# MODELING RUNOFF RESPONSE TO LAND COVER AND RAINFALL SPATIAL VARIABILITY IN SEMI-ARID WATERSHEDS

MARIANO HERNANDEZ[1], SCOTT N. MILLER[1], DAVID C. GOODRICH[1], BRUCE F. GOFF[1], WILLIAM G. KEPNER[2], CURTIS M. EDMONDS[2] and K. BRUCE JONES[2]

*[1]U.S.Department of Agriculture–Agricultural Research Service, Southwest Watershed Research Center, 2000 East Allen Rd., Tucson, Arizona 85719 USA; [2]U.S. Environmental Protection Agency, National Exposure Research Laboratory, P.O. Box 93478, Las Vegas, NV 89193 USA*

**Abstract.** Hydrologic response is an integrated indicator of watershed condition, and significant changes in land cover may affect the overall health and function of a watershed. This paper describes a procedure for evaluating the effects of land cover change and rainfall spatial variability on watershed response. Two hydrologic models were applied on a small semi-arid watershed; one model is event-based with a one-minute time step (KINEROS), and the second is a continuous model with a daily time step (SWAT). The inputs to the models were derived from Geographic Information System (GIS) theme layers of USGS digital elevation models, the State Soil Geographic Database (STATSGO) and the Landsat-based North American Landscape Characterization classification (NALC) in conjunction with available literature and look up tables. Rainfall data from a network of 10 raingauges and historical stream flow data were used to calibrate runoff depth using the continuous hydrologic model from 1966 to 1974. No calibration was carried out for the event-based model, in which six storms from the same period were used in the calculation of runoff depth and peak runoff. The assumption on which much of this study is based is that land cover change and rainfall spatial variability affect the rainfall-runoff relationships on the watershed. To validate this assumption, simulations were carried out wherein the entire watershed was transformed from the 1972 NALC land cover, which consisted of a mixture of desertscrub and grassland, to a single uniform land cover type such as riparian, forest, oak woodland, mesquite woodland, desertscrub, grassland, urban, agriculture, and barren. This study demonstrates the feasibility of using widely available data sets for parameterizing hydrologic simulation models. The simulation results show that both models were able to characterize the runoff response of the watershed due to changes of land cover.

**Keywords:** watershed modeling simulation, surface water hydrology, GIS

## 1. Introduction

A governing principle of land management is that changes in land cover result in commensurate changes in watershed condition and hydrologic response. Rainfall-runoff relationships within a watershed are the result of the interplay of many factors, but are driven primarily by the interaction of climate, land cover, and soils. Watershed response in the form of runoff depth and peak discharge can therefore be used as indicators of condition and as predictors for the ramifications associated with land cover change.

A large proportion of the western United States is classified as arid or semi-arid. These regions are characterized by larger relative extremes in compo-

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nents of the hydrologic cycle than in the humid climates, including: 1) low annual precipitation but high-intensity storms with significant spatial variability, 2) high potential evaporation, 3) low annual runoff but short-term high volume runoff, and 4) runoff losses in ephemeral channels (Branson et al. 1981). Furthermore, these regions are especially prone to erosion. Hydrologic models must therefore adequately account for these factors if they are to be used to assess the impacts of landscape change on hydrologic response in the western United States.

Surface runoff, or overland flow, occurs when the soil is no longer capable of absorbing rainwater, nor removing it via the processes of transpiration, infiltration, and sub-surface runoff. Overland flow depends on the simultaneous action of a multitude of factors which can be classified into two groups: 1) abiotic factors: relief and geomorphological characteristics, parent rock and soil composition, and climate (primarily the intensity and amount of rainfall), and 2) biotic factors: vegetative cover of the slope, land use, anthropogenic factors, etc. Vegetation cover represents one of the most powerful factors influencing the runoff regime, since it modifies and moderates many others. Annual and storm discharge are very important indicators of the runoff regime in a watershed, necessary in research and projects aiming at reclamation, water supply, hydropower, etc.

It should be noted that methods for transforming various land cover and land use characteristics into distributed hydrologic model parameters are not well developed for a wide range of conditions. For management purposes, many approaches rely largely on empirical studies of small plots and watersheds to relate land cover and land use to hydrologic model parameters. The curve number method (USDA-SCS 1972) is an example of this type of approach to relate land cover and land use to hydrologic model parameters.

The purpose of this paper is to assess the effects of land cover and rainfall spatial variability on runoff response based on a ten class land cover system derived from Landsat imagery (the North American Landscape Characterization, or NALC) (USGS 1999) and two raingauge network configurations. The Soil Water Assessment Tool (SWAT) (Arnold et al. 1994) and the KINematic runoff and EROSion (KINEROS) (Smith et al. 1995) models were run on a small subwatershed (Watershed 11) of the Walnut Gulch Experimental Watershed (WGEW) operated by the United States Department of Agriculture, Agricultural Research Service, Southwest Watershed Research Center. In the evaluation of watershed response, emphasis is placed on the procedure for transforming various land cover patterns into distributed hydrologic model parameters and the subsequent relative effects of the 10 NALC land cover classes on runoff depth and peak discharge. The land cover classification includes a broad range of cover types ranging from forest to urban conditions. The effects of raingauge network density are addressed by considering two raingauge network configurations representing spatially distributed and uniform rainfall.

## 2. Description of the Study Area and Data Sources

The Walnut Gulch Experimental Watershed encompasses approximately 150 km$^2$. It is located in southeastern Arizona, USA (Figure 1) surrounding the historical town of Tombstone. Walnut Gulch is a tributary of the San Pedro River, which originates in Sonora, Mexico and flows north into the United States as part of the Lower Colorado River Basin. A dense network of 88 raingauges distributed across the watershed provides long-term climatological information necessary for hydrologic research. Ten of these gauges are used to estimate rainfall across Watershed 11. Mean annual precipitation is approximately 324 mm, and the average annual temperature in Tombstone is 17.6°C.

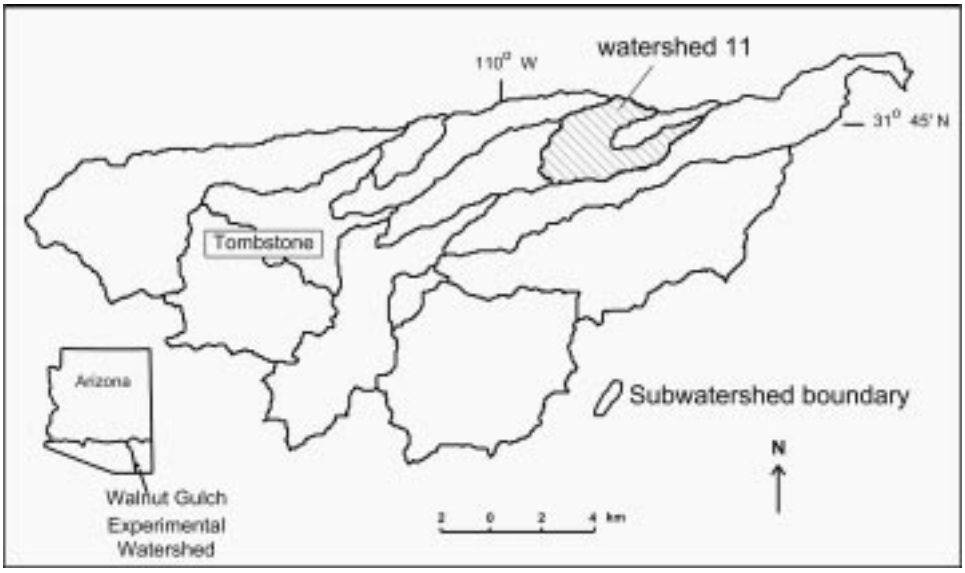


***Figure 1.*** *Location of the Walnut Gulch Experiment Watershed showing nested Watershed 11.*

Watershed 11, located below the steep slopes of the Dragoon Mountains, encompasses approximately 8.23 km$^2$, of which approximately 2 km$^2$ rarely contributes runoff due to the presence of a retention pond (Figure 1). Breckenfield et al. (1995) found that five soils are located within the watershed. These soils are primarily deep very gravelly sandy loams. The eastern portion of the watershed is characterized as grassland composed of sideoats grama, black grama, and blue threeawn with scattered mesquite, while the western portion is desertscrub dominated by whitethorn, creaosotebush, and tarbush.

The NALC dataset was provided by the U.S. EPA National Exposure Research Laboratory (Table I). The NALC project is a component of the NASA Landsat Pathfinder program to study global change issues (USGS 1999), whose main objective is to produce standardized remote sensing data sets that consist of three or more registered Landsat Multi-Spectral Scanner (MSS) images corresponding to the 1990s, 1980s, and 1970s. On average, a NALC data set consists of one scene from the 1990s and 1980s and two from the 1970s.

**Table I**
Land Cover Classification

| Cover Class Number | Cover Class Name | Cover Class Number | Cover Class Name |
|---|---|---|---|
| 1 | Forest | 6 | Riparian |
| 2 | Oak Woodland | 7 | Agriculture |
| 3 | Mesquite Woodland | 8 | Urban |
| 4 | Grassland | 9 | Water |
| 5 | Desertscrub | 10 | Barren |

The soil data used in runoff modeling were obtained from the STATSGO (USDA-NRCS, 1994) database. The STATSGO database was designed primarily for regional, multi-state, river basin, multi-county resource planning, management, and monitoring. In general, STATSGO data are compiled by generalizing more detailed soil survey maps. Where more detailed soil survey maps are not available, data on geology, topography, vegetation, and climate are assembled in association with Landsat images.

Some differences between ground-based observations and the GIS data used in this analysis are apparent. Soils within the watershed are characterized by STATSGO as AZ061, a complex composed of a very gravelly loam (60%), a gravelly fine sandy loam (25%), and a very fine sandy loam (15%). Vegetation is classified in the 1972 NALC scene as grassland (54%) and desertscrub (46%).

Rainfall data were extracted for Watershed 11 from the SWRC long-term rainfall database. Daily rainfall depths from 1966 to 1974 were collected for input to SWAT and time-depth pairs for 6 events during the same time period were prepared as input to KINEROS. The selection of the number of events and time period of simulation is somewhat arbitrary, since the purpose of this study is to demonstrate the relative impact of land use change, rather than to optimize the model behavior based on efficiency. The selection of the storm events was carried out showing a range in volume, intensity, and duration. To assess the effects of the spatial variability of rainfall and the resolution of raingauge network density on runoff response, two network configurations were considered. One configuration

consisted of 10 raingauges located within and around the watershed, enabling the characterization of the spatial variability of rainfall. The second configuration consisted only of raingauge 88, resulting in uniform rainfall across the watershed (Figure 2). Hernandez et al. (1997) conducted a study, based on information theory, depicting the watershed response to different raingauges network density configurations. They showed that for one raingauge configuration, raingauge 88 captures the maximum information for Watershed 11.

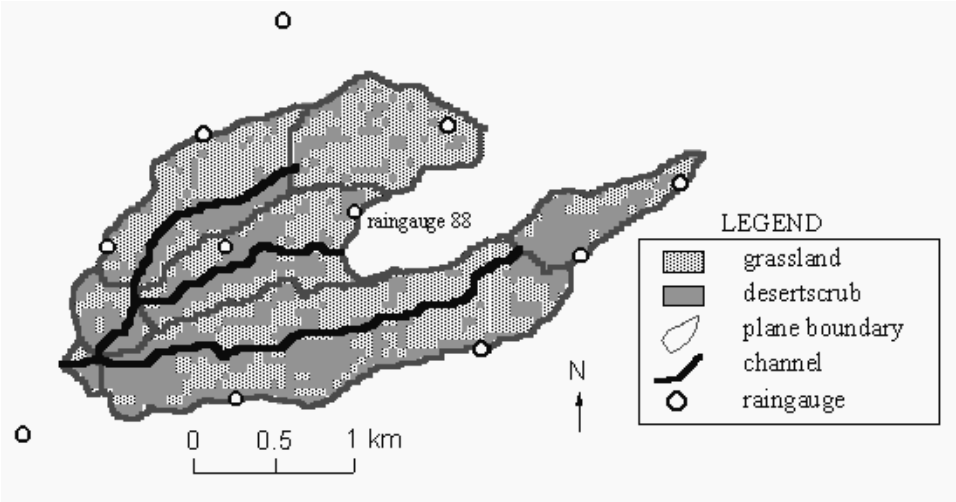


***Figure 2****.Configuration of Watershed 11 used to parameterize SWAT and KINEROS. Note that there are 17 elements; 2 upland, 10 lateral, and 5 channel elements. The 10 raingauges used to distribute rainfall are overlain with special emphasis placed on gauge 88, which was used to simulate uniform rainfall. The uppermost section of the watershed is excluded because it drains to a retention pond that did not yield runoff during the simulation period.*

## 3. Methods of Analysis

The study was carried out in three steps. First, the models were parameterized according to GIS data and runoff simulated for the selected time period and rainfall events. Second, the hydrologic model efficiency was assessed for both models by comparing simulated and observed average annual runoff depth for the continuous model and average storm runoff depth and peak runoff rate for the event-based model. Third, in order to test the assumption that land cover change will affect watershed rainfall-runoff response, further simulations were performed wherein the entire Watershed 11 was transformed from the 1972 NALC classification mixture of Desertscrub and Grassland to a uniform land cover of each of the NALC cover classes in Table I except water.

### 3.1 HYDROLOGIC SIMULATION MODELS

KINEROS is a distributed, event-oriented, physically based model that describes the processes of surface runoff and erosion from small watersheds. The watershed surface and channel network are represented by a cascade of planes and channels described by a set of unique parameters, initial conditions, and precipitation inputs (Smith et al. 1995). As an event-based model, it does not account for evapotranspiration and soil water movement between storms. Initial conditions for soil moisture were determined using a multi-layer water balance and analysis of the rainfall record at each of the gauges in the days leading up modeled events (Goodrich 1990). Canopy cover was assumed to be constant and was determined using published estimates found in scientific literature.

SWAT was developed to predict the effects of alternative management practices on water, sediment, and chemical yields from ungauged rural basins (Arnold et al. 1994). The model can simulate a basin subdivided into grid cells or subwatersheds. Operating on a daily time step and efficient enough to simulate many years, it is intended as a long term yield model and is not capable of detailed, single-event flood routing. The subbasin components can be placed into eight major divisions – hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management.

### 3.2 MODEL PARAMETERIZATION

The watershed characterization tool TOPAZ (Garbrecht and Martz 1995) was used to delineate the hydrologic elements within Watershed 11. TOPAZ uses an algorithm to determine direction and accumulation of flow. The user specifies the smallest allowable upland area, and the watershed is automatically subdivided into upland and lateral planes and channels (Figure 2). The minimum allowable area in this exercise was 50 ha, which resulted in the watershed being subdivided into 12 planar elements and 5 channels.

The parameters that have the strongest influence on runoff from a land cover perspective for KINEROS are saturated hydraulic conductivity, canopy cover, and Manning's roughness coefficient (n), while for SWAT the Curve Number (CN) is the most important. The procedures for determining the hydrologic parameter values for each model are described as follows.

#### 3.2.1 *Saturated Hydraulic Conductivity*

Saturated hydraulic conductivity (Ks) is of particular relevance to rainfall-runoff modeling in semi-arid regions and is the most critical parameter for accurately simulating runoff using KINEROS. Rawls et al. (1982) developed a technique for estimating Ks from soil texture; a look-up table based on this work is contained in the KINEROS documentation (Woolhiser et al. 1990). Soil texture was determined from the STATSGO database, and an area-weighted estimate of Ks was derived from the KINEROS look-up tables for the watershed. This initial estimate

was reduced by half to account for entrapped air following Bouwer (1966), and further reduced to account for the decrease in pore space caused by the presence of rocks by Ks*(1-volumetric rock content) (Woolhiser et al. 1990). Finally, this reduced Ks value was adjusted for the effects of vegetation by a power function suggested by Stone et al. (1992): $Ksf = Ks * e^{(0.015*\text{percent canopy cover})}$. This power function relates vegetation cover and runoff by increasing infiltration with increasing vegetal cover. The input parameters used in KINEROS for each of the land cover classes are presented in Table II. Stream channel sediment, while not discriminated in the STATSGO GIS coverage, was assumed to be well-sorted sand, and the value for Ks was estimated from published scientific literature (Woolhiser et al. 1990). KINEROS accounts for the small scale spatial variability of infiltration through an estimate of the coefficient of variation for Ks with the assumption that Ks is lognormally distributed. Estimates of these coefficients were taken from Jury (1985).

**Table II**
Estimated parameter values based on land classification for application of KINEROS.

| Land Cover | Parameter | Canopy Cover | Ks | Manning n |
|---|---|---|---|---|
| | Units: | Percent | mm/hr | |
| | Source: | Expert opinion | KINEROS table | KINEROS table |
| Forest | | 30 | 13.10 | 0.07 |
| Oak, mesquite woodlands | | 20 | 11.27 | 0.04 |
| Grasslands | | 25 | 12.15 | 0.05 |
| Desertscrub | | 10 | 9.70 | 0.055 |
| Riparian | | 70 | 23.86 | 0.06 |
| Agriculture | | 50 | 17.68 | 0.04 |
| Urban | | 0 | 8.35 | 0.01 |
| Barren | | 0 | 8.35 | 0.035 |
| NALC 1972 Classification | | 22–28 | 10.03–11.47 | 0.050–0.058 |

### 3.2.2 *Canopy Interception*

During a rainfall event on vegetated surfaces, some portion of the rainfall will be retained on the vegetation by tension forces. This portion of the rainfall does not contribute to infiltration or runoff, therefore, an interception depth should be subtracted from the rainfall before infiltration or runoff are performed. In KINEROS, a total depth of interception may be specified for each runoff element, based on the

vegetation or other surface condition. This amount is taken from the earliest rainfall pulses until the potential interception depth is filled. The modified rainfall pulse data then becomes input to the soil surface. While interception is highly variable both among species and for a given species throughout the year, general estimates for interception by vegetation are given by Woolhiser et al. (1990) as a function of canopy cover that were used to derive interception estimates for the various land cover classes based on cover estimated from expert opinion (Fox 1999). In SWAT, the canopy interception is implicitly accounted for in the retention parameter of the curve number method (USDA-SCS 1972).

### 3.2.3 *Manning's Roughness Coefficient*

Manning's roughness coefficient (*n*) is a principle factor in the determination of runoff velocity and, consequently, infiltrated depth. KINEROS uses Manning's equation in the determination of coefficients for solving the kinematic wave equations for routing water across planar elements and channels. A survey of published literature was used to determine estimated values for Manning's n based on the land cover classification. Where multiple land covers characterized a given subwatershed element, a weighted n value was used.

### 3.2.4 *Curve Number*

The major factors that determine the CN are hydrologic soil group, hydrologic condition, cover type, treatment, and antecedent runoff condition. The hydrologic group classification was determined from the STATSGO soil description, in which soils in Watershed 11 are classified as hydrologic soil group B. The hydrologic condition, which indicates the effect of cover type and treatment on infiltration and runoff, was selected according to the USDA-SCS (1986) procedures. The appropriate CN for Watershed 11, assuming fair cover conditions, was calculated by referring to Table II 2d of the same source. Since Grassland is given a CN of 71 and Desertscrub a CN of 80, the area-weighted CN is calculated as: CN = 54%*(71) + 46%*(80) = 75.1. Curve Number values were selected for the 10 land cover classes assuming uniform land cover conditions for the entire Watershed 11. Table III shows the CN values for each class cover.

**Table III**
Estimated CN values based on NALC land classification for application of SWAT.

| Cover Class Name | Curve Number (CN) | Cover Class Name | Curve Number (CN) |
|---|---|---|---|
| Forest | 64 | Riparian | 70 |
| Oak Woodland | 66 | Agriculture | 72 |
| Mesquite Woodland | 68 | Urban | 92 |
| Grassland | 71 | Barren | 95 |
| Desertscrub | 80 | NALC 1972 Classification | 75.1 |

## 4. Results and Discussion

The results of the simulation for each model are presented and discussed as follows. In general, for both models, simulation results showed a wide range of watershed response due to the varying cover classes and rainfall distribution.

### 4.1 KINEROS

Runoff depth (per watershed area) was simulated with reasonable accuracy using KINEROS for six runoff events. Figure 3(a) shows the results of using distributed and uniform rainfall to simulate runoff. Regression relationships were derived between the observed and simulated values to demonstrate the goodness of fit of the results. Note that the use of a single rain gauge for estimation of rainfall resulted in a greater range in predicted values and an overall reduction in model efficiency, expressed as the coefficient of determination from linear regression. The use of 10 raingauges improved model efficiency from 0.60 to 0.90. In general, the model under-predicted runoff for small events and over-predicted runoff for larger storms. The application of a uniform rainfall across the watershed resulted in over-prediction of runoff for five of the six storms.

Similar trends in model results were found for the prediction of peak runoff with KINEROS, although the overall efficiency of prediction was significantly

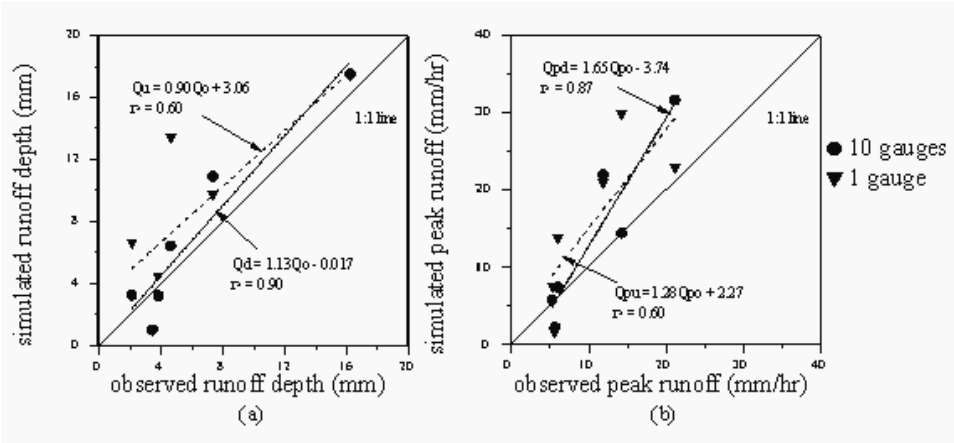


***Figure 3.*** *Simulation results for six runoff events on Watershed 11 with linear regression models between simulated and observed values superimposed for (a) total runoff depth, and (b) peak runoff rate, where Qo=observed runoff depth, Qd=simulated runoff depth with distributed rainfall, Qu=simulated runoff depth with uniform rainfall, Qpu=simulated peak runoff rate with uniform rainfall. Simulations were performed using distributed (10 gauges) and uniform (1 gauge) rainfall; solid lines represent regressions for distributed rainfall; dashed lines for uniform rainfall.*

poorer for peak runoff than for runoff depth. Using a single gauge resulted in a lower correlation between simulated and observed values with the uniform rainfall yielding a greater range in the estimated values (Figure 3b). Regression relationships illustrate this point, with the coefficient of determination dropping from 0.87 for the case of distributed rainfall to 0.60 for uniform rainfall. Overall, peak discharge was over-estimated. This is a source of concern for the future application of this model in the prediction of sediment discharge since erosion in alluvial channels is largely a function of runoff velocity.

Simulation results for transformed land cover of Watershed 11 from mixed desertscrub and grassland to a uniform cover of each of the NALC cover categories showed that the procedures for estimating model parameters are sensitive to land cover. In general, the trends in model results were as expected; increasing vegetation cover resulted in decreased runoff. The mechanisms responsible for this inverse relationship were canopy cover, which affects interception depth and infiltration (Ks) and roughness, expressed by Manning's n value, which inhibits overland flow and increases infiltration and storage. Figure 4 shows the model results for each land cover simulation. The range in runoff depth was from 8.21 mm (riparian) to 22.9 mm (urban), a range of 180%. Peak discharge followed the same trend; the minimum peak runoff rate was 16.3 mm/hr (riparian), and the maximum rate was 43.8 mm/hr (urban), a range of 170%. Further research into the impact of

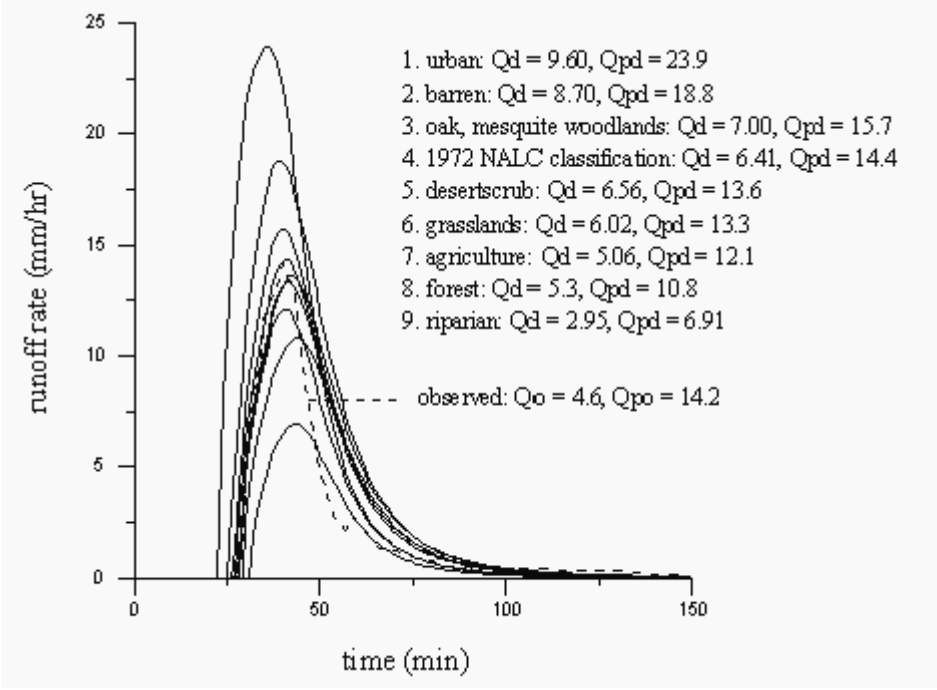


***Figure 4.*** *Runoff hydrographs for simulated land cover change for storm occurring August 5, 1968. Rankings indicate hierarchy of magnitude of peak flow.*

small-scale land cover transformations is necessary to investigate the impact of incremental land cover change on hydrologic response, but these data illustrate the sensitivity of KINEROS prediction to land cover.

Results from KINEROS simulations using parameters derived from STATSGO and NALC GIS data combined with expert opinion and commonly available look-up tables are encouraging. No adjustments were made to the hydrologic parameters to minimize the difference between simulated and observed values. However, given that Goodrich (1990) and Syed (1999) demonstrated that KINEROS can be successfully calibrated to predict runoff depth and peak discharge with a high model efficiency, future research into modification of parameter estimation procedures will likely improve the model's predictive ability given the input data sources.

## 4.2 SWAT

SWAT model simulation results showed a wide range of watershed response due to variation of cover classes. Note that land cover affects only one parameter in SWAT (the CN), as opposed to 3 parameters as is the case with KINEROS. The CN was varied within SWAT and the difference between simulated and observed minimized to demonstrate the effects of using a value for the CN from readily available look-up tables and an optimized value. Runoff calibration was carried out using distributed rainfall for the period 1966 to 1974 with an initial CN value of 75.1. The CN value was then adjusted to optimize the correspondence between observed and simulated annual runoff volume, resulting in an optimal CN value of 83. Figure 5 shows results obtained from uncalibrated and calibrated simulation runs. Runoff depths calculated using the initial CN value of 75.1 and distributed

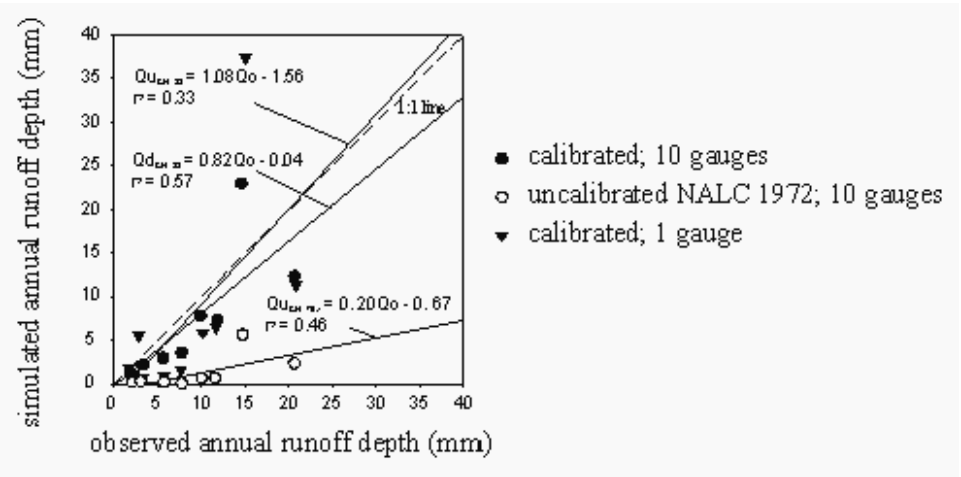


***Figure 5**. Simulation results of annual runoff depth for the period 1966 to 1974 using SWAT. Simulations were carried out using distributed (10 gauges) and uniform (1 gauge) rainfall.*

rainfall were related to observed values with a $r^2$ of 0.46. Calibrated average annual runoff depths simulated using distributed rainfall were related to observed values with an $r^2$ of 0.57. Runoff depths simulated using uniform rainfall and optimized CN were related to observed values with a $r^2$ of 0.33. Note that by adjusting the CN from 75.1 to 83, the model efficiency improved by 11%. A 24% improvement is achieved in simulated annual runoff depth if accounting for the spatial variability of rainfall. Based on 91measured runoff events, the mean annual runoff depth for the 9-year period was 8.74 mm. The simulated mean annual runoff depth for uniform and distributed rainfall were 5.50 mm and 4.72 mm, respectively.

Figure 6 illustrates simulated average annual runoff depth for the period 1966 to 1974 resulting from transforming land cover of Watershed 11 from mixed Desertscrub and Grassland to each of the 10 NALC cover classification using 10 raingauges. Model results were as expected; increasing vegetation cover resulted in decreased runoff. The range in runoff depth was from 0.07 mm (Forest) to 59.71 mm (Barren). Results from the SWAT simulations show that the model can characterize the relative effects of different land cover conditions. However, if the SWAT model is to be used for quantitatively evaluating the effects of land cover change on watershed response, it is necessary to adjust the CN parameter to improve model efficiency.

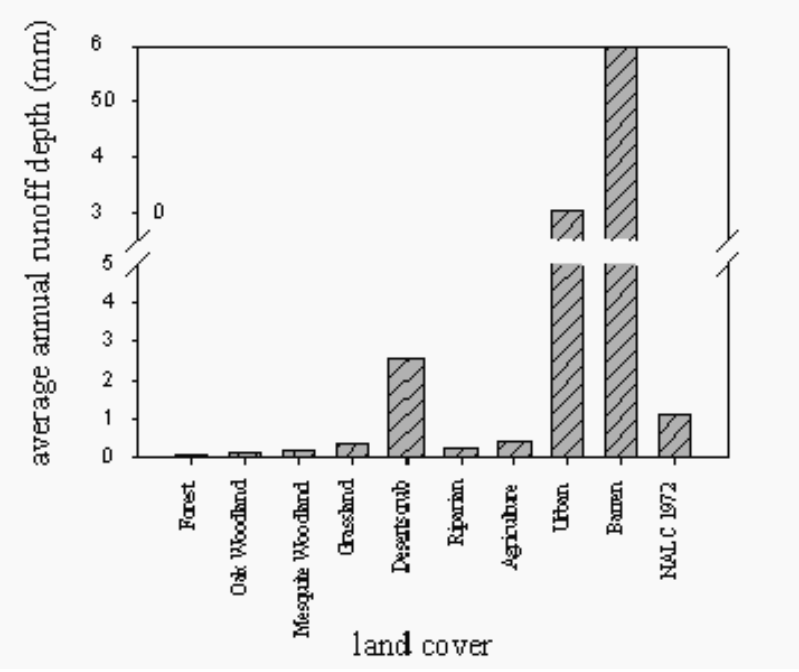


***Figure 6.*** *Average annual runoff depth for simulated land cover change for the period 1966–1974.*

## 5. Conclusions

This study demonstrates the feasibility of using existing data sets for parameterizing hydrologic simulation models. USGS digital elevation models, the STATSGO soil database and the 1972 NALC land cover classification were used as primary inputs for parameterizing the KINEROS and SWAT models. It was found that land cover classes could successfully be used to generate model inputs to assess the impact of land cover change on watershed response. However, it is important to recognize that large variations on the response of the watershed can be expected due to the variability in acceptable of hydrologic parameter values such as the curve number or saturated hydraulic conductivity. Results from the KINEROS model were obtained without conducting any optimization on the hydrologic parameters. Therefore, a higher model efficiency can be expected if an optimization procedure is implemented. In the SWAT model, results suggest that calibration is required to improve model efficiency in simulating runoff depth. In regions without dense raingauge networks, the lack of distributed rainfall data will likely be a limiting factor in model performance. However, this does not limit the use of these models to assess relative impacts resulting from land cover change using design rainfall for input after verification of the methodology on data-rich watersheds. This study illustrates the potential for using commonly available data sets in the assessment of hydrologic response to land cover change.

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