Simulation of a Costa Rican Watershed: Resolution Effects and Fractals

By Jeffrey D. Colby[1]

Abstract: Simulation of runoff from the Navarro watershed in Costa Rica was undertaken using the U.S. Geological Survey's Precipitation Runoff Modeling System, developed and operated within the Modular Modeling System. A geographic information system (GIS) database of watershed characteristics, and GIS-based methodology for delineating modeling response units (MRU) were utilized to enhance the spatial representation of watershed features and physical processes. Simulations were carried out using a series of MRU resolutions (from 90 m^2 to 1,260 m^2) in order to determine the range through which the hydrologic response could be accurately modeled. Fractal characterization provided a method to measure the relationship of the MRU patterns (based primarily on land cover) at the different resolutions. The range of self-similarity of the MRU patterns, as determined by fractal characterization, was compared to the range of resolutions through which accurate hydrologic simulations were achieved. The results from this research revealed a strong correspondence between the two ranges, and indicate that a range of data resolutions may be useful in representing tropical watershed characteristics for hydrologic modeling and watershed management.

INTRODUCTION

The spatial representation of watershed characteristics and parameters has been a limiting factor in the development of distributed hydrologic modeling (Huggins and Monke 1968; Freeze and Harlan 1969; Beven 1985; Loague and Freeze 1985; Klemes 1986; Anderson and Rogers 1987; Beven 1989). The integration of hydrologic modeling and geographic information systems (GIS) has provided a mechanism to explore the spatial representation of watershed characteristics (Maidment 1993; Steyaert 1993; Singh and Fiorentino 1996). Within hydrology, the scales over which model components are valid is an important issue (Van Genuchten 1991; Burlando et al. 1996), and a better understanding of the scaling of dynamic behavior was called for in the Eagleson Report (James 1995). This issue has application in the characterization and management of watersheds (NRC 1999), as the search for scale independent, unifying hydrologic principles continues (Goodrich and Woolhiser 1991; Sposito 1998). For example, Wood (1998) and Wood et al. (1988) found that a fundamental or representative elemental area existed at approximately 1 km^2. The behavior of subcatchments below this size was fundamentally different from the behavior of those above it.

The importance of accurate spatial representation of land cover data in hydrologic modeling and watershed management is underscored by Gersmehl et al. (1987a), who found that more than half of the total runoff in a small watershed can be produced by land cover classes that occupy only 10% of the area. Determining whether an optimum scale or range of scales exists to represent land cover patterns is an important consideration in accurately representing the spatial pattern of hydrologic behavior, and in managing watersheds.

Few studies have specifically analyzed the effect that the resolution of land cover data has on the hydrologic modeling response using a GIS. This question was partially addressed by Berry and Sailor (1987), in a study that found that basin disaggregation resulted in increased volume and peak discharge predictions. Using the Soil Conservation Service's TR-55 hydrologic model, Fellows and Ragan (1986) reported that runoff volume was relatively insensitive to increases in soil and land cover cell size.

Brown (1990) linked the ANSWERS hydrologic model with a GIS and found that the timing and amount of runoff in a North Carolina watershed were not significantly affected by aggregation of land cover data at the resolutions of three common remote sensing systems (TM, MSS, and AVHRR). Erosion and soil loss were found to be sensitive to land cover resolution. As the resolution of the land cover data became coarser, rare cover types were lost, and the topological relationships of the cover types were altered. This alteration in topological relationships of the cover types was given as the explanation for the different erosion and sediment yield results.

Using the raster-based CASC2D hydrologic model, Molnar and Julien (2000) tested grid cells ranging from 127 m to 914 m to simulate rainfall-runoff processes. Through application of the model to two watersheds in Mississippi (21 km^2, 560 km^2), the authors found that coarse grid cell sizes could be used to simulate rainfall-runoff in large watersheds.

Frankoski (1994) applied the Precipitation Runoff Modeling System (PRMS) in the Gunnison River Basin in Colorado. The author compared model results from modeling response units (MRU) delineated (from elevation contours, slope, and aspect) at three scales, 3 arc^{-1} (72 × 92 m), 15 arc^{-1} (360 × 460 m), and 30 arc^{-1} (720 × 920 m). The author found that when working with the entire watershed (1,372.7 km^2), the spatial resolution of the data had no notable effect on the model results. However, when 20-km sample areas were utilized, spatial resolution of the MRUs did have an effect.

In the present research, the U.S. Geological Survey's PRMS (Leavesley et al. 1983) was developed and operated within the Modular Modeling System (MMS) (Leavesley et al. 1996a,b) to simulate the hydrologic response of the Navarro watershed in Costa Rica. To enhance this modeling effort, a GIS database of watershed characteristics was utilized (Colby 1996) along with a method for delineating MRUs (Colby 1995). MRUs are units of a watershed partitioned on the basis of characteristics such as vegetation type, precipitation distribution, slope, aspect, and soil type.

An analysis was undertaken regarding the effects that a series of spatial resolutions of MRUs have on the accuracy of simulating hydrologic response. Specifically, the analysis attempted to first determine whether a range of spatial resolutions existed at which a satisfactory hydrologic response could be simulated. One method for measuring the similarity of MRU patterns at different resolutions is fractal characterization. The fractal characters of the MRU patterns were then

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calculated for the series of resolutions. Of particular interest was the question of whether the range through which satisfactory hydrologic simulations were achieved corresponded with the range of self-similarity of MRU patterns.

One of the principal questions addressed is whether critical thresholds exist beyond which dramatic changes occur in MRU characterization and in hydrologic simulation. This determination will contribute to an understanding of the nature of integrated units, such as MRUs, how their patterns (in this research, based primarily on land cover) change with resolution, and the effect of these changes on hydrologic behavior. Knowledge of the range of spatial resolutions, which can be used to simulate the hydrologic response in this watershed, can provide information to better understand the scaling of hydrologic model components, particularly in the tropics. Practical benefits for watershed management include information to guide the selection of data resolution for characterizing similar watersheds, which may also enable the conservation of human and computer resources in regard to data acquisition, processing, storage, and analysis.

Whether a range of self-similarity (according to fractal characterization) exists for MRU patterns at a series of resolutions was investigated. If a relationship can be determined to exist between the range of self-similarity and the range of resolutions at which an acceptable hydrologic response was achieved, then an initial step will be provided in establishing a linkage between fractal characterization and the optimum scales at which to represent watershed characteristics. This could lead, for example, to the application of fractal analysis in determining the most appropriate scales of data for hydrologic simulations, variable scale model parameterization, and watershed management.

ISSUES OF SCALE

The application of landscape units to the study of physical processes raises many theoretical issues of scale. For example, how does spatial scale affect the assessment of features such as land cover? Does an optimum scale or range of scales exist for representing natural or human influenced features? Do scale thresholds exist beyond which the character of the data changes? If so, how do they change? Are there critical thresholds in the spatial patterns of physical processes (Turner 1990)? One of the most difficult problems in environmental research remains the extrapolation of results across broad spatial scales (Quattrochi et al. 1997).

In addition, issues of scale provide difficult practical problems to the analysis of spatial data. For example, how are the choices of scale for feature representation in a GIS database usually made? It may be reasonable to assume that the resolution sought is the highest that can be acquired, or can be handled within available computer hardware or software limitations. Ideally, the choice of scale is that which best represents the critical features for the analysis at hand. However, the resolution of data layers may often be determined by availability and computational demands (Hodgson et al. 1995), rather than appropriateness, in part, because the appropriate level of resolution may not be known.

Fractals, as introduced by Mandelbrot (1982), have two primary characteristics. They retain the quality of self-similarity, which describes the manner in which variations in features are repeated at different scales. And, they have a fractal character or dimension, which can be used to describe the level of variation at each scale, and can be measured using a single parameter, the fractal dimension D (Burrough 1987). According to Goodchild and Mark (1987, pp. 267, 275), "the numerical value of D may be the most important single parameter of an irregular cartographic feature, "..." with application in the prediction of the effects of generalization and scale change."

A variety of spatial phenomena have indicated statistical self-similarity only over certain ranges of scales (Cao and Lam 1997). However, this can be used to advantage to summarize scale changes and to relate or separate variations at different scales, which could be the result of natural processes (Lam and Quattrochi 1992). In the field of Geographic Information Science (GIScience), the study of resolution and scale has become an important research direction (Lam and Quattrochi 1992; Steyaert 1993; Quattrochi and Goodchild 1997).

STUDY AREA

The Navarro watershed is an important watershed in Costa Rica in regard to water resources. The watershed is approximately 279 km^2 in size and is located at the headwaters of the Reventazón River basin (Fig. 1), which may be the most important drainage unit in the country in regard to hydropower potential (Quesada 1979). High sediment loads and streamflow variability affect the nearby Cachí reservoir (Quesada 1979; Jansson and Rodriguez 1992) and planned hydroelectric projects. Due to rich volcanic soils, the watershed is also a significant producer of agricultural products for the country (Cortés and Onconitrillo 1987).

The watershed is also of interest due to its increasing population and susceptibility to natural hazards. The city of Cartago is located in the watershed and is part of the Gran Area Metropolitana (GAM). The GAM is the primary population center of the country, and affects of increasing population growth raises important environmental issues (Monzón 1993). The watershed is susceptible to numerous natural hazards, including volcanic eruptions and debris flows (Waldron 1967; Alvarado and Schmincke 1993), landslides (Mora et al. 1985; Alvarado and Boschini 1988), floods (Solís et al. 1991; Baltodano and Hidalgo 1992), and seismic activity. Deforestation has also caused flooding in the watershed (Quesada 1979).

The watershed is located in the tropics, whereas most of the modeling efforts utilizing PRMS have been undertaken in more developed temperate regions. The application of GIScience technologies (e.g., GIS and remote sensing) to hydrologic modeling and water resources management is also less prevalent in tropical developing regions. Specific water resources management concerns in the Navarro watershed in-

FIG. 1. Upper Watersheds of the Reventazon River Basin (Reprinted by Permission, *International Journal of Remote Sensing*)

clude the management of surface and subsurface water, particularly for hydroelectric power and water supply.

Hydrologic research efforts at various scales have been undertaken in this region of Costa Rica. For example, Mojica (1972) attempted to predict daily streamflow in the Reventazón River basin using a multivariate statistical model and to analyze the validity of streamflow models to represent land use effects. According to Mojica (1972), the effects of increases in streamflow due to deforestation were best observed in the Navarro watershed, as compared to other upper and middle watersheds of the Reventazón River basin.

For the upper watersheds of the Reventazón River basin, Quesada (1979) developed a methodology to assess the effects of sedimentation and the deviations in monthly streamflow on hydroelectric power generation. Studying the Cachí reservoir, he found that significant changes in hydropower can occur with changes in land use. Also, in the upper Reventazón River basin, Sanchez-Azofeifa and Harriss (1994) integrated Landsat TM satellite and digital elevation data to study the relationship between land cover and topography. The authors were able to define areas of high erosion on steep slopes related to agricultural activities.

The objectives of Elizondo (1979) were to provide a preliminary evaluation of the hydrologic resources and the general hydrogeologic conditions of the Navarro watershed. Hydrologic simulation was undertaken using an annual lumped water balance, utilizing the components of precipitation, runoff (surface and subsurface), and actual evapotranspiration. Conclusions from this study include the possible existence of two aquifers in the central section of the watershed—one superficial aquifer located in alluvial materials, and the other found in deeper volcanic materials.

A hydrologic and hydraulic study was undertaken by Solís et al. (1991) for determining the maximum potential flood and design of flood control works along the Purires River, which drains a subbasin of the Navarro watershed. The authors applied the Hydrologic Engineering Center (HEC)-1 and HEC-2 models for selected storm events to the Purires subbasin and used the Navarro watershed for calibration. The conclusions of this study underscored the importance of gathering accurate land cover information.

The only published report to focus specifically on modeling runoff of the Navarro watershed utilized a water balance equation and did not include a spatial representation of watershed characteristics (Elizondo 1979). In the present study, a representation of the spatial characteristics of the Navarro watershed in the hydrologic simulation of daily flows was undertaken. Parameterization and application of the PRMS provided a useful tool for hydrologic analysis as well as an aid to the management of the watershed.

GIS DATABASE PREPROCESSING AND DEVELOPMENT

Three types of data were utilized to develop GIS layers for the delineation of MRUs—elevation, remotely sensed digital satellite data, and precipitation. The primary elevation data used were the National Imagery and Mapping Agency's digital terrain elevation data (DTED) data. DTED data are distributed in 1° by 1° or smaller cells, with a 16-bit range of elevation values. Two cells of DTED level 1 data were utilized in this study. The boundaries of these cells extended from 9° North to 10° North and from −83° West to −85° West. The DTED data were provided in a 3 arc second format and a geographic coordinate system (i.e., latitude/longitude). The original resolution of these data between 9° north and 10° north latitude was approximately 92 m^2. Conversion of the DTED data from geographic coordinates to planar coordinates was undertaken using a Lambert Conformal Conic projection, and the data were resampled to 90 m^2 using a bilinear interpolation (Colby and Keating 1998). Physical characterization of the Navarro watershed using the DTED data including drainage network and watershed delineation processing was carried out using a GIS, based on algorithms introduced by Jenson and Domingue (1988; Colby 1996).

A digital Landsat TM satellite image from 1986 was classified to provide land cover characterization. Black and white aerial photographs for the north-central part of the watershed (1989) at a scale of 1:20,000 and for the southern section of the watershed (1992) at a scale of 1:60,000 were obtained from the Instituto Geographico Nacional (IGN). Also, 1:10,000 scale land use maps (field checked in 1989) were obtained for the central part of the watershed from IGN. The aerial photographs and land use maps provided reference information for classification of the TM image. The TM image was rectified using a Lambert Conformal Conic projection and resampled to 90 m^2 to match the resolution of the DTED data. Colby and Keating (1998) described the preprocessing (including a reduction in anisotropic reflectance) of the satellite imagery and land cover classification for the watershed.

To derive an image of the spatial distribution of precipitation across the watershed, a number of trend surface analyses were undertaken using a GIS, and mean annual rainfall figures from 7 to 22 stations were calculated from complete years of data for the 20 year period between 1967 and 1986 (IMN 1988). The range of annual precipitation recorded at stations used in this study was nearly 2,000 mm per year. A second-order trend surface with an R^2 value of 91.35% was created using 14 stations.

MRU DELINEATION

The fundamental theoretical basis used for delineation of the MRUs was to balance the trade-off between minimizing the internal unit variance and maximizing the external unit variance (Band et al. 1991). The variables considered for developing MRUs according to Leavesley et al. (1983) include "... the number of physical characteristics used in the partitioning scheme, the number and location of precipitation gauges available, and the problem to be addressed by the model." Use of the fewest number of watershed characteristic data layers with the greatest information content was sought for delineating MRUs.

Using the elevation, Landsat TM, and precipitation data, the following four GIS data layers were derived for use in the MRU delineation process: (1) subbasins; (2) a distance buffer from the channels; (3) precipitation distribution; and (4) land cover. A subbasin data layer was selected for the MRU delineation process to restrain the location of MRUs to one physically defined area of the watershed to avoid problems associated with parameterizing MRUs scattered throughout the watershed. Seven subbasins were derived using the elevation data and the same algorithms with which the watershed was delineated, and were based on management issues or research related criteria (Colby 1995).

A distance buffer from the channel layer was included to enhance the spatial representation of MRUs within the watershed. The inclusion of this layer was based in part on the variable source area concept (Troendle 1985). The concept is appropriate in humid regions where infiltration is not a limiting factor (Dunne and Leopold 1978). The soils in the Navarro watershed are generally well drained and very permeable. The hillsides along channels are steep and border narrow valley floors. Potential practical applications of a distance layer include parameterizing MRUs using subsurface flow coefficients that could be adjusted according to subsurface reservoir locations within the distance categories. For example, it may be expected that subsurface reservoirs located farther from channels contribute a greater volume to ground-water flow than to surface runoff. Two distances from the channel categories were calculated in a GIS based on a 630 m buffer.

The second-order trend surface described above was aggregated to the following three categories for the MRU delineation process: 1,274–1,786 mm, 1,787–2,569 mm, and 2,570–3,152 mm per year. It was believed that these three categories represented significant differences in the spatial distribution of precipitation in the watershed. For example, a rain shadow attributed to Volcan Irazú located to the north was represented, as well as the heavier distribution of rainfall found in the southern section of the watershed.

After data preprocessing, the following 12 land cover subclassifications were chosen for identification from a 1986 Landsat TM satellite image, based on two classification schemes (Anderson et al. 1972; Campbell et al. 1980), personal site visits, and spectral differences:

1. Bare areas 1—wet soil, agricultural fields
2. Bare areas 2—exposed rock, stripmines, or quarries
3. Grass 1—predominantly dry grass
4. Grass 2—lush-growing, green grass
5. Grass 3—dry grass with brush component, charall
6. Coffee
7. Crops
8. Brush
9. Forest
10. Urban
11. Residential
12. Invernadernos (greenhouses covered with a finely woven polyethylene screen)

These 12 subcategories were then collapsed or grouped into the five more general hydrologic classifications used by PRMS for hydrologic simulation—bare areas, grass, shrubs, forests, and impervious areas (Colby and Keating 1998).

A GIS-based overlay method for MRU delineation was developed. Using this process, 114 MRUs were created, which needed to be reduced to a number manageable for parameterization. After the editing of smaller MRUs that fell below a minimum threshold (i.e., 0.5% of the watershed area or approximately 140 ha) through a process of merging them into larger MRUs based on common characteristics and adjacency, 52 MRUs remained for parameterization. The final pattern of MRUs was primarily influenced by the land cover pattern, due to the fact that land cover was the final layer integrated in the MRU delineation process and it had the finest spatial resolution of the combined layers.

RUNOFF SIMULATION

The PRMS is a modular system designed to evaluate impacts of climate and land use on surface runoff, sediment yields, and general basin hydrology (Leavesley et al. 1983). The total system response of the watershed is conceptualized as the combined output from a series of reservoirs. The MMS is a UNIX-based integrated computer software system, which provides an operational framework for the development of algorithms and their application toward modeling physical processes (Leavesley et al. 1996a,b). Selected modules from the library are graphically coupled to create a model suitable for a desired application.

Time Series Data

Three types of daily time series data were utilized in this study—precipitation, minimum and maximum temperature, and pan evaporation. Precipitation data from six rainfall stations were used to derive the spatial distribution of rainfall in the watershed for input to the hydrologic model (Table 1), and were chosen based on location and completeness of their record. There were no missing precipitation values for the time periods modeled, May 1986 through April 1989.

TABLE 1. Precipitation Stations Used in Hydrologic Analysis

Station	Mean annual precipitation (mm) 1985–89	Mean annual precipitation (mm) 1967–1986
Belen	3,040.9	3,264
Concavas	1,550	—[a]
El Llano	3,014.98	3,080
La Cangreja	1,815.42	1,762
Linda Vista	1,262.04	1,477
Sanatorio Duran	1,297.66	1,611

[a]Not available.

To represent precipitation across the watershed, three steps were carried out—the creation of Thiessen polygons, and the derivation of two correction factors per MRU (one spatial and one temporal). For the allocation of precipitation, each MRU is linked with one precipitation station. A method for determining this linkage is the application of Thiessen polygons. Thiessen polygons were created in this study based on the location of the six precipitation stations using a GIS.

The amount of precipitation falling on an MRU may vary significantly from that falling at the precipitation station to which it is linked. Therefore, two correction factors were combined to improve the representation of precipitation at each MRU. First, a spatial correction was undertaken. A mean precipitation value for each MRU was calculated from the second-order trend surface, using a GIS overlay combining the trend surface and MRU data layers. This value was divided by the average annual precipitation for the station to which the MRU was linked, for the same 20-year time period from which the trend surface was derived. This ratio represented the relationship between the average annual precipitation of an MRU and the average annual precipitation received at the station to which it was linked. A temporal correction was also applied based on the annual values from the five-year time period, 1985–89. An overall correction factor (range = 0.71–1.57, mean = 1.05) was applied to the precipitation allocated to each MRU.

The Linda Vista site provided a record of daily temperature data for the time period of interest. It was necessary to estimate approximately 3% of the total number of temperature values used for the time period modeled. These missing values were replaced with the corresponding mean monthly value. Minimum and maximum temperature lapse rates were calculated using data from the Linda Vista and Volcan Irazú stations, located at 1,401 m and 3,402 m elevations, respectively. The lapse rates were calculated for 1984, because it represented the closest full year of data available to the time period modeled.

Daily pan evaporation data were available from the Cachí station. This station is located approximately 7 km to the east and downstream of the La Troya streamflow gauge. Two correction factors were combined to modify the pan evaporation data. The first factor (0.94) was derived using a relationship between evaporation at the Linda Vista and Cachí stations from monthly values for four years (1989–92). An additional estimated pan evaporation coefficient (0.85) was combined with the first factor for a final (0.799) correction factor.

Parameterization

MRU Parameters

The PRMS parameterization process was undertaken within the MMS utilizing spreadsheets. In addition to daily precipitation, temperature, and evaporation values, a number of physical characteristics for each MRU were derived directly from GIS data layers

1. Area in acres
2. Mean elevation
3. Slope
4. Aspect in degrees from north
5. Impervious area
6. Land use/cover type; bare, grasses, shrubs, and trees

Data for hydrologic modeling in the present study were collected in metric units, and then converted into English units for use in the PRMS model. Hydrologic modeling results are reported in English units in this paper.

Percent impervious and land cover areas were determined from the original 12-category land cover image (Colby and Keating 1998). Urban areas and invernadernos were considered 100% impervious, and residential areas were estimated as 50% impervious. An impervious figure per MRU was then calculated using these figures. Additional vegetation parameters such as summer and winter vegetation cover density and interception storage capacity were estimated.

Soil parameters were calculated or estimated using a variety of sources (Colby 1995). The maximum available water holding capacity of the soil profile was derived using water holding capacity figures and the average rooting depth of the soil. Water holding capacity was determined according to reports, maps (soils, geology, and geomorphology), and advice from Costa Rican soil scientists. The majority of vegetation types in the watershed may have roots no deeper than 30 cm (Dr. Alfredo Alvarado, personal communication, November, 1993). Parker (1985) found, under rainforest hillslopes in Costa Rica, that the majority of roots were 30 cm or shallower, and 80% of the cumulative root biomass was located within the first 40 cm of soil. Additional parameters and coefficients were estimated or obtained from initial model runs, and adjusted during calibration if necessary. Calibration did not require a significant amount of adjustment of the parameters and coefficients.

Subsurface Parameters

PRMS includes representation of both a subsurface reservoir and a separate ground-water reservoir. Each MRU is linked to one subsurface reservoir. Two subsurface reservoirs were designated in this study, one each for the subbasins providing streamflow to the Agua Caliente and Navarro Rivers. Additional subsurface reservoirs could be designated according to the distance from the channel categories.

Ground-Water Parameters

Three ground-water parameters, initial ground-water storage, a ground-water to stream routing coefficient, and a ground-water sink coefficient, were estimated for two ground-water reservoirs in the watershed. One reservoir each was utilized for the subbasins drained by the Agua Caliente and Navarro Rivers. Initial ground-water storage was estimated from initial model runs. A ground-water to stream routing coefficient was estimated from recession curves from initial model runs and was adjusted during calibration. The ground-water sink coefficient is multiplied by the ground-water reservoir storage to compute seepage from ground water to a ground-water sink. Elizondo (1979) estimated the reservoir storage as 206×10^6 m^3/year.

Calibration and Validation

Time Periods

The water year in Costa Rica runs from May through April. Three years of data, from May 1986 through April 1989, were utilized for calibration, validation, and simulation. The wettest year in this series, 1988–89, was used for calibration. The next most divergent flow pattern was found in the driest water year of 1986–87, and was used for validation. The wettest period during the water year was sought for modeling in order to include sufficient events to represent all of the physical processes, and to calibrate key parameters. Therefore, the time period from August through January was simulated for each year.

Calibration

The first group of parameters focused upon in the calibration process were those involving volume, or water balance, and the second involved the timing of flows (James and Burgess 1982). Optimization of the hydrographs was not undertaken. It was felt that further mathematical modification of the predicted values could have obscured the effects of MRU patterns at various resolutions on the hydrologic response.

Four methods were utilized to evaluate hydrologic simulation accuracy. A visual assessment was made between observed and predicted runoff, annual flow volume agreement, monthly average flow volume agreement, and the quantitative assessment of the hydrograph fit using the Nash-Sutcliffe coefficient (Nash and Sutcliffe 1970; Garrick et al. 1978). A "least-squares" fitting criterion was proposed by Nash and Sutcliffe (1970; Garrick et al. 1978), wherein

$$F_1^2 = \sum (q - q')^2 \tag{1}$$

where q = series of actual discharges; and q' = corresponding discharges computed by the model, and

$$F_0^2 = \sum (q - \bar{q})^2 \tag{2}$$

where $\bar{q}$ = mean of the observed discharges. The correlation coefficient R^2 is then calculated as

$$R^2 = (F_0^2 - F_1^2)/F_0^2 \tag{3}$$

Criticism of this coefficient was based on the grounds that poor models could produce high values (80 or 90%), and the best models may not produce impressively higher values (Garrick et al. 1978). A correlation of efficiency (or, as termed in this study, the Nash-Sutcliffe coefficient) can be calculated to address this objection

$$ntd = 1 - F_1^2/F_0^2 \tag{4}$$

The observed and predicted flow hydrographs were produced following iterative calibration runs. The hydrographs displayed a reasonable fit between the timing of peak flows. The percent error in seasonal and average monthly flow volumes was close to 10%, the desired value for volume calibration (James and Burgess 1982).

Validation

Validation of the model was undertaken using data from the water year 1986–87. An improvement in the overall fit was obtained for this drier year, which is reflected in the percent error in flow volume comparisons and the Nash-Sutcliffe coefficient (Table 2).

Simulation

The water year 1987–88 had the second highest flows of the three years, and was used for simulation. As found for the validation period, flow volumes were higher than observed values (Table 2). The Nash-Sutcliffe coefficient of 0.8 is higher than that calculated for the calibration period. However, the percent error in flow volumes is also higher than that calculated for the calibration period. Assessment of the predicted

TABLE 2. Simulation Evaluation Parameters

Time periods	*tot-fl* (in.)[a]	*ms-fl* (in.)	*err pct*	*pred* (cfs)	*obs* (cfs)	*err pct*	*ntd*
Calibration August 1988–January 1989	34.7	39.1	−11.25	545.74	616.04	−11.41	0.73
Validation August 1986–January 1987	15.0	14.1	6.38	235.81	221.79	6.32	0.86
Simulation August 1987–January 1988	21.9	19.1	14.66	342.51	299.75	14.26	0.80
Simulation September 1987–January 1988	16.4	15.2	7.90	308.22	287.44	7.23	0.82

[a]Units are English, as used by PRMS.

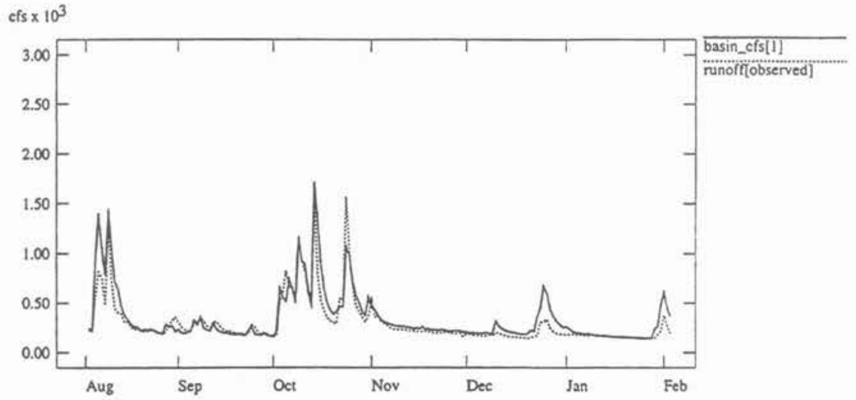

FIG. 2. Comparison of Observed and Predicted Flow for August through January 1987–88

versus observed hydrograph suggested that a ground-water recharge phenomenon occurring at the end of the dry season in August may still be occurring during the early part of the simulation period (Fig. 2). An additional simulation was run, excluding the month of August, and the percent error in seasonal and averaged monthly flows was almost halved (Table 2). The month of August was included in succeeding simulations, as its inclusion was thought to be more representative of the actual conditions in the watershed.

The parameterization of the PRMS within the MMS provided a more detailed spatial representation of the hydrologic character of the Navarro watershed than those found in previously published studies. In addition, a reasonable fit between observed and predicted flows was obtained, sufficient to support further hydrologic analysis.

LAND COVER RESOLUTION AND FRACTAL CHARACTERIZATION

Aggregation Process

For this research, a nearest neighbor resampling method was chosen to undertake the aggregation process. In resampling to a different resolution, the nearest neighbor method assigns a new grid cell value according to the value of the closest grid cell in the original layer (Lillesand and Kiefer 1994). This method is not mathematically complex, and is appropriate for categorical data, as it retains the original values of the thematic data layer.

A series of resolutions were utilized to assess the effects of spatial resolution on the hydrologic response. The MRUs were first delineated at a resolution of 90 m^2 (90 m × 90 m). This 90 m^2 layer was then resampled using the nearest neighbor method to the following sequential resolutions: 180 m^2; 270 m^2; 360 m^2; 450 m^2; 540 m^2; 630 m^2; 720 m^2; 810 m^2; 900 m^2; 990 m^2; 1,080 m^2; 1,170 m^2; and 1,260 m^2. This series of resolutions was thought to provide an adequate set of intervals through which significant changes in the hydrologic response, and a range of self-similarity could be detected.

TABLE 3. MRUs Omitted through Merging during Resampling

Resolution (m^2)	Number of MRUs	MRUs omitted
810	1	87
900	1	92
990	1	3
1,080	3	30, 49, 99
1,170	5	6, 29, 57, 93, 109
1,260	6	27, 28, 47, 57, 93, 102

After aggregation, the area of each MRU was calculated for each resolution. This area measurement was then entered into a separate parameter file in PRMS for each resolution. The area value was the only parameter that was changed for each resolution; however, this did affect the areal representation of other parameters. Additionally, beginning at 810 m, MRUs were lost through merging in the resampling process (Table 3).

Simulation

Simulations were undertaken for the series of resolutions, using data from August 1987 through January 1988, and the results can be found in Table 4. Examination of the table reveals a similar percent error range for seasonal and average monthly flows for resolutions from 90 m through 900 m. At the 810 m resolution, the Nash-Sutcliffe coefficient is at its highest (the same as for 360 m), and begins to drop at the 900 m resolution.

The lowest percent error for the measurement of total flow was obtained using 450 m resolution data, and the lowest percent error for the measurement of monthly average flow was obtained using 810 m resolution data. The highest errors from both flow measurements were obtained at the 990 m and 1,260 m resolutions. The lowest Nash-Sutcliffe coefficients were also found at these resolutions. Graphs of the monthly average flow and Nash-Sutcliffe coefficients are found in Figs. 3 and 4. Between the 90 m and 810 m resolutions, the pattern of the

TABLE 4. Simulation Measurements

Resolution (m^2)	Total Flow Predicted (in.)	Total Flow Measured (in.)	Total Flow Error (%)	Mean Monthly Flow Predicted (cfs)	Mean Monthly Flow Measured (cfs)	Mean Monthly Flow Error (%)	*ntd* coefficient
90	21.8	19.1	14.14	342.51	299.75	14.26	0.799
180	21.8	19.1	14.14	341.45	299.75	13.91	0.800
270	21.8	19.1	14.14	342.21	299.75	14.16	0.800
360	21.7	19.2	13.02	338.98	299.75	13.09	0.804
450	21.6	19.2	12.50	338.44	299.75	12.91	0.799
540	21.6	19.1	13.09	339.14	299.75	13.14	0.800
630	22.0	19.0	15.79	345.96	299.75	15.42	0.797
720	21.8	19.0	14.74	343.96	299.75	14.75	0.797
810	21.9	19.4	12.89	337.46	299.75	12.58	0.804
900	21.8	19.1	14.14	343.18	299.75	14.49	0.793
990	23.9	19.3	23.83	370.40	299.75	23.57	0.752
1,080	23.1	19.1	20.94	363.06	299.75	21.12	0.768
1,170	23.6	19.4	21.65	365.46	299.75	21.92	0.772
1,260	23.3	18.7	24.60	372.80	299.75	24.37	0.758

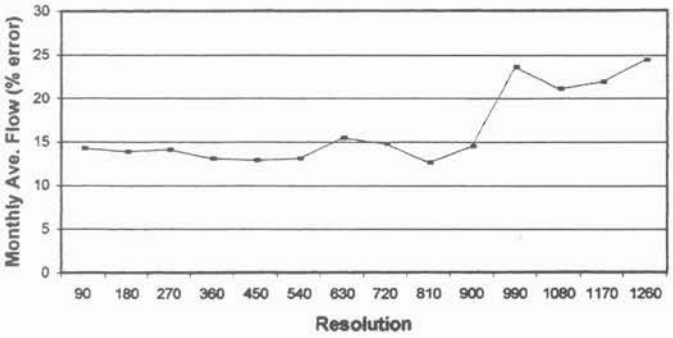

FIG. 3. Percent Error of Monthly Average Flow Measurements

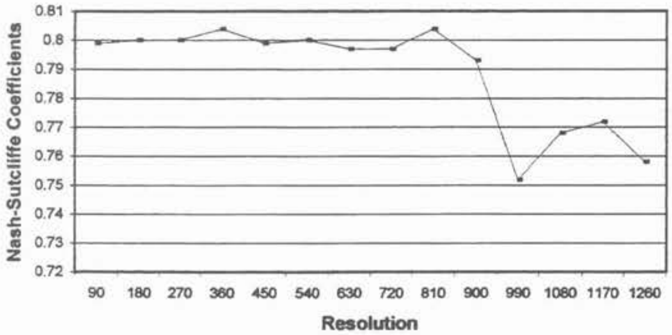

FIG. 4. Nash-Sutcliffe Coefficients

monthly average flow error measurements generally coincides with the pattern of the Nash-Sutcliffe coefficients.

Fractal Characterization

Extrapolating environmental processes across spatial scales is a difficult problem. Fractals may provide a robust method for investigating these linkages. Self-similarity is the property underlying fractals. The property of self-similarity exists, if the basic shape of a figure remains similar through aggregation to coarser resolutions (Laurini and Thompson 1992). The fractal dimension D can be used to test for self-similarity (i.e., with a constant D value at all scales). Most real-world phenomena are not pure fractals, however, as D varies across a range of scales (Lam and Quattrochi 1992). Additionally, as mentioned above, "a wide variety of spatial phenomena have been shown to be statistically self-similar over only certain ranges of scales" (Cao and Lam 1997, p. 67). Identifying the range of scales over which spatial phenomena are self-similar can be applied toward separating scales of variation due to natural processes (Lam and Quattrochi 1992).

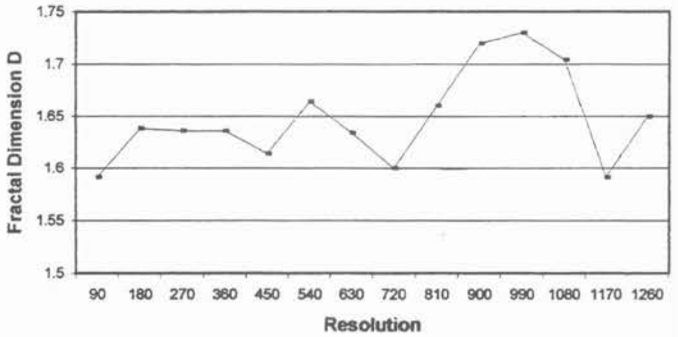

FIG. 5. Fractal Dimension D Values

In the present research, fractal characterization of the MRU patterns at sequential resolutions was investigated to attempt to identify the range through which an accurate hydrologic response could be simulated. Fractal characterization of the MRU patterns was undertaken using an area-perimeter relationship (Burrough 1987)

$$A = kP^{2/D} \tag{5}$$

where A = estimated area; P = estimated perimeter; and k = constant.

To solve for D or the fractal dimension, log A was plotted against log $P/4$, and D equals twice the slope of the regression line. Dividing the perimeter by 4 is a method applied to grid cell data (Turner 1990).

The fractal dimension was calculated for the MRU patterns at each resolution, depicted in Fig. 5. The pattern of the D values ranges from 1.59 to 1.66 between 90 and 810 m resolutions. Then at the 900 m resolution, there is an increase in the D value to 1.72, which then peaks at 990 m (1.73). The D value remains high at the 1,080 m resolution, then drops to 1.59 at the 1,170 m resolution. The range of self-similarity for these data is estimated to extend from 90 m to 810 m. After the 810 m resolution, the rise at 900 m and continued ascension to 990 m appear to break the pattern.

MRUs were lost through merging in the resampling process, beginning at the 810 m resolution. This seems to coincide with a change in the pattern of self-similarity beginning at 900 m. However, the series of resolutions at 810 m, 900 m, and 990 m all have 51 MRUs (rather than 52), yet their fractal D values differ. The difference in patterns is also underscored by noting that different MRUs were lost at each resampled resolution (Table 3).

Simulation Results and Fractal Characterization

A comparison of Figs. 3–5 reveals a correspondence between the range of resolutions at which the most accurate simulations resulted and the range of self-similarity of the MRU patterns. According to the seasonal and average monthly flow measurements, this range extends from 90 m to approximately 900 m. According to the Nash-Sutcliffe coefficient, this range extends from 90 m to approximately 810 m. The range of self-similarity of the MRU patterns is interpreted to extend from 90 m to 810 m. In all three cases, a significant break in the patterns occurs at the 990 m resolution. Figs. 3 and 4 indicate that the decrease in hydrologic simulation accuracy found at the 990 m resolution continues through coarser resolutions, and a second significant decrease occurs at the 1,260 m resolution.

DISCUSSION

Distribution of Land Cover

An initial assessment of the distribution of land cover patterns was undertaken to better understand the less accurate hydrologic simulation results generated at the 990 m and 1,260 m resolutions. Measurements of hydrologic processes occurring during the simulation at selected resolutions are provided in Table 5. Examination of the processes occurring during the simulation at 990 m reveals that the highest incident precipitation (*ppt*), net precipitation (*n-ppt*), soil moisture (*smav*), ground-water storage (*gwsto*), ground-water flow (*gwflow*), subsurface flow (*ssflow*), and total flow (*tot-fl*) occurred at this resolution. However, it also has the lowest surface runoff (*sroff*) of the resolutions depicted. The processes occurring at the 1,260 m resolution include the third highest incident precipitation (*ppt*), lowest actual evapotranspiration (*actet*), and highest surface runoff (*sroff*). A higher amount of incident precipitation appears to be driving the higher amounts of runoff. However, different processes are occurring at the two resolutions.

The relatively high amount of incident precipitation at 1,260 m could be attributed to the large area of the watershed at that resolution. At the 1,260 m resolution, the area of the watershed is the largest for the resolutions listed in Table 5. The same logic cannot be applied at the 990 m resolution, as the watershed at that scale has the third smallest area of the resolutions listed. An explanation for the higher incident precipitation at the 990 m resolution is perhaps more complex, but is likely to be based on an increase in the area of MRUs that receive a higher proportion of precipitation.

The distribution of land cover for the watershed at the selected resolutions was also evaluated. A higher proportion of bare areas was found at the 1,260 m resolution, which corresponded with the lower values of actual evapotranspiration and higher surface runoff values occurring at that resolution. Analysis at the subbasin level revealed that at the 990 m resolution, 126 ha of impervious area were lost, which is close to 10% of the impervious area in the watershed. Hectares of impervious area were lost through merging during resampling. In comparison, at the 1,260 m resolution, 280 ha of impervious area were gained. These changes in land cover begin to help explain the difference in hydrologic behavior at the different resolutions.

CONCLUSIONS AND IMPLICATIONS

Published efforts at modeling runoff in the Navarro watershed have not incorporated the distributed representation of watershed characteristics. Physical characterization of this watershed and the delineation of MRUs were carried out using GIScience methods and technology (i.e., remote sensing, GIS), which enabled the spatial distribution of the watershed characteristics to be integrated in modeling the hydrologic response (Colby 1996; Colby and Keating 1998). The watershed characteristics that were derived included the watershed boundary and drainage pattern, elevation, slope, aspect, subbasins, precipitation distribution, distance buffer to the channel categories, and land cover.

The initial objective of this research was to simulate runoff of the Navarro watershed with sufficient accuracy to enable further investigations regarding the effects of changes in the resolution of data representation on simulation accuracy. After this had been accomplished, two specific research questions were addressed—(1) whether a range of spatial resolution existed at which a satisfactory hydrologic response could be simulated; and (2) whether the range of self-similarity of MRU patterns (as defined by fractal characterization) corresponded with the range through which satisfactory hydrologic simulations were achieved.

Based on the accepted level of simulation accuracy at 90 m, it was determined that a range of resolutions did exist at which accurate hydrologic simulation was achieved. It was also determined that, according to fractal characterization, a range of self-similarity existed for the MRU patterns. Further, the extent of these ranges corresponded (90 m to approximately 810 m). Moreover, a significant break occurred in the patterns at the 990 m resolution, and a second decrease in hydrologic simulation accuracy occurred at the 1,260 m resolution. An initial assessment of the spatial representation of land cover at the 990 m and 1,260 m resolutions helped to explain the different hydrologic processes occurring at these resolutions.

The importance of managing the water resources in this dynamic tropical watershed for hydropower, agricultural production, and water supply is evident. The PRMS/MMS modeling structure has been useful in studying the effects of resolution on runoff simulation, and these results indicate that it may also be useful in managing water resources in the Navarro watershed. For example, the model appears sensitive to alterations in land cover due to changes in resolution. Simulated discharge from the watershed was affected by the proportion of impervious and bare areas, according to the parameterization of the model in this study. This implies that the effects of urban growth, deforestation, and perhaps the impacts of nat-

TABLE 5. Hydrologic Processes

Resolution (m^2)	Area (acre)	*ppt* (in.) (total)	*n-ppt* (in.) (total)	*actet* (in.) (total)	*smav* (in.) (average)	*gwsto* (in.) (average)	*sssto* (in.) (average)	*gwflow* (in.) (total)	*ssflow* (in.) (total)	*sroff* (in.) (total)	*tot-fl* (in.)	*pred* (cfs)	*obs* (cfs)	*err pct*	*ntd*
90	68,836	40.79	35.69	10.09	1.112	7.88	0.17	11.77	7.70	2.38	21.38	342.51	299.75	14.26	0.799
720	69,175	40.96	35.93	10.23	1.12	7.91	0.18	11.80	7.81	2.20	21.80	343.96	299.75	14.75	0.797
810	67,770	40.79	35.63	10.01	1.112	7.88	0.17	11.78	7.73	2.34	21.85	337.46	299.75	12.58	0.804
900	69,055	40.79	35.76	10.18	1.113	7.89	0.17	11.79	7.73	2.27	21.80	343.18	299.75	14.49	0.793
990	68,056	43.8	38.63	10.15	1.14	8.49	0.19	12.60	9.11	2.18	23.87	370.40	299.75	23.57	0.752
1,080	68,887	42.48	37.61	10.22	1.12	8.16	0.19	12.14	8.44	2.55	23.12	363.06	299.75	21.12	0.768
1,170	67,992	43.19	38.04	10.0	1.123	8.32	0.19	12.36	8.80	2.40	23.57	365.46	299.75	21.92	0.772
1,260	70,223	42.65	37.56	9.96	1.12	8.20	0.18	12.19	8.21	2.90	23.28	372.80	299.75	24.37	0.758

Note: *ppt* = precipitation; *n-ppt* = net precipitation; *actet* = actual evapotranspiration; *smav* = current available water in soil profile; *gwsto* = ground-water storage; *sssto* = subsurface storage; *gwflow* = ground-water flow; *ssflow* = subsurface flow; *sroff* = surface runoff; *tot-fl* = total flow; *pred* = predicted discharge; *obs* = observed flow; *err pct* = percent error; and *ntd* = Nash-Sutcliffe coefficient.

ural hazard alterations of terrain features on surface and subsurface flow can be studied.

Further research into the definition of MRUs is needed—for example, representative size determination. The resolution after which a significant change in the hydrologic response was indicated in this study was approximately 810 m, which is similar to the 1 km^2 resolution found by Wood et al. (1988), and recommended by Gersmehl et al. (1987b). In addition, these results support previous investigations (Frankoski 1994; Molnar and Julien 2000) that found that relatively coarser resolution grid cells could be used for hydrologic simulation. Further investigation into the robust character of this resolution as representative of watershed behavior could prove constructive to support GIS database development for hydrologic modeling and watershed management efforts in this and similar watersheds.

The potential existence of a relationship between the fractal character of MRUs and land cover patterns, and the hydrologic response raises interesting possibilities. Additional research is recommended to support the relationship found in this study. If this relationship can be further established, then it could serve as a basis for the prediction of the resolutions of land surface characteristics that may be appropriate for various environmental analyses. The correspondence found between fractal characterization and hydrologic response supports the suggestion by Lam and Quattrochi (1992) that a useful perspective on predicting spatial, environmental and ecological system dynamics may be provided by identifying the self-similarity of phenomena at different scales.

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