. 1. Daily values of LAI for evaluating GCFACTOR were obtained from the vegetation growth submodel. Hydrologic processes such as rainfall runoff and infiltration of water upward into the rooting zone were not explicitly incorporated into this submodel. An initial amount of soil water was specified at the start of the simulation. ET was assumed to equal PET on the day following each rainfall event to simulate evaporation from the moist soil surface.

Vegetation Growth Submodel

The formulation of the vegetation growth submodel is similar to that used in earlier agricultural crop growth models (Maas, 1988a, 1988b, 1991a, 1991b, 1992; Maas et al., 1989). Operating with a daily time step, the submodel simulated the change in aboveground vegetation biomass (AGBM) and LAI using the stepwise process depicted in Fig. 2.

Photosynthetically active radiation (PAR) was assumed to comprise 45% of the total daily solar irradiance (Brown, 1969). The fraction of PAR absorbed by the vegetation canopy (FAPAR) was computed using the relationship,

$$\mathrm{FAPAR} = 1 - e^{-k \cdot \mathrm{LAI}} \qquad (4)$$

in which k is the extinction coefficient (Charles-Edwards et al., 1986). Production of new biomass (ΔAGBM) was determined using the relationship,

$$\Delta\mathrm{AGBM} = \mathrm{FAPAR} \cdot \mathrm{PAR} \cdot e \cdot f(\mathrm{TEMP}) \cdot \mathrm{SWFACTOR} \qquad (5)$$

where the parameter e is the "energy conversion efficiency" (Charles-Edwards et al., 1986) and f(TEMP) is a function that reduces the rate of biomass production at suboptimum air temperatures. New leaf area in the canopy is determined by partitioning a fraction of ΔAGBM to leaf biomass and multiplying this quantity by the specific leaf area (i.e., the m^2 of leaf area per kg of leaf biomass) of the vegetation. The leaf partitioning fraction decreases through the growing season as a relatively greater portion of ΔAGDM is partitioned to stems and reproductive organs. Water stress, acting through the value of SWFACTOR, reduces biomass production and increases the senescence of existing leaf area.

Within-season Calibration

Maas (1988a) showed that the most effective method of incorporating infrequent remotely sensed information into plant growth models was through reinitialization and/or reparameterization. In these procedures, which are collectively termed "within-season calibration", the values of certain model initial conditions and/or parameters are manipulated until the model simulation of a quantity fits a corresponding set of remotely sensed observations. An iterative numerical procedure is built into the model to manipulate the initial conditions and/or parameters so that they converge on values that result in the

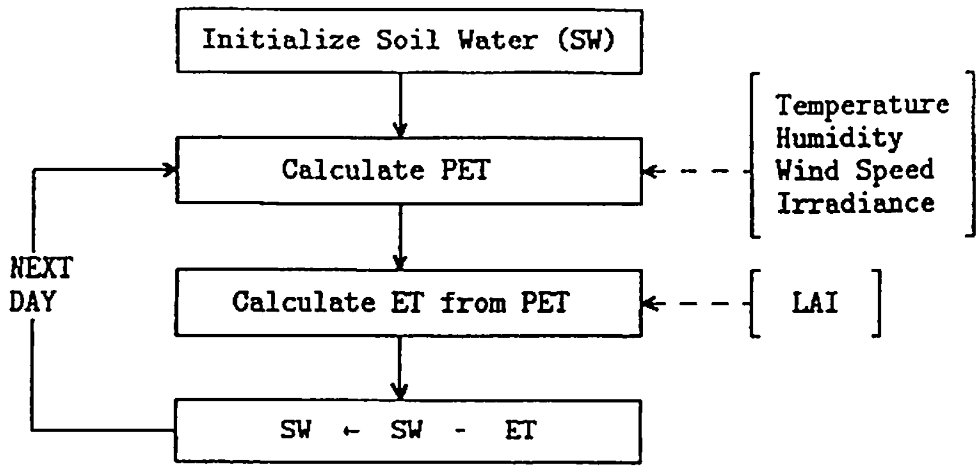

Figure 1. Sequence of steps in computing daily PET, ET, and soil water (SW) in the soil water balance submodel.

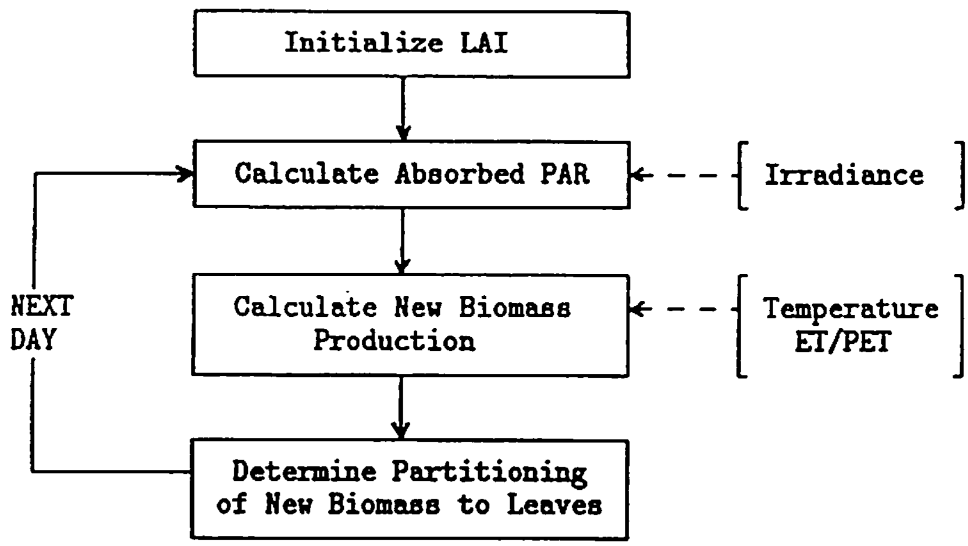

Figure 2. Sequence of steps in computing daily biomass growth and changes in canopy leaf area index in the vegetation growth submodel.

Fig. 3). Haas (1991a, 1991b) demonstrated that within-season calibration could significantly improve the accuracy of agricultural crop growth models.

For this study, remotely sensed observations of ET were used to calibrate the soil water balance submodel, while remotely sensed obsevations of FAPAR were used to calibrate the vegetation growth submodel. In the soil water balance submodel, the initial value of soil water and the value of field capacity were manipulated to bring the ET simulation into agreement with the corresponding observations. In the vegetation growth submodel, the initial value of LAI, the value of parameter e, and the value of the parameter that controls the partitioning of new biomass to leaves were manipulated to bring the FAPAR simulation into agreement

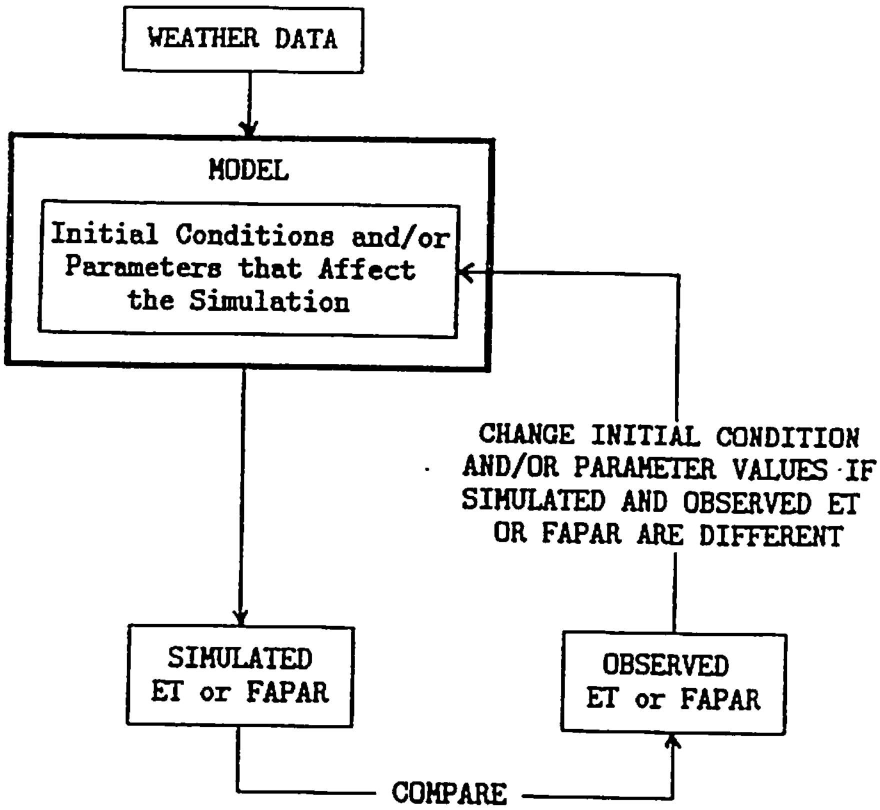

Figure 3. Diagrammatic representation of the within-season calibration procedure.

In simulating evapotranspiration and biomass production using this model, the vegetation growth submodel is run first assuming no water stress (SWFACTOR = 1) and calibrated using the remotely sensed FAPAR observations. The resulting set of simulated daily LAI values are then used in a run of the soil water balance submodel, which is calibrated using the remotely sensed ET observations. The resulting simulation of daily SWFACTOR values is used in a second run of the vegetation growth submodel. A revised set of daily LAI values is produced, which is used in a second run of the soil water balance submodel. This sequence of alternating runs of the vegetation growth and soil water balance submodels continues until the difference between succeeding simulations of total biomass becomes negligible.

TEST OF THE MODEL

In an earlier study (Maas et al., 1992) involving a model of this type, evapotranspiration and biomass production of irrigated alfalfa (*Medicago sativa* L.) in an arid environment were modeled. In this study, the model was used to simulate evapotranspiration and biomass production of a natural, semi-arid rangeland.

Test Data

The data were collected in 1992 from sites within the Walnut Gulch Experimental Watershed located in southeastern Arizona (Kustas et al., 1991). Micrometeorological observations, including air temperature, humidity, wind speed, and solar irradiance, were obtained at eight cover, and soil moisture were measured periodically at these locations during the study period. Daily evapotranspiration was determined at each site using a simplified energy balance,

$$ET = RNET - SENS - SOIL \qquad (6)$$

where RNET is net radiation, SENS is sensible heat flux, and SOIL is soil heat flux. RNET and SOIL were measured at each site, while SENS was computed from micrometeorological observations at each site.

Data from the north-facing slope of the Kendall subwatershed site were used in this modeling effort. Aboveground biomass included the dry mass of grasses (the predominant vegetation at this site), forbs, and shrubs. Biomass was measured in fenced enclosures that prevented grazing by cattle.

Remotely sensed data were collected periodically within the enclosures using a 8-band Barnes MMR spectroradiometer. Data from the red and near-infrared spectral bands were used to calculate values of the soil-adjusted vegetation index (SAVI),

$$SAVI = [(NIR-RED)/(NIR+RED+L)] \cdot (1+L) \qquad (7)$$

where RED and NIR are, respectively, the reflectances in the red and near-infrared wavebands, and L is a soil-related correction term with a value of 0.5 (Huete, 1988). Percent ground cover (GC%) was estimated from the vegetation index data using the empirical relationship,

$$GC\% = 101.4 \cdot SAVI + 9.6 \qquad (8)$$

which was developed from data collected at that site in 1991. Percent FAPAR was assumed to be approximately equal to GC%. Leaf area index (LAI) was estimated from GC% using the relationship,

$$LAI = GC\% / 33.333 \qquad (9)$$

which assumes that complete ground cover occurs at an LAI of approximately 3. Remotely sensed surface temperature (TSURF) was used to estimate ET using the relationship,

$$ET = RNET - 0.059 \cdot (TSURF-TAIR)^n \qquad (10)$$

in which TAIR is the ambient air temperature and n is a factor related to stability (Seguin and Itier, 1983).

Test Results

Biomass production and evapotranspiration were simulated over the period from day 78 through day 218 of 1992. Simulated leaf area index is presented in Fig. 4 along with remotely sensed estimates of LAI obtained from Eqn. 9. Simulated aboveground biomass is presented in Fig. 5 along with corresponding biomass values obtained from ground sampling. The simulations in Figs. 4 and 5 both reasonably match the approximate magnitudes and trends of the corresponding observed data.

Simulated evapotranspiration is shown in Fig. 6 along with remotely sensed estimates of ET obtained from Eqn. 10 and ground observations of ET obtained using Eqn. 6. Both the remotely sensed estimates and the ground observations of ET show gradual trends over the study period.

to 218. The ET simulation is more dynamic, exhibiting pronounced peaks around days 118 and 198. The first peak is associated with the attainment of maximum LAI values by the range vegetation (see Fig. 4). The second peak is associated with the return of monsoon rains following a period of relative dryness during which early-season soil moisture was depleted.

CONCLUSIONS

In this preliminary application, the model appeared to be capable of reasonably simulating the basic aspects of evapotranspiration and biomass growth for this semiarid test site. Additional tests will allow refinement of the model and will indicate the degree of accuracy to be expected from this type of model.

ACKOWLEDGMENTS

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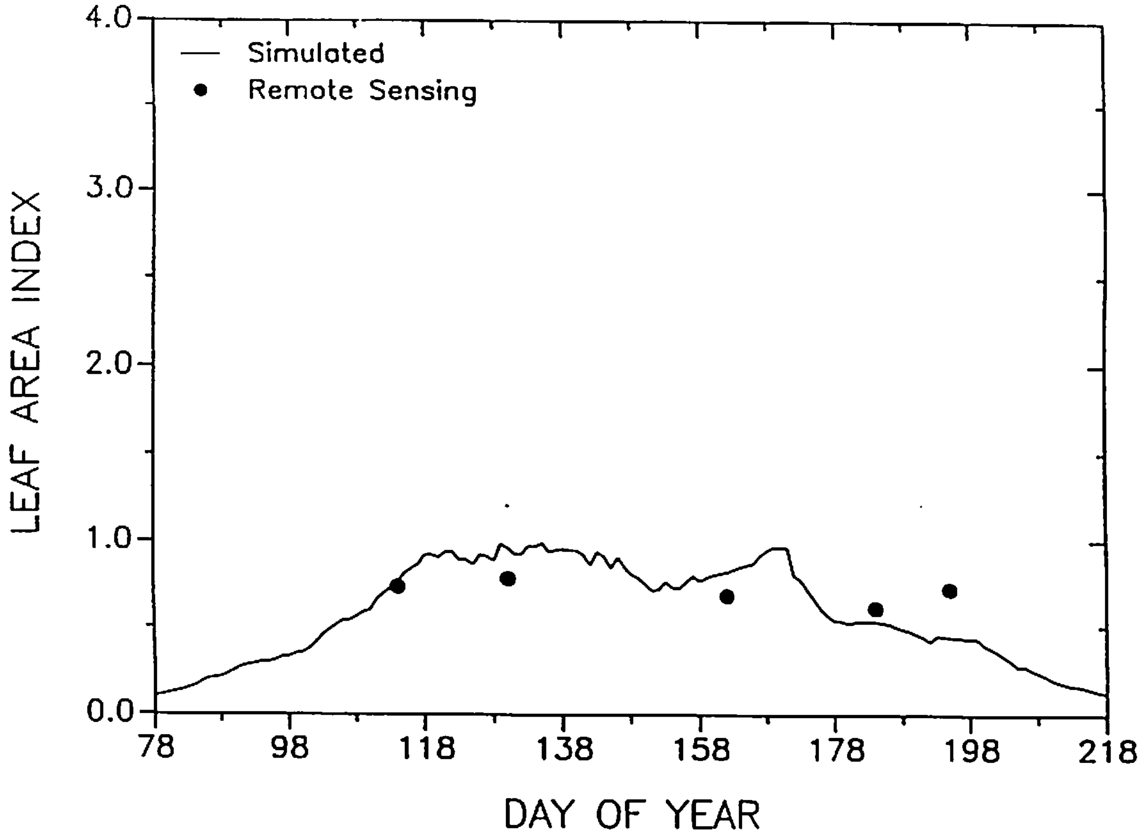
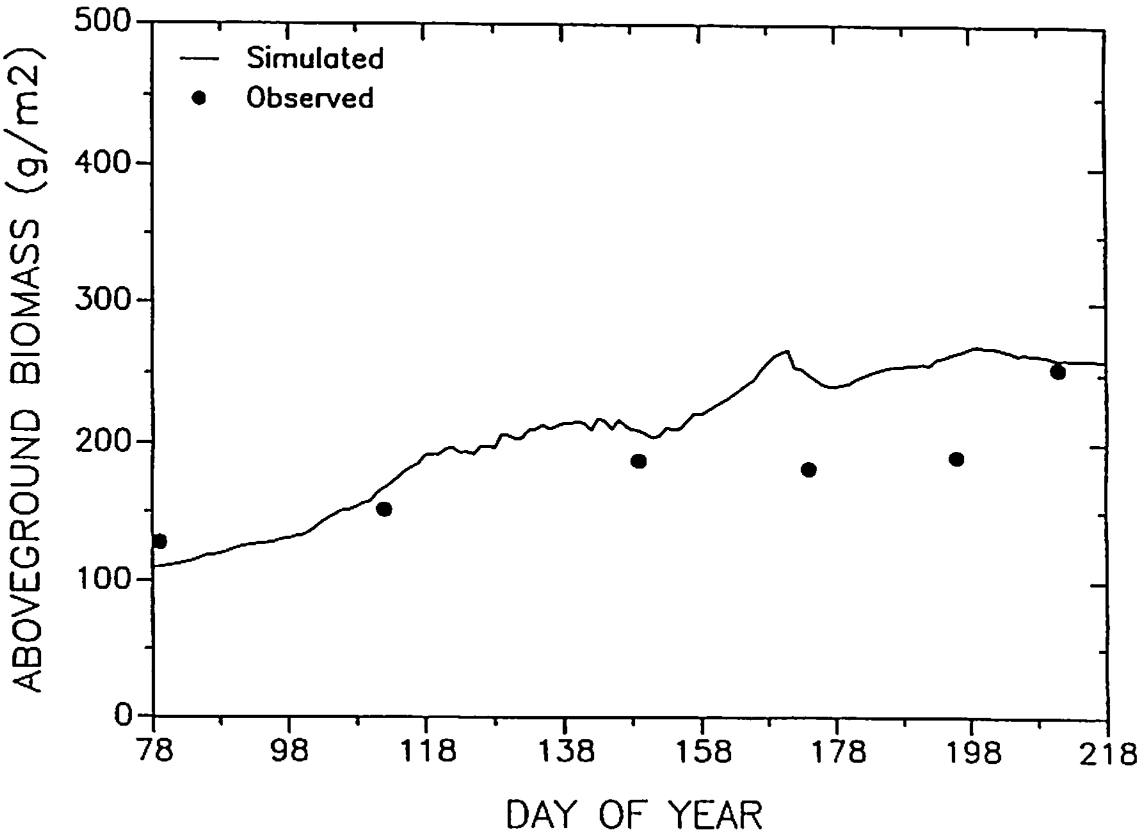


Figure 4. Simulated and estimated (from remotely sensed surface reflectance data) leaf area index at the Kendall subwatershed site in 1992.



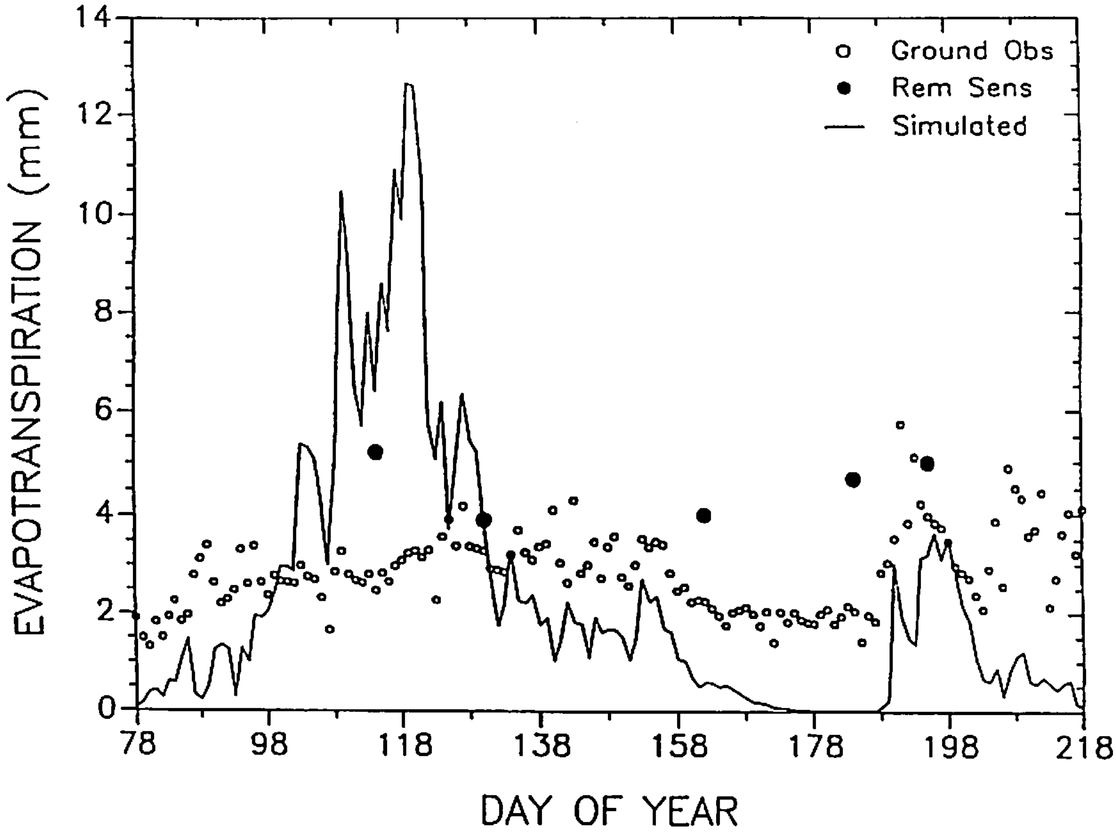


Figure 6. Simulated, estimated (from remotely sensed surface temperature data), and observed daily evapotranspiration at the Kendall subwatershed site in 1992.