DEVELOPMENT OF A MODEL FOR EVAPOTRANSPIRATION ESTIMATES USING SATELLITE DATA

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SUMMARY

Water planning for Oklahoma necessitates a precise understanding of the components of the water budget. Of these components evapotranspiration is recognized to be of major importance. Yet, the very nature of evapotranspiration renders measurement difficult and expensive. Confounding matters is the fact that Oklahoma possesses amazing spatial and temporal variability in evapotranspiration. Evapotranspiration can not be accurately portrayed through averaging daily pan evaporation measurements for a location. Nor can existing pan evaporation sites be considered adequate to characterize the place-to-place differences in evapotranspiration. The purpose of this work was to develop a model for estimating place to place differences in evapotranspiration over large areas of Oklahoma. A geographic information system was used to concatenate precipitation, clope angle, slope aspect, soils, and satellite-derived landcover data to numerically produce a monthly evapotranspiration estimate for each 200 x 200 m grid cell in the upper Little Washita River drainage basin in south central Oklahoma. The total of per-grid-cell evapotranspiration estimates closely coincides with runoff measured at a stream gage. Three main advantages are associated with this method: 1) The models uses data which are already available for all areas of Oklahoma 2) The information system approach allows specific meteorologic events (e.g. drought) to be readily simulated 3) The effects of various land use strategies (e.g. increasing the acreage of irrigated crops) can be modeled.

PROBLEM

Water availability is a key issue in Oklahoma and undoubtedly a limiting factor on the near-future growth of the state. Oklahoma has seriously considered coordinated water planning. Vast interbasin transfers of water have been proposed. Despite much study and debate, one fact remains clear: the state will experience increasing demands on the water resource making water increasingly scarce. In the mileu of scarcity, a detailed spatial knowledge of the components of the water budget assumes a special importance. How much is available at a location at a particular time is a question that has practical significance.

The physical environment of Oklahoma is one of transition from the humid, forested areas of the southeast to the sub-humid, grassland regions of the northwest. Thus exists a marked geographical diversity in the nature of the landscape and climate within the state. Additionally, at individual locations, there are substantial temporal variations with which to contend. In the zone of collision between polar and tropical air masses, Oklahoma's meteorological parameters exhibit considerable interdiurnal variability. Moreover, year-to-year shifts in the upper westerly flow means Oklahoma is subject to large differences in seasonal meteorologic conditions: the "average" in Oklahoma cannot be counted on.

Well-appreciated within Oklahoma is the capriciousness of the rainfall regimes. Obviously, precipitation is one control of water variability on the landscape. Within the context of increasing water demands of population, industry, and agriculture, the temporal and spatial aspects of evapotranspiration--the water demand of the atmospheric environment--tend to be overlooked.

Evapotranspiration is an exceedingly complex and important phenomenon, especially in subhumid areas. Methods for estimation and measurement of evapotranspiration have received much attention. Yet, these estimates have been largely point-specific; water planning for an area as large and physically diverse as Oklahoma's 180,000 + square kilometers suggests the need for regionally evaluating evapotranspiration.

Although known to be a large component of midlatitude water budgets, the very nature of evapotranspiration makes exact measurement difficult. Therefore, an extensive volume of research has sought to quantify evapotranspiration. One category of effort has been the characterization of evaporation through pan measurements. Although relatively inexpensive and available for at least several sites in every state, the data obtained have been labeled "of doubtful meteorological value"[1] due to their susceptibility to low-level turbulence.

Other on-site measurements have met with considerable success. Lysimeters, transducers, and other means have been employed to estimate evapotranspiration. Drawbacks associated with these techniques are their expense and their tendency to be site-specific.[2] Thus, their applicability over a region is subject to much modification. Their paucity in Oklahoma make regional applications impossible. Indeed, Oklahoma does not contain a single lysimeter with long-term records.

Remote sensing techniques have been applied to estimate evapotranspiration over large areas. Although aircraft and satellite platforms cannot be used to directly estimate evapotranspiration, reasonable inferences can be made through remote assessment of landcover and climatic parameters. Culler and his coworkers produced acceptable estimates of evapotranspiration from phreatophytes along Arizona's Gila River through densitometric analysis of color infrared aerial photography.[3] Essentially the amount of greenness was a measure of evapotranspiration. Later workers have inferred evapotranspiration through the thermal remote sensing response of crop canopies[4, 5, 6, 7]. Although such studies are of great theoretical and practical significance, they are limited in that temperature is not the only factor affecting evapotranspiration.

Estimations of evapotranspiration can be made from meteorological and climatological parameters. A number of approaches exist and have been summarized by Mather.[8] Some of the more sophisticated methods require inputs of data types which are not commonly available in climatological records. This presents considerable difficulty when attempting to apply these methods to regions. Doorenbus and Pruitt have discussed methods which define "reference crop" evapotranspiration under ideal soil moisture conditions.[9] These evapotranspiration estimates are rather readily applied in any situation for which first-order weather station data are available. Yet, these estimates are tied to the weather station data in such a manner that local differences in the terrain and landcover types are not fully addressed.

Jensen and Chery, Jr. combined crop types derived from digitial LANDSAT classification with meteorological data from a nearby observation station to derive the water balance for a small (15.5km^2) watershed in Georgia.[10] Given that little of the world has been intensively studied with respect to evapotranspiration, the regional view offered by LANDSAT data holds the prospect of assisting in the estimation of evapotranspiration over substantial areas. In our research, we have expanded the LANDSAT-based view of the landscape to several layers of geographically-referenced information for a moderate-sized watershed in Oklahoma. These layers were manipulated through a geographical information system to provide an evapotranspiration estimate for each geographical cell in the study area.

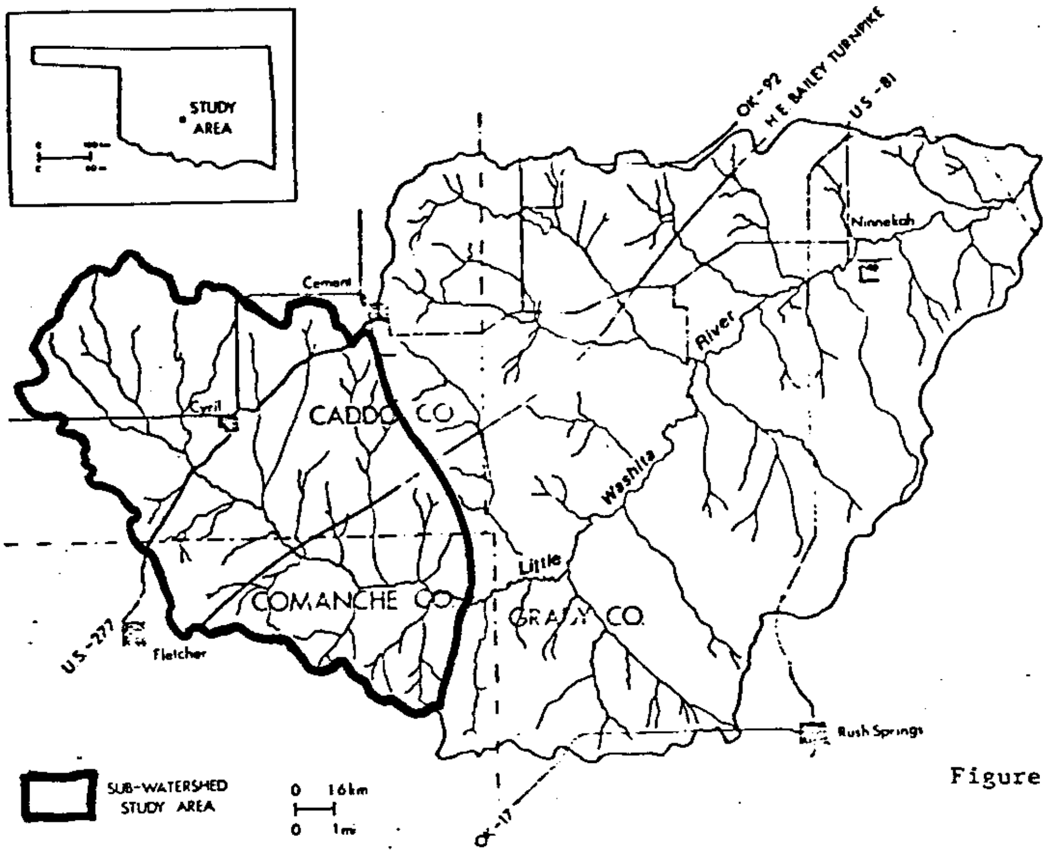
Given the measurement problems inherent to evapotranspiration, the purpose of this work was to derive a method by which to estimate evapotranspiration for large areas. This method is not dependent upon measurements of evapotranspiration, but, rather, characteristics of soils, terrain, and landcover which are easily obtained for all points in the state. The method we have devised uses these disparate data types within a geographic information system. Evapotranspiration is calculated per 200 x 200 m grid cell in an area using numerical attributes of the data.

RESULTS AND OBSERVATIONS

A. THE STUDY AREA

The study area comprises the upstream portion of the Little Washita drainage basin in Commanche and Caddo counties in southern Oklahoma (Figure 1). Covering approximately 159.6km^2, the study area embraces the ecotone between the forests of the east and the grasslands of the west. The range of elevations is from 370m to 450m above sea level. Topography can be described as varying from virtually flat to broadly rolling to steeply rolling. Over 85 soil types are present in the study area thus making for considerable differences among permeability, available water capacity, and other soil properties. More than 90 percent of the area is devoted to agriculture with greater than half of that total in pasture and range. Dominant agricultural crops are wheat, alfalfa, peanuts, and cotton. At the date of the LANDSAT overpass used for this work, cotton and peanuts had not yet formed a significant green canopy so they were included in the bare soil class. The town of Cyril is in the study area. However, the small size of its "built-up" areas were taken to be insignificant for the purpose of this work.

The climate of the area is moist sub-humid with a mean annual temperature of 17°C and mean annual precipitation of 95cm., with the majority of that total concentrated in warm season convection storms.[11] As noted above, Oklahoma is subject to considerable vagaries in climate. A hot, dry May can be followed by a cool, wet June with broad swings in the evapotranspiration from the landscape. The usual situation is for spring rains to fill the soils to capacity and then for the hot, summer days (average maximum temperatures > 32°C) to demand moisture from the landscape. To avoid the limitations which hot, dry conditions impose on the landscape the month preceding 08 April 1981 was chosen



LITTLE WASHITA WATERSHED

Figure 1

for study. This particular date was convenient because of clear-sky conditions at the time of a LANDSAT overpass, moderate amounts of precipitation fell in the preceding month, and moisture conditions at the beginning of the March/ April study period left the soils reasonably close to their capacities. The wheat and alfalfa crops had complete canopies and were well along in their development. The trees were leafed out, and the native grasses had come alive. In all, the study period was a time of much transpiration on the landscape with slight limitations with respect to water availability for transpiration.

The Little Washita drainage basin has been intensively studied for some time by several government agencies. Of importance to this study was the fact that a regularly-speced network of rain gauges was in daily operation throughout the study period. Daily rainfall totals were available for a dozen locations in and adjacent to the upper drainage basin of the Little Washita River. As shown below, these data provided a somewhat detailed series of observations which were extrapolated to each grid cell.

B. DATA SOURCES

The primary source of landcover data for this work was the LANDSAT Multispectral Scanner (MSS). The Multispectral Scanner is an electro-optical scanner that senses energy reflected from the Earth's surface in four wavelength intervals or bands ranging from 0.5 to 1.1 microns, through the visible and into the infrared wavelengths.

By scanning two visible and two infrared radiation bands, the Landsat multispectral scanners collect data regarding energy reflected from vegetation and other surface features. Computer analysis of the digital data identifies reflectance patterns or signatures that can be related to particular land cover types. Coupled with ground verification, the computer-produced analysis have great value in characterizing and quantifying spatial variations in surface characteristics. Output products can illustrate vegetative patterns and distribution, presence and extent of surface waters, land use change, and many other conditions of interest. In this case, the general landcover type was of prime importance.

The steps of analysis followed in the production of landcover types from unprocessed LANDSAT data included: first, preprocessing of the LANDSAT data for removal of unnecessary banding or striping of the data, and reformating to put the data in a more efficient format; second, identification of the boundaries of the Little Washita subwatershed to limit the overall processing time to a minimum; third, development of a set of spectral categories using the "SEARCH" routine,[12] this procedure establishes the foundation for the maximum likilihood classifier; fourth, running of the maximum likelihood classification program "MAXL" for the study area deriving a completed thematic classification of the land cover present and "recognized" by LANDSAT; fifth, fine tuning of the classification by combining spectral classes as necessary; sixth, geographically referencing the LANDSAT landcover classification to the Universal Transverse Mercator (UTM) coordinate system producing a geometrically and spatially accurate map.

An 08 April 1981 Landsat digital tape (ID #82226816272X0) was processed for landcover extraction. The initial unsupervised classification yielded 33 distinct statistical classes. Statistical analysis and field checking within the watershed provided the mechanism for efficient combining of classes into meaningful landcover types with respect to evapotranspirative differences. Derived landcover classes included wheat, alfalfa, forest, water, bare soil, and pasture 1-4 (based primarily on grass density, from lush to sparse). The original pixels were aggregated via a computer routine to 200 x 200 m grid cells and the dominant landcover for each grid cell determined. The 08 April 1981 digital tape represented somewhat wetter-than-average soil moisture conditions, so the drainage basin was dominated by transpiring, green vegetation.

Soils information, regarding type, permeability, available water capacity, and hydrologic groups were digitized from Soil Conservation Service (SCS) county soils survey sheets. The x and y digitized coordinates of each cell related to the UTM position, while the z value indicated the dominant value within the cell. The soils data were aggregated and digitized at 200 x 200 m grid cells which coincided with the grid cells used to aggregate all variables.

Permeability is estimated by SCS on the basis of known relationships among the soil characteristics observed in the field, soil structure, porosity, and texture, that influence the downward movement of water in the soil.

Available water holding capacity is rated by SCS on the basis of soil characteristics that influence the ability of the soil to hold water and make it available to plants. Important characteristics are content of organic matter, soil texture, and soil structure. The hydrologic groups are used by SCS to estimate runoff after rainfall. Soil properties that influence the minimum rate of infiltration into the bare soil after prolonged wetting are depth to a water table, permeability, and depth to layers of slowly or very slowly permeable soil.

Slope angle, slope aspect, and elevation data were secured from National Cartographic Information Center (NCIC) digital terrain tapes covering the study area. Processing of these tapes yielded slope angle classes for the watershed of 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, 8-10 percent; slope aspect classes of north, northeast, east, southeast, south, southwest, west, and northwest; and elevation classes in 20 foot intervals from 1200-1520 feet.

Precipitation data were obtained from the network of rain gauges that are regularly distributed throughout the watershed. These point measures of precipitation were interpolated into per cell measures of monthly precipitation through use of the Theissen Polygon approach.[13] Twelve polygons were thus identified for precipitation and each cell within a particular polygon assigned the precipitation total from the rain gauge within the polygon.

A similar approach was utilized to obtain area measures of mean monthly temperature. Since no stations within the watershed regularly record temperature, nearby state weather stations provided the data for construction of three Thiessen polygons of temperature. Grid cells within each of the three polygons were digitized to contain the mean monthly temperature of the appropriate recording station.

C. DATA PROCESSING AND MANIPULATION

The data sets produced through digitizing and processing of the digital data were displayed on an image processing system. An initial color table and function were developed for the data sets. All data sets were referenced to the digitized watershed outline and oriented as geographically referenced layers of spatial information. The individual data sets were color coded by variable intensity. The ability to turn analog information into digital data, and then to edit, store, and display the data as maps or color images is effective in examining the consequences of interaction between disparate data sources.[14] This ability is of great value in analyzing geographically referenced layers of spatial information.

The development and implementation of a geographic information system can successfully accommodate data integration problems and the time-consuming process of synthesizing tremendous amounts of information for the spatial examination of evapotranspiration. An information system can input, manipulate, and analyze geographically referenced data in order to support the decision-making process of an organization.[15] In general, a geographic information system may be regarded as layers of spatially oriented information.[16] Technologies of the 1980's include remote sensing and geographic information systems. Their capability for large and small area analysis, integration of numerous variables into the evaluation process, and the ease of updating the data base make their use attractive.[17] The data elements entered into the system, data resolution, analysis models, type of data output products, and the particular system applications are dependent upon the investigator and the desired informational requirements. The work for this paper used a geographic information to combine terrain, landcover, soils, and climate by grid cell to obtain estimates of evapotranspiration.

The Oklahoma State University Center for Applications of Remote Sensing (CARS) has developed the Oklahoma Geographic Information Retrieval System (OGIRS), which is a highly interactive data collection, storage, and manipulation software package.[18] OGIRS was developed in response to a need for a computer based geographically referenced natural resource information system within the state of Oklahoma. The primary objectives of the OGIRS software package are to provide a means to collect data from disparate sources, store all data in a common format, provide data editing capabilities, convert stored data into symbol maps, allow selective mapping from stored data, provide composite map building functions, and provide a variety of output products.

OGIRS is resident on CARS' Perkin-Elmer 8/32 minicomputer equipped with a 300 megabyte disk drive, two 1600 bpi magnetic tape drives, two remote terminals, a 300 line per inch line printer, a Versatec electrstatic printer/plotter, an Altek graphic digitizer, and a Comtal image processor. The program with subroutines for allocation of indexed and contiguous disk files, opening and closing logical units, file name entry, editing, mapping, and data manipulation.[18]

The data entry modules of OGIRS allow several different data sources to be stored in the consistent format required by the applications modules. An interface with the graphic digitizer allows input of grid point x, y, and z coordinate values. The x and y values relate to the geographic position of the grid point or cell, while the z value indicates the value of the cell, such as (soil type, percent slope angle, etc.). Points may be digitized and thereby geographically located in the Landsat element/scan line coordinate system, the University Transverse Mercator (UTM) grid system or in a user defined coordinate system.[14]

All data are stored in a consistent format in thematic libraries. The thematic library system is more a convenience to the user than a system necessity. Thematic libraries allow the user to organize the input data into major categories and then subdivide the major headings into smaller units representing the individual data sets.

OGIRS output products are available as line printer symbol maps, electrostatic printer/plotter maps, and color images, In addition to the two dimensional map representations, the z values for a data set may be listed in tabular format.

Manipulation of stored data is by five value selection modes and three mapping functions.[18] The value selection modes are: equal value, greater than a value, less than a value, greater than and less than a value, and less than a value or greater than a value.[18] The three mapping functions allow any number of individual data sets from any number of data libraries to be combined as the union, intersection, or exclusion.

The five relational modes each generate a new data set that is a subset of the original. Each of the three mapping functions: union, intersection, and exclusion first allow the user to place conditional restrictions on the data sets with one of the five relational modes. Finally, the selected mapping function is applied to the resulting restricted data sets to produce a new output data set or map.

D. THE REGIONAL EVAPOTRANSPIRATION MODEL

Mather has noted evapotranspiration depends upon 1) net radiation, wind velocity, and humidity; 2) type of soil and soil moisture content; 3) type of vegetation and depth of rooting, and 4) land management practices.[8] The model developed in this research was designed to use readily acquired landscape attributes to address each of the four functions. The landscape attributes used to determine evapotranspiration at each grid cell are given in Table 1.

TABLE 1

LANDSCAPE ATTRIBUTES STORED AS INFORMATION LAYERS AND USED AS VARIABLES IN THE MODEL

ATTRIBUTE	ORIGINAL UNITS
Slope Angle	10 classes (%)
Slope Aspect	8 Directions
Soil Hydrologic Group	A through D
Soil Permeability	6 classes (inches per hour)
Available Water Capacity	6 classes (inches per inch)
Depth of Soil	Inches
Landcover Type	9 classes
Mean Temperature for the Month Prior to 08 April 1981	2 classes (degrees Fahrenheit)
Precipitation Total for the Month Prior to 08 April 1981	12 classes (inches)

Basically, the model calculates the amount of soil water available for evapotranspiration in each grid cell and modifies that amount through multiplication by coefficients derived from terrain, landcover, and soil attributes. Thus, grid cell evapotranspiration estimates are made via consideration of the landscape attributes contained as layers of information in the geographic information system. Once the various types of data are arranged in the data base, calculation and adjustment of evapotranspiration estimates can be quickly accomplished.

The formulas used to calculate grid cell evapotranspiration are given below as equations (1)-(5).

$$K_s \times K_c \times K_p \times [W] = ET_{estimate} \qquad (1)$$

$$S_A + S_I - L = W \qquad (2)$$

$$(P-.2S)^2/(P+.8S) = Q \qquad (3)$$

$$S=(1000/\text{SCS Runoff Curve Number})-10 \qquad (4)$$

$$P - Q = S_I \qquad (5)$$

In equation (1) K_s is a coefficient based on the energy incident at a site; K_c is a coefficient based on the moisture loss characteristics of the dominant cover type; K_p is a coefficient based on the ease of water withdrawal by plants from the dominant soil series; W is the amount of water in inches available for evapotranspiration, and $ET_{estimate}$ is the estimate of evapotranspiration in inches derived from the multiplication of the water available by the three coefficients.

The energy characteristics of a site help drive evapotranspiration. In general, under conditions of light to moderate winds and moderate relative humidities, which were present in the study area during the month previous to the LANDSAT overpass, the amount of evapotranspiration is positively related to the amount of energy incident at the surface. Soil moisture was sufficient so as not to present widespread limitation to evapotranspiration. Incident energy can be considered in regional and site-specific contexts. From a regional standpoint, the model can consider latitudinal differences in energy receipt if the study area is large enough. The maximum difference between the north and south boundaries of the upper drainage basin was 16km., so latitude was dropped as a modifier in this case. Computation of the mean monthly temperatures for the month preceeding the LANDSAT overpass showed less than $1^{o}C$ of difference between the temperature recording stations nearest the study, so latitudinal adjustments to the K_s coefficient would have been meaningless. In larger study areas, latitudinal differences in energy receipt could become significant and could readily be assessed by the K_s coefficient at every grid cell through use of the known UTM location of each cell.

From a site standpoint, incident energy can be approximated through an examination of terrain. The terrain elements of slope angle and slope aspect were stored as information layers for each grid cell in the study area. For the purpose of estimating incident energy, slope angles were dichotomized into low slopes (0-3%) and high slopes (> 3%). In the most steeply rolling part of the upper Little Washita drainage basin, all but a few of the grid cells had dominant slope angles of greater than 10 degrees, so this dichotomization was appropriate to the study area. Slope aspects were stored as 8 classes (north, northeast, east, etc.). To derive the K_s coefficients, slope aspect/angle combinations were used. Two classes of slope angle and 8 classes of slope aspect created 16 (8 x 2) aspect/angle combinations. For each aspect/angle combination the percentage of incident energy as compared to a flat surface at that latitude was derived from data presented by Buffo, Fritschen, and Murphy.[19] Thus, the K_s coefficient was the relative amount of energy present at that site. In the study area, the value of the K_s coefficient ranged from .95 to 1.00. If there had been a greater range of slope angles, a greater range of K_s values would have existed. The larger the value of the K_s coefficient, the greater the temperature at that location and, hence, the greater the evapotranspiration.

The landcover type present at a particular location greatly influences evapotranspiration. Landcover types present in the study area were assessed as to their relative contributions to evapotranspiration. The crop coefficient concept so widely applied in evapotranspiration literature was applied here. A crop coefficient is a cover specific adjustment to evapotranspiration based on a "reference crop" which is healthy and has no limitations in soil moisture or fertility. A "landcover" coefficient for each landcover type was determined from the literature in general and Doorenbos and Pruitt in particular.[9] A value of the landcover coefficient, K_c, was identified for each landcover type with respect to the growth calendar for each type and the meteorologic conditions of the study period. Values varied up to a value of 1.00 and the assumption was that the higher the value of K_c the greater the amount of evapotranspiration.

The coefficient K_p was an attempt to adjust evapotranspiration through recognition of the ease with which water can be withdrawn from the soil via evaporation and transpiration. Given similar terrain, landcover, and soil moisture storage characteristics, some soils present greater amounts of water to the atmosphere than do others. Soil permeability was used as an approximation of ease of water withdrawal. The soil permeability characteristics of the A horizon of the soils were divided into 6 classes based on ranges of permeability values. The high value in each range was used to characterize soils in the class corresponding to the range. Classes with rapid permeability were taken to have a K_p value of 1.00. The remaining classes were scaled relative to the 1.00 value. Underlying the use of K_p was the assumption that, other factors being equal, soils with high K_p values were associated with greater amounts of evapotranspiration.

In equation (1), W is taken to be the water available for evapotranspiration. W is a summation of the water in storage at the start of the study period, loss to groundwater and subsurface runoff, and the addition of water to storage via infiltration of precipitation. The water in storage at the start of the study period is a product of the water holding capacity and depth of the soil corrected for by using antecedent moisture conditions. The equation for determing W is given as (2), where S_A is storage in the soil carried over from times antecedent to the study period, S_I is additions in storage via infiltration of precipitation, and L is the loss of water to the groundwater supply.

Storage carryover from the times antecedent to the study period was calculated from the storage properties of the soil. The month prior to the study period has been normal in precipitation and the week before the start of the study period (08 March) had been wet with three rain days. The last rain day occurred on 07 March. Thus, for the case of the study period, it was assumed that the soils of the study area were at or near field capacity. Water available for evapotrsnapiration was determined for each grid cell by the multiplication of available water holding capacity (inches per inch) by the depth of the soil (inches). For drier conditions, this carryover storage would have to be adjusted accordingly.

The addition of storage via infiltration of precipitation was calculated using the standard runoff curves of the SCS.[20] Runoff is calculated from formula (3), where P is precipitation, S a number derived from equation (4), and Q is runoff in inches. In equation (4) the SCS runoff curve number identifies a member of a family of curves which plot runoff versus precipitation. The curve number at each grid cell was determined by the land cover type and hydrologic group combination at that location. Thus having computed Q, the addition to soil moisture via infiltration was calculated from equation (5).

Loss to groundwater was considered insignificant compared to the other components of the water budget during the study period. Hence, L was assumed to be 0 for the slightly-drier than normal period from 08 March to 08 April.

The above equations were employed to estimate evapotranspiration cell by cell. The layers of information in Table 1 were used to derive variable values for each grid cell. The computation of evapotranspiration estimates was effectively accomplished within the geographic information system approach for the 3,990 grid cells of the study area.

Figure 2 is an electrostatic plotter map of the monthly evapotranspiration

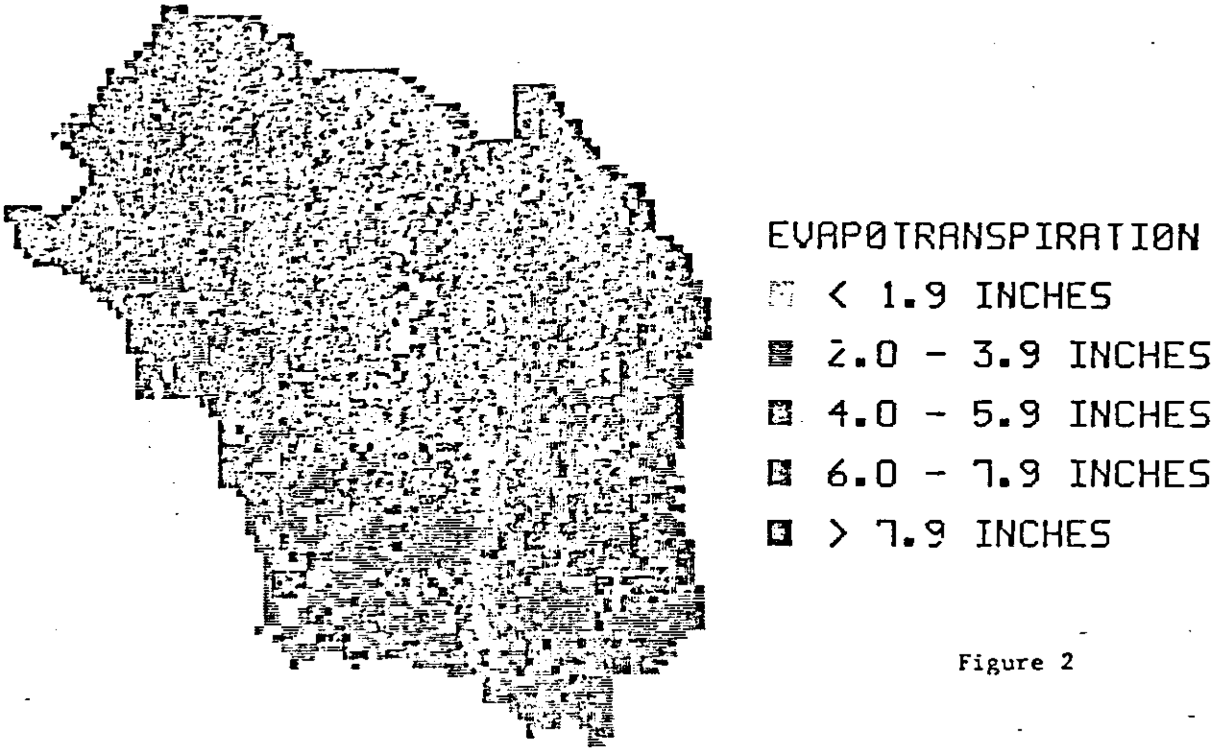


Figure 2

amounts in the Little Washita subwatershed study area. The map is the result of the application of equation (1) to each grid cell in the study area, using the combination of landscape components present at each cell. Computed monthly evapotranspiration estimates ranged from 0.4 inches to 10.1 inches. The values were classed into 5 categories to facilitate map display. Approximately 40 percent of the grid cells had evapotranspiration totals of from 4.1 to 5.9 inches.

Figure 2 exhibits the variability of evapotranspiration within the watershed. Of note is the fact that within the variability can be found some spatial regularities. More of the highest evapotranspiration amounts occur in the eastern portion of the study area. This is reflective of the sandier, more permeable soils and greater forest cover in the east, and the less permeable clay soils in the west. The evapotranspiration map also shows north/south differences. The portion of the subwatershed to the north of the Little Washita has a substantially greater frequency of south, southeast, and southwest aspects. This results in greater energy receipt and correspondingly greater evapotranspiration estimates.

Cells of greatest evapotranspiration are closely associated with forest cover on permeable soils. Cells of least evapotranspiration tend to have bare soils of low permeability within rainfall polygons containing relatively low rainfall totals.

Close examination of Figure 2 shows a certain amount of linearity which can be associated with the drainage pattern in Figure 1. Although gross generalizations relating elevation and evapotranspiration cannot be discerned in the data, some of the inherent linearities in the terrain and soils data have been transmitted to the evapotranspiration map. Inspection of the data shows various combinations of the attributes of Table 1 can be responsible for a particular cell value of monthly evapotranspiration.

The model appears to be reasonably accurate in its monthly evapotranspiration estimates. An examination of the combined factors creating this middle range evapotranspiration estimates shows agricultural crops on soils of moderate to moderately rapid permeability to be heavily represented. Values of 5.34 inches per month and 4.81 inches per month were obtained for a healthy, unstressed "reference crop" using, respectively, the radiation method and the Blaney-Criddle formula.[9] Additionally, measured stream gage runoff at the most downstream portion of the upper Little Washita was compared against the total of the per-grid-cell estimates of runoff. The runoff was .13 inches for the month in both cases. We cannot claim this correspondence means extreme accuracy in our evapotranspiration estimates, but it indirectly confirms that we are on the correct order of magnitude on a regional basis.

BENEFITS

The method employed by this work could be employed by a number of users, particularly those interested in the water requirements associated with agricultural cover types. The water needs of a particular crop on a particular landscape can be assessed and proper irrigation more readily planned. From a regional perspective, if the water demands of the particular mix of cover types present on the landscape are known, the task of determining how much water to transport to where becomes simpler. In all, the benefits of this project are in the fact that the disparate elements of the landscape can be portrayed in their relationship to evapotranspiration.

CONTRIBUTIONS TO KNOWLEDGE

This study is the forefront of current, large-area hydrologic modeling. Geographic information systems applied to distributions of phenomena are not unique. However, our approach is fresh in that we use the combination of numerical landscape attributes to arrive at per cell estimates of evapotranspiration.

Oklahoma's physical diversity and resulting uneven distribution if its water resources make a flexible method of regional estimation of evapotranspiration highly desirable when calculating water budgets. The simplicity of the model suggests the viability of using this technique to evaluate evapotranspiration for other times and at other places in the state.

The data requirements of the model are such that updates are readily accomplished. Once terrain and soils data are entered into the geographic information system database, the meteorological data can be altered to reflect conditions earlier or later in the growing season, or simulate the impact of stressful conditions (e.g. drought) on regional evapotranspiration. Reliable landcover information is vital to the model. Processed LANDSAT data offer the prospect of inventorying the landcover types and their vigor several times during a growing season. In this way, evapotranspiration estimates can include the variations induced by seasonal physical changes in the landcover.

Manipulation of information in a geographic information facilitates the examination of interactions between multiple variables. For instance, the landcover layer of information of an area could be simulated to estimate the effect of a particular landcover change on evapotranspiration. Such simulation is the forte of geographic information systems and is not possible in any other setting.

The strengths of the model should not be viewed as absolute. This model attempts only to provide a *regional* view of the variability in evapotranspiration. In order to process manageable amounts of information at the regional scale, generalization has gone into each information layer for each grid cell. Obviously, major differences in evapotranspiration can take place within a 200 x 200 m area. It is not our intent to supplant previous, site-specific methods with the present model. Indeed, the sophistication of estimates using site-specific methods exceeds the precision possible with a regional model. The value of this work lies in its regional perspective: the evapotranspiration estimates for the Little Washita subwatershed provide a level of detail appropriate for regional analysis unobtainable through interpolation of site-specific measurements.

Potentially, the knowledge gained can be applied in a most fascinating way. Work on this study has forged a link between CARS and the National Severe Storms Laboratory in Norman, Oklahoma. Doppler radar is able to detect low-level atmospheric convergence which is a necessary precondition for storm development. With the evapotranspiration model developed for the current project, CARS is able to determine which areas of the Oklahoma landscape give up the most moisture. If modeled evapotranspiration is linked to Doppler echoes through a geographic information system approach, the moisture and convergence patterns of the boundary layer of the atmosphere could be modeled in such a way that the influence of the landscape upon storm development might be discerned. Currently, a preproposal for such a project has been sent to the National Science Foundation.

MEETINGS AND PRESENTATIONS

Various aspects of the project were presented at three meetings. Papers given include:

Association of American Geographers, Denver, April 1983

Stephen J. Stadler, and Stephen J. Walsh, "Regional Evapotranspiration Estimates Using Landcover, Soils, and Atmospheric Data".

Margaret A. Williams, Stephen J. Walsh, and Stephen J. Stadler. "Utilization of Landsat Digital Data to Estimate Evapotranspiration".

Western Social Science Association and Arid Lands Association, Albequerque, April 1983

Stephen J. Stadler and Stephen J. Walsh. "Water Loss to the Atmosphere: A Geographic Information System Approach".

Ninth International Symposium on Machine Processing of Remotely Sensed Data, Purdue University, June 1983

Stephen J. Stadler and Stephen J. Walsh. "Regional Evapotranspiration Modeling of Oklahoma's Little Washita Drainage Basin."

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