Spatially distributed storm runoff depth estimation using Landsat images and GIS

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Abstract

The use of geographic information systems (GISs) and remote sensing to facilitate the estimation of runoff from watershed and agricultural fields has gained increasing attention in recent years. This is mainly due to the fact that rainfall-runoff models include both spatial and geomorphologic variations. The US Department of Agriculture, Natural Resources Conservation Service Curve Number (USDA-NRCS-CN) method was used in this study for determining the runoff depth. Runoff curve number was determined based on the factors of hydrologic soil group, land use, land treatment, and hydrologic conditions. GIS and remote sensing were used to provide quantitative measurements of drainage basin morphology for input into runoff models so as to estimate runoff response. The study was conducted on the S-65A sub-basin of the Kissimmee River basin in south Florida. Land use from Landsat images for 1980, 1990 and 2000 were considered in the study. The process of determining spatially distributed runoff curve numbers from Landsat images is presented in this study using GIS and image processing software. Spatially distributed runoff curve numbers and runoff depth were determined for the watershed for different land use classes. Results of the study show that land use changes determined from Landsat images are useful in studying the runoff response of the basin. It is shown that the S-65A sub-basin has undergone land use and runoff response changes over the 20 years period of time. The area covered by water and wetlands in 2000 is higher than in 1980 and 1990. In 2000 areas having CN of greater than 90 accounted for 3% compared to 0.9 and 0.6% in 1980 and 1990 respectively. This was due to the increase in wetlands and water covered areas attributed to the Kissimmee River restoration work, which started in 1997 and aimed at restoring lost wetlands and floodplains. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Land use is an important characteristic of the runoff process that affects infiltration, erosion, and evapotranspiration. Hydrologic models, distributed models in particular, need specific data on land use and its location within the basin.

Remote sensing can provide measurements of many of the hydrologic variables used in hydrologic and environmental model applications, either as direct measurements comparable to traditional forms, as surrogates of traditional forms, or as entirely new data set. The pixel format of digital remote sensing data makes it suitable to merge it with geographic information system (GIS).

Most of the previous work on adapting remote sensing to hydrologic modeling has involved the Natural Resources Conservation Service (NRCS) runoff curve number (CN) model (US Department of Agriculture, 1972). This involvement used remote sensing data as a substitute for land cover maps which had been obtained by conventional means (Jackson et al., 1977; Bondelid et al., 1982). Still and Shih (1984, 1985, 1991) used Landsat data to develop a basin-wide runoff index and successfully demonstrated how remotely sensed data can be used to track the changes in runoff that occur in a basin due to land use change.

GIS is a computer-based tool that displays, stores, analyzes, retrieves and generates spatial and non-spatial (attribute) data. The GIS technology provides suitable alternatives for efficient management of large and complex databases. It is used in hydrologic modeling to facilitate processing, management and interpretation of hydrologic data.

Several studies have been done to incorporate GIS in to hydrologic modeling of watersheds. These studies have different scopes and can be generally grouped in to four categories. Computation of input parameters for existing hydrologic models (Muzik and Pomeroy, 1990; Stuebe and Johnson, 1990; Djokic and Maidment, 1991; Olivera and Maidment, 1999) is the most active area in GIS related hydrology. Unlike lumped models, distributed models require large amounts of spatial data, which can be computed using GIS. Hydrologic assessment (Moeller, 1991; Ragan and Kossicki, 1991) refers to the mapping and display in GIS of hydrologic factors that pertain to some situation. Measuring the spatial extent of hydrologic variables from paper maps may be tedious, labor-intensive and error-prone. Watershed surface mapping (Band, 1989; Sasowsky and Gardner, 1991; Smith and Brilly, 1992) refers to the uses of GIS in representation of watershed surface through the use of digital elevation model and gridded geographic data. Identification of hydrologic response units (Vieux, 1991) is also another contribution of GIS to identify areas of watershed’s having similar hydrologic response.

The traditional method for establishing CN on small watersheds includes field surveys and interpretations of aerial photographs. For large drainage basins, field surveys are prohibitively expensive and an excessive number of aerial photographs may be required for complete coverage. A further disadvantage of conventional techniques may be the infrequency of the surveys and the consequent failure to account for changes in vegetative cover and land use.
Objectives of this research work are to outline the strategy of employing Landsat images from different sensors and GIS in determining spatially distributed runoff and to estimate spatially variable runoff depth using GIS. This is demonstrated for three different years, to account for temporal changes in a sub-basin of Kissimmee River basin in south Florida.

2. Materials and methods

2.1. NRCS runoff curve number

In the NRCS runoff equation, the ratio of amount of actual retention to watershed storage is assumed to be equal to the ratio of actual direct runoff to the effective rainfall (total rainfall minus initial abstraction). The assumed relationship in mathematical form is (USDA, 1972):

\[ \frac{F}{S} = \frac{Q}{P - I} \]  

(1)

where \( F \), actual retention (mm); \( S \), watershed storage (mm); \( Q \), actual direct runoff (mm); \( P \), total rainfall (mm); \( I \), initial abstraction (mm).

From the well-known water balance equation, the amount of actual retention can be expressed as

\[ F = (P - I) - Q \]  

(2)

To eliminate the necessity of estimating both parameters \( I \) and \( S \) in the above equation, the relation between \( I \) and \( S \) was developed by analyzing rainfall-runoff data for many small watersheds. The empirical relationship is

\[ I = 0.2S \]  

(3)

substituting Eq. (3) into Eq. (1) and 2 yields

\[ Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (P \geq 0.2S) \]  

(4)

Eq. (4) is the rainfall-runoff equation used by the NRCS for estimating depth of direct runoff from storm rainfall. The parameter \( S \) in Eq. (4) is related to \( CN \) by

\[ S = \frac{25400}{CN} - 254 \]  

(5)

The \( CN \) is a dimensionless runoff index determined based on hydrologic soil group (HSG), land use, land treatment, hydrologic conditions and antecedent moisture condition (AMC). The \( CN \) method is able to reflect the effect of changes in land use on runoff. The \( CN \) values range between 1 and 100. Higher values of \( CN \) indicate higher runoff. The NRCS runoff equation is widely used in estimating direct runoff because of its simplicity, flexibility and versatility.
Soils are classified into four HSGs (A, B, C, and D) according to their minimum infiltration rate, which is obtained for a bare soil after prolonged wetting. Soils in group A have lowest runoff potential, soils in group B have moderately low runoff potential, soils in group C have moderately high runoff potential and group D soils have the highest runoff potential.

Land cover complex classification depends on three factors: land use, treatment, and hydrologic condition. Land use is watershed cover; it includes all agricultural and non-agricultural lands. Land treatment refers mainly to mechanical practices (e.g., contouring or terracing) and management practices (e.g., grazing control, crop rotation or conservation tillage). The hydrologic condition reflects the level of land treatment and is divided into three classes: poor, fair, and good.

AMC is an indicator of watershed wetness and availability of soil storage prior to a storm. Three levels of AMC are used: AMC-I for dry, AMC-II for normal, and AMC-III for wet conditions.

2.2. The study area

The lower Kissimmee River water management basin is one of the main water conveyance systems in to the northern part of Lake Okeechobee (Downey, 1999). The S-65A sub-basin (Fig. 1) is located south of Lake Kissimmee and covers about 41,833 hectares. The S-65A sub-basin contributes to the first reach, Pool A, of the Kissimmee River and outflow from the sub-basin is controlled by the water control structure S-65A.

Between 1962 and 1971, the Kissimmee River was channelized and transformed into a series of impounded reservoirs (SFWMD, 2000). The channelization has
changed the hydrologic response characteristics of the basin and largely eliminated river and floodplain wetlands. The meandering river was transformed into a 90-km-long, 9-meter-deep, 91-meter-wide canal. Excavation of the canal and deposition of the resulting soil eliminated approximately 56 km of river channel and 2509 ha of floodplain wetland habitat. The results of these physical and ecological changes were presumed to have various effects on the sub-basin including its hydrology. To understand and assess these changes on the hydrology, particularly on the peak runoff depth of the sub-basin, the NRCS CN method was employed. A temporal series of images from the Landsat program, including Multi-Spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced TM Plus (ETM+) were analyzed to determine the land cover. To address the spatial variability of runoff, the study considered runoff to be spatially distributed. GIS and image processing software were used to handle and process these data.

To better understand the various changes in the sub-basin and their effect on the runoff, land use was studied for the dates of 1980, 1990 and 2000. Until 1972 the sub-basin was part of the large flood plain of the Kissimmee basin and after channelization, the sub-basin was drained and was subjected to developmental activities. In 1992 congress approved the restoration and the work began in 1997 (SFWMD, 2000).

2.3. Landsat images

The MSS instrument available since 1972, responds to the earth-reflected sunlight in four spectral bands of varying radiometric ranges with 76-m spatial resolution (USGS, 2000). The TM instrument, available since 1982, also detects the reflected radiation from the earth’s surface in the visible and infrared (IR) wavelength, but with its seven spectral bands provides more radiometric information than the MSS instrument. The wavelength range of TM is from the visible through the mid-IR in 30-m spatial resolution, and in the thermal portion of the electromagnetic spectrum with 120-m spatial resolution. The ETM+ instrument on Landsat 7, available since 2000, is similar to the TM, but includes new features such as a panchromatic band with 15-m spatial resolution, on board 5% absolute radiometric calibration and a thermal IR band with 60-m spatial resolution. The spatial resolution of the ETM+ bands from the visible to mid-infrared is 30-m.

3. Results and discussion

Land cover for December 08, 1980 was determined from a radiometrically corrected Landsat MSS image scene of the basin. Further processing of the image included geometric correction, classification and vectorisation. The image was first classified using an unsupervised classification technique and 30 classes were generated. Since this image has only four bands, to improve the classification a normalized difference vegetation index (NDVI) was created and added to the image as an additional layer. The scatter diagram of infrared bands versus NDVI helped to
distinguish between the vegetative and non-vegetative part of the image. The results of land use classification from this image indicate that cropland (including pastureland) accounted for 51% and rangeland constituted about 26% of the sub-basin.

Land cover for December 09, 1990 was determined from a Landsat TM scene. This image was processed as above. To ground truth the accuracy of the classification, land use developed from Digital Orthophoto Quarter Quadrangle data of the same year was used. This GIS layer is at the scale of 1: 24000 and distributed by the University of Florida Geoplan Center. It categorizes land use as per the florida land use and cover classification system level 2 classification (Kuyper et al., 1981). The 1990 TM-based land use classification shows that cropland (including pastureland) accounted for 21.4% and the rangeland accounted for 54.3% of the sub-basin’s land use.

The January 11, 2000 land use was determined from a Landsat ETM+ image. This image was processed as above. Results of the 2000 Landsat ETM+ image classification shows that cropland (including pastureland) constituted 31% of the sub-basin’s land use, and rangeland accounted for 29% of the entire sub-basin’s land use.

For 1990, the iterative self-organizing data analysis technique (ISODATA) (Tou and Gonzales, 1974) classification yielded 10 classes and later regrouped in to 7 level 1 (Anderson et al., 1976) classes. This will give visually smooth or uniform maps when grids are created. On the other hand for 1980 and 2000, the ISODATA classification yields 30 classes and later regrouped into 7 classes. This will capture more reflectance data and resulted less uniform grids. But in both cases, the classification ends up with 7 classes and the apparent difference is only visual.
To estimate curve numbers and runoff depth for the entire sub-basin, vector coverage of soil showing the HSG, and land cover with class descriptions which correspond to the USGS land cover and land use classification (Anderson et al., 1976) were overlain on to each other. The soil layer was obtained from the state soils geographic NRCS database and converted to grids with a 30 meters cell size (Fig. 2). In addition to the land cover descriptions of the database, records of hydrologic soils group, curve number, runoff depth and runoff volumes were added to the attribute table of the intersected soils-land cover layers.

Based on the information of soil and land cover, curve numbers were calculated for each grid cell using the NRCS 1972 National Engineering Handbook (NEH 4) guidelines. Using the grids of runoff curve number, runoff depth was calculated for

Fig. 3. Map of runoff curve number for 1980 land cover.

Fig. 4. Map of runoff curve number for 1990 land cover.
the case of 190.5 mm of rainfall, which is a 10 year 48-h rain fall for the S-65A sub-basin.

From the histogram of curve numbers generated at an interval of 10 units from 20 to 100, the 1980 land cover shows that, 27% of the sub-basin had CN values between 81 and 90 and 0.9% had CN values of greater than 90. Similarly, for the year 1990, 24% of the sub-basin had CN values between 81 and 90 and only 0.6% of the sub-basin had CN values greater than 90. The 2000 land use data indicates 21% of the sub-basin has CN value between 81 and 90 and about 3% of the sub-basin has CN value of greater than 90. Fig. 3, Fig. 4 and Fig. 5 show the runoff curve number grids for 1980, 1990 and 2000 respectively. Fig. 6 summarized areas of the watershed
falling in the shown curve numbers classes. The spatial distribution of runoff depth calculated from 190.5 mm of rainfall indicated that, 1, 0.7 and 2% of the sub-basin’s land use had runoff depths greater than 180 mm for 1980, 1990 and 2000 land uses respectively. Fig. 7, Fig. 8 and Fig. 9 show the runoff depth grids for 1980, 1990 and 2000 respectively.

4. Conclusions

The results of the study showed that Landsat images were helpful in identifying the runoff response of watersheds regardless of their somewhat varied spatial
resolution. The Landsat programs continuity over decades makes Landsat images useful for tracking land use changes and hence runoff characteristics of watersheds at different times when such studies are critical.

As explained in the results and discussion part of the paper, the water and wetland covered areas are higher in 2000 compared to 1980 and 1990. This is an indication of recovering of the lost wetlands and floodplains as the result of the restoration work. The land use change analysis did not indicate any changes in urban built-ups, which can also alter the runoff response of the watershed by increasing runoff volume, reducing time to peak and increasing peak runoff. This is not the case in S-65A. The change in the runoff response is due to the increase in water and wetland covered areas. These areas are characterized as having high CN values and runoff volume. The spatial distribution of CN and runoff depth reflects the change in the runoff response of the watershed due to change in land use. This shows the shift in the hydrology of the study area.

References


