REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM IN RUNOFF COEFFICIENT ESTIMATION IN CHINA TAIPEI

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ABSTRACT

Emerging technologies of remote sensing and GIS were integrated to estimate runoff for watershed basins in China Taipei and Florida. Two basins were selected in each region, with each pair representing a static and a developing case. Remotely sensed images from the Landsat 4, 5, and 7 satellites were used to develop land cover maps of the study areas for the years 1990, 1995, and 2000. GIS analysis, based on land-cover and soil map data, was used to estimate NRCS-CN curve numbers on a 30-meter grid and to compute runoff depths for a 10-year maximum rainfall event. Runoff coefficients were computed by the Rational method for each year of the study. Temporal changes in spatial distribution of land cover, runoff coefficients, and runoff volume were estimated. A runoff hydrograph, based on the above information and digital elevation model, was developed for a representative watershed in Etonia basin, Florida. The land cover for both the study regions in China Taipei and Florida showed an increase in urban area and a corresponding decrease in agricultural area. A significant increase in modeled runoff volume and peak flow is attributed to this change in land cover. The results of this study indicate a need for planning and designing new control structures to reduce the effect of floods in the developing basins.

1. INTRODUCTION

Accurate estimation of runoff from either rainfall or irrigation is critical for water resource management. In the recent years, the use of remote sensing and Geographic Information System (GIS) technologies in runoff estimation from watersheds, and particularly from agricultural fields, has gained increasing attention. This is primarily because a good runoff model has to include spatially variable geomorphologic parameters such as rainfall, soil characteristics, and land use change (Shih, 1996; Melesse and Shih, 2000a, 2000b). Regions in Florida and China Taipei have been experienced rapid development and population growth over the past twenty years. This development and growth has put pressure on the agriculture and overall hydrology of the regions. Significant changes can be expected in runoff, drainage, and irrigation, with resulting economic and environmental impacts, such as exacerbated floods and droughts. In China Taipei, severe floods have resulted from lack of an upgraded drainage system. Accurate estimation of runoff and drainage are critical to plan upgraded water-management facilities in China Taipei. Typical runoff estimation models require spatially distributed parameters, such as precipitation, land use change, soil characteristics, irrigated area, and drainage facilities. In addition, some agricultural practices involve periodic changes in inputs to the runoff models, such as field drainage and vegetation cover conditions.

Conventional ground-based methods of gathering runoff model parameter values are time and labor-consuming. Integrated use of satellite remote sensing and GIS technologies can provide spatially and temporally distributed input parameters for runoff models. The purpose of this research is to demonstrate and evaluate the use of satellite imagery for obtaining periodic regional updates of these parameters, and the use of GIS for integrating information from different sources, such as field measurements, maps, and satellite imagery in the developing regions. The Irrigation Associations in China Taipei can then carry out the application of these technologies to drainage planning and management.

2. Materials and Methods

Many methods for estimating runoff exist (Haan et al., 1982; Chow et al., 1988). Runoff volume or rate estimation involves estimating the amount of rainfall exceeding infiltration and initial abstractions, which must be satisfied before the occurrence of runoff. Infiltration excess runoff can be estimated using different techniques. The USDA, Natural Resources Conservation Service-Curve Number (NRCS-CN) is a widely used method and combines remotely-sensed land use data and soils information to determine soil's abstraction. The Rational Formula estimates peak runoff rate using remotely-sensed land use data and soils information to determine a runoff coefficient. The coefficient gives the percent of rainfall converted into runoff. Both the NRCS-CN and the Rational Formula are discussed in this study.

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 duration equal to the time of concentration. The Rational Formula is expressed as (Haan et al., 1982)

$$Q = c \cdot i \cdot A \tag{1}$$

where Q is the peak runoff rate (ft3/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 ft3/s by 0.0283 to obtain m3/s).

Although originally designed for use on watersheds of 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)

$$c = \frac{1}{A} \sum_j c_j A_j \tag{2}$$

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)

$$c = 7.2(10^{-7})CN^{3}T^{0.05}[(0.01CN)^{0.6}]^{-(s^{**0.2})}(0.001CN^{1.48})^{(0.15-0.1i)}[(p+1)/2]^{0.7} \tag{3}$$

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, Ia)

$$\frac{F}{S} = \frac{Q}{(P - I_a)} \tag{4}$$

where $F = P - I_a - Q$, and all terms are volumes (expressed as mm). The second part holds that

$$I_a = 0.2S \tag{5}$$

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):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{6}$$

where $P > I_a$. The third part holds that

$$S = \frac{25400}{CN} - 254 \tag{7}$$

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:

$$CN = \frac{1}{A}\sum_{j} CN_j A_j \tag{8}$$

where CNj is the curve number for land-cover type j, and Aj is the area of land-cover type j, and the other terms are as previously described.

2.3 Study Areas

This study includes two parts in Florida and China Taipei. 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. The China Taipei Basin was located in Kaohsiung County, China Taipei, with a humid subtropical climate, 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.

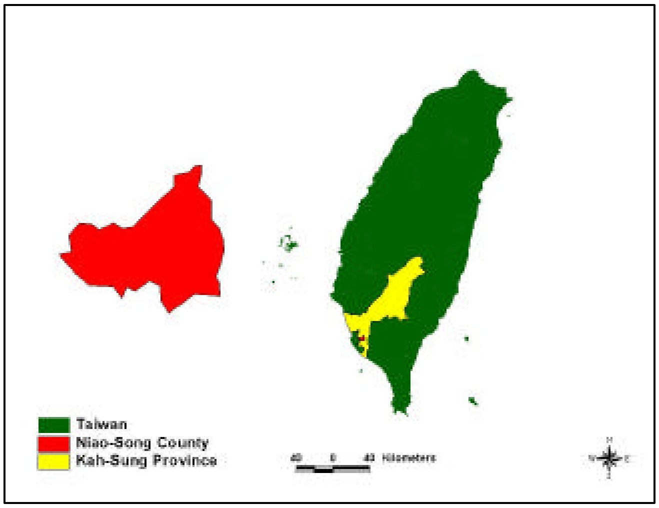

Figure 1. Map of Niao-Song watershed in Kaohsiung area.

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.

2.4 GIS Database

Three types of datasets were used for this study. The first was a set of four input layers that were used as the foundation for the GIS database. These consisted of the basin boundaries, the digital elevation model (DEM), the soil types, and the roads. The second was a set of images from the Landsat satellite. These were obtained to study the land cover and land use changes from 1990 to 2000. The third was field data, which included rainfall, discharge and set of ground truth, or the data collected at the study areas. The ground truth included the detailed land cover data from actual field survey done by members of the Center for Remote Sensing. The GIS data layers used in the study were listed in Table 1.

Table 1. GIS Data Layers in the study.

				Basin			
Data layer	Year	Spatial resolution (m)	Data type	Etonia	Econ.	Mei-Nong	Niao-Song
Boundary	---	N/A	Vector	Yes	Yes	Yes	Yes
Roads	---	N/A	Vector	Yes	Yes	Yes	Yes
Soil type[1]	---	30	Raster	Yes	Yes	Yes	Yes
DEM[2]	---	30	Raster	Yes	Yes	Yes	Yes
Landcover[3]	1990	30	Raster	Yes	Yes	No	Yes
Landcover[3]	1995	30	Raster	Yes	Yes	Yes	Yes
Landcover[3]	2000	30	Raster	Yes	Yes	Yes	Yes
Curve Number	1990	30	Raster	Yes	Yes	No	Yes
Curve Number	1995	30	Raster	Yes	Yes	Yes	Yes
Curve Number	2000	30	Raster	Yes	Yes	Yes	Yes
Runoff Depth[4]	1990	30	Raster	Yes	Yes	No	Yes
Runoff Depth[4]	1995	30	Raster	Yes	Yes	Yes	Yes
Runoff Depth[4]	2000	30	Raster	Yes	Yes	Yes	Yes
Runoff Coefficient	1990	30	Raster	No	No	No	Yes
Runoff Coefficient	1995	30	Raster	No	No	Yes	Yes
Runoff Coefficient	2000	30	Raster	No	No	Yes	Yes

[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).

Similarly for China Taipei basins 135 mm of rainfall was selected to compute the runoff depth.

2.5 Runoff Estimation

The methodology of assessing the spatial and temporal variations of the runoff response of the study areas using spatially distributed NRCS-Runoff CN and rational formula is shown. A DEM-GIS based routing technique of the excess rainfall from each grid cells to the watershed outlet based on the spatially distributed unit hydrograph is presented for Florida basin.

2.5.1 Output Layers

Four GIS layers were used to estimate runoff and generate runoff hydrograph in this project. These included land cover, curve number, runoff depth, and runoff coefficients. Each study area/year had a raster layer of land-cover, which was derived from image processing of Landsat images to USGS LULC system Level-1 land-cover types. For China Taipei basins, land cover maps were obtained from vector GIS layer for year the 1995. 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. A few specific sites were selected for ground truth assisted by Global Positioning System (GPS) to obtain more detailed land-cover identifications. The

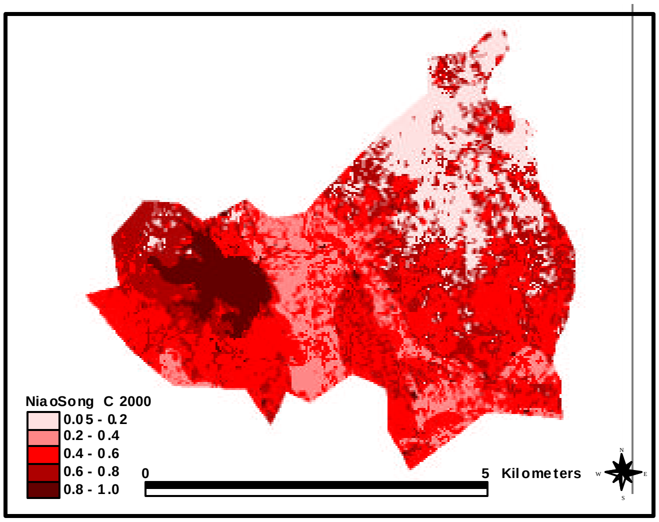

Figure 2. NRCS curve number, C, for Niao-Song area in 2000.

land-cover and HSG layers were used to produce an NRCS curve number layer for each studied year. Figures 2 shows the Niao-Song NRCS curve number in year 2000. Table 2 shows runoff curve number values, modified from Rawls et al. (1980), McCuen (1982), and Still and Shih (1985, 1991), for various land cover and soil type.

Table 2. Curve Numbers for NRCS-CN Method.

HSG[2] →	A			B			C			D		
AMC[3]→ Land-cover	I	II	III	I	II	III	I	II	III	I	II	III
Agricultural land	52	72	86	64	81	91	75	88	94	81	91	96
Rangeland	18	35	55	35	56	75	49	70	84	58	77	89
Forestland	19	36	56	39	60	78	53	73	86	61	79	90
Wetland	100	100	100	100	100	100	100	100	100	100	100	100
Water	100	100	100	100	100	100	100	100	100	100	100	100
Barrenland	58	77	89	72	86	93	81	91	96	87	94	97
Urban	77	89	95	83	92	96	86	94	97	89	95	98

[1] USGS LULC Level-1 (Anderson et al., 1976).

[2] Hydrologic soil group [A = well-drained/high permeability (7.62-11.43 mm/hr infiltration rate), B = well- to moderately-drained/ moderate permeability (3.81-7.62 mm/hr infiltration rate), C = moderately- to poorly-drained/low permeability (1.27-3.81 mm/hr infiltration rate), D = poorly-drained/very low permeability (0-1.27 mm/hr infiltration rate)].

An antecedent moisture condition (AMC) of II (average condition) was assumed. For the two basins of Etonia and Econlockhatchee the NRCS 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 contain most of the spatial variation in surface type that is relevant to runoff depth. The runoff depth for Mei-Nong and Niao-Song basins were estimated using a 24-hour maximum rainfall of 135 mm for the basins.

Runoff coefficients for the Rational Method were determined from soil and land use information for China Taipei basins. Using the weighted average of the runoff coefficients, the peak flows were estimated using the Rational formula for each of the study years. Since runoff hydrographs could not be developed for China Taipei basins due to lack of gage data, the design storm for runoff depth estimation was computed from the average daily rainfall record of Southern China Taipei. For this study, the average 24-hour maximum rainfall for the areas was computed to be 135 mm. To develop spatially distributed unit hydrographs and verify the simulated runoff hydrograph with observed runoff, a part of the Etonia sub-basin was considered. Using three of the rainfall gages, Thiessen polygons were constructed using ArcView to determine the spatial distribution of storm for computation of spatially variable excess rainfall. Grids of rainfall was computed and mapped for selected storm events. Storms were selected based on some practical criterion to improve the estimation of storm hydrograph. There are several methods of determining weighting coefficients in determining the spatial distribution of rainfall. And all of them yield slightly different variations of rainfall patterns across an area. Develop of the runoff hydrograph at the outlet of the watershed involved determining abstractions from land cover, soils, and rainfall information followed by routing the spatially distributed runoff using topographic data.

The cumulative travel time of the storm runoff to the watershed outlet was computed by summing these travel time along the optimum flow path of the respective runoff from each cell following the flow directions. An ArcView script was written to compute the overland and channel flow velocities, cumulative travel time, reclassify the cumulative travel time to 1-hour, and compute the corresponding watershed area drained for each travel time. The time-area curve was drawn from the histograms of the area drained and the corresponding travel time. From the time-area diagram, applying the standard S-hydrograph method (Chow et al.1988), a spatially-distributed unit hydrograph was derived. The standard S-hydrograph method lags the time-area curve by one hour and subtracts the lagged curve from the original curve. The result gives a 1-hour unit hydrograph. This method of lagging assumes the linear response of the watershed is not influenced by previous storms, i.e., hydrographs can be superimposed and offset in time and the flows are directly additive.

3. RESULTS AND DISCUSSIONS

From 1990 to 1995, the urban area and the area covered by rice paddy in Niao-Song increased by 5.5% and 40%, respectively. Water and barren land areas increased by 3.6% and 25%, respectively, while the areas covered by forest and wetlands decreased by 36% and 73.4%, respectively. From 1995 to 2000, urban and agricultural areas in Niao-Song increased by 19.6% and 27%, respectively. Forest, wetland and paddy rice areas have decreased by 25%, 34% and 75%, respectively. From 1995 to 2000, the urban area in Mei-Nong increased by 15%, while areas covered by forest and barren land decreased by 20.4% and 48.5%, respectively. Areas covered by agricultural and rice paddy also increased over that period. From the 1995 land cover data, there was no rice paddy area, whereas in 2000 6.5% of the Mei-Nong area was covered by rice paddy field.

For both study areas in China Taipei, the change in runoff volume and runoff hydrographs are calculated for 1990 and 2000 land use. Spatially distributed runoff coefficients and the weighted runoff coefficients are calculated for China Taipei basins. Figure 3 and 4 shows the runoff volume change and runoff coefficient, respectively in 1990, 1995, and 2000 in the Niao-Song area.

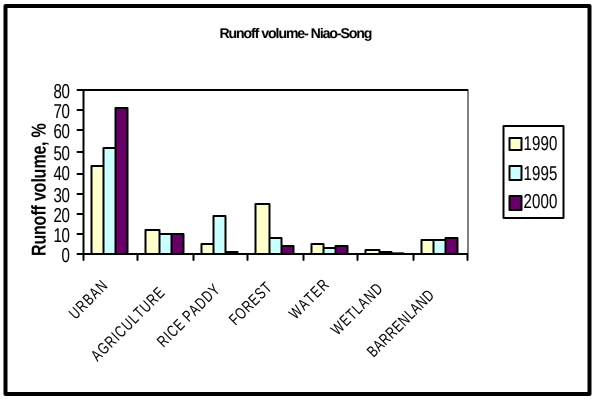

Figure 3. Comparison of runoff volume change in 1990, 1995 and 2000 in the Niao-Song area.

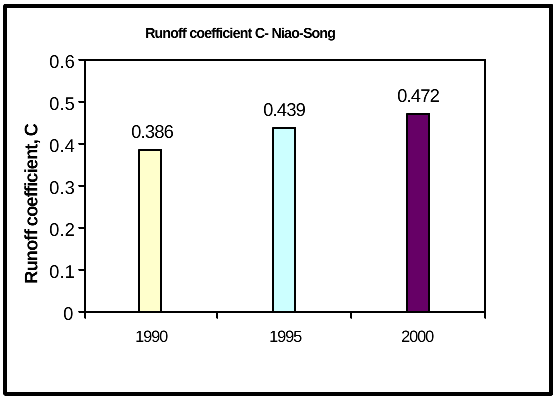

Figure 4. Comparison of runoff coefficient in 1990, 1995 and 2000 in the Niao-Song area.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The land use in China Taipei basins have shown an increase in urban area and reduction in agricultural area over the study period. Due to this change in land use, the runoff coefficient from the Rational Method increased for both Niao-Song and Mei-Nong basins during the 10-year study period. The trend for both basins suggests that there will be a further increase in urban developed area and a decrease in agricultural area, which will increase impervious surface, runoff volume, and peak discharge. This trend will likely be more pronounced for Niao-Song than for Mei-Nong. This will result in a need for planning and design of the new control structures to reduce the effect of floods.

4.2 Recommendations

Since the study areas considered in this research are relatively small in size and land use changes are so dynamic, images with better spatial and temporal resolution are recommended. Finer resolution data will significantly improve the classification accuracy, especially an agricultural diverse region as China Taipei. However, cost and other restrictions are factors in its feasibility, especially for 1-4 m resolution satellite from private-sector and for airborne data. Radar imagery from airborne and/or satellite sources should also be investigated as possible sources of all-weather land-cover data. The NRCS-CN method, developed in the United States can predict runoff fairly well in China Taipei, but the relation I = 0.2S was developed based on gauged watersheds in United States. Any attempt to improve the method should consider re-calibration to determine the appropriate relationship. This will be a substantial project involving national and local water agencies.

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