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Evaluation of the use of remotely sensed evapotranspiration estimates into AnnAGNPS pollution model

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ABSTRACT

The utilization of evapotranspiration (ET) estimates, derived from satellite remote sensing, into the Annualized Agricultural Non-Point Source (AnnAGNPS) pollution model was investigated. Modifications within AnnAGNPS were performed to allow the internal calculations of ET based on climate parameters, collected from ground-based measurements, to be replaced by ET estimates produced with the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. Direct comparison of these sources of ET indicated that AnnAGNPS calculated ET estimates were 35% higher than the MODIS-calculated ET estimates resulting in a 10% increase in runoff at the outlet of the Yalobusha River Watershed for 2004. Simulated monthly runoff values based on MODIS and AnnAGNPS ET estimates for the year 2004 were compared with observed values from stream gages indicating slightly better agreement from the simulation using MODIS-derived ET. Analysis of the spatial distribution of the percent difference in runoff between AnnAGNPS-based ET and MODIS-based ET simulations showed higher differences at the most downstream and upstream of the watershed. These differences could be attributed to different soil properties or to the effect of distant field/weather station assigned to these locations. Although these findings should not be generalized to watersheds located in different ecosystems, the results indicate that the utilization of remotely sensed ET in hydrological modelling is feasible and that use of MODIS to estimate ET provided a more comprehensive spatial coverage than the often available through ground-based measurements. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS evapotranspiration; remote sensing; MODIS; AnnAGNPS; hydrological modelling; watersheds

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INTRODUCTION

Evapotranspiration (ET) represents the water lost to the atmosphere through the combination of soil evaporation and canopy transpiration (Anderson and Kustas, 2008). Accurate estimation of ET values allows for better understanding of the surface fluxes and thus having a significant impact on our understanding of hydrological cycles. The correct estimation of ET values represents an important component of the hydrological modelling process designed to predict surface runoff. Applications relying on proper estimation of ET values include, but not limited to, drought monitoring, irrigation and water consumption management, hydrological modelling, environmental studies, weather forecasting, and many others.

Due to its importance, scientists and engineers have developed various methods to accurately estimate ET. One of the most accepted methods, recommended by the Food and Agriculture Organization (FAO) of the United Nations (Courault *et al.*, 2005), is based on the Penman–Monteith (PM) method (Penman, 1948). Despite its large acceptance and reported accuracy when compared with other methods (Jensen *et al.*, 1990), this method relies on ground-based parameters such as wind speed, humidity, air temperature, solar radiation, and others. Yet, the spatial distribution of field climate stations is often either limited or even non-existing. This poses a problem for hydrological modelling due to increased uncertainty generated as result of the spatial generalization required to derive ET at the resolution needed by the models.

Advances have been made in the development of methods to estimate surface flux, (including ET) from satellite remote sensing; either by using remotely sensed data exclusively or by a combination of remotely sensed data and field measurements. The use of satellite remote sensing to estimate ET has increased the interest of the scientific community due to the unique temporal and spatial coverage provided by these systems (Nishida *et al.*, 2003; Sobrino *et al.*, 2007). Courault *et al.* (2005) have provided a review of the most accepted methods to estimate ET using remote sensing-based techniques. The methods described by Courault vary in the level of complexity, input requirements, and remote sensing parameters. Nonetheless, existing research results have shown the potential of using remotely sensed results to provide alternative sources for input streams with equal temporal resolution but with improved spatial coverage.

In this study, the utilization of remotely sensed ET estimates into the existing Annualized Agricultural Non-Point Source (AnnAGNPS) pollution model was evaluated (Bingner *et al.*, 2007). This model has been

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extensively used by a wide range of agencies in local, state, federal, and international levels as a unique tool to evaluate existing and suggested agricultural practices to promote agricultural efficiency and to reduce the impact on the environment of soil erosion (Yuan *et al.*, 2001; Kuhnle *et al.*, 2008; Yuan *et al.*, 2008). AnnAGNPS is a continuous watershed-scale computer simulation model used to generate loading estimates for many constituents of agricultural non-point source pollution (Yuan *et al.*, 2003; Licciardello *et al.*, 2007). Current ET estimates required by the AnnAGNPS pollution model are computed using the PM method from data supplied by the user that is often collected at field stations. In this approach, AnnAGNPS subareas that spatially divide the watershed into homogeneous areas (cells) can be assigned to a climate zone such as based on its distance to the nearest field climate/weather station. However, simulations of large watersheds with limited or non-existing field climate stations increases the end-results uncertainty due to the climate assumptions and generalizations needed to conduct the simulation.

To address this issue, we investigated the feasibility of using satellite remote sensing as source of ET estimates for AnnAGNPS pollution model. ET data generated with the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor is used as source of ET into the AnnAGNPS pollution model. Two AnnAGNPS simulations are performed using two distinct sources of ET, MODIS-based and field-based using the PM method. Direct comparison of ET estimates from both methods is discussed. AnnAGNPS simulation results from each method of computing ET estimates were compared with observed values obtained from stream gages. The value of this experiment lies in the integration and evaluation of remotely sensed inputs so that the model will have an alternative source of data, with improved spatial distribution.

BACKGROUND

Overview of the AnnAGNPS non-point source pollution model

The AnnAGNPS non-point source simulates runoff, as well as sediment, nutrient, and pesticide contributions from agricultural and non-agricultural lands to streams as a result of storm flow, routing all flow through the watershed daily. Runoff volume, peak flow, sediment, total nitrogen, and total phosphorus are some of the model's main output (Usery *et al.*, 2001). These outputs can be specified from any desired source and watershed location such as specific cells, reaches, feedlots, and point sources.

AnnAGNPS can be used as an evaluation tool for watershed management applications (e.g. evaluation of best management practices [BMP] or changes in land use) to address many total-maximum-daily-load (TMDL) and nutrient-criteria issues that are related to the identification and management of natural and/or anthropogenic nutrient levels and effects on the receiving water bodies (Dabney *et al.*, 2002).

The AnnAGNPS model has been developed and is being used by the US Department of Agriculture to evaluate the effect of management decisions impacting a watershed system. This computer model is the result of a joint research effort between USDA-Agricultural Research Service (ARS) and Natural Resources Conservation Service (NRCS) to predict non-point source pollutant loadings within agricultural watersheds. At the present time, AnnAGNPS has been used by a wide range of organizations in more than 50 countries.

Despite the usage of the model in a wide variety of watersheds and conditions, input preparation for AnnAGNPS can be time consuming. To use AnnAGNPS, the watershed of interest is subdivided into cells of a size that is user-defined and it is often based on the experience and watershed size. Each of these cells requires many parameters to describe its antecedent conditions, physical characteristics (e.g. soil type and slope steepness), management practices, and climate data. Even with the use of available interfaces, users of AnnAGNPS can spend considerable time preparing data for input to describe the system. Researchers such as Finn *et al.* (2003) have investigated automated methods to generate the needed inputs. Climatic data is the principle information required within AnnAGNPS to determine runoff and the resulting transport of pollutants downstream. Daily precipitation is the prime driver of the hydrologic cycle, temperatures are used to define frozen conditions as well as ET, and remaining climate elements are used in computing ET.

AnnAGNPS-derived evapotranspiration

In the standard AnnAGNPS simulation, ET is computed using the principle of the energy budget procedure (USFWS, 1984; ASCE, 1996). Parameters such as temperature, cloud coverage, wind speed, and precipitation from field weather/climate stations are used in different calculations to obtain parameters required by the Penman's Equation (Jensen *et al.*, 1990) to derive potential ET. The Penman's Equation is listed below and a brief explanation is provided in the next paragraphs. For detailed explanation of each term in Equation (1), please refer to Bingner *et al.* (2007).

$$\mathrm{ET_p} = \frac{1}{H_\mathrm{v}}\left[\left(\frac{\Delta}{\Delta+\gamma}\right)(R-G) + \left(\frac{\gamma}{\Delta+\gamma}\right)W(e_\mathrm{sat}-e)\right] \quad (1)$$

where $\mathrm{ET_p}$ is the potential evapotranspiration (mm), H_v the latent heat of vapourization (MJ/kg), Δ the slope of saturation vapour pressure (kPa/°C), R the net radiation (MJ/m^2), γ the psychrometric constant (kPa/°C), G the soil heat flux (MJ/m^2), W the wind function (−), e_sat the saturation vapour pressure (kPa), e the actual vapour pressure (kPa).

As a preliminary item, mean air temperature T for a day is calculated as the average of the day's maximum

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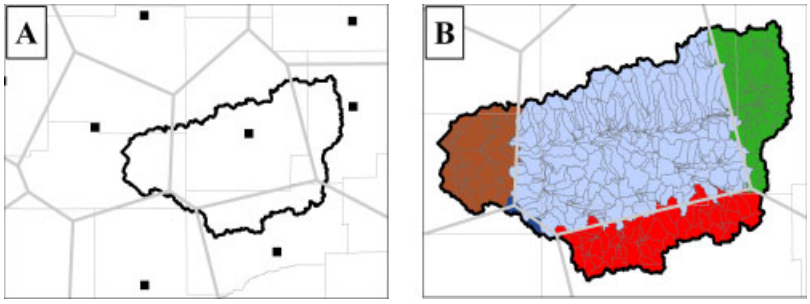

Figure 1. Schematic illustrating the assignment of AnnAGNPS cells to climate zones based on Thiessen polygons of field climate stations.

and minimum temperatures. The latent heat of vapourization is a function of the mean air temperature for day, T (°C), and is calculated as:

$$H_v = 2{\cdot}501 - 0{\cdot}0022T \tag{2}$$

The saturation vapour pressure is also a function of air temperature:

$$e_{sat} = 0{\cdot}1\ \exp\left(54{\cdot}879 - 5{\cdot}029\ \ln\ T_k - \frac{6790{\cdot}5}{T_k}\right) \tag{3}$$

where $T_k = T + 273 \cdot 18$, that is, temperature in K. Actual vapour pressure is simply:

$$e = \mathrm{RH}e_{sat} \tag{4}$$

where RH is the relative humidity (fraction) computed from the input of dew point and temperature. The slope of the saturation vapour pressure–temperature curve is calculated as:

$$\Delta = \left(\frac{e_{sat}}{T_k}\right)\left(\frac{6790{\cdot}5}{T_k} - 5{\cdot}029\right) \tag{5}$$

The psychrometric constant is calculated as:

$$\gamma = 6{\cdot}6 \times 10^{-4}(101 - 0{\cdot}0115\ Z + 5{\cdot}44 \times 10^{-7}Z_e{}^2) \tag{6}$$

where the quantity in parentheses is an estimate of barometric pressure and is a function of elevation, Z_e (m). This is stored as a constant parameter, as it does not vary with time.

The soil heat flux is calculated as a function of the air temperature for the current day and the 3 previous days:

$$G = 0{\cdot}12\left[T_0 - \left(\frac{T_{-1} + T_{-2} + T_{-3}}{3}\right)\right] \tag{7}$$

where T_0 is the current day's temperature, and the other subscripts on T refer to the number of days prior to the current day.

Using the original Penman wind function, which is valid for a height of 2 m (Jensen *et al.*, 1990):

$$W = 6{\cdot}43 + 3{\cdot}4079U \tag{8}$$

where U = wind speed (m/s).

Actual ET is determined based on the potential ET and the soil moisture levels available to support the potential ET demand. If the soil moisture levels do not support all of the potential ET, then only the amount of water available in the soil will be used for actual ET, as explained in Section AnnAGNPS Required Modifications.

Each AnnAGNPS cell is assigned to one climate station based on user-defined information that can be determined using the containment determined using Thiessen polygon approach. In this approach, watersheds located in areas lacking of field climate stations, require the creation of large climate zones encompassing different land use/land cover types, thus increasing the overall uncertainty of the simulation. Figure 1 shows a schematic illustrating the process of climate zone creation and how this may affect each AnnAGNPS cell. In Figure 1A, black squares represent the field climate stations in and around the watershed. In Figure 1B, each colour represents a different climate zone. All the AnnAGNPS cells within each Thiessen polygon are assigned the same climate parameters, such as minimum and maximum temperatures, precipitation, and others.

MODIS-derived evapotranspiration

At the time of writing, MODIS evapotranspiration product (MOD16) was in the final stages of evaluation before being released, and thus proxy-datasets were used. The MODIS-derived actual ET estimates were obtained through the algorithm described in Mu *et al.* (2007) and Cleugh *et al.* (2007). This algorithm, initially proposed by Cleugh *et al.* (2007), was designed to provide global land surface actual evaporation using a combination of optical and thermal satellite data. Remote sensing datasets were used in methods combining radiative surface temperature to estimate evaporation with the PM model. A revised version of the algorithm (Mu *et al.*, 2007) incorporated additional variables such as vapour pressure deficit and minimum air temperature. In addition, in the revised version, the estimation of the vegetation cover fraction replaced the use of the Normalized Difference Vegetation Index (NDVI) with the Enhanced Vegetation Index (EVI) and also included the calculation of soil evaporation (Mu *et al.*, 2007).

The final algorithm uses Penman–Monteith model and the required parameters are computed through a combination of global meteorological data and satellite remote sensing from the MODIS sensor on board of Aqua and Terra satellites. The global meteorological

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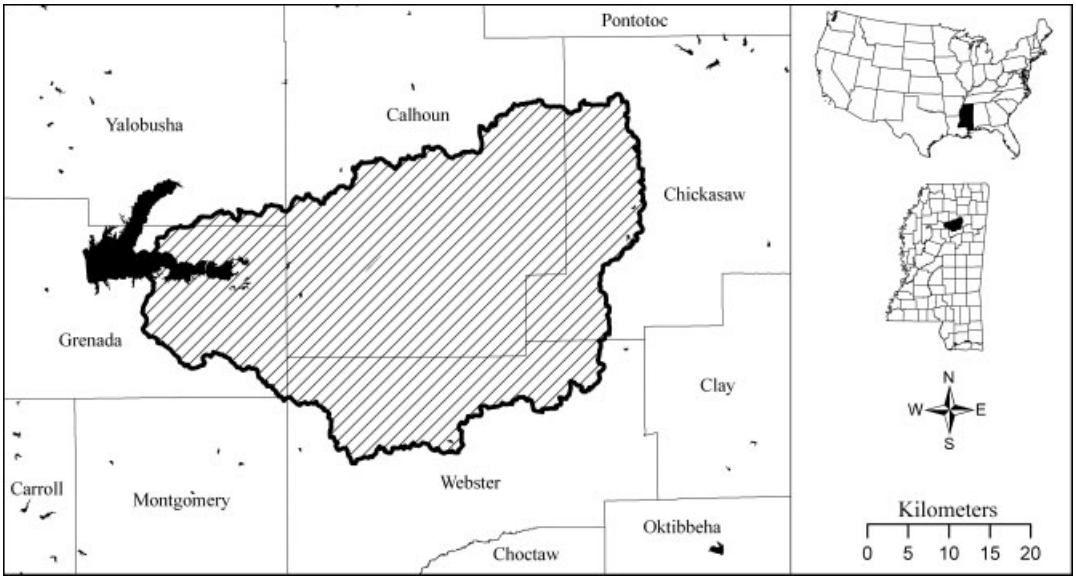

Figure 2. Yalobusha watershed was selected for the evaluation of the integration of MODIS-derived ET into AnnAGNPS pollution model.

input data include temperature, vapour pressure, and solar radiation. The remote sensing input data comprise land cover (MOD12Q1), vegetation indices (MOD13A2), leaf area index (MOD15A2), and albedo (MOD43C1). Mu *et al*. (2007) reported correlation of coefficients of 0·7 and higher when comparing estimated actual ET values to values measured from meteorological towers.

METHODS

Study site description

The Yalobusha River Watershed (YRW), located in Mississippi, is one of the 24 Conservation Effects Assessment Project (CEAP) watershed projects throughout the United States (Kuhnle *et al*., 2005). Problems of channel instability and stream bank erosion have severely degraded stream and riparian habitats in YRW and are responsible for localized sediment loss estimated as twice the United States national average.

The YRW covers an area of 168 750 ha (1687·5 square miles) and is shown in Figure 2. Land use in the YRW consists of 18% cropland, 19% pasture or grassed areas, 53% forested areas, 6% wetland that is largely forest, and 4% surface water or urban areas. USDA is currently installing additional instruments (climate and gages) in the southern part of the watershed (Toposhaw Creek Canal).

Remote sensing data

Converting proxy-MOD16 data into AnnAGNPS file format. The proxy MODIS ET product (proxy-MOD16) images were provided by scientists at The University of Montana through the utilization of the algorithm described in Nishida *et al*. (2003), Cleugh *et al*. (2007), and Mu *et al*. (2007). These daily images were provided as raw binary images with a ground sampling distance (GSD) of approximately 5000 m.

To meet the file format requirements of AnnAGNPS, a conversion tool was developed to translate the 8-day composite files, originally in raw binary format, into the required AnnAGNPS Input Editor ASCII file format. The tool processes a year of MODIS-derived ET data by applying the necessary coefficients to convert from 8-day composite in scaled integer format into daily ET. During this process, the tool defines "virtual" climate stations as being the geometric centre of each MODIS cell. The final output consists of a comma separated ASCII file with rows representing the day of the year (DOY) and columns representing the daily actual ET values for each of the "virtual" climate stations.

Figure 3 illustrates the concept of "virtual" climate stations in the AnnAGNPS simulation process. Similarly to the process previously described for the physical climate stations, polygons are created and climate zones are assigned based on the containment of AnnAGNPS

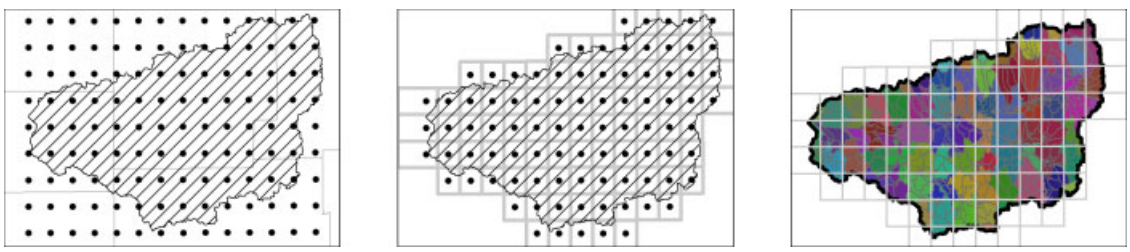

Figure 3. Schematic illustrating the assignment of AnnAGNPS cells to climate zones based on the "virtual" climate stations generated from remotely sensed gridded data.

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cells to each of the MODIS polygons. In this approach, smaller climate zones are created and each AnnAGNPS cell is assigned an ET value that is more associated to the land cover/land use type.

AnnAGNPS required modifications

Modifications within AnnAGNPS were implemented to provide the end-user the option to input potential and actual ET for any day during the simulation and as provided by MODIS. Enhancements within AnnAGNPS were performed to account for the effect of user-supplied ET parameters, which directly impacts soil moisture levels in each cell. Actual ET can be defined for each day by the user within the AnnAGNPS climate file, typically through the AnnAGNPS Input Editor, where the internally calculated ET by AnnAGNPS will be replaced with the user-supplied ET. As there are two soil layers defined by AnnAGNPS for a cell, the actual ET is first allocated to the top layer up to the level of soil moisture available for ET. Any unused ET in the top layer is allocated to the bottom layer, up to the available soil moisture in the bottom layer. If there is not enough soil moisture in the soil layers to meet the ET level defined by the user, then the remaining ET will not be used. If potential ET values were supplied by the user, then the internally calculated potential ET would be replaced with the user-supplied values, and the determination of AnnAGNPS actual ET would continue.

Data preparation

Figure 1A shows the Yalobusha watershed and the existing climate field stations. Only one climate field station (Calhoun City, MS) fell within the watershed boundary. The other climate stations influenced the watershed by their close proximity to its boundaries. Their effect was estimated using a Theissen weighted approach to assign the appropriate climate station to an AnnAGNPS cell (Figure 1B). Although six climate parameters are required by the model, only daily maximum and minimum temperatures, and precipitation were available as measured parameters at each climate station. The other parameters (dew point, cloud cover, and wind speed) for each climate station were estimated using the synthetic weather generator (GEM) (Johnson *et al.*, 2000). The generated values were associated with the climate station measured parameters for each day and used in the AnnAGNPS simulations.

Each MODIS ET cell (pixel) was assigned a unique name that would be used by AnnAGNPS as individual "virtual" climate stations. The other AnnAGNPS climate parameters required (min and max temperature, dew point, cloud cover, and wind speed) were assigned to this "virtual" climate station based on the grid's location within a Theissen polygon associated with the field climate station.

Through the standard simulation procedure, AnnAGNPS assigns an ET value for each simulation day for each of the AnnAGNPS cells. The conversion from

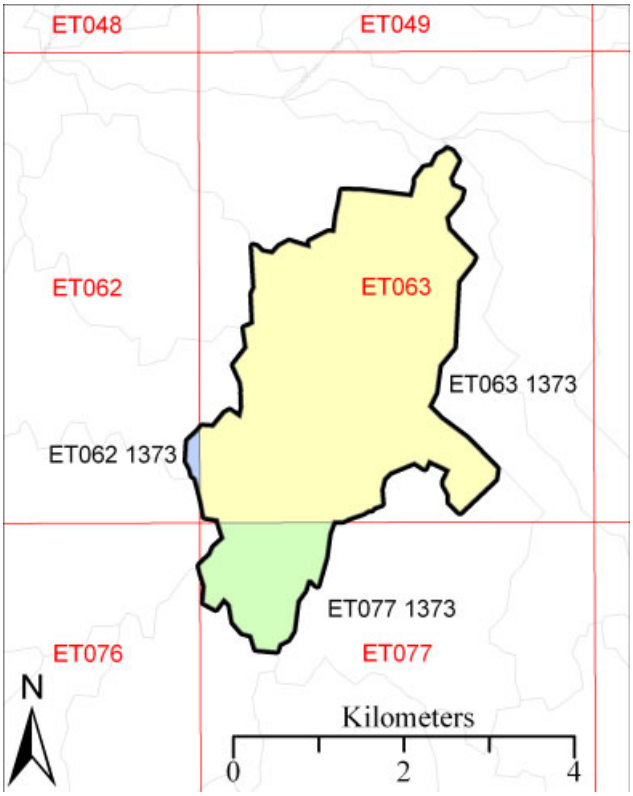

Figure 4. Illustration of the assignment of MODIS-derived ET values to AnnAGNPS sub-watersheds (AnnAGNPS cells).

MODIS-derived ET (gridded format) to AnnAGNPS sub-watersheds (AnnAGNPS cells) was performed by a weighted average process. The weights were determined based on the area. Figure 4 illustrates the process of assigning MODIS ET to AnnANGPS cells. Each MODIS cell received an identification number starting with 'ET', whereas each AnnANGPS cell has a numeric identification number.

The conversion from MODIS-derived ET (gridded format) to AnnAGNPS sub-watersheds (AnnAGNPS cells) was performed by a weighted average process. The weights were determined based on the area. A numerical example is illustrated in Figure 4. The AnnAGNPS cell 1373 is contained in three different MODIS cells (ET062, ET063, and ET077). Therefore, the assignment of the MODIS ET from three different cells to the AnnAGNPS cells is performed by using a percentage of the area. In the example provided, ET value at the AnnAGNPS cell 1373 is computed by:

$$\mathrm{ET}_{1373} = \left(\frac{\mathrm{ET}_{063} \times A_{\mathrm{ET063-1373}}}{A_{1373}}\right) + \left(\frac{\mathrm{ET}_{077} \times A_{\mathrm{ET077-1373}}}{A_{1373}}\right) + \left(\frac{\mathrm{ET}_{062} \times A_{\mathrm{ET062-1373}}}{A_{1373}}\right) \quad (9)$$

In this equation, A_{1373} represents the total area of the polygon 1373 and the terms $A_{\mathrm{ET063-1373}}$, $A_{\mathrm{ET077-1373}}$, and $A_{\mathrm{ET062-1373}}$ represent the area of the 1373 polygon

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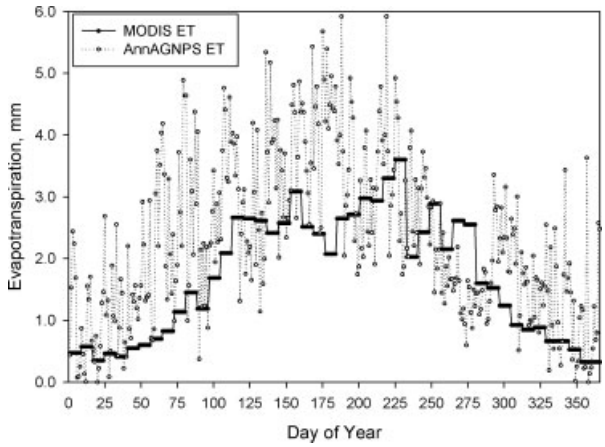

Figure 5. Comparison of ET estimates at the Yalobusha watershed for 2004.

contained in the ET063, ET077, and ET062 polygons, respectively. Two AnnAGNPS input and climate files were used, one with ET calculated with AnnAGNPS and another using the MODIS-derived ET.

EXPERIMENTAL RESULTS

Direct evapotranspiration comparison

ET estimates computed using the PM method using field measured parameters, referred to as AnnAGNPS ET, were compared with ET estimates provided by remote sensing, referred to as MODIS ET, at the field climate station located within the watershed boundaries for 2004 (MODIS cell ET051) (Figure 5). The step-wise shape of the MODIS curve is due to the conversion of 8-day accumulated composite into daily values. ET is variable throughout the year and the AnnAGNPS ET is generally higher than MODIS ET for each day. MODIS ET surpasses AnnAGNPS ET during the interval of DOY 260–285 (mid-September to mid-October). The July–September, 2004 period showed some of the more extreme differences (Figure 5).

Throughout the watershed for 2004 the differences in ET determined by AnnGNPS and MODIS are mostly the same, but with some locations showing higher or lower than average differences. A total of 366 ET maps for each of the ET sources (AnnAGNPS and MODIS) were originally created. To simplify the comparison process, 24 monthly average maps were produced (12 for each source of ET). Finally, the spatial distribution was observed by computing a percent difference between each AnnAGNPS cells with AnnANGPS ET and MODIS ET values, using the following formula:

$$\left(\frac{\mathrm{AnnAGNPS_{ET}} - \mathrm{MODIS_{ET}}}{\mathrm{AnnANGPS_{ET}}}\right) \times 100 \qquad (10)$$

This resulted in 12 maps showing the percentage difference in average ET (one for each month of the year). Figure 6 shows examples of spatial distribution of the monthly differences for a catchment area located in the Southeast part of the watershed. In March of 2004, all the sub-watershed polygons displayed positive values, indicating higher ET values generated with the AnnAGNPS methodology than with the MODIS methodology. However, in September, the majority of the polygons displayed negative values, indicating higher ET values computed with the MODIS methodology than the AnnANGPS methodology. It is important to note that some polygons, in the September difference map, also displayed positive values. The sum of the monthly percent difference for all the cells in this catchment area is also plotted in Figure 6.

Comparison of AnnAGNPS simulation results

The simulations of AnnAGNPS using MODIS ET to replace the internally calculated ET by AnnAGNPS were performed to illustrate the impact of MODIS ET on the runoff from the Yalobusha watershed. For 2004, the precipitation throughout the watershed was 1739 mm with annual runoff at the outlet for MODIS ET as 650 mm and for AnnAGNPS calculated ET as 593 mm. Daily runoff is nearly the same early in the simulation with increases, resulting from MODIS ET, after 100 days of simulation (Figure 7).

The spatial distribution of the percent difference in runoff shows differences in runoff from AnnAGNPS and MODIS ET estimates with higher differences in the most downstream and upstream portions of the watershed (Figure 8).

Three United States Geological Survey (USGS) stream gages are located within the watershed (Figure 9). These gages provided daily discharge values from 2000 to 2005. The daily discharge values associated with rainfall events were converted into runoff by separation and removal of the base flow. Monthly minimum flows were subtracted from the daily flow values.

Figure 10 shows comparisons of observed and simulated monthly runoff for stations 7281960 and 7282090. The upper plots in Figure 10 show monthly runoff values from 2000 to 2005. Yearly accumulated flow values for observed and simulated are listed in Table I. The simulated results agree with the observed values although no calibration of the model was performed. The lower plots show only the period of 2004 as a result of the limited availability of proxy-MOD16 data. There is a better agreement between the simulated runoff at the stream gage 7281960 (Northern catchment area) than 7282090 (Southern catchment area). This corresponds to somewhat higher differences in ET estimates at these locations.

These higher and lower differences could be from the influence of different climate stations, such as in the upper and lower sections of the watersheds, but it could be from the influence of soil properties affecting soil moisture differently and thus affecting ET. Figure 11 shows the AnnAGNPS cells with the difference of soil field capacity and wilting point (top map) and soil saturated hydraulic conductivity (bottom map). In locations with high available soil moisture and low hydraulic saturated conductivity, the runoff from the

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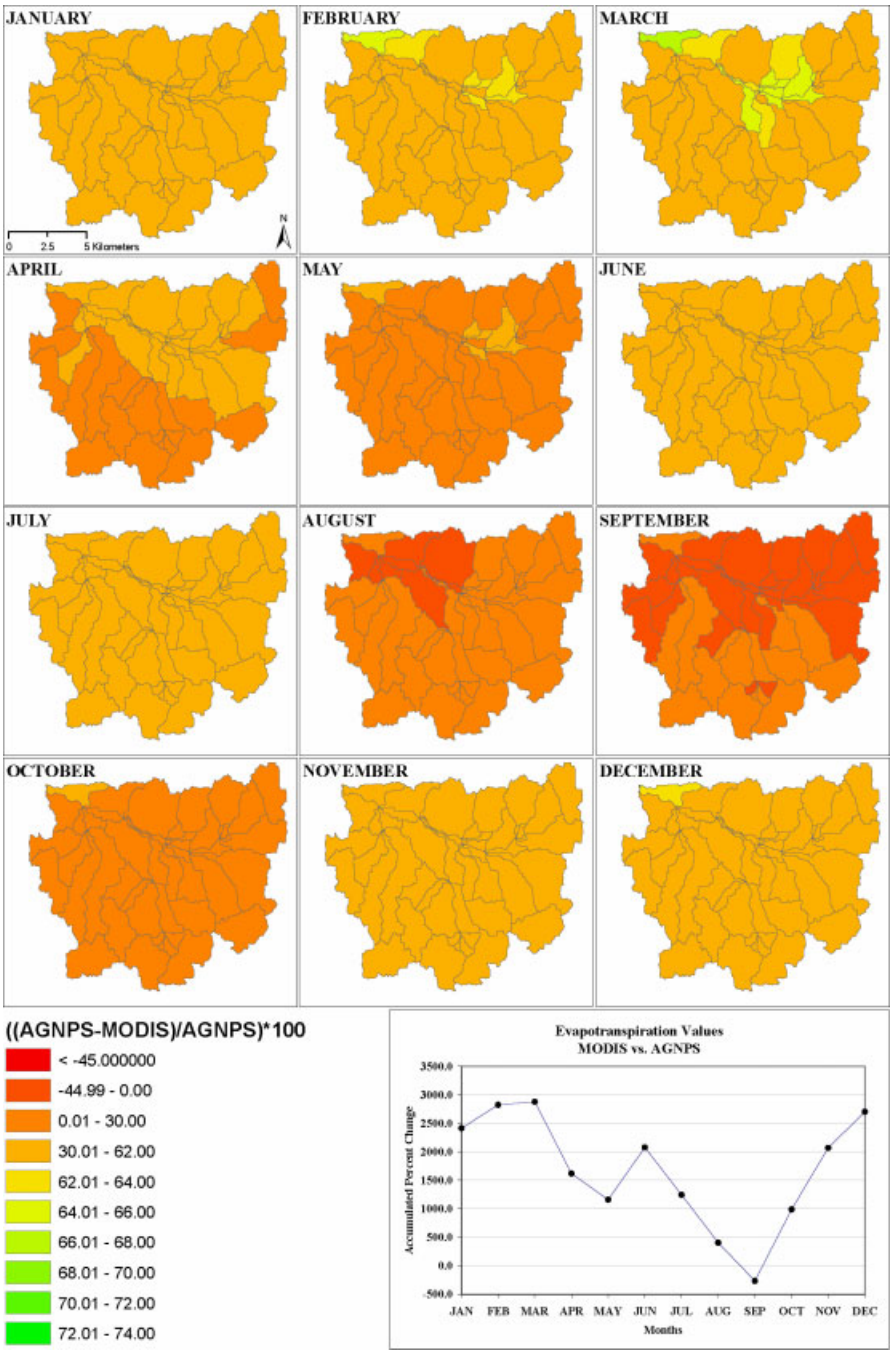

Figure 6. Spatial distribution of the 2004 monthly percent difference between evapotranspiration estimated from AnnAGNPS and from MODIS.

AnnAGNPS ET simulation was slightly higher than the MODIS ET simulation. The recent modifications to the MOD16 algorithm to estimate the latent heat flux by calculating the amount of transpiration (from vegetation) and of soil evaporation independently and then adding them up (Mu *et al.*, 2007) seems to contribute for the improved runoff determinations in this areas.

CONCLUSIONS

The objective of this research project was to investigate the feasibility of using remotely sensed results to generate ET estimates for use as input into the USDA's AnnAGNPS non-point source simulation model. An approach linking MODIS ET with the application of AnnAGNPS was successfully performed. Enhancements within AnnAGNPS to integrate MODIS ET values were completed allowing users to replace the internal calculation of ET within AnnAGNPS with measured ET values. The use of MODIS ET can reduce the need to collect/generate dew point, wind speed, and cloud coverage used in the AnnAGNPS determination of ET. Reducing uncertainty in input parameters will reduce the uncertainty in the model results. In addition, these values usually have temporal and spatial variability that are not easily taken into consideration when computing ET values.

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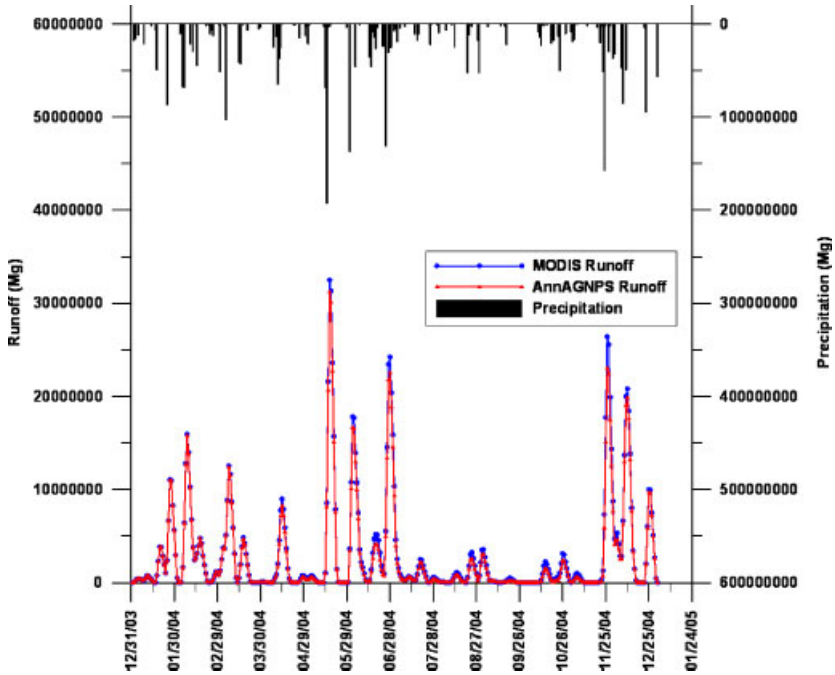

Figure 7. AnnAGNPS daily runoff at the outlet based on using MODIS ET and AnnAGNPS calculated ET (Penman Equation).

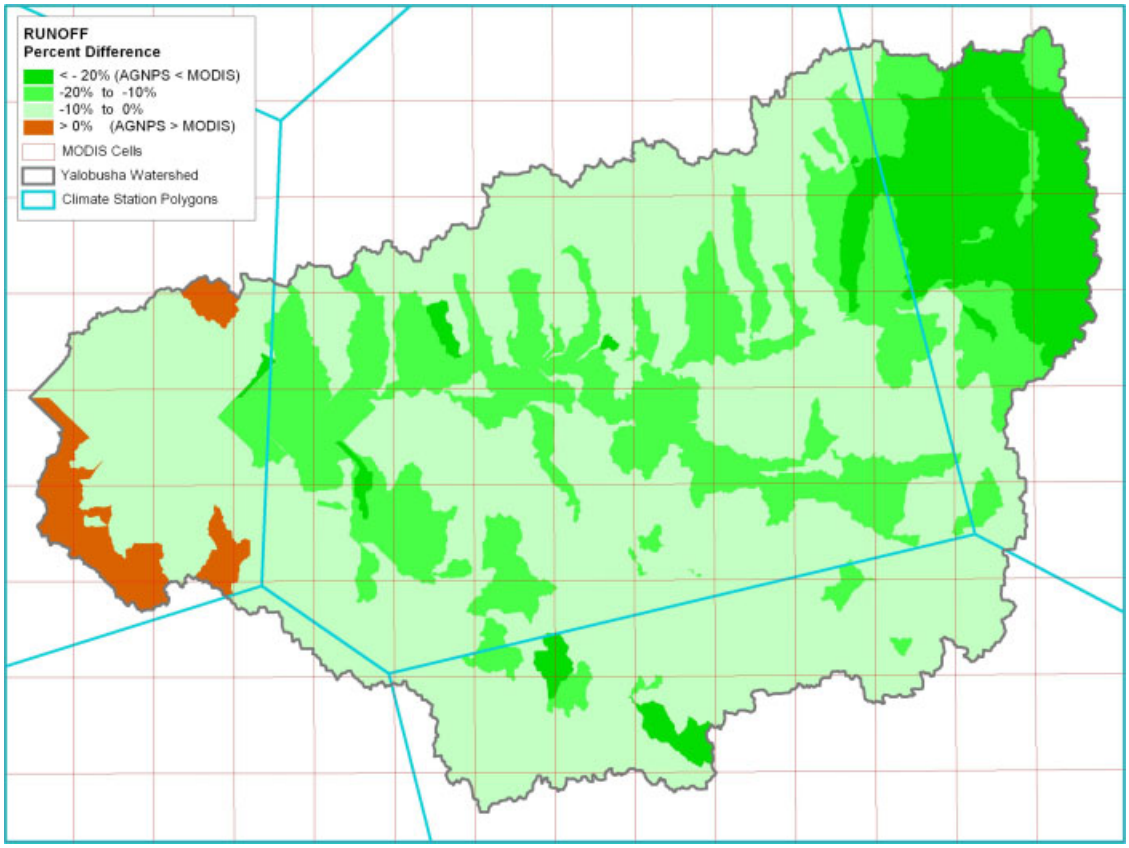

Figure 8. AnnAGNPS daily runoff at individual cells based on using MODIS ET and AnnAGNPS calculated ET (Penman–Monteith Equation).

Two independent AnnAGNPS simulations were performed by varying the source of ET. The use of MODIS in determining ET produced 35% less ET than calculated within AnnAGNPS and resulted in a 10% increase in runoff at the outlet of Yalobusha River Watershed for 2004. Comparisons of MODIS estimated ET with field observations reported lower values from MOD16 algorithm in spring and summer (Mu *et al.*, 2007) coinciding with the differences in ET that were more pronounced during the warmer periods of the year, which also coincided with periods of less precipitation. Future research should focus on characterizing the effects

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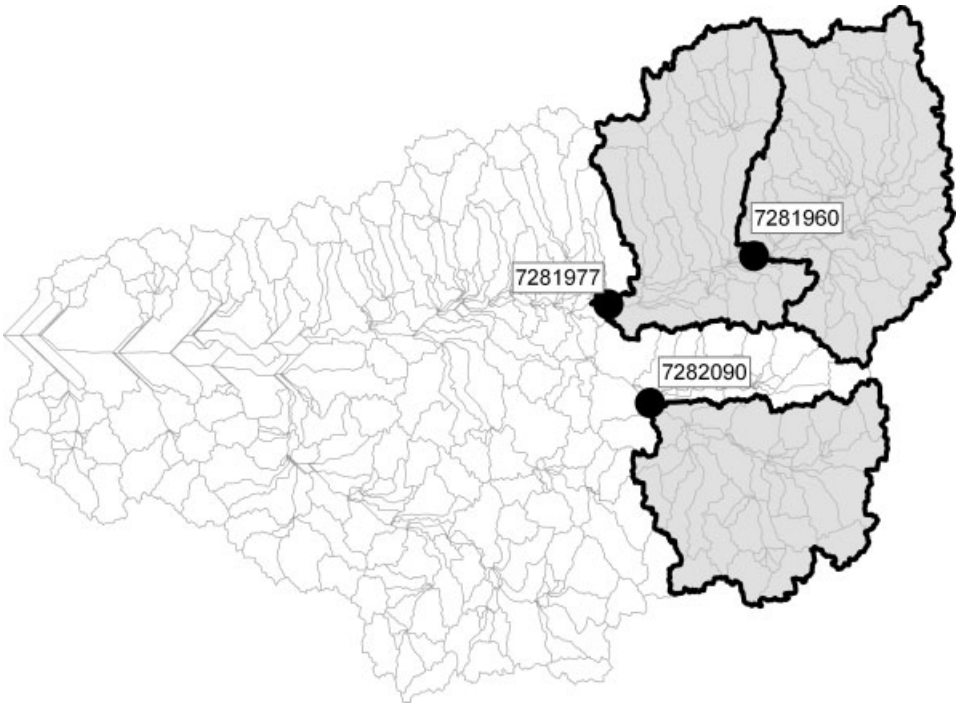

Figure 9. United States Geological Survey (USGS) stream gage locations within Yalobusha River Watershed.

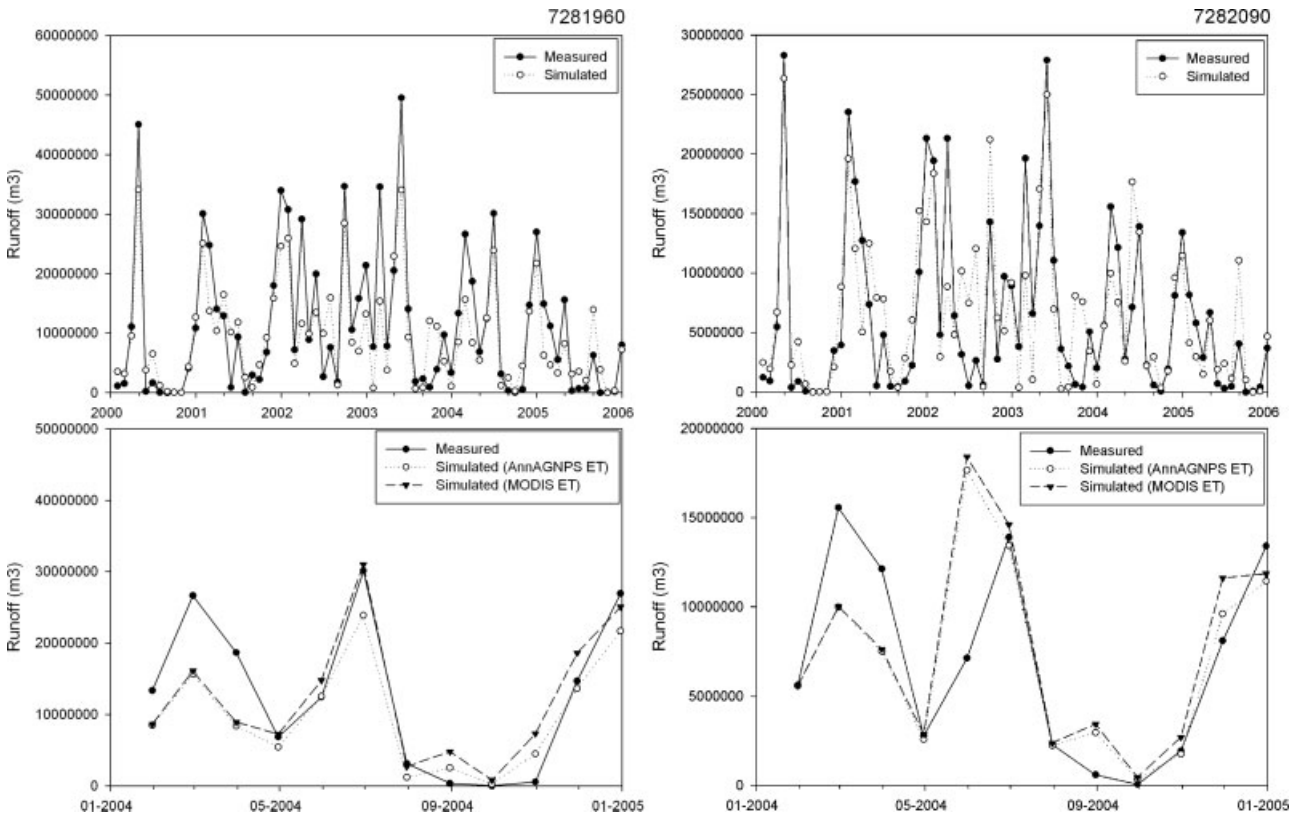

Figure 10. Measured and simulated monthly runoff at stream gages located within Yalobusha watershed. Upper plots show simulated results using AnnAGNPS ET from 2000 to 2005. Lower plot shows measured and simulated results for 2004.

of soil properties and vegetation cover on the remotely sensed ET values.

The present research incurred into some limitations. At the time of this study, the MOD16 product was in beta or provisional stage and only 1 year of this proxy dataset was available for this study. As the MOD16 product matures, it is expected that more evaluation is performed to the MOD16 algorithm and as a result a better product developed. Additionally, in this study, only one watershed located in southeast of the United

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Table I. Comparison of observed versus simulated accumulated yearly runoff at three stream gages at the Yalobusha watershed.

		2000	2001	2002	2003	2004[a]	2005[b]	AVE
7281977	Observed	360	754	850	667	564	34	658
	Simulated AnnAGNPS	354	660	675	518	403	32	552
	Simulated MODIS[c]					458		
7281960	Observed	361	745	909	746	735	303	633
	Simulated AnnAGNPS	378	695	717	560	565	270	531
	Simulated MODIS[c]					698		
7282090	Observed	264	660	558	517	492	196	447
	Simulated AnnAGNPS	328	622	630	476	502	217	463
	Simulated MODIS[c]					540		

[a] Results reflect January 1—September 30 only.
[b] Results reflect October 1—December 31 only.
[c] MODIS results are only for 2004.

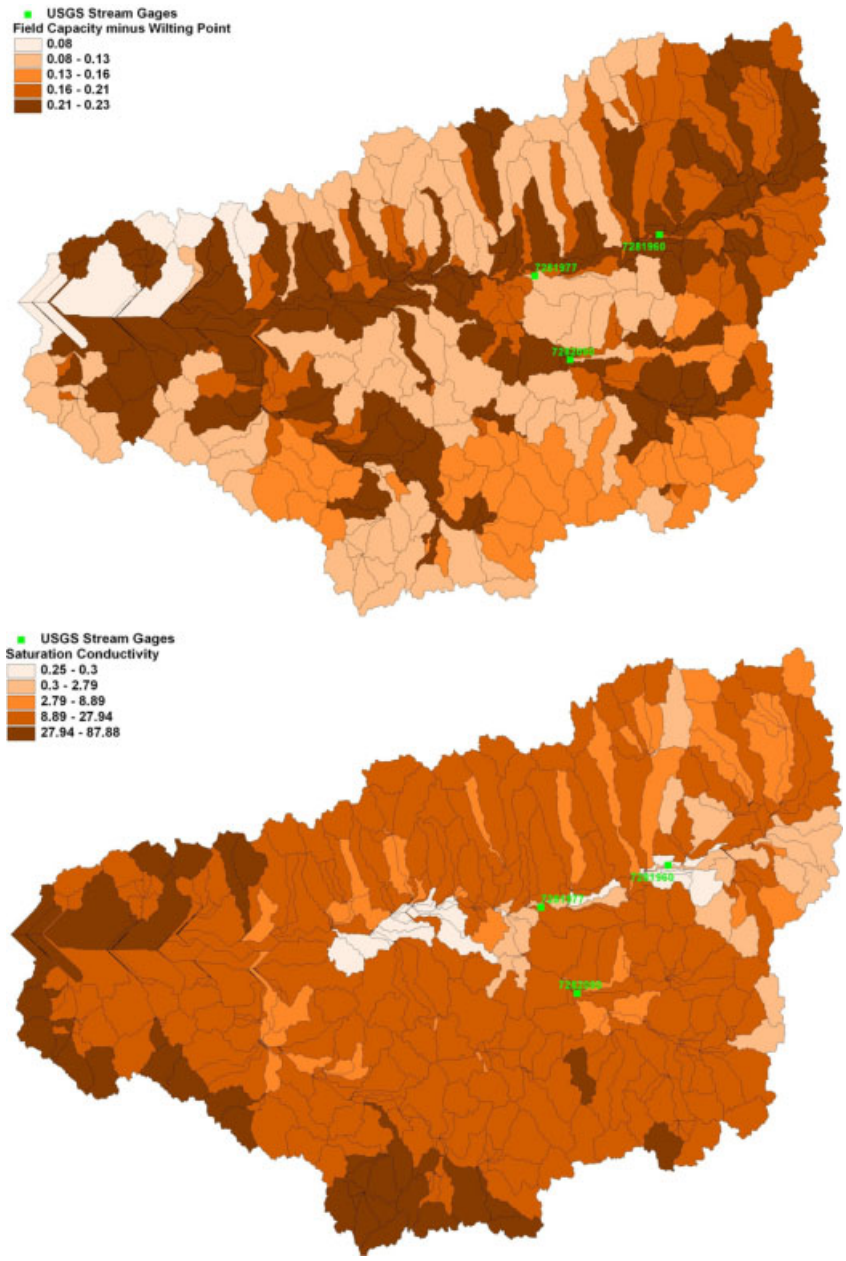

Figure 11. Upper map shows soil moisture availability and lower map shows saturation conductivity (mm/h) for each AnnAGNPS cell in the Yalobusha watershed.

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States was investigated, and we advocate caution when generalizing these results to other geographical locations.

Nonetheless, the results indicate that the utilization of remotely sensed ET is feasible. Within a large watershed system, climate parameters can be highly variable around the watershed and without an extensive climate station network can be difficult to obtain. The use of MODIS to estimate ET provided a more comprehensive spatial variability capability than is often available from measured climate stations. Variability in ET estimates between the two approaches was shown throughout the watershed to be mostly constant, but higher and lower differences were present and could be associated with the application of widely spaced climate stations affecting the measured climate parameters. Additional remotely sensed data describing precipitation and temperature, that is temporal and spatially distributed, would also provide a major improvement to the description of climate throughout a watershed system.

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