REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM IN RUNOFF COEFFICIENT ESTIMATION FOR IRRIGATED REGIONS

C. H. Tan\textsuperscript{1}, S. F. Shih\textsuperscript{2}, A. M. Melesse\textsuperscript{2}, J.D. Jordan\textsuperscript{2}, and S. S. Yeh\textsuperscript{3}

Abstract

Fast economic development and population growth has been the major impression in Taiwan for the past twenty years. However, the development has put pressure on the agriculture and overall hydrology of the nation. For example, peak runoff increases significantly in the urbanized area due to the increase of runoff coefficient, which was caused by the over-development of neighboring farmland, the construction of new houses, roads, factories, nursery and plastic-mulched farms. Furthermore, the drainage system has not been upgraded accordingly and, as a result, poor drainage and severe floods have occurred. A runoff and drainage estimation model should be developed. Major parameters in the model should include hourly rainfall (maximum hourly rainfall, daily rainfall, etc.), land use change, soil characteristics, irrigated area, and drainage facilities. The rainfall records in the weather stations can be used to model rainfall parameters at first. Later, real-time information from radar, lightning data and satellite cloud imagery can be used to model more reliable rainfall parameters. Soil characteristics can be derived from existing data. The land use/cover change and actual irrigation area, if based only on traditional gathering and analysis methods, will be time and labor consuming. The use of satellite data and Geographic Information System (GIS) to facilitate the solution of the problem should be studied, evaluated and applied soon.

Remote sensing and GIS are excellent tools for acquiring and managing spatially distributed data. This is mainly due to the fact that a good rainfall-runoff model has to include the spatial and geomorphologic variation in the model. Early studies on remote sensing runoff estimation focused on the estimation of runoff coefficient values from satellite data, and then applied the Rational Formula or Soil Conservation Service (SCS) Curve Number method for runoff estimation.

The developments of satellite and GIS technologies are the steps that the Taiwan government has taken in order to promote high technology and economy. There will be a tremendous benefit in bringing high technology to the Taiwanese people and the agriculture and water resources

\textsuperscript{1} Agricultural Engineering Research Center, Chung-Li, 32043, Taiwan, R.O.C.
\textsuperscript{2} Center for Remote Sensing, University of Florida, Gainesville, FL 32611, U.S.A.
\textsuperscript{3} Tsao-Jin Agric. Memorial Foundation for R & D for Agriculture and Irrigation, Kaohsung, Taiwan, R.O.C.
departments. There is an urgent need to integrate satellite data and GIS technology in estimating runoff for irrigation area in Taiwan. Therefore, the objectives of this study are 1) to assess the runoff coefficient varied with regions that have involved historically different land use changes; 2) to investigate the early drainage design and runoff model and evaluate their current applicability in Taiwan; 3) to study the widely used rational formula method and the USDA Soil Conservation Service Curve Number (SCS-CN) method, and develop parameters applicable for Taiwan’s irrigation field and; 4) to develop a model which integrates remote sensing and GIS for near real-time runoff estimation.

Keywords: remote sensing, GIS, runoff coefficient, rational method, SCS curve number.

1. Introduction

The use of remote sensing and Geographic Information System (GIS) technologies to facilitate the estimation of runoff from watersheds, and particularly agricultural fields, has gained increasing attention in recent years. This is mainly due to the fact that a good rainfall-runoff model has to include geomorphologic parameters, which are spatially variable (Shih, 1996; Melesse and Shih, 2000a, 2000b). Remote sensing and GIS are excellent tools for acquiring and managing spatially distributed data (Lang, 1998; Lillesand and Kiefer, 2000). Studies on remote sensing runoff estimation have focused on the estimation of runoff coefficient values from satellite data, with subsequent application of the Rational Formula or the United States Department of Agriculture Soil Conservation Service Curve Number (SCS-CN) method for computing the runoff. Still and Shih (1984, 1985, 1991) used Landsat satellite imagery 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.

Regions such as Florida and Taiwan are experiencing rapid development and population growth (Reynolds, 2000; Tsai and Hu, 2000), which expand urban land use onto formerly agricultural areas, and agricultural land use onto formerly natural areas, can be expected to experience changes in runoff, drainage, and irrigation, with resulting economic and environmental impacts (exacerbated floods and droughts) and a corresponding need for new runoff estimates in order to plan upgraded water-management facilities. In addition, some agricultural practices involve periodic changes in runoff model inputs such as field drainage and vegetation cover conditions. Conventional ground-based methods of gathering runoff model parameter values are time- and labor-consuming. The purpose of this research is to demonstrate and evaluate the use of satellite imagery for obtaining periodic regional updates of those parameters which are subject to rapid changes, together with GIS for performing analyses of the image, map, and point information, in such developing regions, exemplified by Taiwan and Florida. The application of these advanced technologies to drainage planning and management can then be carried out by the Irrigation Associations of Taiwan.

2. Materials and methods

Many methods for estimating runoff exist (Schwab et al., 1971; Haan et al., 1982; Chow et al.,
1988). But the most widely used are the Rational Formula for peak runoff rate, and the Soil Conservation Service Curve Number (SCS-CN) method for direct runoff volume.

2.1. Rational Formula Method

The Rational Formula for estimating peak runoff rate, introduced in the USA in 1889 (Viessman et al., 1989) has become widely used as a tool for drainage design, particularly for sizing water-conveyance structures. It is an empirically developed model, with simplifying assumptions including uniform rainfall with uniform intensity over the entire watershed for a duration equal to the time of concentration. The Rational Formula is expressed as (Haan et al., 1982)

\[ Q = c \cdot i \cdot A \]

where \( Q \) is the peak runoff rate (ft\(^3\)/s), \( c \) is the runoff coefficient (unitless, ranging from 0 to 1), \( i \) is the rainfall intensity (in./hr), and \( A \) is the watershed area (acres). The coefficient \( c \) is determined from a table, based on land-cover, topography, soil type, condition (management practice), and storm return period. Outputs from the Rational Formula, which must itself be left in English units, can be converted to metric-system equivalents (multiply ft\(^3\)/s by 0.0283 to obtain m\(^3\)/s).

Although originally designed for use on watersheds of \( \leq 2,000 \) acres (809 ha), it has been modified by some users (Jackson et al., 1976; Still and Shih, 1984, 1985, 1991) for application to larger watersheds, principally by land-cover based area weighting of coefficients. This is done using the formula (Chow et al., 1988)

\[ c = \frac{1}{A} \sum_j c_j A_j \]

where \( c_j \) is the runoff coefficient for land-cover type \( j \), and \( A_j \) is the area of land-cover type \( j \), and the other terms are as previously described.

Since the precision of the runoff coefficient value depends on local topography, land-management, and storm pattern conditions, it is desirable, when possible, to develop a locally applicable table. This is accomplished by the formula (Viessman et al., 1989)

\[ c = 7.2(10^{-7})CN^3T^{0.05}[(0.01CN)^{0.6} - (s + 0.2)^{(0.01CN^{1.48})^{0.15 - 0.13}}][(p + 1)/2]^{0.7} \]

where \( CN \) is the SCS curve number, \( T \) is the storm return period (years), \( s \) is the average terrain slope (%), \( i \) is the rainfall intensity (in./hr), and \( p \) is the imperviousness (%).

2.2 SCS Curve Number Method

The SCS-CN method for estimating direct runoff volume has become widely used as a tool for drainage design, particularly for impoundment structures on ungaged watersheds (Haan et al., 1982; USDA-SCS, 1985, 1986). It has three empirically based parts, based on data from a large number of gaged watersheds distributed throughout the United States (Haan et al., 1982). The first part holds that the ratio of the amount of actual retention, \( F \), to maximum potential watershed storage, \( S \), is equal to the ratio of actual direct runoff volume, \( Q \), to the effective rainfall (total rainfall, \( P \), minus initial abstraction, \( I_a \))
\[ F = \frac{Q}{S(P - I_a)} \]  
where \( F = P - I_a - Q \), and all terms are volumes (expressed as mm). The second part holds that

\[ I_a = 0.2S \]  
where \( I_a \) is the portion of the rainfall that will not appear as runoff. Substituting equation (5) into equation (3) and solving for \( Q \) gives the typical expression of the SCS-CN method (Haan et al., 1982; McCuen, 1982):

\[ Q = \frac{(P - 0.2S)^2}{P + 0.8S} \]  
where \( P > I_a \). The third part holds that

\[ S = \frac{25400}{CN} - 254 \]  
where the SCS curve number, \( CN \) (unit-less, ranging from 0 to 100), is determined from a table, based on land-cover, hydrologic soil group (HSG), and antecedent moisture condition (AMC). Land-cover is expressed in the multi-level United States Geological Survey (USGS) land-cover classification system (Anderson et al., 1976). HSG is expressed as four groups, according to the soil’s minimum infiltration rate, which is obtained for a bare soil after prolonged wetting. AMC is expressed as three levels, according to rainfall limits for dormant and growing seasons. Although originally designed for use on watersheds of \( 1,500 \) ha (3,707 acres), it has been modified by some users (Jackson et al., 1976; Rawls et al., 1981; Still and Shih, 1984, 1985, 1991) for application to larger watersheds, principally by land-cover based area-weighting of curve numbers. This is done using the formula:

\[ CN = \frac{1}{A} \sum_j CN_j A_j \]  
where \( CN_j \) is the curve number for land-cover type \( j \), and \( A_j \) is the area of land-cover type \( j \), and the other terms are as previously described.

2.3 Study Areas

This project includes two parts–Florida and Taiwan. Each part includes an analysis of land-cover and runoff changes, performed on a pair of basins. One basin of each pair is essentially static, while the other is undergoing rapid land-cover change.

2.3.1 United States Basins

The east-central portion of the state of Florida, United States of America, has a humid subtropical climate, with 1,321 mm average annual rainfall distributed in a summer wet season from June through September and a winter-spring dry season from October through May (Fernald and Patton, 1984; Schmidt, 1992). The terrain is low-relief, with sandy soils predominating, except in wetland areas where organic soils occur. Natural vegetation consists of a mixture of warm-temperate and subtropical species, forming scrubs, forests, swamps, or marshes depending on soil type and drainage (FDNR, 1990; Bailey, 1995).
The Florida basins studied in this research were located in Putnam and Seminole counties. These counties are encompassed by the Saint Johns River Water Management District (SJRWMD). The SJRWMD is one of the five regional water districts established within the state of Florida, which in cooperation with national water agencies, provide management of water quantity and quality for urban, agricultural, and environmental use (Fernald and Patton, 1984).

2.3.2 Taiwan Basins

Kaohsiung County, Taiwan, Republic of China, has a humid subtropical climate, with 1,679 mm average annual rainfall distributed in a summer wet season from May through September and a winter-spring dry season from October through April (KIA, 1992). The terrain varies from mountainous in the north to low-relief in the south, with about half the area in sandy soils and half in silt or clay soils (KIA, 1992). Natural vegetation consists of warm-temperate and tropical species, forming forests and wetlands depending on soil type and drainage.

Agriculture in Kaohsiung (irrigated area over 18,000 ha) is served by more than 2,181 km of irrigation canals, and more than 667 km of drainage canals (KIA, 1992). Irrigated farmland consists of approximately 11,900 ha of double paddy-rice, 3,300 ha of single paddy-rice, 2,700 ha of sugarcane, and 800 ha of upland crops (KIA, 1992). Irrigation in Kaohsiung is performed by networks of canals and ditches, and is supplied primarily (98%) by surface water, which is obtained primarily from rivers and large reservoirs, with a lesser amount from small reservoirs and groundwater (KIA, 1992; Chen et al., 1997; Tsai and Hu, 2000). Drainage of cropland is by the networks of ditches and canals, which ultimately discharge into rivers or the ocean. Peak water use, an order of magnitude higher than normal use, occurs during the early land-preparation period of rice cultivation (Chen et al., 1997), so that irrigation of a rice farm during this period is performed by field block rotations over several days, in order to lower the overall peak water demand of the farm.

3. Results and discussions

Remote sensing offers a means of frequently gathering land-cover information at various spatial resolutions for wide areas. A major consideration for hydrologic applications is that remote sensing data be of sufficiently fine resolution to handle the level of heterogeneity in a watershed’s land-cover (Rawls et al., 1981; Bondelid et al., 1982). For example, agricultural areas typically contain a few individual buildings surrounded by small-grassed lawns, dirt parking lots, and large cropped fields, so that remote sensing imagery of fine spatial resolution is needed to separate the different surfaces within such areas.

3.1 Image classification

Remote sensing of land-cover is based on the difference between spectral reflectance characteristics of the various land-cover types (Lillesand and Kiefer, 2000). There are obvious
visible-color differences between some land-cover types, for example, between a parking lot and a forest. However, there are subtle shortwave-infrared differences between some land-cover types that would otherwise appear similar in visible-color images, for example, between a healthy crop and a stressed crop, or between forest trees and swamp trees. The conventional method (Lillesand and Kiefer, 2000) for classification of remotely sensed landcover is by the image-processing technique consisting of a combination of statistical multidimensional clustering (supervised, or for more rigor, unsupervised) and a statistical multidimensional maximum-likelihood assignment of each picture element (pixel) of an image to one of the clusters (spectral classes). The spectral wavelength portions (bands) used in this method are the reflectance bands, ranging from ultraviolet to visible colors to shortwave-infrared. Other inputs include ground-based identification (ground-truthing) of a few representative examples of the statistically derived spectral-classes, so that their identities in a standard land-cover system (such as USGS LULC system) can be determined for the whole region, and GIS work can proceed.

3.2 Geographic information system database layers

Data layers within the GIS database of this project are summarized in Table 1. The coordinate system for all data layers in the Florida basins consists of Universal Transverse Mercator (UTM) map projection, zone 17N, with North American Datum of 1983 (NAD83). All data layers for the Taiwan basins are in Transverse Mercator map-projection, with Clarke 1866 ellipsoid. The image processing of the raster layers was done using ERDAS Imagine v.8, while the GIS analysis was performed in ESRI ArcView v.3.2 with Spatial Analyst module. Four different input layers were included in the GIS database of this project. These included Basin Boundaries, Roads, Soil Type (Figure 1), and Digital Elevation Model (Figure 2). Three different output layers were included in the GIS database of this project for the second year. These included Land-Cover (Figure 3), Curve Number (Figure 4), and Runoff Depth (Figure 5).

Each study area/year has a raster layer of land-cover (ERDAS Imagine format), which was derived from image-processing of Landsat images (30 m spatial resolution) to USGS LULC system Level-1 land-cover types, except for the 1995 Florida basins case. The satellite images were processed using an unsupervised technique; the resulting spectral classes were given a Level-1 land-cover identification based on band scatter-diagrams, and then a few specific sites were selected for Global Positioning System (GPS) assisted ground-truthing to obtain more detailed land-cover identifications.

The 1995 Florida basins land-cover was obtained in the form of a vector layer (Arc-Info format, 1:40,000 scale) from the SJRWMD; it was based on SJRWMD interpretation of USGS digital orthophotos. For this research, it was converted into a 30 m gridded raster. Since it used the FLUCCS system, it was converted to USGS LULC system for this research. For the three basins of Etonia, Econlockhatchee, and Niao-Song, the land-cover and HSG layers were used to produce an SCS curve number layer for each studied year. An antecedent moisture condition (AMC) of II (average condition) was assumed. For the three basins of Etonia, Econlockhatchee, and Niao-Song, the SCS curve number layer was used with a Florida design storm (10 year return period, 24 hr duration, 165.1 mm) to produce a runoff depth layer for each studied year. The fine spatial resolution of 30 m should hold most of the spatial variation in surface type that
is relevant to runoff depth.

### Table 1 GIS Data Layers in this study.

<table>
<thead>
<tr>
<th>Data layer</th>
<th>Year</th>
<th>Spatial resolution (m)</th>
<th>Data Type</th>
<th>Etonia</th>
<th>Econ.</th>
</tr>
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<tbody>
<tr>
<td>Boundary</td>
<td>---</td>
<td>N/A</td>
<td>Vector</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Roads</td>
<td>---</td>
<td>N/A</td>
<td>Vector</td>
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<tr>
<td>Soil type¹</td>
<td>---</td>
<td>30</td>
<td>Raster</td>
<td>Yes</td>
<td>No⁵</td>
</tr>
<tr>
<td>DEM²</td>
<td>---</td>
<td>30</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Landcover³</td>
<td>1990</td>
<td>30</td>
<td>Raster</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Landcover³</td>
<td>1995</td>
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<tr>
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<td>30</td>
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<td>Curve Num.¹⁹⁹⁰</td>
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<td>30</td>
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<td>Runoff Depth⁴</td>
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<td>Raster</td>
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<td>No</td>
</tr>
<tr>
<td>Coefficient</td>
<td>1990</td>
<td>30</td>
<td>Raster</td>
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<td>No</td>
</tr>
<tr>
<td>Peak Runoff</td>
<td>1990</td>
<td>30</td>
<td>Raster</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

¹ Expressed as hydrologic soil group (HSG); originally vector, converted to raster.
² Digital elevation model.
³ Expressed as USGS LULC Level-1 (converted for case of 1995 Florida basins). From processing of Landsat images, except for 1995 Florida basins, which were obtained as prepared orthophoto-based GIS layers from SJRWMD.
⁴ For Florida basin design storm of 10 year return period, 24 hr duration, 165.1 mm) and antecedent moisture condition (AMC) of II (average).

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**Fig. 1** Etonia Basin, Hydrologic Soil Groups.
Fig. 2 Etonia Basin, Digital Elevation Model (m).

Fig. 3 Etonia Basin, 2000 Land Cover.
4. Summary

Several image datasets (1990, 1995, 2000) were acquired and processed to USGS LULC Level-1 land-cover, and runoff modeling was performed using an assumption of AMC II and Florida design storm. This was done for the Etonia, Econlockhatchee, and Niao-Song basins. A more detailed land-cover (USGS LULC Level-2, etc.) and remotely-sensed AMC conditions for computing runoff depth, and that peak runoff will be computed using C values tailored for each basin will be studied in the future. Also, a GIS change analysis over the studied years will
be performed to find trends in land-cover and runoff.

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