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ASSESSMENT OF THE IMPACT OF LAND USE CHANGE ON TROPICAL STEEPLAND HYDROLOGY

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EXECUTIVE SUMMARY

Current development pressures threaten the hydrologic balance and productivity of humid tropical steepland watersheds. This study is an initial effort to develop procedures to analyze the effects of land use and technology alternatives on the sustainability of these areas. Project results add to applied science in spatial decision support systems and ecosystem management.

Field research, data collection, and computer hydrologic analysis were performed on two rural prototype watersheds: Cerrillos, Puerto Rico, and Guayabal, Dominican Republic. A basin-scale computer hydrologic model (SWRRB) was used to simulate the disturbance and remediation of alternative land use practices. A data bank model was designed to extrapolate from well-instrumented watersheds to poorly-instrumented basins, to overcome the paucity of climate and hydrology data in the tropical steeplands. A geographic information data management system, coupled to the drainage morphometry of the watershed hydrologic model, provided a spatial evaluation framework for basin and sub-basin analysis.

The results of the research indicate that the approach merits further refinement. Unique steepland characteristics, including drainage basin morphology, rainfall regime, land use practices and their effects on watershed responses. can be simulated by SWRRB (and other computer models), and generalized into land use unit areas at appropriate field scales. While the identification of site vulnerability and remediation affords pragmatic insight into local ecosystems, further spatial and temporal extrapolation experiments are needed. The limited availability of empirical data on system driving forces and local geographic variability are serious constraints to model prediction accuracy. A geographic information system compatible with drainage basin morphology has been designed to resolve this data problem. The Cerrillos - Guayabal case study offers baseline data for extrapolation to the Las Cuevas region in the Dominican Republic.

Dominican scientists participated in several project stages. The apprenticeship training provided to Dominican collaborators will enable local scientists to pursue proposed future work. The results of the study will be translated into Spanish and published in the Dominican Republic. After publication, a series of presentations and technical workshops will be conducted.

RESEARCH OBJECTIVES

The project objectives were to develop a methodology to evaluate the impact of changing land use -- at large scale, small area -- on the sustainable productivity of humid tropical steepland watersheds, and to develop a conceptual model for extrapolation from well-instrumented watersheds to poorly-instrumented basins situated in a similar hydro-geographic region, as the Caribbean and Central America.

The vulnerability of humid tropical steeplands as a hazard-prone region, potentially capable of greater sustainable use levels with suitable management practices, is a recognized dilemma in the less developed countries (LDCs). Current development pressures threaten continuing productivity of these areas. Intense precipitation, high local relief and shallow soils, juxtaposed with deforestation and land conversion to crop and pasture cause soil erosion, gullying, mass wasting and local and regional flooding by sediment loaded streams. The hydrologic balance of tropical steepland watersheds is upset by the cumulative effects of such practices.

The present study fits into a rapidly growing body of scientific inquiry that attempts to construct spatial decision support systems for ecosystem management (1,2,3). This research recognizes that an appropriate conceptual framework is the key to successful ecosystem management (4). The long time-frames and multiple scenarios inherent in ecosystem change make environmental models -- hydrologic, bio-economic -- and geographic information systems (GIS) particularly useful components of spatial decision support systems (5,6). Investigations dealing with impacts of natural and man-made disturbances on tropical ecosystem stability will provide information concerning the bounds of sustainability and will supply the necessary decision criteria for effective operational use of spatial decision support systems (7,8). Increased knowledge of ecosystem form and function are necessary to improve environmental models (9). Many current process studies are especially useful in the parameterization of upland tropical basins where data are lacking (10,11).

This study reviewed procedures to analyze land use and technology alternatives as interventions that affect farm land sustainability in humid tropical steeplands. Watersheds are examined in a time-space perspective. The watershed, drainage basin, or catchment, is the project's unit of analysis. Hydrologic and ecologic unity is achieved by the recursive symbiotic effects of water-driven dynamics on basin components -- fluvial, weather and climate, vegetation, geomorphology and geology, soil, and anthropogenic technology -- examined separately and/or jointly. The watershed was treated as a dynamic ecologic fluvial geomorphic network to which an array of field practices was applied on steeply sloping, inter-stream, ground surfaces. A basin-scale computer simulation watershed model (SWRRB) was linked to a geographic information data

management system to provide an holistic framework to identify the influence of field technology on soil and water management decisions at basin and sub-basin scales.

Modelling of a watershed system, using inputs and outputs based on physical principles, empirical observations, and local experience, may be used to simulate the disturbance and remediation of alternative land practices. In this study, field research, data collection, and hydrologic modelling are performed on two rural prototype watersheds in the humid tropical steeplands of Puerto Rico and the Dominican Republic. The results are extrapolated within the humid steeplands of the larger Caribbean area. Extrapolation from gauged experimental watersheds was necessary because of the paucity of historic and geographic climate and hydrology data on the spatially complex humid tropical steeplands.

The Universidad Nacional Pedro Henríquez Ureña (UNPHU) and the University of Florida supported this project in the form of faculty release and student assistant time, computer services, and clerical assistance. Additional support was provided by the John D. and Catherine T. MacArthur Foundation to one of the Dominican collaborating scientists in the form of a two-year, Tropical Conservation and Development Program, fellowship for doctorate-level geography training in watershed management at the University of Florida.

METHODS AND RESULTS

1. Conceptual Models

a. The Caribbean as a Distinctive Land-Water Resource Region

The geographically scattered and politically fragmented lands of the Caribbean exhibit a striking physical and cultural similarity that is the result of their common resource base and development histories. The latter is well documented and can be traced to the 15th century occupation of the area by the European countries who imposed the technology of a colonial export-oriented social and bio-physical production system on the pre-Columbian indigenous population and on the natural landscape. Contemporary issues, including environmental degradation and sustainable productivity of Caribbean lands, are a byproduct of 500 years of resource development history.

The Caribbean natural resource base is fragile. Local geology is extremely complex and is related to plate tectonics, to sub-aerial denudational processes, and to the behavior of water as a transformation agent. These processes and physical agents alter the spatial distribution of surface and subsurface rock type, thereby creating landform regions of complex bedrock and disturbed geologic structures,

with dissected surface configurations, and with irregularities of slopes, soils and associated streams. The interaction of these features with regional governing atmospheric-oceanic climate controls, particularly with regard to the direction of rain-bearing easterly waves and hurricane storm events, has engendered a complex natural mosaic of environmental ecosystems. Biotic life zones are highly sensitive to these local environments of the humid steeplands. Spatially repetitive large scale (small area) geographic site variation is a basic characteristic of the Caribbean bio-physical landscape.

b. Hydrologic and Ecologic Unity of the Watershed

The stages and transformations that water experiences as it goes through the local hydrologic cycle are shown by Figure 1. Table 1 spatially organizes the hydro-system of Figure 1 into a nested hierarchy of connected watersheds and/or basins arranged according to stream and basin order numbers, progressively from Basin Order 6-8, at the highest level, to 1-2 at the lowest. The basin order is defined by its highest stream order. The stream order depends on branching and linkage of stream channel segments in the basin area. A given basin order level includes all basin lower order levels that are members of the same drainage system. Thus, Basin Order 4-6 includes 2-4 and 1-2. However, it does not include 6-8 and >8. Basin Order >8 occupies the largest area, while Order 1-2 delimits the smallest area. In this manner, the fluvial morphometry of the watershed and its entire areal extent, including sub-basins, may be mapped.

The processes of Figure 1 occur spatially within the selected basin order area or watershed. Table 1 areally extends the hierarchical fluvial network system to include the environmental components of the watershed ecology arranged in a correspondent hierarchy: geology - landform, climate - weather, life zone, soil, anthropogenic activities. Thus, a given basin order may be characterized by the interacting watershed management components diagrammed in Figure 2 (12).

Topographic divides partition basins into sub-basins and direct the flow of water. A basin is drained by a network of stream channels whose sizes increase downstream. Stream development begins with sheet and rill flows on the hill slope (interfluve) land surface which progressively expand into gullies, small channels, streams, and rivers as the amount of water and transported sediment increases. The flows are joined and concentrated toward lower elevations driven by gravitational energy. Streams enlarge their source reaches at higher elevations by eroding land in headwater areas. Streams cut channels and valleys and deposit eroded material to form floodplains, while hill slopes and ridges evolve as residual precipitation-receiving land surfaces from which runoff water drains into the

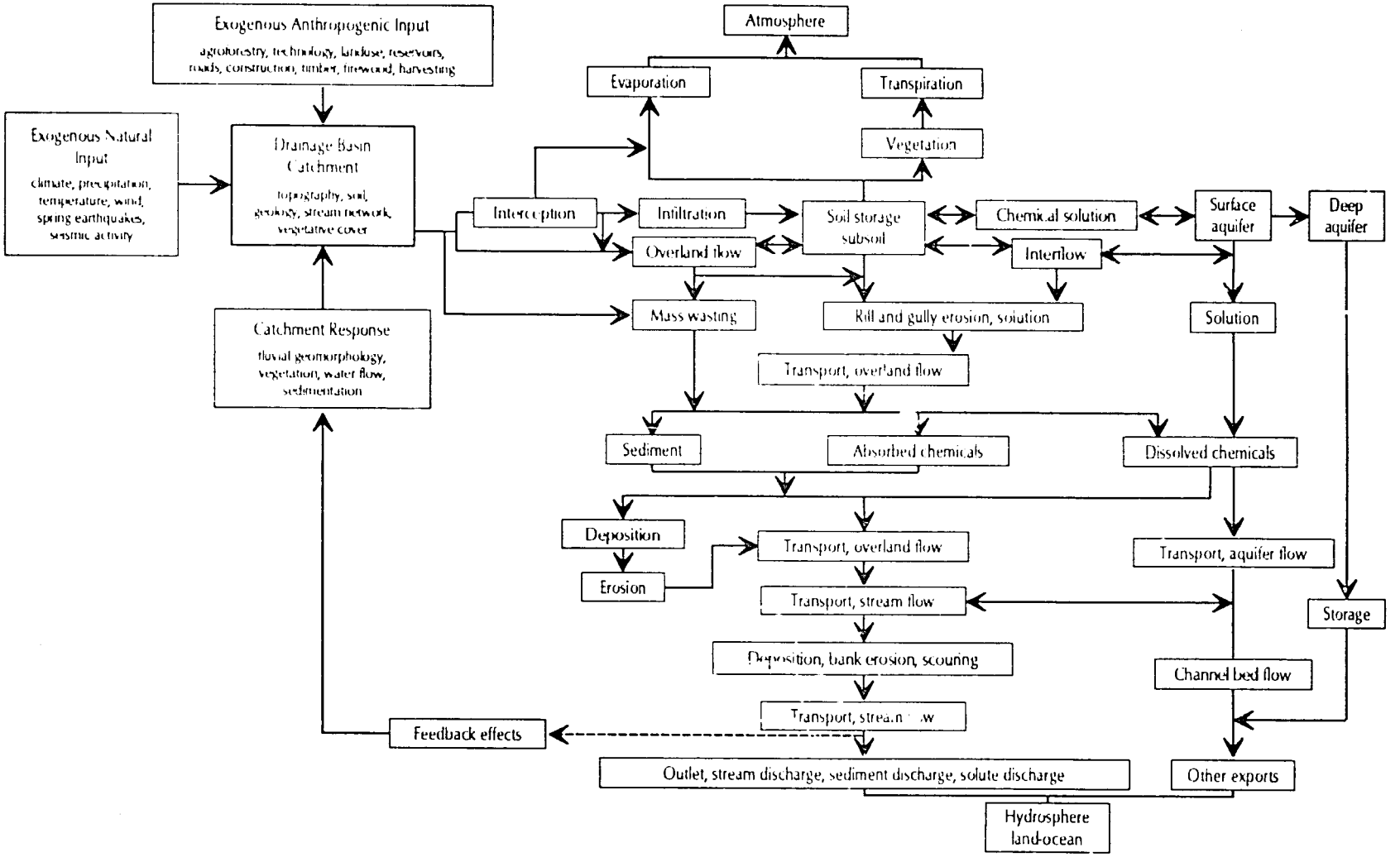

Figure 1. Generalized Watershed Hydrology

TABLE 1. NESTED HIERARCHY OF WATERSHED MANAGEMENT COMPONENTS

BASIN ORDER	FLUVIAL SYSTEM Level	FLUVIAL SYSTEM Water Flow	GEOLOGY - LANDFORM Level	GEOLOGY - LANDFORM Morphometry	CLIMATE - WEATHER Level	CLIMATE - WEATHER Control	LIFE ZONE Level	LIFE ZONE Vegetation - Climate	SOIL Level	SOIL Hydrology	ANTHROPOGENIC Level	ANTHROPOGENIC Activity
> 8 *	Regional watershed	Master river	Region	Landform units dissected mts , hills (mature, submature, young) extensive plains, general geology	Macro-climate	Location (coastal, interior)	Zone	Forest**, biotemperature, precipitation	Order Suborder***	Ultisols, Entisols, Inceptisols, Alfisols ager - wetness fluv - floodplain ud - humid	Region	Land use, forestry, agriculture
6 - 8	Watershed	River	Subregion	Lithologic units (igneous, sedimentary, metamorphic), structure (orientation, controls); topographic and drainage complexity	Air Mass	Source, properties, invasion, frequency (annual, monthly)	Half Zone	Forest**, frostline, biotemperature, precipitation	Order Suborder***	Ultisols, Entisols, Inceptisols, Alfisols ager - wetness fluv - floodplain ud - humid	Vertical zonation	Temperature, precipitation
4 - 6	Basin	Stream	Terrain	Topographic and drainage pattern, relief, slope, aspect, elevation, depth of weathering, substrate, permeability	Meso-climate	Easterlies, hurricane frequency, seasonality	Transition	Forest**, biotemperature, precipitation	Great Group Subgroup	hyd - water ust - dry summer torr - hot, dry xer - dry season	Topography	Slope class, aspect, accessibility
2 - 4	Sub-basin	Tributary	Landscape	Drainage density, climate relation to surface form and configuration, ruggedness	Zonation	Temperature, precipitation, vertical - horizontal zonation	Atmosphere Edaphic Hydric	Temperature, humidity Soil drainage, fertility, texture Water table	Family	Texture class, mineralogy	Soil	Series, phase, depth, fertility
1 - 2	Interfluve	Gully, rill, sheet	Hill / Slope	Aspect, length, mass wasting, soil	Micro-climate	Aspect, shadow effect, precipitation, elevation, radiation	Seral	Human use, crop, pasture, grazing, logging, secondary growth, agro-forestry, natural	Series****	Moisture storage and availability, infiltration, permeability, erodibility	Site use	Forest, grazing, agriculture, agro-forestry, erosion tolerance sustainability

* Fluvial order depends on regional drainage density
** Life zone forest type present in study area
*** Moisture modifier and formative element terms used in nomenclature of orders, great groups, and subgroups
**** Other classes not in official taxonomy (phase, association, conassociation, map unit, catena)

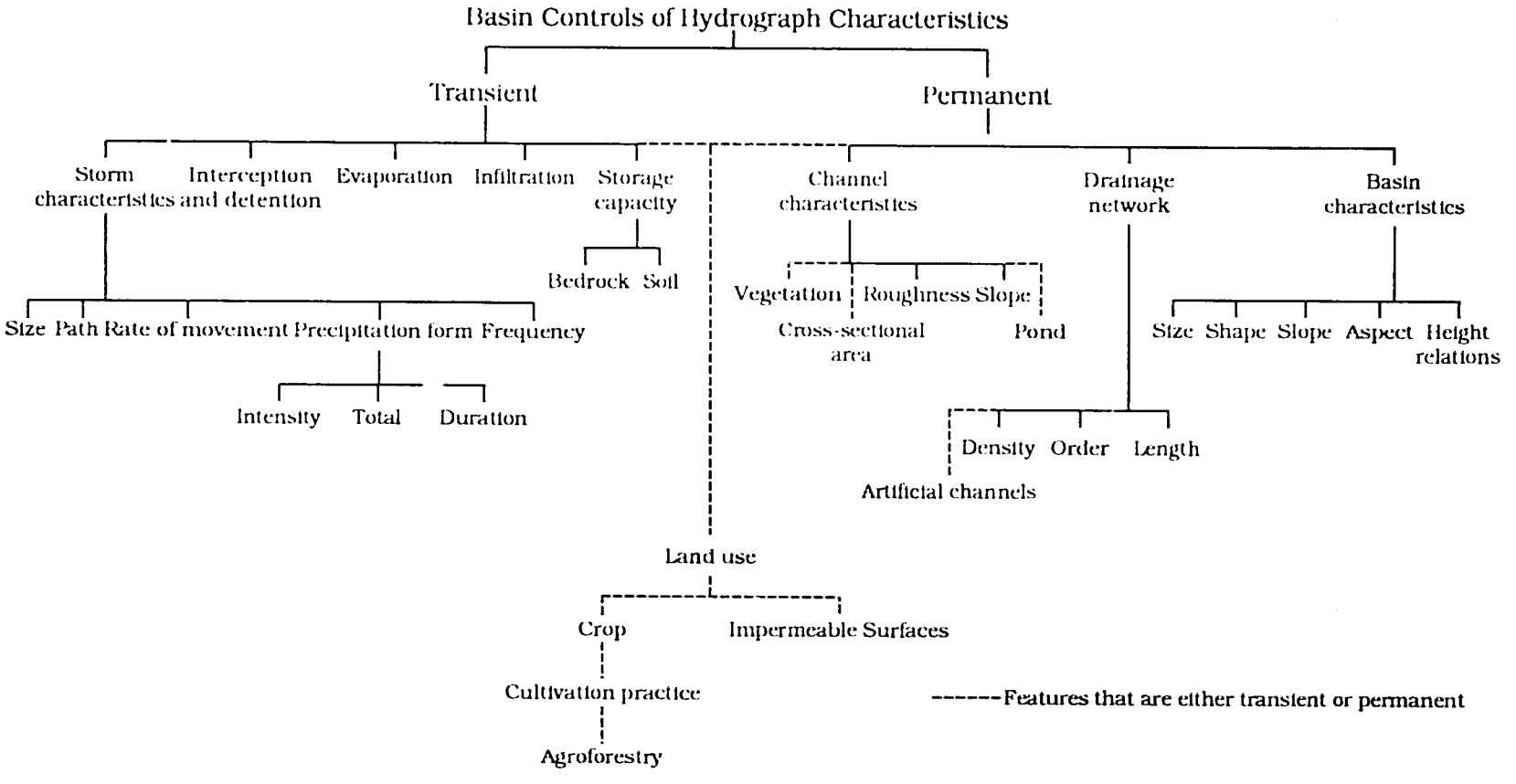

Figure 2. Basin Controls of Hydrograph Characteristics (Adapted from Rodda, 1969)

channels. Surface, subsurface and stream flows, thus, are responsible for the general and local geometry of landforms in the watershed. The Caribbean landscape is composed of distinct watersheds linked in a nested hierarchy of stream channels and basins, each of which has its own catchment of various sizes, shapes, and other characteristics.

Stream networks and catchment areas are important elements of the morphometric classification of erosional landscapes because they may be used to locate spatially distributed basin components, and aid in forming spatial systems of linked segmentations of hydro-ecologic basin entities. Geographic information system (GIS) capabilities make it possible to integrate the spatial dimension with transformation rate intensities for material and process variables. The coupling of GIS with basin system elements permits the assessment of the role of the spatial dimension of watershed - basin - sub-basin - catchment field hydro-dynamics as extrapolations of laboratory and plot studies.

Basin component clusters of the humid tropical steeplands are distributed in the Caribbean, spatially (vertically, horizontally) and temporally. In order to dimensionally coordinate intersections among the changing dynamics of basin components in hydrologic response areas, five component clusters are decomposed spatially and fitted to the fluvial system hierarchy of stream and basin orders: (a) geology - landform, (b) climate - weather, (c) life zone - vegetation, (d) soil associations - pedology, (e) anthropogenic use (Table 1). The separate components are reconciled spatially and diachronically in a geographic information data management system. The coupling of this system to a watershed model permits interactions to occur among the components in user selected space and time.

Geology and landforms exert a very strong control at all hierarchy levels. They are difficult to associate precisely with a corresponding specific basin order because the controlling skeletal geographic frame was established by tectonic forces antecedent to the present drainage system. In the humid tropical steeplands, influence of geology is pervasive at all levels. Table 1 fits geology to the fluvial system hierarchy. At the upper levels of a river, a stream may flow across several geologic structures; at lower levels, a stream course and gradient may exhibit abrupt changes.

Climate and weather controls operate at several fluvial system hierarchical levels because of interactions between the atmosphere and the form elements and materials of the catchment. Through its impact on weathering, receipts of radiation, and precipitation, the atmosphere has influenced the development of drainage basin patterns. Table 1 gives the relation between hierarchy structure and basin orders. A striking feature of the humid tropical steeplands is the vertical and

horizontal zonation of climate that results from the interaction of altitudinal, topographical, and directional changes on precipitation and radiation.

Life zones represent ecosystems adjusted to long-term macro- and meso-climatic and other environmental conditions, as soils and geology. Life zone definition is based on precipitation, bio-temperature, and evapo-transpiration, but it allows for modification of the direct controls by three locational factors (latitude, longitude, and elevation). Boundaries are drawn along observed plant formation lines which are associated with environmental controls. The result is a nested spatial hierarchy in which plant formations are the *taxa* whose geographic locations and positions in the life zone structure are influenced by environmental controls operating at various levels. At the lower levels, local governing variables are soil, water-table depth, aspect, meso- and micro-climate, and land use, which may be used to calculate runoff and soil moisture budgets if precipitation is known or can be estimated reliably.

The soil classification system (Table 1) is arranged as a taxonomic hierarchy of six levels: order, suborder, great group, subgroup, family, and series (13). Soil hydrology is a taxonomic criterion that appears in the diagnostic nomenclature of three levels: suborder, great group, and subgroup. The prefix in the *taxa* name, which refers to soil moisture, denotes moisture held at tension, depth of water-table in the soil profile, seasonal variation in water content, and alluvial deposits. Lateral conductivity is not a criterion at the upper levels of the taxonomy. Information about the depth and thickness of soil layers, structure, texture, porosity, and water conductivity, is included at the series level, and for field mapping units. Soils are delineated at Basin Order 1, the interfluve. When composited at higher basin orders, for several interfluves, soil hydrologic properties are weighted areally.

Within the humid tropical steeplands, the spatial distribution of land use exhibits a clear response to vertical climatic variations caused by differences in site elevations, *tierra caliente, tierra templada, tierra fria, tierra helada.* The zonation corresponds to the global latitudinal relations between climate and agriculture. The dissected topography, steep slopes with shadow effects, and young soils, are responsible for a widely dispersed pattern of varied uses which may be arranged as a nested hierarchy. The conceptual arrangement can be fitted to the fluvial basin order system structure. As indicated by Table 1, the vertical zonation is captured in Basin Orders 1 and 2. This is to be expected from the effect of the geologic structure and lithology on the geomorphology of the steeplands. As pointed out earlier, the steeplands are characterized by a scattered mosaic of small developable land sites.

Sustainable use and hydrologic balance of the watershed require the preservation of equilibria among component processes to constrain basin land

denudation by water erosion to natural tolerable rates. A change in one basin parameter often causes a syndrome of complex interactions, that affects the behavior of water in ways that may transform a near steady-state equilibrium to an adverse non-sustaining transient state. Computer watershed models may be used to conduct equilibria simulation experiments on the efficacy of countervailing agro-forestry technologies.

c. Design of the Geographic Information System

Predictive, analytical abilities of watershed models are limited by their capacities to represent spatial processes, a serious obstacle considering the real world fluvial geomorphology of the humid tropical steeplands. A GIS model, therefore, was designed to interface with the watershed hydrologic model, to allow the spatial-temporal process distributions of watershed components to interact hydrodynamically in the same real world space according to the selected watershed model, and to facilitate predictive modelling and evaluation of alternative land and water uses.

The GIS model (Figure 3) fits the vertical and horizontal levels of the nested data bank structure to the nested hierarchy basin order and drainage network topology shown in Table 1. The upper part vertical levels in Figure 3 are indented to indicate a nested arrangement conformant with the drainage basin network. A given level includes the properties below it in the hierarchy; five levels of basin orders are shown, from regional watershed to interfluve, in Table 1.

The lower part of Figure 3, following the direction arrow, shows the upward vertical relations, from larger to smaller fluvial units, of the six components described in Table 1. The size and selection of the study drainage area is made by the user. The Upper Guayabal watershed, for example, has Basin Orders 1-6. (It is marked with an asterisk to indicate that it will be treated as a fluvial unit and that the cartographic and thematic information of the lower level units stored in the GIS will be accessed and merged to describe the Upper Guayabal). The lower part of the diagram meets the upper part at the interfluve; the two parts are hierarchically coordinated. The lower level gives cartographic and thematic information on the five basin components for the Upper Guayabal from the lower level to the highest. The parameter sets are shown hierarchically nested for each component. The vertical direction is upward from the lower layer toward smaller area fluvial units. The vertical level selected should correspond to the same level chosen previously for the Upper Guayabal. The two opposite vertical level directions converge at the interfluve, the hill slope surface where land use management decisions are made.

The horizontal levels of organization describe the classes of information -- nominal, ordinal, interval -- at a specific vertical level. The intersection of a level

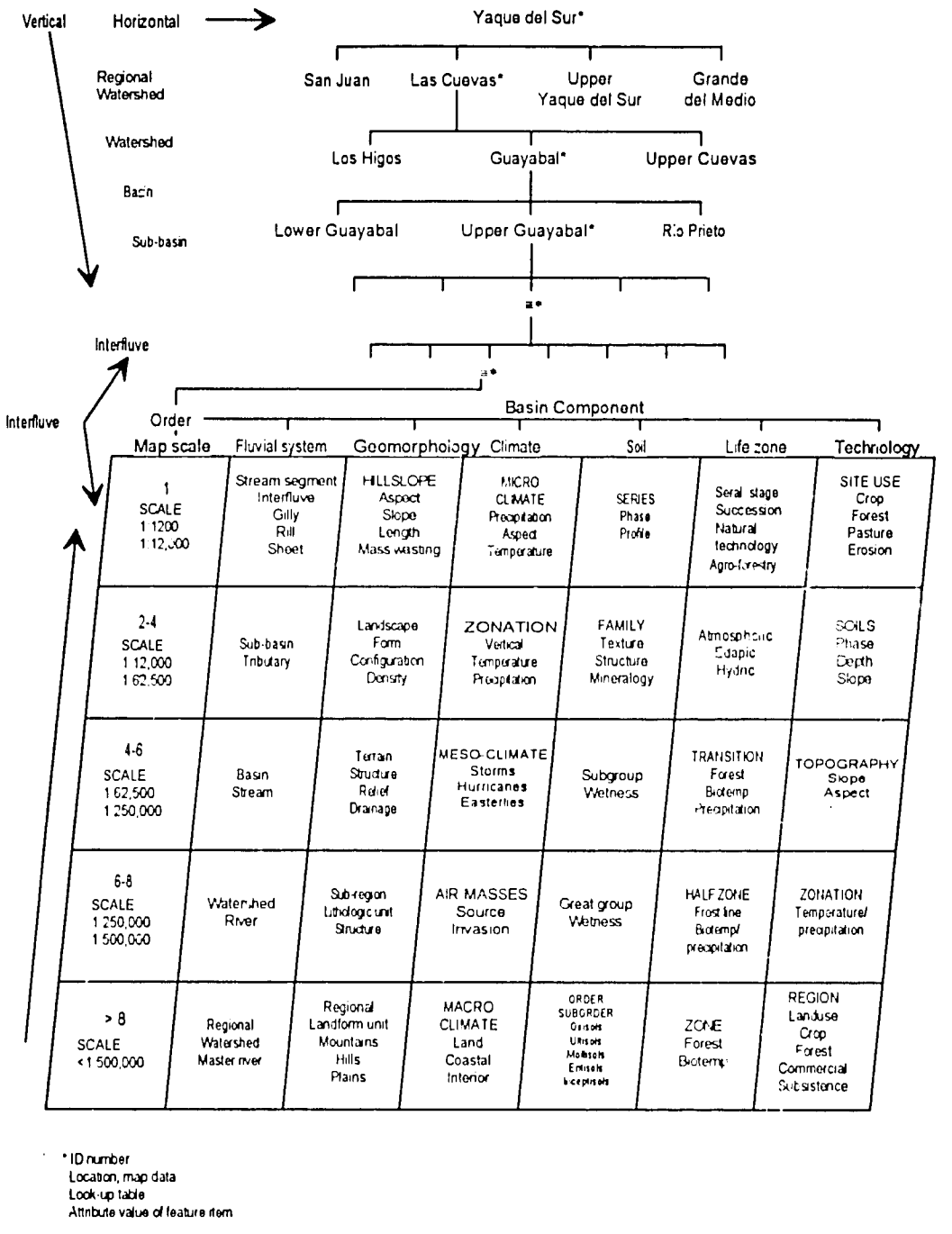

Figure 3. Multi-Level Nested Hierarchy Watershed Data Bank

row and a vertical column defines the state of the environmental component for the selected fluvial subsystem. The upper part of Figure 3 leads to the selection of the drainage system and the level at which it is to be studied and related to other systems. The lower part describes the feature data categories that the hydrologic model will integrate. Interactions may occur across vertical levels for a given horizontal class, along a given level between different horizontal classes, or among different classes and different levels, all at user selected locations. The GIS model, thus, represents the spatial hydrodynamics of watershed land use.

Figure 4 illustrates the value of GIS to supplement tabulated data files and to facilitate analysis. The data may be characterized nominally or numerically, and several interacting feature layers may be shown for the same geographic space. Figure 4 shows 1985 land use and stream order for the drainage basins utilized in this study. The user may opt to show greater detail, and different thematic features, at lower basin order levels.

d. Sustainable Use Ecology

The basic sustainable use question is: what level of perturbation will cause the natural landscape system to become unbalanced? If the system becomes unstable, internal constraints on its components are disrupted or relaxed. The identification of the perturbation level at which a system becomes unstable, relative to site area and condition, is crucial to sustainable land management in order to prevent system degradation beyond the point of resiliency. The relation between resiliency and resistance to irremedial stress is a key parameter of sustainable development.

Hierarchy theory provides a framework for understanding key elements of ecosystem dynamics: (a) the relationships between biota, (b) the function levels within the system, and (c) the impact on system stability of perturbations, natural or designed, separately and/or jointly. Many traditional practices incorporate these relationships as, shifting agriculture, rotational land use, controlled grazing, terracing, etc. Other technologies continue in use, as deforestation, charcoaling, forest grazing, logging roads, slope tillage, and, slash-and-burn clearing. Steepland use pressures continue to mount and modern technologies require a longer commitment of sites to support persistent uses. Maintenance of an imposed technology may have severe degenerative impacts because it prevents incorporation of the perturbation, while relying on engineering and chemical technologies to maintain stability. Meanwhile, the steeplands become more vulnerable to the same levels of normal external perturbation. At the same time, surrounding lowlands are subjected to disastrous impacts from induced flooding, erosion, mass wasting, and reservoir sedimentation. The nested hierarchy model of watershed management components (Table 1) provides a geographic scheme

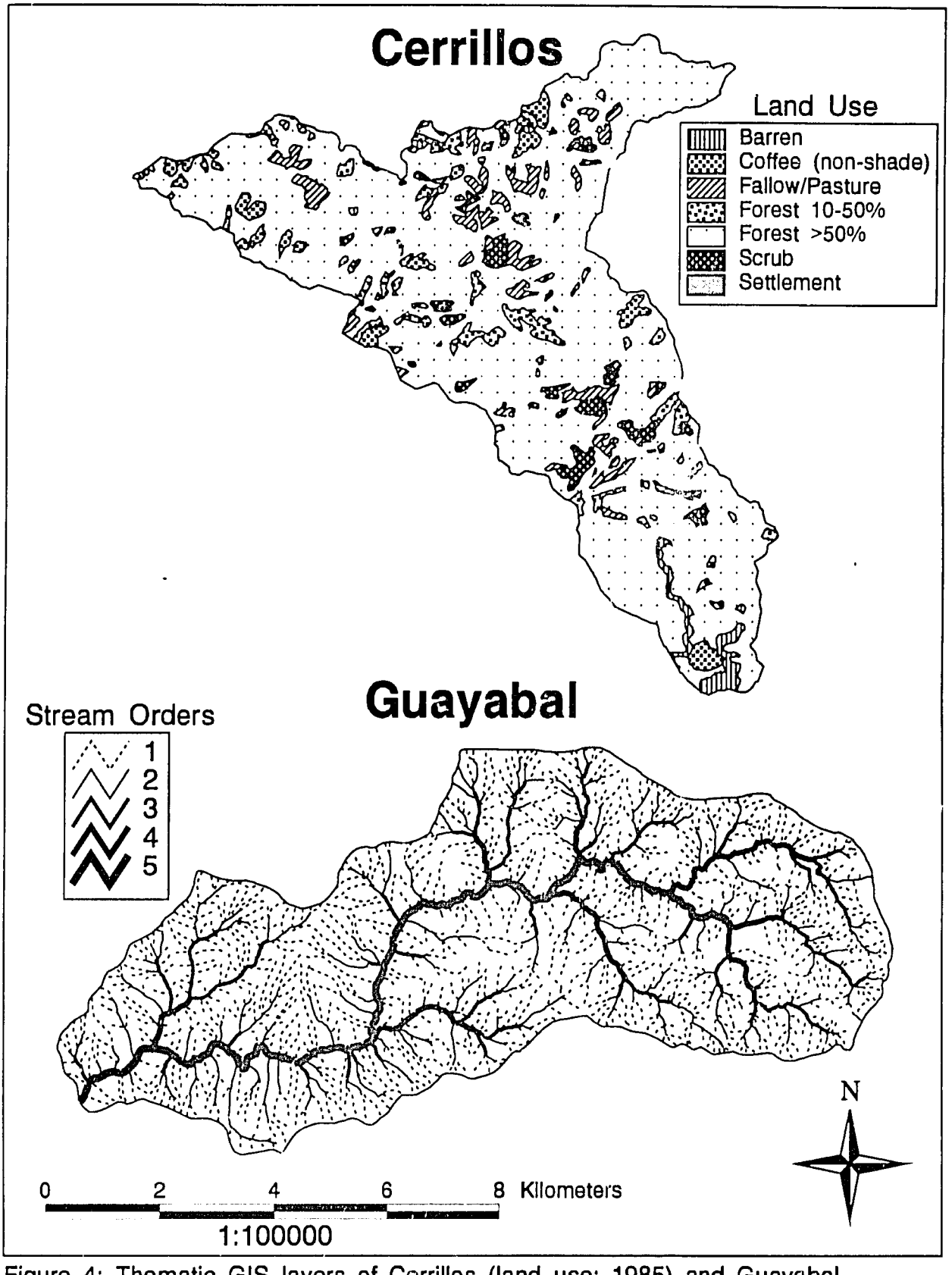

Figure 4: Thematic GIS layers of Cerrillos (land use: 1985) and Guayabal (stream orders).

for delimiting tropical steepland ecosystems threatened by natural perturbations, including those enhanced by anthropogenic technology.

2. Watershed Hydrologic Simulation Model

A review and evaluation of candidate models was carried out in order to select the most appropriate model to meet the research objective of determining the impact of land use change in an ungaged watershed. In LDC's, the necessary data are often inadequate, and thus, a prime consideration in model selection was that it operate under existing data constraints while supplying reliable results. Final model selection was influenced by the availability, type, and appropriateness of data from test basins. Several deterministic models were reviewed to evaluate their adequacy for the present research. They included: STORM (14), CREAMS (15), USDAHL-74 (16), PRMS (17), ANSWERS (18), HSPF (19), SEDIMOT II (20), SWRRB (21). The evaluation concluded that the preferred model should be continuous, utilize daily precipitation inputs, operate on ungaged watersheds of varying sizes, and simulate daily water and sediment yields. SWRRB was chosen from the candidate pool to accomplish the research task. The major hydrologic components included in SWRRB are: surface runoff, peak flow, evapo-transpiration, deep percolation, sub-surface runoff, crack-flow, transmission losses, sediment yield, and crop growth. SWRRB simulates a user selected basin hierarchical level (refer to Table 1) with data inputs for components for a simulation period.

Surface runoff is calculated using a modification of the curve number technique (22), which is based on a continuous soil moisture accounting sub-routine to determine the daily soil moisture status. The current soil moisture storage capacity is used to adjust the curve number and, thus, modify the ability of the sub-basin to generate surface runoff. SWRRB requires that each sub-basin be characterized by the curve number that is representative of normal antecedent moisture conditions.

Precipitation, less surface runoff, infiltrates into the soil. The user must assign the following hydrologically significant parameter values to each soil layer: thickness, texture, saturated conductivity, bulk density, and available water capacity. Each basin is characterized by one soil, or, if multiple soils are present, a composite description that is representative of the various soils. Average parameter values and ranges are available from the U.S. Soil Conservation Service (SCS) and local soil surveys. In the Dominican Republic, this information is available from reconnaissance field surveys.

That portion of soil moisture above field capacity in each layer may be subject to percolation, return flow, and evapo-transpiration. These processes are represented by an exponential decay function. Soil moisture first is given the opportunity to percolate from upper layers to lower layers. The percolation rate, a

function of the current soil moisture capacity, varies from the saturated conductivity rate to near zero at field capacity. Moisture percolated from the bottom layer is lost from the simulated system.

After percolation occurs, the remaining soil moisture above field capacity contributes to sub-surface lateral flow. Return flow travel time is a function of the soil moisture status as reflected by hydraulic conductivity. SWRRB includes a vertical equivalent hydraulic conductivity to account for impermeable and semipermeable layers (23). The user assigns a basin lag time which determines the number of subsequent days that sub-surface flow derived from a particular storm event will contribute to streamflow.

Non-darcian flow is represented by an exponential decay crack-flow model which accounts for soil drying and cracking. Crack-flow may occur in layers with a moisture status below field capacity and is a function of the layer's moisture level and clay content.

Ritchie's evapo-transpiration model provides the conceptual basis for the evaporation and transpiration components in SWRRB (24). The daily potential evaporation rate is a function of average daily solar radiation for each month and the surface albedo. Albedo is determined by weighting soil and crop albedo with above ground biomass and crop residue as supplied by the crop yield model. Plant evapo-transpiration is a function of the leaf area index which is continuously adjusted by the crop yield model.

Total basin water yield is the sum of the sub-basin outflows. Surface flow reaches the basin outlet on the day of occurrence, while sub-surface flow is lagged according to a user defined constant. SWRRB accounts for stream channel transmission losses, as a function of main channel length, main channel width, and the effective hydraulic conductivity of the main channel alluvium.

Soil erosion and sedimentation are handled by a combination of the modified Universal Soil Loss Equation (USLE) and transport functions.

3. Study Watersheds

The Cerrillos basin (46.1 Km^2), located on the southern slopes of the Cordillera Central in Puerto Rico, is centered at 18^0 05' N. Lat., 66^0 45' W. Long. Clastic sedimentary rocks underlie the piedmont in lower basin locations while volcanics are situated at higher elevations. Basin topography ranges from 100 to 1338 meters and basin slopes average 45 degrees. Temperatures range from 19.4^0C. in January to 28^0C. in August, while the recorded mean annual precipitation ranges from 508 mm to 1524 mm. The months of highest rainfall are from May through November.

The Guayabal basin (59.8 km^2), located on the southwestern flank of the Central Cordillera in the Dominican Republic, is centered at 18^0 42′ N. Lat., 70^0 40′ W. Long. More than 80% of the basin is mountainous with moderately sloping to very steeply sloping topography underlain by volcanic, metamorphic, and sedimentary rocks. Elevations range from approximately 840 to 2600 meters. Mean annual temperature is 22.4^0 C. and varies seasonally from 21.1^0 C. in January to 23.7^0C. in July. Precipitation varies seasonally and ranges from 14 mm in January to 194 mm in May.

4. Data Availability and Acquisition

Data sets were compiled for Cerrillos basin, Puerto Rico and Guayabal basin, Dominican Republic. The GIS served to store and retrieve SWRRB input data and to derive certain input parameters required by the model. Puerto Rican site data were obtained from U.S. government agency sources, as U.S. Geological Survey, Soil Conservation Service, National Weather Service, and U.S. Army Corps of Engineers. Comparable sources are lacking in the Dominican Republic except where collected under special circumstances. The Guayabal basin was chosen because extensive information was collected during the 1980's by faculty and graduate students from the University of Florida . This research included the collection of 50 variables recorded from 483 1/4 $kilometer^2$ field observation cells in an area which contains the Guayabal basin (25).

SWRRB operates on a daily time-step and requires climate data for complete calendar years for each year of simulation. Climate data may be entered for the entire basin or unique values may be entered for each sub-basin. Observed daily precipitation values were used in both the Cerrillos and Guayabal model runs in order to compare SWRRB predicted discharge values with recorded discharge values.

Representative daily precipitation values for Cerrillos watershed were obtained from Cerro Maravilla station, 18^0 9′ N. Lat., 66^0 33′ W. Long., at 1217 meters above sea level (26). Ten years of precipitation data were utilized. The 1971-1975 period was used to calibrate SWRRB, while the 1976-1980 period was used to validate the model. Representative daily precipitation values for Guayabal were available from Guayabal-Padre Las Casas station for June, 1976 to April, 1987. This station is located at 18^0 45′ N. Lat., 70^0 50′ W. Long., at 710 meters above sea level. Only two complete years (1983-1984) of daily precipitation values were available. Station rainfall values were modified by averaging observations reported for six other stations at elevations more representative of the upper Guayabal basin (27).

The 10-year frequency rainfall amount for 1/2 hour and 6-hour intervals for Cerrillos were obtained from the U.S. Department of Commerce (28), while those

for Guayabal were obtained from published data for La Florida station at 18° 49' 40" N. Lat., 71° 05' 28" W. Long., at 520 meters above sea level. The average annual precipitation at La Florida is 1193 mm (29).

The monthly maximum 1/2-hour rainfall for Cerrillos was obtained by halving the monthly maximum hourly rainfall recorded in hourly data published for Cerro Maravilla. The monthly maximum 1/2-hour rainfall for Guayabal was obtained from 1/2-hour intensity measurements recorded at Guayabal-Padre Las Casas for the May, 1979-June, 1985 period.

Maximum and minimum daily temperatures for Cerrillos, covering a 24-year period, were obtained from Adjuntas, 18° 11' N. Lat., 66° 58' W. Long., at 556 meters above sea level. Complete years of recorded temperature data were unavailable for Guayabal and, thus, average monthly maximum and minimum air temperature and the coefficient of variation for monthly temperature were calculated from available data, from which SWRRB generated daily values. The statistical summaries were calculated using data from Guayabal-Padre Las Casas. Only complete months of temperature observations were utilized.

SWRRB simulates daily solar radiation as a function of the basin Latitude and monthly average daily solar radiation. Mean daily solar radiation, by month, from Miami, Florida was used for both Cerrillos and Guayabal.

Stream discharge data for Cerrillos were obtained from a U.S. Geological Survey gaging station, 18° 04' 15" N. Lat., 66° 34' 51" W. Long., at 77 meters above mean sea level. The recorded drainage area for the gage is 46.1 km^2 and the record is from May, 1964. Daily stream discharge records for Guayabal were available from Guayabal-La Guama gaging station, 18° 43' 43" N. Lat., 70° 48' 47" W. Long., at 755 meters above sea level. The recorded drainage area for the gage is 59.8 km^2 and the record is from January, 1982 to October, 1988.

Good mapping-quality vertical black-and-white panchromatic aerial photographic coverage was available for both watersheds. The Cerrillos coverage was for 1964 and 1985 at 1:20,000 and 1:43,000; the Guayabal coverage was for 1966 and 1983 at 1:20,000 and 1:40,000. A direct interpretation method was followed to identify and map land use, land cover, and cultural features. Ground-truthing, in Cerrillos and Guayabal, was implemented to verify the interpretation process and to determine the hydrologic condition of terrain units. A zoom transferscope was used to rectify radial line displacement: 1:20,000-scale topographic maps provided the plotting base for Cerrillos and 1:50,000-scale topographic maps were used for Guayabal.

Aerial photography provided complete coverage except for the 1964 mission over Cerrillos which excluded 1/3 of the lower basin. An analysis of the 1964 and

1985 aerial photography was conducted to estimate the areal distribution of land use within the excluded portion. Cerrillos was subdivided according to life zones and areal percentages of land use were compared within each zone for each year. No significant differences were found in the 1964-1985 land use distributions between life zones. On this basis, the 1964 land use areal percentages for subtropical wet forest were projected to that portion of the basin not covered by areal photography.

SWRRB requires a Class II SCS curve number, representative of normal antecedent moisture conditions, for each basin. The curve number, which may vary from 0 to 100, represents the average percent surface runoff expected from a precipitation event and is based on long-term averages. The curve number assigned to a land unit is a function of three factors: 1) the hydrologic soil group, a measure of soil permeability, 2) the land use/land cover, and 3) the hydrologic condition, a function of management practices.

In order to determine curve numbers for the Cerrillos and Guayabal basins, ARC/INFO coverages for land use and soil hydrologic groups were topologically overlain. Soil hydrologic group classifications for Cerrillos were obtained from a published survey (30), while those of Guayabal were estimated based on field observations of soil drainage characteristics (25) and a published soil survey, with comparable profile descriptions, for Las Cuevas watershed (31). All combinations of the three curve number factors were delineated for each sub-basin and a composite curve number for each sub-basin was determined by areal weighting.

SWRRB requires a number of parameters to characterize main channel properties within each sub-basin. These parameters are used to estimate the time of concentration for channel flow, peak runoff rates, and the erosion and transmission losses that occur within the stream network. User supplied parameters include the main channel length, slope, width, and depth; and the effective hydraulic conductivity of the channel alluvium and the USLE K and C factors for the channel (32).

The stream channel network for Cerrillos basin was interpolated from 1:20,000 USGS maps using the crenulation method (33) and then digitized into ARC/INFO. In order to estimate the time of concentration of surface flow, the user must supply Manning's N value for overland flow and the average slope length and steepness. The average slope length was determined using the drainage density method (34).

The basin drainage density for Cerrillos was determined by dividing the total length of all stream channels, as calculated within the GIS, by the watershed area. To determine the drainage density for the Guayabal basin, a 14% sample of 1-kilometer^2 grids was delineated on the 1:50,000-scale topographic maps. The

stream channels within each grid were interpolated using the crenulation method, digitized, and the total stream length determined. The drainage density was calculated as the total stream length divided by total area.

The average ground slope was measured for each site. This was determined for Cerrillos from the soil survey (30), in which each soil series is categorized according to slope. The average basin slope was calculated as the summation of each series slope weighted by its areal extent within the watershed. Slope data for Guayabal were obtained by field survey (25).

SWRRB requires the following soil parameters for each soil layer: 1) depth to the bottom of the layer, 2) bulk density (m/m^3), 3) saturated hydraulic conductivity (mm/hr), 4) available water capacity (mm/mm), 5) clay content (%), 6) percent soil passing a #200 sieve, 7) Universal Soil Loss Equation (USLE) K-factor.

The soils data for Cerrillos were obtained from a local soil survey (30). In most instances maximum, minimum, and mid-point parameter values are given for each soil series. This provides the opportunity for model calibration by adjusting parameter values within the stated range until the simulated results closely match recorded values. The boundaries of soil series within the Cerrillos basin were digitized from orthophotos at a scale of 1:20,000. Areal weighting was used to derive a composite soil for each sub-basin, since SWRRB allows only one soil description per sub-basin. Soils information on the Guayabal watershed was obtained from the earlier field survey of the 483 sites and the Dominican soil survey of the region (25).

Crop information, whether annual or perennial, planting and harvest dates, tillage operations, and the average annual C factor, are required inputs that must be lumped at the sub-basin level. Cerrillos and Guayabal are covered predominately by forest, and thus, were designated as perennial "crops" with planting dates which reflect the growing season, zero tillage, and a maximum leaf area index of 5 which is indicative of the humid conditions in both watersheds. The average annual C factor for both watersheds was initially obtained from Rocheleau (35). These were further modified by SWRRB sensitivities to changes in crop parameters.

5. Field Application of Simulation Models

The sequence of Figures 1, 2, 3 and Table 1 describes the conceptual structure of the field application of the SWRRB simulation model to Cerrillos and Guayabal. SWRRB parameter input values, operating program controls and user options, and format specifications also must be satisfied. Table 2 presents a synopsis of the simulation process and includes 4 sub-tables: **A. Program Controls, B. Rainfall, C. Water Yield**, and **D. Statistical Analysis**. Separate simulations, each with unique input data sets, are identified in sub-tables A, B, and C as C-1, C-2, and C-3 for Cerrillos, and as G-1 and G-2 for Guayabal. C-1 refers to a 5-year calibration period (1971-1975 weather inputs), C-2 refers to a 5-year validation period (1976-1980 weather inputs), and C-3 used program generated (GE) rainfall data. Similarly, G-1 and G-2 refer to 2-year simulations for the same time period, 1983-1984, in which rainfall was observed (OB) for G-2 and program generated (GE) for G-1. The rainfall factor in sub-table A is a correction factor used, when appropriate, to adjust point precipitation measurements. The land use C factor in sub-table A is a water erosion parameter value. Sub-table D is a statistical evaluation of the total water yield (surface and sub-surface flow), in which observed water yields are compared to predicted yields.

IMPACT, RELEVANCE AND TECHNOLOGY TRANSFER

Massive degradation continues in the humid tropical steeplands of the Dominican Republic. Millions of tons of soil are washed away each year as hillslope areas are exposed to heavy tropical rains by inappropriate land uses, indiscriminate deforestation, improper road-building, intensive slash-and-burn agriculture, overgrazing, and poor agricultural practices. Though the effects of different land management practices on erosion and sediment yields are better understood, the ability to model these yields is limited by the sparsity of scientific data in ungaged basins. The project is an initial effort to provide an analytical system to evaluate the functional relationship between hydrologic response units and sustainable land use schemes based on the spatial-physical landscape of maturely dissected, poorly-instrumented, small, tropical watersheds. The Guayabal study offers baseline data for extrapolation to the Las Cuevas region and to the Jiguey and Aguacate reservoir projects under development in the adjoining Nizao watershed.

An important objective of the project's collaborative aspect was to offer Dominican scientists training in state-of-the-art research methodologies. Three Dominicans -- Marcos Peña Franjul, Fernando Durán, and Hector René Ledesma, participated in crucial phases of the project: review of watershed models (Peña), data collection (Peña, Durán, Ledesma), ground-truthing (Peña), design of the data management system (Peña), remote sensing (Ledesma), and GIS applications

TABLE 2

SWRRB WATER YIELD PREDICTIONS AND OBSERVATIONS UNDER ALTERNATE PROGRAM CONTROLS AND ENVIRONMENTAL INPUTS.

A. PROGRAM CONTROLS

BASIN / AREA (km²)		YEARS	RAINFALL		TEMP	LAND USE	
CERRILLOS			OB / GE	FACTOR	OB / GE	C FACTOR	TILLAGE
C-1	46.1	5 71-75	X	1.0	X	0.9	3
C-2	46.1	5 76-80	X	1.0	X	0.9	3
C-3	46.1	5 76-80	X	1.0	X	0.9	3
GUAYABAL							
G-1	59.8	2 83-84	X	1.5	X	0.09	4
G-1	59.8	2 83-84	X	1.4	X	0.09	4

B. RAINFALL (mm)

BASIN	AVERAGE ANNUAL	MONTHLY AVERAGES											
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
C-1	2042	69	60	120	139	141	167	162	167	368	333	195	120
C-2	2220	72	94	82	166	275	144	155	279	393	302	181	76
C-3	1554	72	76	77	63	156	337	126	163	218	180	24	57
G-1	1622	37	55	66	83	295	211	80	213	125	319	84	55
G-2	1117	36	30	51	60	151	167	96	175	140	144	64	1

C. WATER YIELD mm (Monthly Averages)

BASIN													
C-1	PREDICTED	10	4	24	32	46	43	17	14	113	115	125	65
	OBSERVED	20	14	20	22	20	35	43	49	142	110	105	43
C-2	PREDICTED	13	12	10	32	88	66	30	39	95	157	121	39
	OBSERVED	21	15	15	22	51	37	40	49	112	148	91	30
C-3	PREDICTED	8	9	10	16	19	43	24	16	22	17	13	10
	OBSERVED	20	14	20	22	20	35	43	49	141	110	105	43
G-1	PREDICTED	8	10	12	17	86	84	24	53	16	97	71	34
	OBSERVED	42	37	38	36	46	73	66	63	3	147	79	51
G-2	PREDICTED	1	3	4	5	31	26	9	9	10	27	25	3
	OBSERVED	42	40	38	36	46	73	67	63	103	147	79	51

D. STATISTICAL ANALYSIS

BASIN C, n=60		BASIN G, n=24	
MEAN	STD. DEV.	R^2	REG. SLOPE
0.51	0.73	0.736	0.713
0.52	0.61		
0.59	0.63	0.726	0.686
0.53	0.50		
0.21	0.97	0.708	-1.876
0.62	0.21		
0.43	0.40	0.053	0.209
0.65	0.36		
0.13	0.16	0.058	0.544
0.65	0.36		

(Ledesma). A conscious effort was made to expand use of GIS well beyond the original intent contemplated by the proposal in order to capture fuller use of this new technology, to enrich the research findings, and to make a valuable contribution to the training dimension of our Dominican collaborators. One of the Dominican scientists obtained a leave of absence from UNPHU in 1991 and joined the research team on a part-time basis while he pursued a Ph.D in Geography at the University of Florida with support from the John D. and Catherine T. MacArthur Foundation, the Florida Sea Grant Program and the University of Florida He is utilizing the hydrologic - GIS training to carry out his dissertation research on the effects of reservoir sedimentation and the economics of watershed management in the Nizao Basin, Dominican Republic. This scientist can provide UNPHU, the collaborating country institution, with local expertise to pursue proposed future work.

PROJECT ACTIVITIES AND OUTPUTS

Preliminary findings were presented in 1992 at the Conference of Latin Americanist Geographers in the Dominican Republic. A 180-page monograph has been prepared and a condensed draft copy was sent to USAID/Washington for review in February 1995. We have requested support from the University of Florida to translate the monograph and to present findings in the Dominican Republic. We have approached UNPHU, our collaborating institution, about publishing the research findings in Spanish, and of our willingness to offer both technical workshops and presentations for the general public.

PROJECT PRODUCTIVITY

The project is an initial effort to develop a method to assess the impact of land use change on the hydrology and sustainable productivity of the humid tropical steeplands. The research strategy followed was to adapt computer models developed in the United States and other countries to predict hydrologic responses of watersheds to agro-forestry practices. The models require field data inputs, not widely available for tropical steeplands. The approach followed two strategies: (1) to extrapolate from two selected prototype basins, one well-instrumented (Cerrillos, P.R.) and the other, poorly instrumented (Guayabal, D.R.); and (2) to spatially couple nested hierarchical systems of land management bio-physical ecological components and drainage basin morphometry. The results can be applied to other basins with further research. The technology transfer strategy was to offer an apprenticeship learning experience to Dominican collaborators which would serve then as a catalyst for more advanced training and the application of the project methodology to other regions. This is occurring through a collaborator's current dissertation research in the Nizao basin.

FUTURE WORK

A logical extension of this research is to facilitate the adaptation and application of computer models, developed for use in the mid-latitudes, to the unique land-water-technology environments of the humid tropical steeplands. Two classes of researchable problems are recognized: rainfall-runoff relations (in-stream and subsurface), and non-point source pollution from agricultural chemicals. Model process evaluations are greatly enhanced by the incorporation of geographic information systems (GIS) in order to capture the spatial dimensions, including accurate and localized data collections, independent validations, and dynamic process refinements. Suggested research themes include: flow generation mechanisms and pathways (overland flow, interflow, groundwater); solute transport and stream chemistry; the role of complex topography on hydrologic flow in small watersheds (particularly the effect of hill slope geometry -- elevation, slope, curvature, aspect -- on hydrologic storage-responses), absolutely and in relation to temporal and spatial storm patterns; and, the effect of catchment spatial resolution, as stored in raster or vector GIS data bases, on the accuracy and efficiency of surface runoff models used in conjunction with GIS should be explored.

Promising opportunities exist to broaden this upland research to include companion coastal, nearshore analysis by incorporating a bay water assimilation-capacity element to trace the movement and transformation of discharged materials into bay waters and estuaries. We have discussed this possibility through the Integrated Coastal Marine Planning Program in the Dominican Republic.

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