INTRODUCTION

As part of its Global Change Hydrology Program, the U.S. Geological Survey (USGS) is investigating the potential effects of climate change on the water resources of several river basins in the United States. The American River Basin in California represents the windward slope of the north-central Sierra Nevada, and the Carson River Basin, most of which is in Nevada, represents the leeward slope. Parts of the American River and Carson River Basins—the North Fork American River and East Fork Carson River watersheds, both in California—were studied to determine the sensitivity of water resources to potential climate change. The water resources of both basins are derived primarily from snowmelt. A geographic information system (GIS) data base has been created to facilitate paired-basin analysis. The GIS data base incorporates (1) land-surface data, which include elevation, land use and land cover, soil type, and geology; (2) hydrologic data, such as stream networks and streamflow-gaging stations; and (3) climatic data, such as snow-course, snow-telemetry, radiosonde, and meteorological data. Precipitation-runoff models were developed and calibrated for the North Fork watershed within the American River Basin and for the East Fork watershed within the Carson River Basin. (These watersheds were selected to represent the climatic and physiographic variability of the two larger basins.) Synthesized climate scenarios then were used in the model to predict potential effects of climate change.

The Precipitation-Runoff Modeling System (PRMS), developed by Leavesley and others (1983) of the USGS, was used to model the watersheds. The PRMS is a physically based, deterministic computer model designed to simulate snowpack accumulation, snowmelt, and precipitation-runoff processes. To simulate basin runoff, the model partitions watersheds into areas or land units known as hydrologic-response units (HRU's). Each HRU is assumed to exhibit a homogeneous hydrologic response, uniformly distributing precipitation or snowmelt runoff, and is characterized primarily by physiographic properties. A digital GIS of elevation, slope, aspect, soil, and land-use and land-cover data was created for each watershed. These watershed GIS data bases were used to delineate the HRU's, which have a noncontiguous distribution, and objectively derive HRU data layers for each watershed.

The digital data layers of the GIS can be analyzed to meet a broad spectrum of watershed-analysis and modeling requirements. This publication documents the map data and basinwide summary statistics that were used in the watershed-characterization process and the type and distribution of HRU's delineated by using the described techniques. Included for each watershed are (1) the source maps and summary statistics for each of the five data layers used in the process, (2) maps of the source data grouped for the delineation of the HRU's, and (3) the final HRU maps and summary statistics used to develop the PRMS model.

Precipitation–Runoff Modeling System and Hydrologic-Response Units

The PRMS is a physically based, deterministic, distributed-parameter model designed to simulate watershed processes, which include snowpack accumulation, snowmelt, precipitation infiltration, and runoff. The spatial variability of watershed characteristics that affect runoff is accounted for by conceptually dividing the watershed into HRU's. Each HRU is assumed to exhibit a uniform hydrologic response to precipitation or snowmelt and is characterized by the physical properties of a basin, which include elevation, slope, aspect, vegetation, soil, geology, and climate. Theoretically, each HRU has a unique water-and-energy budget. The PRMS is an accounting model that sums the water-and-energy budgets of each HRU on a weighted-area basis to yield a basinwide response. For each HRU, the model requires that 40 model parameters be determined. These parameters jointly describe how, when, and where water moves through the watershed.

Techniques that use vector and raster data and a digital GIS were developed to define the spatial variability of watershed characteristics and to assist in determining model parameters. The techniques used for HRU delineation are summarized in this publication with an emphasis on graphic presentation of the watershed data and on the final HRU's.

Acknowledgments

The authors thank G.P. Thelin (U.S. Geological Survey), who mosaicked the data sets for the digital elevation model, and J.C. Stone (U.S. Geological Survey), whose technical expertise and visual creativity in computer graphics were essential in developing and assembling the individual components of this publication.

WATERSHED DESCRIPTIONS

The geographic setting of the American River and Carson River Basins and of the North Fork American River and East Fork Carson River watersheds is shown in the location maps (upper right).

The North Fork American River watershed is in California on the windward slopes of the Sierra Nevada, west of Lake Tahoe. The North Fork is one of three major forks of the American River. The vegetation in the watershed is characterized mostly by evergreen forest with shrub-and-brush rangeland, although deciduous forests are found at lower elevations and large areas of bare rock at higher elevations. The geology of the area is dominated by igneous rocks (volcanic and granitic), although metasedimentary rocks are also common. The soils, primarily clay loams and coarse sandy loams, are typical products of such parent material.

The physiographic setting of the North Fork American River watershed is characteristic of the windward slopes of the Sierra Nevada. Streamflow is measured at the North Fork Dam, which is 6.4 kilometers northeast of Auburn, Calif. The streamflow-gaging station monitors a drainage area of 886 square kilometers. The elevation of the watershed ranges from 218 meters to 2,745 meters above sea level; the median elevation is 1,270 meters. The average slope in the watershed is about 17 degrees, and the dominant aspect is westward.

The North Fork American River watershed is in the Sacramento Drainage Climatic Division of California (Elford, 1970), which was described by Felton (1965). Precipitation occurs primarily during fall and winter as snow at higher elevations and rain at lower elevations. The average annual precipitation ranges from about 813 millimeters near the streamflow-gaging station to 1,651 millimeters at higher elevations. Almost 70 percent of the annual runoff occurs from December through April and is uniformly distributed throughout this time. Over the years, land cover in the watershed has changed as a result of logging, residential development, and forest fires.

The East Fork Carson River watershed is in California on the leeward slopes of the Sierra Nevada southeast of Lake Tahoe. The East Fork Carson is one of two forks that form the headwaters of the Carson River, which flows into the Carson Sink near Fallon, Nev. The vegetation in the watershed is dominated by evergreen forest. Shrub-and-brush rangeland and some deciduous forest are typical at the lower elevations, and tundra-type vegetation is found at higher elevations. Granitic and volcanic formations characterize the geology. Mechanical weathering has created zones of coarse alluvial fill. The soils are dominated by shallow gravelly sands throughout the watershed; clayey soils and loams are found in some valleys.

The physiographic setting of the East Fork Carson River watershed is characteristic of the leeward slopes of the Sierra Nevada and the headwaters of the Carson River Basin. Streamflow is measured at a site that is 2.4 kilometers north-northeast of Markleeville, Calif. The streamflow-gaging station monitors a drainage area of 715 square kilometers. The elevation of the watershed ranges from 1,646 to 3,493 meters above sea level; the median elevation is 2,417 meters. The average slope in the watershed is about 21 degrees, and the east-northeast-facing aspect is slightly dominant.

The East Fork Carson River watershed is in the Northeast Interior Basins Climatic Division (Felton, 1965; Elford, 1970). Precipitation occurs primarily during fall and winter as snow, but some also occurs during summer as thunderstorms. The average annual precipitation ranges from approximately 559 millimeters near the streamflow-gaging station to 1,244 millimeters at higher elevations. Approximately 55 percent of the annual runoff occurs almost equally during April, May, and June.

DESCRIPTION OF THE SOURCE DATA

An integrated GIS data base was developed for the purpose of paired-basin analysis and model development. Source data were acquired for the watershed GIS in many forms, including paper maps and data records, digital vector (line-based) format, and grid and image (cell-based) raster formats. The data were either manually digitized by using a digitizing table or automatically scanned and converted to a digital data format. All data layers shown on color-coded maps for each watershed in the source-data columns are from digital data in raster format.

Elevation Data

The digital elevation data (U.S. Geological Survey, 1987) are a subset of a data base originally derived by the Defense Mapping Agency from 1- by 2-degree topographic maps compiled at a scale of 1:250,000. These data, known as a digital elevation model (DEM), represent an irregular land surface by interpolation to fit a digital regular grid. The cell size of each grid cell is 3 arc-seconds, representing about 63 by 63 meters. The data set used in the study is a mosaic of eight DEM's. Thelin and Pike (1991) described restoration of DEM data and edge matching of the data sets and provided other relevant background information.

Slope and Aspect Data

The attributes of slope and aspect were determined from the elevation data set by using digital image-processing techniques. The slope and aspect are computed from the DEM by comparing the elevation value associated with each cell or picture element (pixel) with those associated with its neighboring cells. Slope and aspect are determined by moving a three-by-three-pixel window across the data array and evaluating the central pixel. A linear plane surface is fitted to the elevation values in the window. The gradient of the resulting surface is then defined as the slope. Aspect is defined by the compass direction of the sloping surface. In this publication, slope is shown in degrees, and aspect is reduced to one of the eight primary compass directions or is defined as level.

Soil Data

For the North Fork American River watershed, digital soil boundaries and selected attributes were obtained from the preliminary State Soil Geographic Data Base (STATSGO) (U.S. Soil Conservation Service, 1991) and were reformatted for use in the watershed GIS data base. The STATSGO soil maps were compiled at a scale of 1:250,000 by generalizing from more-detailed soil-survey maps. The STATSGO data base is designed to be used primarily for river-basin, regional, or statewide applications.

STATSGO data were not yet available for the East Fork Carson River watershed. Soil data were obtained from the U.S. Forest Service (H.B. Summerfield, written commun., 1991). These data, which had been plotted on 1:62,500-scale U.S. Forest Service maps, were digitized manually for use in the watershed GIS data base. (The source maps are part of an unpublished land-use planning report for Alpine County, Calif., that is on file at offices of the U.S. Forest Service, Carson City, Nev.)

Land-Use and Land-Cover Data

Land-use and land-cover data were digitized by the U.S. Geological Survey (1986) from high-altitude aerial photographs acquired during the late 1970's and early 1980's. Land-use and land-cover classes were mapped according to a two-tiered classification system developed by Anderson and others (1976). The minimum mapping-unit size ranged from 4 to 16 hectares, depending on the mapped land-cover class. The data were compiled at a scale of 1:250,000. These digital data were produced by using the Geographic Information Retrieval and Analysis System (Mitchell and others, 1977).

Hydrologic Data

The USGS delineated watershed boundaries upstream from streamflow-gaging stations and other hydrographic data on 1:24,000-scale maps or, if those were unavailable, on 1:62,500-scale maps. Locations and boundary lines were plotted on these maps, verified, digitized manually, and then incorporated into the GIS data base.

WATERSHED CHARACTERIZATION

Previously, basin characteristics and the HRU's were determined for the PRMS by using maps, reports, and digital spatial data. Basin characteristics generally were restricted spatially to hydrographic subbasin boundaries (Kuhn, 1988) or data were represented by larger (5-kilometer) grid cells (Parker and others, 1992). For this study, however, a process was developed to delineate land units (the HRU's) by using the GIS data base. An HRU is a spatially noncontiguous and discrete land unit defined by the GIS data layers. Its boundaries are not restricted by subbasin boundaries but are derived from the spatial distributions of the data layers. The method developed to delineate HRU's was designed from the raster-based pattern-recognition process (Lillesand and Kiefer, 1979) that is used in image classification. This process identifies and tabulates all patterns of the input data layers. (A pattern is defined as a unique combination of the input data layers and is not to be confused with salient patterns of remotely sensed image data.) The pattern table can be analyzed and edited. Patterns can remain unique in the table, be associated with other patterns, or be removed from the table. The modified pattern table then is used to assign a value to or to classify each pattern of the input data layers. This process creates a single new data layer.

Process Used to Delineate Hydrologic-Response Units

The data layers of elevation, slope, aspect, soil, and land use and land cover were used to delineate HRU's in this study. The source-data categories within each GIS data layer were regrouped into fewer, new categories (grouped data) according to hydrologic-response characteristics and sensitivity to climatic factors (see section "Grouped Source Data Used to Delineate Hydrologic-Response Units"). Each of the five grouped-data layers was converted to raster format at a cell resolution of 100 by 100 meters. Each cell of each of the five data layers has a characteristic pattern or combination of the grouped-data categories. All possible combinations of the five grouped-data layers were determined and then tabulated and separately tallied for the watershed. Each pattern was given a unique pattern identification number (PIN). For example, for the East Fork Carson River watershed, PIN 18 is described by the following combination: elevation, 1,646 to 1,981 meters; slope, 8 to 30 degrees; aspect, north facing; soil, gravelly sand; and land use and land cover, evergreen forest. Within the grid representing this watershed, 338 cells have this pattern.

The number of entries in the table depends on the number of data layers used and the number of grouped-data categories in each data layer. For each watershed, almost 500 PIN's were identified. Although each PIN could be used to define an HRU, the PRMS can accommodate only 50 HRU's. Therefore the patterns were analyzed and the total number of unique PIN's reduced by using relational data-base-management techniques within the GIS. Selected patterns were combined by reassigning a single value to their PIN table entries. Unlike previous steps, this PIN-reassigning process requires some subjectivity to identify the hydrologically most significant areas. The final pattern table can have the same number of entries as before reassigning PIN's but only 50 unique PIN values. If an entry is removed from the table, that pattern cannot be identified later. This final table, known as the HRU-characterization table for the watershed, was used to assign an HRU number (one of the 50 unique PIN's) to each cell. Each cell of the five grouped-data layers used to create the PIN table was compared with the HRU-characterization table. When a match was found, the assigned HRU number was placed in a new output data layer or image. A null value was assigned to the output data layer if no match was found.

Grouped Source Data Used to Delineate Hydrologic-Response Units

Maps based on the grouped source data used to delineate the HRU's are shown and categories are explained in the grouped-data column for each watershed. The categories, as defined by the hydrologic modelers, may differ among watersheds. Several considerations are used to define categories for each data layer. The elevation categories are based on differences in precipitation distribution resulting from orographic effects and regional weather patterns. The HRU's are defined so that they do not cross elevation-category boundaries. The slope categories are based on geomorphology and soil properties. The aspect categories are derived from potential-solar-radiation properties. The soil categories are grouped primarily on the basis of the textural properties of each soil. All land-use and land-cover categories from the source data are used directly except for water bodies, transition zones, residential areas, and other categories of limited areal extent. (The exceptions are assigned values corresponding to adjacent land-use and land-cover categories.)

Maps of Hydrologic-Response Units

The HRU maps for the North Fork American River and East Fork Carson River watersheds are shown below the grouped-data columns. The HRU map for each watershed shows a small part of the watershed enlarged, and an accompanying bar graph indicates what percentage of the watershed corresponds to each HRU. In the enlargement, selected HRU's are keyed to a list of the defining attributes of each. All 50 HRU's for each watershed are listed in tables 1 and 2. For the North Fork American River watershed, the HRU numbers, HRU-area percentages, and attributes defining the HRU's are shown in table 1; corresponding information for the East Fork Carson River watershed is given in table 2. As explained in the section "Process Used to Delineate Hydrologic-Response Units," many PIN entries in the HRU-characterization table can have the same HRU number; therefore, the characteristics of the dominant PIN for each of the 50 HRU's are listed in tables 1 and 2.

The HRU map of each watershed is color coded to reflect land-use and land-cover types and to show the noncontiguous distribution and overall spatial patterns of HRU's resulting from the model-building process. Nominal filtering was applied to the HRU data set to reassign the value of an adjacent pixel to any individual pixel that was not in contact with at least three other pixels of the same value. Therefore, because the cell size is 100 by 100 meters, the minimum size of an HRU mapping unit is 4 hectares. For the North Fork American River watershed, the average size of an HRU is 25.8 hectares; for the East Fork Carson River watershed, it is 18.8 hectares.

DISCUSSION

The technique developed for this study to delineate the HRU's for the PRMS is an objective method for characterizing a watershed by using diverse digital data in a GIS. The final color-coded maps show the noncontiguous distribution and spatial patterns of the HRU's delineated by this model-building process, which has the flexibility to model very different hydrologic settings. The calibrated models developed for the two watersheds by using this technique acceptably simulate measured basin streamflow (A.E. Jeton, U.S. Geological Survey, oral commun., 1992).

The distribution and density of the HRU's are controlled by the number of data layers used, the criteria used to group the source data, the maximum allowable number of HRU's, and limitations or characteristics of the GIS (such as compilation scale). The HRU's delineated by using this technique may not be appropriate for hydrologic-routing modeling. However, the HRU data base has been used as input to watershed models for climate-change sensitivity studies. Planned future work includes analysis of individual HRU response, analysis of HRU sensitivity to climate change, and a sensitivity analysis to determine the minimum or threshold number of HRU's required to simulate watershed-scale hydrologic processes.

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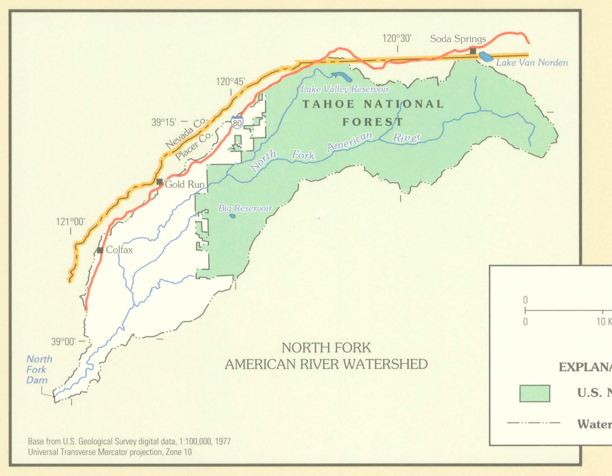
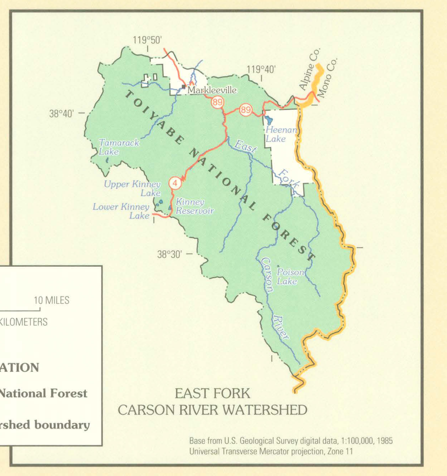
Multiply	By	To obtain
hectare	2.471	acre
kilometer	0.6214	mile
meter	3.281	foot
millimeter	0.0394	inch
square meter	10.76	square foot
square kilometer	0.3861	square mile

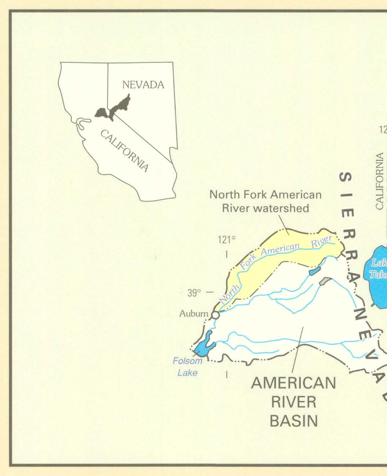
Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

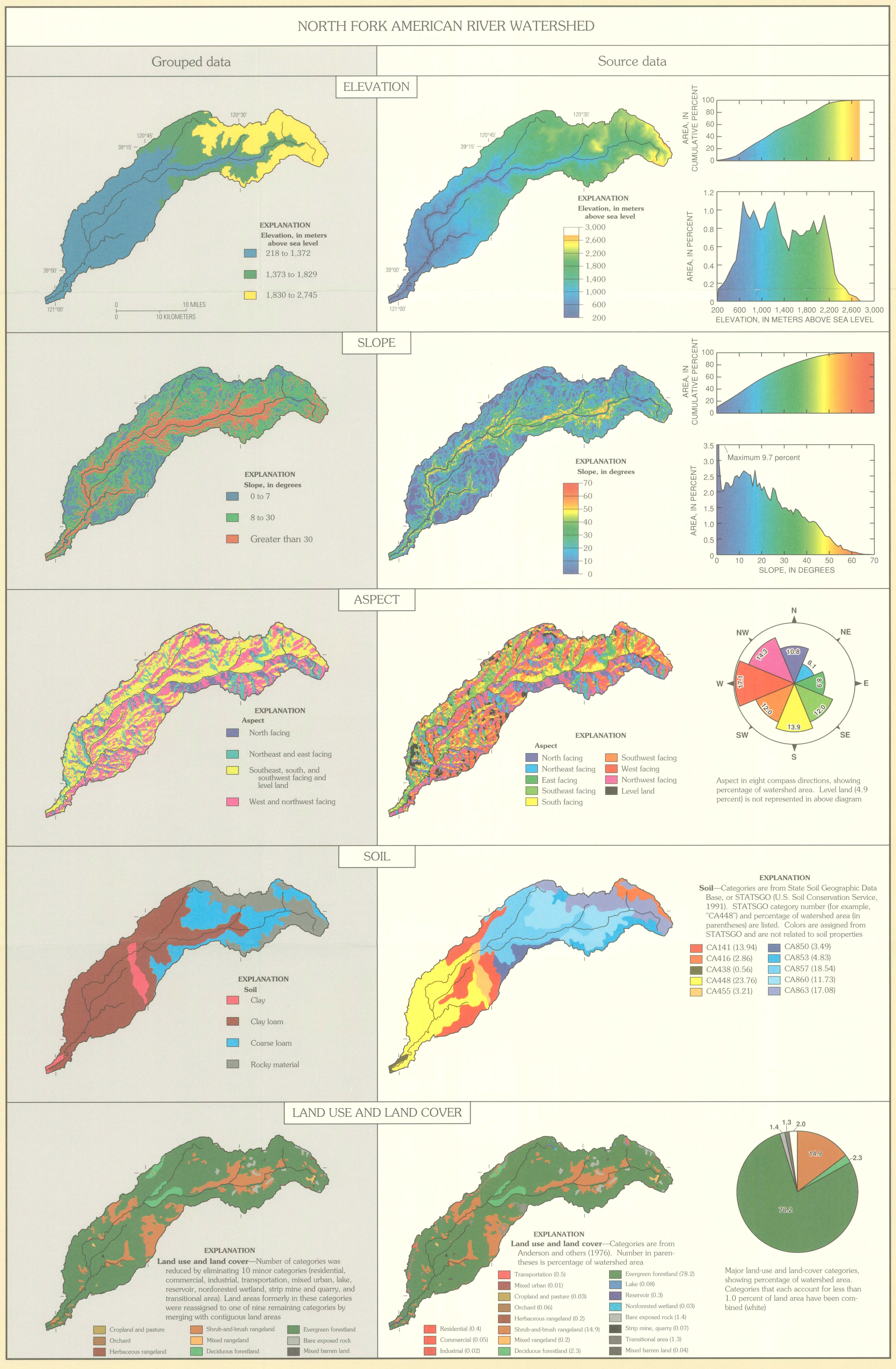
DESCRIPTION OF THIS SHEET

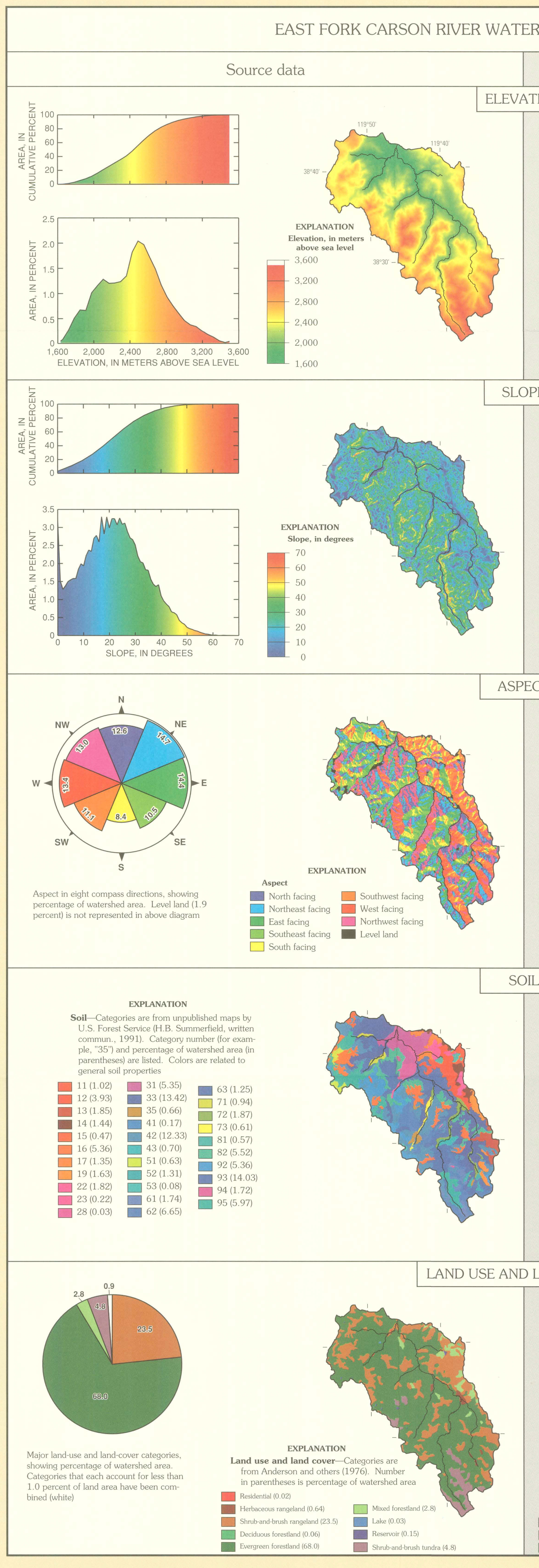
Graphic and tabulated information on the watersheds is separated into two corresponding halves, one for the North Fork American River watershed (below, left) and the other for the East Fork Carson River watershed. (See location maps, right.) The upper part of each half is divided into two columnar sections, bearing the headings "Source data" (inner section) and "Grouped data" (outer section). Beneath the "Grouped Data" sections are the respective final hydrologic-response-unit (HRU) maps (and representative enlarged areas) and the HRU statistics in histogram form; beneath the "Source Data" sections are the corresponding tabulated HRU-characterization data. The source-data sections include color-coded maps and summary statistics for each of the five data layers; the statistics are presented graphically (as frequency, rose, or pie diagrams) or in the map explanation, as appropriate. The grouped-data sections show each of the source-data layers regrouped into the categories that were used as input to the HRU-delineation process. Color-coded explanations describe the categories used in each map. Although a digitally unique color has been assigned to each category within individual images, not all the colors are discernible visually. Instead, color is used to associate similar data categories and to show overall spatial patterns.



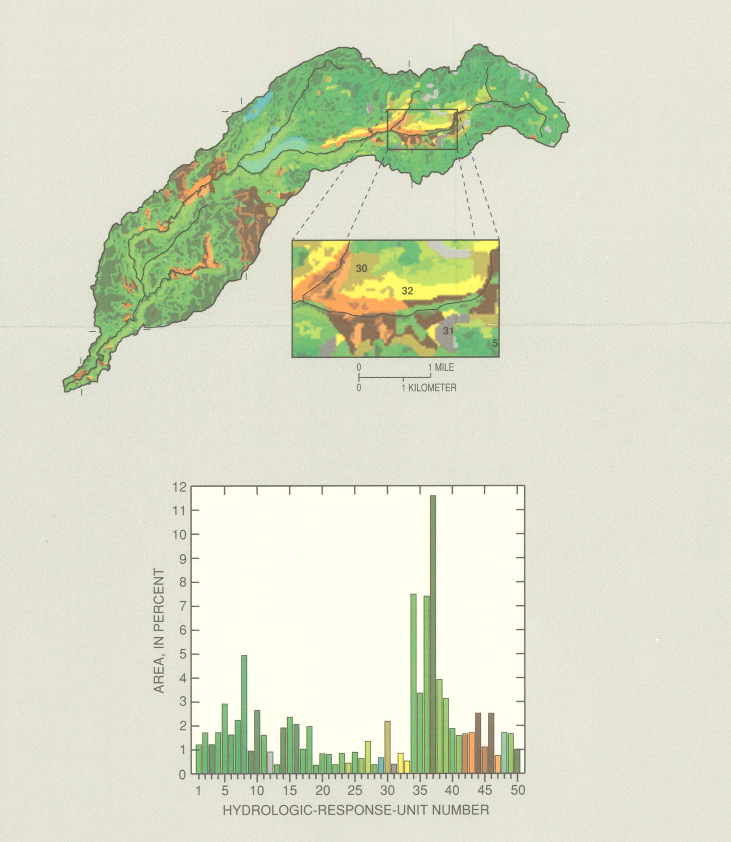








HYDROLOGIC-RESPONSE UNITS



Hydrologic-response-unit (HRU) map and histogram for North Fork American River watershed—Enlarged area shows selected HRU's that are identified by HRU number.

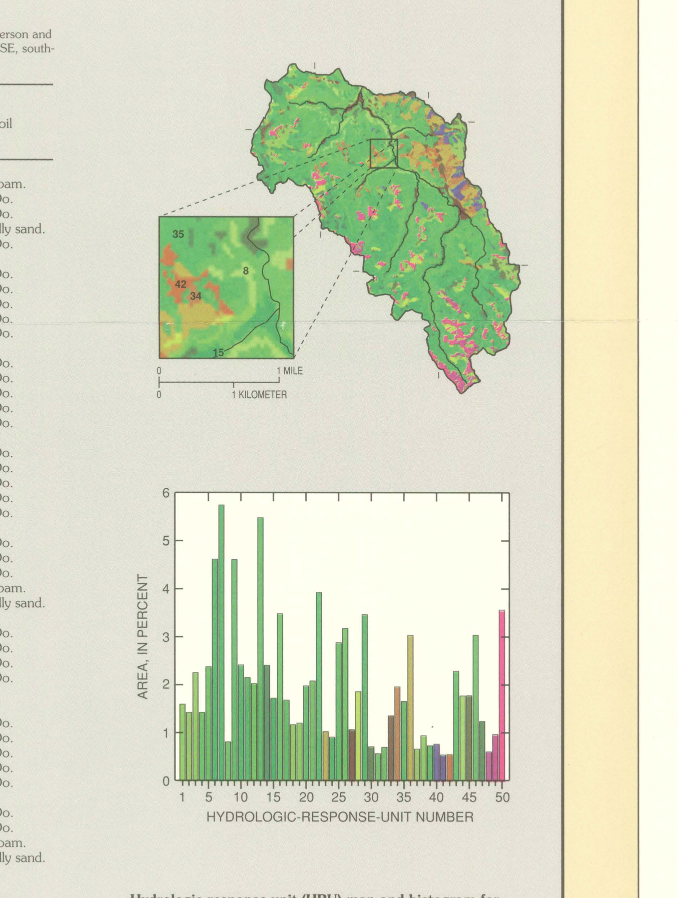
Table 1. Characterization of hydrologic-response units, North Fork American River watershed

HRU no.	Area (percent)	Land-use and land-cover classification	Slope (degrees)	Aspect	Elevation range (meters above sea level)	Soil
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

HYDROLOGIC-RESPONSE UNITS

Table 2. Characterization of hydrologic-response units, East Fork Carson River watershed

HRU no.	Area (percent)	Land-use and land-cover classification	Slope (degrees)	Aspect	Elevation range (meters above sea level)	Soil
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



Hydrologic-response-unit (HRU) map and histogram for East Fork Carson River watershed—Enlarged area shows selected HRU's that are identified by HRU number.

WATERSHED CHARACTERIZATION FOR PRECIPITATION–RUNOFF MODELING SYSTEM, NORTH FORK AMERICAN RIVER AND EAST FORK CARSON RIVER WATERSHEDS, CALIFORNIA

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1995