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HYDROLOGIC-BALANCE MODELING OF THE RATTLESNAKE CREEK WATERSHED, KANSAS

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ABSTRACT

A detailed and simple hydrologic budget for the entire Rattlesnake basin ($1,455 \text{ mi}^2$) in south-central Kansas was developed. With this budget, using minimal daily-weather input data and the soil-plant-water system-analysis methodology, we were able to characterize the spatial distribution of the hydrologic components of the water balance within the basin. A combination of classification and meteorological methods resulted in a basinwide integration methodology. The classification method consisted of dividing the basin into climatic subregions, grouping soil series into major soil associations, dividing each soil association into land-use classes such as irrigated and nonirrigated cropland and grassland, and finally superimposing a crop-rotation practice on the land usage. The meteorological method consisted of running a water-budget procedure repeatedly for each soil series, crop type, land-use practice, and climatic region combination. Area-weighted averages were then calculated to integrate the soil-plant-weather complexes on a watershed scale. Using this methodology, we found that, in addition to obvious climatic controls, soil, vegetation, and land-use factors also exert considerable influence on the water balance of the area. The available water capacity (AWC) of soil profiles plays a dominant role in soil-water-deficit development and deep drainage. Vegetation and dryland or irrigated farming particularly affect the evapotranspiration (ET) components, with ET from irrigated corn and alfalfa being two to three times that from wheat. Deep drainage from irrigated wheat fields was found to be significantly higher than that from grassland and dryland wheat; deep drainage from alfalfa is practically nil. We demonstrated how vegetation changes may affect components of the hydrologic cycle. We also showed that different portions of the watershed have different water-balance components and that use of single average values of hydrologic

variables in management practices may not be realistic.

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INTRODUCTION

Statement of problem: The Groundwater Management District No. 5 (GMD#5), which encompasses most of the Rattlesnake watershed (fig. 1), is concerned with declining ground-water supplies and potentially deteriorating water quality. Ground-water resources are being depleted as a result of continuous ground-water-based irrigation development. In the Rattlesnake watershed, five irrigation wells were in use in the 1940's compared to 1,700 wells in 1984 (fig. 2), thus currently extracting a substantial proportion from an appropriated ground-water amount of approximately 390,000 acre-ft from the Rattlesnake basin alone. During the decade from 1970 to 1980, the number of ground-water-appropriation rights issued more than triple the entire amount of ground-water rights existing during the previous three decades. Estimated natural-recharge rates in the region generally are smaller than ground-water withdrawals. In certain areas, intensive ground-water withdrawals cause saltwater from deeper formations to intrude into shallower usable ground-water supplies. Water-level-decline areas of more than 10 ft since the 1940's have occured mainly in northeast Edwards and northwest Stafford counties. In addition, average streamflows in the Rattlesnake Creek, the major stream draining the basin and fed predominantly by ground water, have been in continuous decline since the early seventies (fig. 3). A 4-yr average streamflow in the early 1960's was approximately 43 ft^3/sec (cfs) at the Macksville streamgaging station, compared to 9 cfs for a 4-yr average in the early 1980's.

As a consequence of these trends, the GMD#5 adopted a safe-yield program to safeguard and prolong the life of the ground-water supplies on which agricultural and other development depends. However, the safe-yield program depends on a single average value of ground-water recharge, which may not be representative of all areas within the district.

Detailed information on the spatial distribution of ground-water declines and recharge rates are essential to sound planning for the conservation of the ground-water resources of the Rattlesnake watershed. As the need for water continues to grow, integrated approaches in assessing and predicting the components of the hydrologic cycle are needed to fully understand and utilize the area's water supplies in an efficient manner. One such planning tool is a basinwide water-balance simulator.

Purpose of study: The purpose of this study is to develop a detailed, yet simple, hydrologic budget of the entire Rattlesnake basin, which is able to characterize the spatial distribution of the hydrologic components of the water balance within the basin using the soil-plant-water system-analysis methodology.

Location of area: The Rattlesnake basin (fig. 1) is approximately 1,455 mi^2 in area and is located within the Great Bend Prairie of south-central Kansas. It is an elongated basin approximately 95 mi long and 18 mi wide with the long axis oriented in a southwest to northeast direction. The southwest-extreme boundary has a latitude of 37.26° and a longitude of 99.50°, while the northeast-extreme boundary has a latitude of 38.17° and 97.21° longitude. Parts of Rice, Barton, Reno, Stafford, Pawnee, Edwards, Kiowa, Pratt, Ford, and Clark counties are included in the Rattlesnake basin, with Stafford, Kiowa, and Edwards counties covering more than 82% of the basin area.

BASIN HYDROGEOLOGIC ENVIRONMENT

Physiography and drainage: The Rattlesnake basin is located in two physiographic regions. The upper ~ 85% of the basin is located in the Arkansas River lowlands (Great Bend region); it is a relatively flat alluvial plain characterized by typical sand-dune topography with moderate slopes and small hills separated by small basins (Latta, 1950). The lower 15% of the basin belongs to the High Plains region, which also is a comparatively flat alluvial plain dissected by intermittent streams and exhibiting shallow depressions and gentle swells. Much of the sand-dune area of the basin is covered by vegetation, and a large part of it is farmed; the basin is primarily agricultural.

Of the approximately 1,455 mi^2 contained in the Rattlesnake Creek basin, approximately 780 mi^2 are not contributing to surface runoff (fig. 4). The Rattlesnake basin boundary was constructed based on the highest regional-topographic relief estimated from numerous 7.5-min U.S. Geological Survey quadrangle maps which cover the basin, in combination with Kansas State Highway Commission general-highway maps of counties depicting surface-drainage features.

The basin is drained by the Rattlesnake Creek which is a meandering stream flowing from the High Plains area northeasterly into the Great Bend lowlands area where it empties into the Arkansas River (fig. 4). The creek originates in three tributary forks located in southeastern Ford and northwest and north-central Kiowa counties. The three forks join in north-central Kiowa County to form the mainstream of the creek; it then flows through the remainder of Kiowa County, through Edwards County, across extreme northwest Pratt County, through Stafford County, and into the southwestern corner of Rice County where it empties into the Arkansas River, approximately 6 mi southeast of Raymond, Kansas. The channel slopes about 33 ft/mi for the first 6 mi from its source in the southeast corner of Ford County, then it flattens to a slope of about 7 ft/mi up to St. John, and 4 ft/mi below St. John, as can be inferred from the surface-topography map in fig. 5.

Wetlands contributing to the creek consist of some 60,200 acres (Ray and Coslett, 1972), most of which have high water tables, excessive mineral concentrations, and drainage problems. A portion of these wetlands are located in northeastern Stafford County and are contained within the boundaries of the Quivira National Wildlife Refuge, which is a major migratory waterfowl refuge in the central flyway. This refuge encloses approximatley 33 mi^2, of which the highly saline Big Salt Marsh comprises approximately 16 mi^2. These marshes, which are located on the water table, are broad shallow expanses of water heavily vegetated around the shoreline with a variety of prairie grasses. The Rattlesnake Creek usually is a perennial stream from a point a few miles downstream from St. John to where it turns north near Little Salt Marsh; elsewhere it is intermittent. The valley of Rattlesnake Creek ranges from less than 1/2 mi to about 2 mi in width. Average flow of the Rattlesnake Creek at its mouth is about 24 cfs.

Three surface-water gaging stations are located in the basin, one 8 mi south of Macksville with a period of record since 1959; another one upstream from Little Salt Marsh, 10 mi north of Zenith, with a period of record since 1973; and a third station 3.5 mi south of Raymond with a period of record since 1960 (fig. 4).

Hydrogeology, Pleistocene drainage history and water quality: The Rattlesnake Creek drainage area is composed, for the most part, of unconsolidated deposits of clay, silt, sand, and gravel of Pleistocene age which overlie the eroded surface of Cretaceous- and Permian-age rocks. The unconsolidated materials are comprised of undifferentiated early Pleistocene sediments (Meade formation) and late Pleistocene sediments (Sanborn formation; Latta, 1950). The state-geological map describes the Rattlesnake Creek drainage basin as dune sand with a small area of loess in the headwater area and a thin strip of alluvium adjacent to Rattlesnake Creek.

The 1984 water-table contours in the basin (fig. 6) indicate a general eastward and northeastward ground-water-flow direction. The depth to the water table is shallow, in the order of 10 to 20 ft, in the northeastern portion of the basin; however, it progressively deepens to the southwest, reaching depths of more than 100 ft in Kiowa County (fig. 7). The effects of the large ground-water-based irrigation development in the area can be seen in the 1940-1984 water-table-change map (fig. 8). The largest water-level declines in the basin occured mainly in northeast Edwards and northwest Stafford counties, where the largest irrigation development occurred.

The nature of the unconsolidated deposits permits high rates of infiltration and conversely low rates of storm-water runoff. The deposits extend to variable depths. Accordingly, the depth of saturated water-bearing materials also varies, as shown by the saturated-thickness map (fig. 9). The water table described in figs. 6 and 7 is relatively shallow, and wells yielding 1,000 gal/min are common in the basin. Latta (1950) has produced a number of typical cross sections which define the underlying aquifer.

The Rattlesnake Creek can be considered as the drain, or the overflow spillway from the underground aquifer (Strammel, 1967). As a result, Rattlesnake Creek has been for the most part a perennial stream from a point a few miles downstream from St. John, Kansas, to where it turns north near the Little Salt Marsh.

The Permian bedrock subcrops in a north-south trend in the vicinity of US-281 (fig. 10). For the most part, these deposits contain no important aquifers. However they are significant hydraulically in that they are the source of the poor-quality water, especially the Late Permian "red beds." This poor quality water rises upward and increases the water salinity of the unconsolidated aquifers in the lower reaches of Rattlesnake Creek--in particular, the Quivira Wildlife Refuge area. The mechanical details of the subsurface hydraulic relationships of the consolidated and unconsolidated deposits are not clearly understood. The average chloride load of flow in Rattlesnake Creek at its mouth is about 130 tons/day (U.S. Corps of Engineers, 1973). The water in the vicinity of the salt marshes is believed to be a natural occurrence of artesian salt waters encountered deeper to the west. Here the water flows from the edges of the bedrock formation into the overlying sediments and rises to the surface in the low areas, primarily along Rattlesnake Creek. The upper reaches of Rattlesnake Creek yield fairly good quality water with very little chloride pollution from natural sources. An electrical conductivity survey (Bidleman, 1983) of Rattlesnake Creek during 1983 (fig. 11) indicates that conductivity from eastern Edwards county to just northeast of St. John ranged from 350 μmhos/cm to approximately 625 μmhos/cm . An abrupt rise in conductivity was observed within a three-mile distance one mile east of where Rattlesnake Creek crosses US-281, with values leveling off at 3,000-4,000 μmhos/cm . Upon entering the Quivira National

Wildlife Refuge another rise in conductivity occurs with an abrupt increase to values exceeding 20,000 µmhos/cm within a two-mile stretch (fig. 11). Before discharging into the Arkansas River, however, the creek's conductivity drops to 3141 µmhos/cm . Most of the pollution is from small seeps or marshes in and near the streambed.

The present drainage system of the basin and of central Kansas in general is the result of events that took place during the Pleistocene period. The Pleistocene history of the area is very complex and is marked by the cutting and filling of deep valleys and by major changes in drainage (Frye and Leonard, 1952; Fent, 1950). During early Pleistocene time, the ancestral Arkansas River, instead of following the present course around the "great bend," is thought to have flowed eastward or southeastward across south-central Kansas. This can be seen in the bedrock map (fig. 9), where a number of west-east paleodrainage channels can be seen progressing from south to north throughout the basin.

The Pleistocene drainage patterns of central Kansas record the history of the northeastward migration of through-flowing streams from the Rocky Mountain area. According to Fent (1950), this migration was effected by successive captures of the southern trunk stream by its own northern tributaries. The captures seem to result from the difference in the debris load available in the headwater areas of the streams. Through-flowing streams originating from the Rocky Mountains, such as the Arkansas River, have filled their channels throughout Pleistocene time with coarse igneous-type gravel and sandy alluvium. This material accrued on the surface over which they flowed, causing stream avulsions and the consequent spreading of alluvial material over wide areas. In contrast, the northern tributaries to the southern trunk stream carried only the finer grained, less-permeable sediment load obtained by downcutting in their immediate headwater areas. The silt and fine sand of local origin at the northern Great Bend Prairie, with its low permeability, favored runoff and consequently more erosion and downcutting below the level of the through-flowing streams; this downcutting led to the eventual capture of the through-flowing streams. This is evident in the relative abundance of northern tributaries to the Arkansas River in central Kansas (Fent, 1950).

The overall ground-water quality of the Rattlesnake basin as indicated by the specific conductance of ground-water samples collected during the 1980-85 period is presented in fig. 12. It can be seen that the northeastern portion of the basin, especially along the Rattlesnake Creek and the marsh areas exhibit high specific conductance values, indicating salt water intrusion from the Permian formations into the alluvial aquifer. The best ground-water quality, as indicated by the lowest specific conductance values, is located in the south-central portion of the watershed (fig. 12). It is interesting to note that, in general, the better groundwater quality is usually observed in the inferred bedrock channels, while the lower ground-water quality is observed at locations overlying the bedrock ridges separating the buried channels. Thus, for example, the lower ground-water quality indicated by the 600 μmhos/cm contour in a west-to-east direction in the central portion of the watershed (fig. 12) coincides with a bedrock ridge in that location (fig. 10); the same is true with the 500 μmhos/cm contour in the southwest portion of the watershed. In contrast, the best quality ground water is observed in the south-central portion of the basin, where a number of paleochannels converge into a larger one (fig. 10). It is interesting to note that this area also coincides with the higher permeability soils (fig. 14) and higher recharge portion of the basin as will be shown later. Also, especially at the south side of the ridge outlined by the 600 μmhos/cm contour in the central portion of the basin, a better quality water appears to be in that channel despite its crossing a Permian outcrop at the eastern crossing of the watershed boundary (fig. 10). Similar observations are also expressed in Hathaway et al. (1978).

Soils: The soils of the basin can be placed into two broad categories (Hathaway et al., 1978), deep silty soils of the upland areas (High Plains region) and loamy and sandy soils of the Great Bend region. Most of the upland soils are well drained, while the sandy soils of the Arkansas River lowlands vary from well drained to poorly drained. A generalized soil-association map of the basin (fig. 13) has been produced through a combination and regrouping of Soil Conversation Service soil-survey data available for individual counties.

The soils of the basin formed in several different kinds and ages of parent material, such as sand, loess, and Pleistocene and Holocene sediments.

In early Pleistocene time, alluvium (Meade formation) was deposited over most of the basin. Soils formed in this old wind-modified alluvium include the Farnum, Blanket, and Lubbock soils (Roth, 1973). Carwile soils also formed in old alluvium.

The loess deposits consist of relatively sand-free silty material that was deposited by wind in late Pleistocene time. The dominant soils formed in this parent material are the Harney, Holdrege, and Uly soils.

Eolian material with high sand content is the major parent material of the soils in the sandhills. Most of this material was deposited during the Holocene, after the Pleistocene loess was deposited (Roth, 1973). Tivoli soils formed in fine sand, Attica and Pratt soils in loamy fine sand, and Naron soils in fine sandy loam. Tivoli and Pratt soils occur in areas of undulating to duny topography. Attica, Naron, and Pratt soils occur in areas of nearly level to undulating topography next to sand-dune areas.

The alluvium that has been deposited in the Holocene time is variable, ranging from sand to clay loam. The dominant soils in this parent material are the Hord and Zenda soils, as well as soils of the Natrustolls-Plevna association. The Natrustolls and Plevna soils were formed on floodplains and stream terraces along the Rattlesnake Creek and the Big and Little Salt Marsh areas.

Soil-profile permeability compilations from Soil Conversation Service county soil-survey reports are depicted in fig. 14. The higher permeability, and therefore higher infiltration, regions are clearly indicated. The individual soil permeabilities for all soil-profile depths and all soils composing a soil association all were proportionally averaged. This permeability map should be interpreted cautiously because of the averaging procedure. Thus, for example, a low-permeability layer in the soil profile will control vertical water movement despite the presence of highly permeable layers above and below. Also, an average value of each soil series is used irrespective of its areal or depth location within the soil profile.

Climate: The climate of the Rattlesnake drainage basin can be classified as subhumid with low precipitation, rapid evaporation, and a wide range of temperatures. The mean annual precipitation ranges from approximately 20 inches in Ford County to 26 inches in Rice County. The "effective" precipitation is considerably less than the average annual rainfall (Brown, 1973). A number of light showers occur, and much of this moisture evaporates from the soil with little or no benefit to growing crops. At the other extreme, occasional heavy downpours in spring, summer, and fall cause appreciable runoff from cultivated fields.

Lack of moisture is the most frequent limiting factor in the production of crops on dryland farms in the basin. Summer fallowing, which minimizes the effects of deficient rainfall, is a common practice. Significantly, approximately 75% of the precipitation falls during the growing season of April through September.

Two regional climate controls, the Rocky Mountains and the Gulf of Mexico, contribute to the precipitation pattern in the basin. The Rocky Mountains are effective in producing a "rain shadow" over western Kansas. The Gulf of Mexico is the principal source of moisture for precipitation in the area. Most of the total annual precipitation comes from convective shower activity (Bark, 1978). Thunderstorms move across the basin usually in the evening or at night. Rainfall is most common from 7:00 p.m. to 3:00 a.m. Forty percent of the hours that have rainfall during the 24-hr day occur between midnight and 6:00 a.m. Only 35% of the hours with rainfall occur during the peak outdoor work period of 6:00 a.m. to 6:00 p.m. (Bark, 1978).

Winters, although cold, are not generally severe, and snowfall is light with less than 20 inches of snow accumulation over the winter months (October to March). The mean annual temperature is approximately 55°F in the basin and ranges from winter lows of below -10°F to summer highs above 105°F.

Summer humidity in the region usually is low and annual surface water evaporation ranges from 50 to 85 inches with an average of approximately 60 inches. Wind velocities are commonly high, averaging from 12 to 15 mi per hour. The months of March through June are the windiest months. Occasionally high winter-wind velocities, accompanied by a typical snowfall deposition, may produce blizzard conditions.

Drought conditions have prevailed in the watershed for extensive periods of time. Perhaps the most extensive and notable period was the "Dirty

Thirties" when very low amounts of annual rainfall were received, and high winds created a multitude of dust storms. Drought periods of 3-4-yrs duration are typical in the basin (Ray and Coslett, 1972), and perhaps one of the most severe recent droughts occurred from 1964 to 1967. During 1966, only 14.00 inches (6.88 inches below normal) were received in Bucklin, 13.46 inches in Greensburg (8.47 inches below normal), 17.32 inches at Hudson (6.77 inches below normal), and at Trousdale, in Edwards County, a new record low of 9.29 inches (12.92 inches below normal) was recorded.

APPROACH

Water budget: The hydrologic equation, which is basically a statement of the law of conservation of matter as applied to the hydrologic cycle, defines the water balance. It states that in a specified period of time all water entering a specified area must either go into storage within its boundaries, be consumed therein, be exported therefrom, or flow out either on the surface or underground.

The water-balance method allows the planner to compute a continuous record of soil moisture, actual evapotranspiration, ground-water recharge, and surface runoff from a meteorological record, and some observations on the soil and vegetation.

The power of such a technique in planning is obvious. The water balance has been used for computing seasonal and geographic patterns of irrigation demand, the soil-moisture stress under which crops and natural vegetation can survive, the prediction of streamflow and water-table elevations, the flux of water to lakes, and variations of water level and salinity. The most obvious use of the water balance is in a basic description of the hydrology of a place or region. Maps can be drawn of the annual extreme water deficit or surplus or of the total annual irrigation need or ground-water runoff. Spatial patterns within a region or a large river basin can be employed in planning the distribution of resources.

The water balance also is useful for predicting some of the human impacts on the hydrologic cycle. The hydrologic effects of weather modification or changes of vegetation cover can be quickly estimated at a very early stage in planning. The water balance is, therefore, a valuable tool in the analysis of water problems in a region.

The occurrence and distribution of soil-water is a complex and integral part of any hydrological water balance. Whether the emphasis is on surface runoff, streamflow, evapotranspiration, or ground water, soil water plays a dominant role. The infiltration and evapotranspiration processes, in particular, are strongly related to the time-depth status of the soil-water profile. Most ground-water recharge occurs only after the soil profile becomes significantly wetted. Crop production is also highly dependent on the presence of adequate available soil water throughout the growing season.

Regionalizing point values:

Most direct measurements of hydrologic variables, such as soil moisture and ground-water recharge, provide only point readings and do not integrate such variables in relation to space and time. Unlike common climatological observations, comparable soil-moisture or ground-water-recharge measurements by standardized techniques are rarely available on a network basis. With the exception of runoff, which is an integrated measurement, the problem of areal representativeness of point measurements of the water balance elements exists. The high variations of site characteristics and of physical and physiological properties of plants lead to large water balance differences in vegetated surfaces.

"Classification methods," whereby homogeneous hydrologic-unit areas are identified within the heterogeneous structure of a basin, can be applied to generalize and regionalize site values of the water-balance elements throughout the whole basin (Dyck, 1985). Parameter sets can be determined for each unit area taking into account the close coincidence of geomorphological-soil- and vegetation-distribution patterns. A basic matrix of site-factor complexes can be established for the subdivision of a basin into unit areas. For the Rattlesnake basin these include local climate, main forms of land use, type of soil classes, and vegetation types.

"Meteorological methods" for estimating components of the hydrologic balance from weather data also have been proposed in order to overcome difficulties encountered with point measurements. Because these budgeting techniques keep track of changes of various hydrologic components of the water balance by using standard meteorologic observations together with some soil and vegetation information, they satisfy to some extent the need for a space-time integrating technique.

Basinwide integrating methodology:

In this study we combine aspects of the "classification method" with the "meteorological method" in order to derive a basinwide integration methodology. First the basin is divided into climatic subregions using a Thiessen-type polygon technique. Such a method seems appropriate since the study area generally is a flatland plain. The different soil series within each climatic subregion are then grouped into soil associations of similar soil properties using standard Soil Conservation Service techniques. Each soil association is further subdivided according to land usage into irrigated cropland, nonirrigated cropland, and rangeland or grassland. This classification seems appropriate since our study area is predominantly agricultural, without any forested areas. Finally, a crop-rotation practice is superimposed on the land usage. We superimposed a meteorological water-budgeting procedure on this classification scheme which is repeatedly run for each soil series, crop type, land-use practice, and climatic region. In order to avoid the averaging effects of monthly or other large time intervals on the water balance components, daily input data were adopted in this study. Area-weighted averages were then taken for integrating the soil-plant-weather complexes on a watershed scale.

The described approach is intuitive and simple. The water budgeting procedure, as will be explained in the next section, is not very involved, requires minimal data, and therefore is inexpensive to run. Therein lies the advantage of the proposed integrating technique.

VERSATILE SOIL-MOISTURE BUDGET - VB

Introduction:

Most water-budgeting techniques make use of the well-known concept of potential evapotranspiration as an indicator of the possible maximum loss of water from the soil under conditions where soil-water supply is not limiting. Penman (1963) reviewed the extensive literature pertaining to moisture loss under conditions of nonlimiting water supply. Budgeting methods for estimating soil moisture and actual evapotranspiration from vegetated soil, when water supply is at times limited, are comparatively more complicated, since they account for various soil and plant characteristics that modulate or alter the potential rate. In this report a meteorological soil-moisture budget called "Versatile Budget," which is a multigeneration evolution of the Holmes and Robertson (1959) modulated budget, is employed.

The Versatile Soil-Moisture Budget (VB) requires as minimum input only daily observed data on precipitation and estimates of potential evapotranspiration (PE). The VB computerized procedure simulates variations in daily soil-moisture content by making use of physical and biological concepts of water movement in the soil and water uptake by plant roots (Baier, et al., 1976). The VB output contains daily estimates of actual evapotranspiration (AE), soil-moisture content in several "zones" or layers in the soil profile, and water losses due to runoff and drainage. Because the data from climatological stations usually are considered to be representative of the surrounding area, we can assume that the soil-moisture estimates based on such data also are representative of the soil within this same area.

The basic structure of the budget can be described by the flow chart presented by Baier et al. (1979) shown in fig. 15. Model components can be split into evaporation functions, including all crop and soil-water extraction characteristics, and recharge functions including infiltration, drainage, runoff, and snowpack submodels.

Evapotranspiration

As mentioned previously, daily values of precipitation and PE are required as input to the VB. A variety of techniques may be used to obtain the most reliable daily PE estimates under the local experimental conditions. For the daily calculations of PE from standard climatic data, Thornthwaite's method (Thornthwaite, 1948; Thornthwaite and Mather, 1955), which is mainly based on mean air temperature, was found to be inadequate (Ritjema, 1965). Penman's method (Penman, 1948), which generally is regarded as the most sound, requires observations on vapor pressure, wind, radiation or sunshine, and temperature; these data are often incomplete or not at all available. All other methods for estimating PE involve either special measurements or empirical coefficients of limited regional applicability or are not flexible enough to make efficient use of those meteorological factors which are available for a certain location and time period.

To overcome these shortcomings, Baier and Robertson (1965) proposed a regression technique for estimating daily latent-evaporation rates which can readily be converted to PE, using the standard climatic data that are available. Minimum input-data requirements are daily maximum and minimum temperatures available from various weather stations, and total sky and solar radiation at the top of the atmosphere, (Q_o), available from standard tables (Russelo et al., 1974). The latter is used to evaluate the solar radiation incident upon the earth's surface from easily observable or measureable quantities (Baier and Robertson, 1965). If in addition to the above data, daily values of sunshine, wind, and dew-point temperatures are available, the inclusion of any one or all of these variables in different regression equations usually improves the PE estimates. This method has been used for estimating daily or monthly PE values at different locations in Canada; these estimates were compared with actual observations or estimates from Penman's formula with good reported agreement (Baier and Robertson, 1965; Baier, 1967).

In the VB, water is withdrawn simultaneously from different depths of the soil profile in relation to the rate of PE, rooting patterns of crops, different soil-moisture-release characteristics, and the available water in each of several (usually six) zones of specified water-holding capacities. PE is used as a climatic parameter of the potential (maximum) rate of evapotranspiration from a dense crop freely supplied with water. Adjustments for runoff, drainage, different soil-moisture-release characteristics for upper and lower zones, and the relative effect of the daily atmospheric demand rate on the AE:PE ratio as a function of available soil moisture also are incorporated. The general equation of the VB for estimating daily AE from PE is

$$AE = \sum_{j=1}^{n} Z_j \, k_{ji} \, \frac{S_j}{C_j} \, PE \qquad (1)$$

where AE is the daily actual evapotranspiration, PE is the daily potential evapotranspiration, Z_j is the value from a selected soil-drying curve for the jth zone, k_{ji} is the crop coefficient for root extraction in the jth zone and ith crop-growth stage, S_j is the plant-available water for the jth zone at the start of the day, and C_j is the plant-available water capacity for the jth zone.

For the purpose of this budget, plant-available soil moisture is considered to be the total amount of moisture from field capacity to permanent wilting point. The concepts of field capacity and available water capacity have been helpful in the development of improved water-management practices because of their simplicity, despite the fact that field capacity is not a precise term.

The basic concepts of soil-moisture extraction in the VB are as follows (Baier, 1967)

1. The total soil moisture available to plants is subdivided into six arbitrary "standard zones" of varying water-holding capacities, although a different number of zones also can be used (Dyer and Baier, 1980). Specifically, the six standard zones contain 5.0, 7.5, 12.5, 25.0, 25.0 and 25.0% respectively, of the total capacity for plant-available moisture of the soil profile. The adoption of "standard zones" made it possible to use one set of crop (plant or root) coefficients, k, for a particular crop in any type of soil.

This is possible because it is assumed that the uptake of available water by crops always follows a characteristic pattern which depends on plant-rooting habits. Although the extent of the root system may differ from soil to soil, the fraction of the available water extracted from the different zones remains the same under various environmental conditions. Studies of rooting charcteristics and extraction patterns by various researchers support this assumption (Vazquez and Taylor, 1958; Weaver, 1926).

2. Water is taken up by plants at a rate depending on the ratio of available water present in any zone to the capacity for available water in the same zone.
3. This rate is modified by
    a) the relationship between AE/PE and available water in the particular soil. This relationship is expressed by the adjustment factor z which characterizes different types of soil-dryness curves. The z factor is selected according to moisture characteristics of the soil;
    b) the crop (plant) coefficient, k, which resembles the most probable moisture-extraction pattern according to rooting characteristics and water consumption of plants at their different development stages.

As the soil dries, it becomes increasingly difficult for additional water to be lost by evaporation and transpiration. Different investigators have suggested that the shape of the curve of decreasing evapotranspiration with soil moisture storage can be either concave or convex. These relationships also have been shown to be controlled by soil properties, particularly texture (Baier, 1968; Salter and Williams, 1965). Baier and Robertson (1966) and

Baier (1968, 1969) have combined the various proposals for the relation between AE/PE under different values of soil-moisture content in the form of z tables which are presented in graphical form in fig. 16. Descriptions of available z-tables and some guidelines for their selection and use are given in Baier et al. (1979). An index equation for generalizing drying curves was developed by Dyer and Baier (1979).

The k-coefficient expresses the amount of water (in percent of PE) that can be removed by plant roots from different soil layers during the growing season. To simulate this water uptake, the k-coefficients change during the growing season according to crop-developing stages. The transition dates between crop stages must be read into the program for each year.

The k-coefficients employed in the VB have been determined by iterative comparisons between computed and measured soil moisture or were estimated so that extraction rates resemble the most probable crop-rooting pattern under the prevailing environmental conditions. Dyer and Dwyer (1982) suggested that observed root patterns could be a basis for development of new sets of k-coefficients for different crops. Tables of k-coefficients for different crops and growth stages are given in Baier et al. (1979).

Runoff, infiltration, and drainage

To account for water losses through runoff, a simplified relationship between soil moisture in the top zone, daily-precipitation total, and runoff is included in the VB. On days with precipitation $<$ 1.0 inch, the total amount of precipitation is considered to infiltrate into the soil. On days with precipitation $>$ 1.0 inch, runoff is estimated from equation (2)

$$\text{Runoff}_i = RR_i - I \qquad (2)$$

where $$I = 0.9177 + 1.811 \ln RR_i - 0.97 \ln RR_i \left(\frac{S_j}{C_j}\right) \qquad (3)$$

and I = amount of water infiltrating into soil

RR_i = rainfall, in inches, on day i

S_j = soil moisture in the jth zone on day preceding the rain day

C_j = available water capacity of the jth zone

and $j = 1$.

Equation (3), calculated from data by Linsley et al. (1949), was based on findings by several researchers that the initial soil-moisture content mainly affected the rate of infiltration.

In the VB, we assumed that the water infiltrating into the soil would first bring the moisture content of the top zone to field capacity and that the remainder would infiltrate into the next zone and so forth, until either all infiltration water was used up or all zones were brought to capacity. Drainage is obtained on days when the precipitation exceeds the total of AE, runoff, and the sum of moisture deficits over all zones. Any surplus of water was then designated as drainage.

In estimating AE on days with measurable rainfall, we presumed that most evapotranspiration on day i took place first and at a rate depending on the soil-moisture content at the end of day i-1, but that rainfall occurred later in the ith day. This assumption is based on the fact that rainfall over a land mass in summer is typically of a showery nature and usually associated with the formation of cumulus clouds, which reach their maximum in the afternoon after strong convection earlier in the day.

In climates where snow occurs, the computation of soil moisture includes the amount of water penetrating the soil from snow. A simple snow budget was developed for use in the VB with minimum additional data. The reader is referred to Baier et al. (1979; 1972) and Dyer and Mack (1984) for further details and additional features.

HYDROLOGIC-BUDGET IMPLEMENTATION AND SYNTHESIS

Having outlined the elements of the basin-wide integration methodology and the VB soil-moisture accounting procedure, we will now outline the implementation steps and synthesis of the hydrologic budget for the entire watershed.

a) Climatic zones: The Rattlesnake watershed was subdivided into several climatic zones, based on the distribution of available NOAA climatological stations covering the basin (fig. 4). Three precipitation stations are located in the basin, the Hudson (Hud) station covering the northeastern portion of the watershed, the Trousdale (Trou) station covering the central portion, and the Bucklin (Buck) station covering the southwestern portion of the basin. Only two temperature stations are located in the basin, one, the Hudson station, covering the upper portion of the basin and the other, the Greensburg station, covering the lower portion. Therefore, the basin was divided into the following four climatic zones, where each point in each zone is closest to the named temperature-precipitation station than to any other station: Hud-Hud, Hud-Trou, Gr-Trou, and Gr-Buck (fig. 4).

b) Soils: Thirteen dominant soil associations (composed mainly of 18 different soil series) are found within the basin (fig. 13). For each soil series, the available water capacity was determined from the appropriate county Soil Conservation Service soil survey to depths of 3 and 5 ft. The 3-ft soil depth was used to model the available soil moisture for wheat, since it has a rooting depth of approximately 3 ft. The 5-ft depth, which is generally the depth limit of the Soil Conversation Service soil surveys, was used for all other crop covers in the basin, since the highest root density of most crops is in the upper 5 ft. Soil associations, soil compositions, and available water capacities for each soil are presented in table 1.

Given the sandy nature of most soils in the basin, a z-table typical of sandy soils (curve F in figure 16) was chosen. The z-table represents the relationship between the ratio of AE/PE and the plant-available soil moisture. This ratio remains constant from 100% to 30%, below which the AE/PE ratio declines sharply as an exponential decay-form relationship with the drying of the soil.

The water budgeting procedure was initiated a month before the planting period, with the soil at its maximum available water capacity. This initial condition allowed the soil available water capacity to equilibriate with the local climatic conditions before the time period of interest. In cases of a crop rotation with a summer second crop, a near zero deficit date near the second crop planting period was chosen as the initial soil moisture condition, as will be described) below.

Table 1
Rattlesnake basin soil associations and their available water capacities

Soil Association	Soil Composition (As % of total)	(in) Available Water Capacity (5-ft depth)	(in) Available Water Capacit (3-ft depth)
1 Pratt- Tivoli (P-T)	60% 40%	4.9	3.2
2 Pratt- Carwile (P-C)	71% 29%	7.3	4.7
3 Attica- Pratt- Carwile (A-P-C)	53% 38% 9%	5.6	3.7
4 Naron- Farnum (N-F)	75% 25%	9.7	6.3
5 Naron- Carwile (N-C)	83% 17%	9.2	5.9
6 Farnum- Lubbock (F-L)	70% 30%	11.2	7.0
7 Blanket- Farnum (B-F)	56% 44%	11.2	6.9
8 Natrustolls- Plevna (Na-Pl)	65% 35%	9.7	6.1
9 Carwile- Farnum- Tabler (C-F-T)	42% 36% 22%	10.3	6.3
10 Zenda- Hord- Waldeck (Z-H-W)	43% 37% 20%	9.2	6.1
11 Harney- Uly (H-U)	89% 11%	11.4	7.2

12	Holdredge (Hol)	100%	10.8	6.7
13	Dillwyn-Tivoli (D-T)	65% 35%	4.4	2.8

c) Crops: In the Rattlesnake basin the dominant crop types are winter wheat, sorghum (or milo), alfalfa, soybeans, and corn. Common agricultural practices in the basin include crop rotation and strip farming. The following crop-rotation practices were incorporated into the water-budgeting procedure for 1982-83: winter wheat-sorghum (both irrigated and dryland), winter wheat-soybean (both irrigated and dryland), fallow-winter wheat (both irrigated and dryland), fallow-corn, and continuous alfalfa (both irrigated and dryland). Fallow conditions were simulated during the time periods before planting and after harvest of the various crops. Winter wheat, natural growth (grasses), and alfalfa have dormancy periods simulated during the winter months. For crop rotations in which two crops with different rooting depths are involved, such as the wheat-sorghum or wheat-soybean combinations, one of two procedures outlined in Appendix I.

The vegetation parameters are represented by crop coefficients. Each standard zone has a coefficient and a different set of coefficients for each stage of crop growth. At different plant-growth stages, the roots can utilize the moisture in the soil profile at different depths and rates. Crop coefficients adopted for natural growth (simulated as brome grass), alfalfa, soybean, and corn are those presented in Baier et al. (1979). Crop coefficients for winter wheat were modified from Baier et al. (1979) and Vanderlip and Brown (1974). Crop coefficients for sorghum were calculated from grain sorghum data by Jensen (1968). The various crop-growth stages and corresponding dates, as well as the crop coefficients adopted for this report, are presented in Appendix II.

d) Irrigation: Irrigation amounts for various crops were based on the Soil Conversation Service Kansas Irrigation Guide (U.S. Department of Agriculture, 1977) for the study area, in conjunction with interviews with local county Soil Conversation Service (SCS), Agricultural Stabilization and Conservation Service (ASCS) and extension irrigation specialists. Therefore, the irrigation amounts adopted for the basin crops are as shown in Table 2.

Table 2
Irrigation applications and dates

Crop	Total Irrigation(in)	Irrigation Application Dates										
Corn	15	1983 -	5/11	5/27	6/07	6/11	6/15	6/18	6/21	6/24	6/27	6/30
		7/03	7/06	7/09	7/12	7/15	7/18	7/21	7/24	7/27	7/30	
		8/02	8/05	8/08	8/11	8/14	8/17	8/20	8/23	8/26	8/29	
Alfalfa	23.5	1982 -	10/5	10/12								
		1983 -	4/20	4/27	5/03	5/08	5/13	5/18	5/23	5/31	6/06	6/09
		6/12	6/15	6/18	6/21	6/24	6/27	6/30	7/03	7/06	7/09	
		7/12	7/15	7/18	7/21	7/24	7/27	7/30	8/02	8/05	8/08	
		8/11	8/14	8/17	8/20	8/23	8/26	8/29	8/31	9/03	9/06	
		9/09	9/13	9/17	9/23	9/29						
Winter Wheat	6.0	1982 -	10/23	11/15								
		1983 -	3/11	4/10	4/16	4/25	5/02	5/10	5/17	5/24	5/30	6/06
Sorghum	12.5	1983 -	6/17	7/01	7/04	7/07	7/10	7/13	7/16	7/19	7/22	7/25
		7/28	7/31	8/03	8/06	8/09	8/12	8/15	8/18	8/21	8/24	
		8/27	8/30	9/02	9/05	9/08						
Soybean	12.0	1983 -	7/01	7/04	7/07	7/10	7/13	7/16	7/19	7/22	7/25	7/28
		7/31	8/03	8/06	8/09	8/12	8/15	8/18	8/21	8/24	8/27	
		8/30	9/02	9/05	9/08							

Center pivot sprinklers are the predominant method of water application for irrigation in the basin. Through discussions with local specialists, we concluded that it takes approximately three days on the average for a sprinkler system to complete one revolution and that approximately 0.25 to 0.5 inches of water is applied per sprinkler revolution. Therefore, in simulating irrigation applications for the daily water-budgeting procedure, water is assumed to be applied in 0.5-inch increments with successive irrigation applications at three-day intervals.

The Soil Conservation Service (SCS) Kansas Irrigation Guide (U.S. Department of Agriculture, 1977) was followed for determining the monthly distribution of irrigation applications as percentages of the seasonal totals based on 80% chance rainfall as shown in table 3. The irrigation-application dates employed in the water-balance simulations are also shown in Table 2.

e) Basinwide integration

The VB water-budgeting procedure was applied to each soilseries and crop-cover combination in each hydroclimatic zone in order to obtain daily values of the water balance components within the 1982-83 period of interest. These hydrologic components, valid for each soil series, were then combined into soil-association components using the ratio of each soil series within the soil association as the ratio of the hydrologic components within their respective soil association. Thus, for a soil association consisting of two soil series, for example,

$$\left\{\begin{array}{l}\text{composite average}\\ \text{of hydrologic component } i\\ \text{for soil series A and B}\end{array}\right\} = (\%\ \text{soil series A})\ (\text{component } i \text{ for soil A}) +$$

$$(\%\ \text{soil series B}) \cdot (\text{component } i \text{ for soil B}).$$

Table 3
Monthly distribution of net irrigation requirements,
in percent of seasonal total based on 80% chance rainfall.

Crop	April	May	June	July	August	September	October	Total
Alfalfa	5.1	12.7	17.8	24.6	21.6	13.1	5.1	100
Corn	--	1.4	22.9	43.1	32.6	--	--	100
Sorghum	--	--	1.7	44.6	41.3	12.4	--	100
Soybeans	--	--	--	24.4	52.0	23.6	--	100

Crop	October	November	March	April	May	Total
Wheat	8.2	10.9	13.6	30.0	37.3	100

The composite components of the water balance were expressed in units of length (inches) over an unspecified area. The areas of each soil associaiton and type of vegetation cover within each soil association area were then determined. Soil-association areas within the watershed were measured with an areal planimeter. However, no data specifying areas and types of different crop growth within each soil association in the basin were available. To overcome this problem, the following procedures were followed. First, all irrigation wells within the watershed were plotted from water-rights records available from the Groundwater Management District No. 5 and the Division of Water Resources of the Kansas State Board of Agriculture. The irrigated acreage and the total number of irrigation wells within each county in south-central Kansas were obtained from Cooperative Extension Service surveys and the 1982-83 Kansas Farm Facts report (1985). An average of 129 acres per well were found to be irrigated. Thus, by shading an equivalent area around each well, the irrigated cropland within each soil association of the basin was approximated.

Second, from a 1974 land-use and land-cover map of south-central Kansas (USGS Land Use Series map L-28, 1979), rangeland (grassland) within the watershed was determined assuming that these areas have not been significantly altered by 1982-83; what significantly changed was the proportion of irrigated versus nonirrigated cropland. Third, the remaining areas of the watershed represent predominantly nonirrigated cropland and pasture land. In this manner, the entire watershed, and thus each soil association, was subdivided into three different zones of vegetation cover (fig. 17); namely irrigated cropland, rangeland, and combined nonirrigated cropland and pasture land. These are tabulated in table 4.

Table 4

Land-use acreages for each soil association and climatic zone within the Rattlesnake basin

Climatic Zone	Soil Association	Total Area (mi^2)	Rangeland (mi^2)	Irrigated Land (mi^2)	Dryland Cropland & Pasture (mi^2)
Hud-Hud	P-T	49.0	24.2	5.4	19.4
	P-C	206.0	7.5	42.0	156.5
	N-F	49.9	1.0	14.1	31.8
	N-C	68.3	0.0	18.1	50.2
	B-F	12.1	0.0	1.6	10.5
	Na-Pl	59.3	59.3	.0	0.0
	C-F-T	15.2	3.5	.0	11.7
	D-T	82.2	75.2	1.0	6.0
Hud-Trou	P-T	37.4	25.8	3.6	8.0
	P-C	46.2	1.5	12.3	32.4
	N-F	33.4	.3	7.0	26.1
	N-C	63.7	1.7	15.7	46.3
	Na-Pl	19.7	19.7	.0	0.0
Gr-Trou	P-T	99.8	58.2	20.9	20.7
	A-P-C	167.8	7.7	65.9	94.2
	N-F	32.2	0.0	4.6	27.6
	N-C	64.2	0.0	25.7	38.2
	F-L	42.3	0.0	13.9	28.4
	Z-H-W	5.8	0.0	1.0	4.8
Gr-Buck	P-T	24.4	17.8	4.6	2.0
	A-P-C	62.2	1.0	21.1	40.1
	H-U	177.5	1.0	18.1	158.4
	Hol	36.5	0.0	5.0	31.5

The Kansas State Board of Agriculture 1982-83 Farm Facts report (1985) provides acreages of each major irrigated and nonirrigated crop, as well as the pasture-land acreage for each county in the basin. Three counties (Stafford, Edwards, and Kiowa) were chosen to represent all other counties in the basin based on their large areal coverage within the watershed. Ratios of specific crops were determined within the three above-mentioned vegetation types. We assumed that the ratios or percentages of different crops in any soil association were the same as those within the county.

The areal extent of irrigated cropland, combined pasture and nonirrigated cropland, and rangeland within each soil association can then be estimated using the grid-percentage technique. A grid is placed over a known area and the number of nodes covering each subarea are counted and converted into a percentage of the total nodes covering the area. The known area can then be subdivided by the percentages calculated above.

The percentages of the different irrigated and nonirrigated crops are known for the county, and therefore (by assumption), for each soil association as well as the corresponding areas of the three general types of vegetation cover (irrigated, nonirrigated cropland, and rangeland). Specific crop acreages can thus be determined. The pastureland acreage (known from Farm Facts figures for each county) was separated from the combined pasture-nonirrigated cropland category and then added to the rangeland acreage for simulation purposes, since pasture and rangeland were both simulated as natural growth or grassland in the VB procedure.

A utility program was employed to calculate the components of the water balance in acrefeet units for the different types of vegetation areas of the basin. The required input data were soil-association areas for irrigated cropland and nonirrigated cropland, ratios of specific nonirrigated crops within the respective county, and each composite hydrologic component for each soil association. The program output consisted of tables of each hydrologic component according to vegetative type and soil association, as will be discussed in the results and discussion section.

The hydrologic-component data before and after the above compilation were added by another utility program to check for input errors and to determine the range of error within the calculations. The utility program calculated the hydrologic-balance-equation error as

$$PCP + SD - ET - DR - RO = error \quad (4)$$

where PCP = precipitation

SD = soil deficit

AE = actual evapotranspiration

DR = deep drainage, and

RO = surface runoff.

Large errors were considered to be input errors and were traced to their cause and corrected. Small errors generally less than 1% of total precipitation, were considered to be due to cumulative rounding errors.

The compiled data consisting of the components of the water balance in acre-feet were then used to estimate the total-basin amounts of each hydrologic component in the balance equation by simply adding each component over the entire basin.

A separate utility program was employed to calculate the average value of the water-balance components (in units of length) for the respective areas of irrigated cropland, nonirrigated cropland, and grassland within each soil association. These data were then displayed as a series of maps to be discussed in the section on results and discussion.

The VB program was adopted to run on the Data General MV8000 (later upgraded to MV20000) minicomputer of the Kansas Geological Survey. Several modifications to the program were implemented for this study, such as increasing the number of crop stages, adding irrigation amounts separately, calculating cumulative sums of the components of the water balance, and other minor changes.

RESULTS AND DISCUSSION

Climatic, soil, crop, and land-use parameters all affect the amount and distribution of the various hydrologic variables, namely runoff, evapotranspiration, deep drainage, and soil deficit.

Climatic factors: Solar radiation and temperature greatly affect the evaporative regime of an area; consequently, evapotranspiration varies seasonally and spatially in response to these climatic factors. Thus, during the winter period the evapotranspiration regime is at its minimum. (See figs. 28-31 in temporal-patterns section below.) Local climate, irrigation, variations in transpiration rates among different crops, and soil factors exert additional influences on evapotranspiration, as will be discussed later in the sections on soil factors and crops and land use.

Precipitation, the primary water-supply source in the area, exerts a major influence on the components of the hydrologic cycle. Thus, in the northeastern portion of the basin where precipitation during the 1983 water year was lower than in other parts of the watershed (approximately 18.9 inches at Hudson compared to 23.1 inches in Trousdale and 23.5 inches in Bucklin), all hydrologic variables exhibit lower values compared to the rest of the basin, as will be shown below.

The amount, frequency, duration, and intensity of rain affects the runoff and deep-drainage hydrologic variables in particular. For example, runoff in the Greensburg-Bucklin climatic zone during the 1983 water year is higher than in the other climatic zones because of the higher frequency, intensity, and amounts of rainfall in that area compared to the other basin areas (fig. 18).

Soil factors: The basic soil parameter affecting the hydrologic variables in this model is the available water capacity (AWC) of the root zone. The soil hydraulic conductivity is incorporated indirectly in the model through the choice of a z-table. However, because the detailed physics of soil-water flow are not considered in this model, the AWC of the soil exerts the dominating influence; the AWC of each soil determines the maximum limit of actual evapotranspiration that can be extracted without additional infiltration, and the maximum soil deficit possible. Thus, given the same hydroclimatic conditions and crop cover, a soil with a relatively low AWC will exhibit a relatively small water deficit, and relatively small amounts of water will be lost through ET compared to losses from a soil with higher AWC (figs. 19 and 20). Final soil-deficit values are not monotonically cumulative, like values of precipitation, evapotranspiration, drainage, and runoff, but are a running algebraic total (with positive and negative values). The final soil-deficit total is responsive mainly to the weather conditions of the previous few weeks. The soil deficit for irrigated cropland in fig. 19 is shown to be higher than for nonirrigated cropland for soils with AWC greater than 7 inches. This seemingly paradoxical result is due to the different proportions of individual crops which cause higher or lower soil moisture deficits in the soil (see crops and land use section below).

The AWC also determines the amount of water which can infiltrate into the soil before deep drainage occurs. The AWC acts as a buffer for infiltrating water. Thus, deep drainage decreases with increasing AWC (fig. 21). Given the same initial-moisture conditions, a soil with higher AWC can absorb more infiltrating water than low-AWC soils. The soil-moisture conditions, especially the current soil-moisture deficit, affect the quantity of water that can infiltrate into and run off from the various soils. However, runoff data do not show clear trends with varying AWC because of the dominance of precipitation amounts, intensity, and frequency over soil factors (fig. 22). In some instances, however, higher runoff was produced from low-AWC sandy soils than from high-AWC clayey soils, as may be seen in dryland cropland (fig. 22), indicating that a procedure governing the rate of soil-water movement is needed in the VB program.

Crops and land use: The water balance also is greatly influenced by the plant cover and land-use practice. The largest element of the water balance is the ET component as can be seen for native grassland in fig. 23. The impact of vegetation on the hydrologic balance is complex and depends on factors such as crop coefficients, growth stages, rooting depths, soil, water, and climatic conditions as used in this simulation model.

The crop coefficients vary with the growth of the crop. Mature plants have greater ability to extract soil moisture from all soil horizons and thus have larger coefficients than young plants. If the summation of crop coefficients for the different soil layers during a growth stage is equal to 1.0, AE and PE will be equal during periods of no water deficiency. If the summation is less than 1.0, plants transpire at less than the potential rate, even under well-watered conditions. When plants mature they may transpire at greater than the potential rate because of the increase in leaf area (Dyer and

Dwyer, 1982). The crop with the largest crop coefficients is alfalfa. In addition, alfalfa is continuously grown from one year to the next with multiple harvests without replanting or land fallowing. Prairie grasses have the next highest overall crop coefficients with a long growing season. The various crop coefficients adopted in this study are presented in Appendix II. All other crops have lower crop coefficients and are grown only part of the year. Winter wheat is simulated from October to June with a winter dormant period and a summer (post-harvest) fallow period, or in rotation with another crop from June to October. Corn, sorghum, and soybean simulations are combined with either wheat or fallow conditions to complete the year's growth. Sorghum, soybean, and corn are grown during the summer months when soils are naturally drier and PE is at its highest.

Figs. 24 to 27 indicate some of the effects of vegetation and land-use practice on the various hydrologic variables. All other factors being equal, native grassland (and fallow land) produces the lowest runoff amounts, while irrigated cropland produces the highest runoff amounts, especially irrigated wheat/sorghum or soybean rotations and irrigated wheat (fig. 24), mainly because of the short rooting depth of wheat.

By far the highest actual evapotranspiration amounts from all crops considered in this study are produced from irrigated alfalfa acreages, followed by corn and irrigated wheat-soybean rotations, indicating the high primary productivity of these crops; the lowest amounts were produced from dryland wheat acreages (fig. 25). Note that native-grass evapotranspiration exceeds that of dryland or irrigated wheat followed by fallow or dryland sorghum or soybean. This is because of the deeper rooting system of grassland and its longer lifecycle.

The highest soil-moisture deficit is developed in dryland wheat-soybean rotation fields, followed by corn, alfalfa, and native-grass acreages. The lowest soil deficits are developed in irrigated wheat-sorghum fields (fig. 26). A large proportion of high-soil-moisture-deficit causing crops may result in an overall higher soil-moisture deficit for irrigated cropland than for the nonirrigated cropland in the same climatic zone. For example, as shown in fig. 19, winter wheat which causes a very low soil-moisture deficit, comprises 73% of the nonirrigated cropland, while the highest-soil-moisture-deficit- causing crops, such as corn and alfalfa, are either absent or practically nil (dryland alfalfa in the HUD-TROU and GR-TROU climatic zones comprises approximately 1% of the dryland crops). In contrast, the irrigated cropland includes as the major crops, the highest soil-moisture deficit causing crops such as the wheat-soybean rotation, corn and alfalfa, at an overall proportion of 67% of the total irrigated crops.

The highest deep drainage occurred in irrigated wheat fields, mainly because of the shallow rooting depth of wheat, while the lowest deep-drainage values occured in alfalfa and grassland acreages (fig. 2~~4~~ 27). Interestingly, decreased amounts of deep drainage in the lower precipitation northeastern portion of the basin (fig. 23) are from grasslands, indicating the dominant effect precipitation and vegetation exert on deep drainage.

The scatter of points in all the above graphs is due to precipitation and temperature variations in the central and southwest portions of the watershed from which these data were derived.

<u>Temporal distributions of climatic and hydrologic variables</u>: The time distribution of important climatic and hydrologic components (maximum and minimum air temperature, precipitation plus irrigation, soil-moisture deficit of the root zone, deep drainage and runoff, as well as cumulative values of

potential and actual evapotranspiration and precipitation plus irrigation) are graphically presented for selected plant covers growing in a "typical" soil association from the central portion of the basin (figs. 28 through 31). Compare, for example, the dryland wheat-fallow sequence with the prairie grassland which possesses the deeper rooting system (figs. 28 and 29). Note the lower deep drainage and higher soil deficit in grasslands compared to wheat. Also compare the different characteristics of irrigated wheat-sorghum sequence with those of irrigated alfalfa (figs. 30 and 31), where in fact AE exceeds the VB-calculated PE most of the time; the minimal amounts of deep drainage in alfalfa; and the higher soil deficit compared to that of wheat (of course keep in mind the shallower rooting depths of wheat). Also note that additional irrigation during the summer months for sorghum contributed practically nil for deep drainage. From all these figures, the timing of deep drainage events can be concluded to occur during spring. The high water consumption of grasslands, as reflected by their high crop coefficients, prevents large deep-drainage amounts during spring when most deep drainage occurs, in comparison to other crops.

Areal distribution of hydrologic variables: The distribution of deep drainage, evapotranspiration, and runoff over the entire Rattlesnake watershed resulting from the methodology adopted in this study is shown in figs. 32 to 34, respectively. The same, and additional information also is tabulated in Appendix III, which indicates the amounts, in inches, of the hydrologic variables mentioned above, separated by hydroclimatic region, vegetation cover, and soil association. Appendix IV tabulates the amounts of the above-mentioned hydrologic variables in acre-feet as a function of hydroclimatic zone, soil association, and vegetation cover-land use. Figs. 32-34 represent pictorial views of the complex spatial variation of the various hydrologic parameters. The specific values from these maps can be found in Appendix V, where the values of the various hydrologic variables, in inches, are compiled according to irrigated crops, nonirrigated crops, and natural growth, all as functions of soil and hydroclimatic complexes.

The areal distribution of deep drainage, and thus potential ground-water recharge, is indicated in fig. 32. The highest drainage values (6 to approximately 8.5 inches) occur in the south-central portion of the watershed. This high distribution was the result of the combination of low soil-moisture capacity of the Pratt-Tivoli and Pratt-Attica-Carwile soil associations (see table 1), the high irrigation, and relatively high precipitation in the lower two-thirds of the watershed (compared to the northeastern portion of the watershed). The high deep-drainage region also coincides with the high soil-permeability region of the basin (fig. 14). This high deep-drainage region is corroborated by the fact that no water-level declines (in fact water-level rises) have been observed in this area since the 1940's; water-level declines have been observed in most other locations in the watershed (fig. 8). Note, however, that the water table in this high deep-drainage area is generally in the order of 50-100 ft below land surface (fig. 7), and the deep drainage indicated by fig. 32 is from the bottom of the soil profile, normally 5 ft deep. The drainage figures in this case should be considered as indicating maximum or potential recharge under 1982-83 climatic and land-use conditions because of the likelihood of additional water losses. These losses can be due to 1) deeper-rooted plant usage; 2) subsurface lateral water movement due to thick clay layers which may redirect the downward soil-water flow laterally away from the input area and eventually towards the surface farther away; or 3) the absorption by the available water storage capacity of the deeper unsaturated zone.

The smallest deep drainage values (in the range of 0-2 inches) occurred in the northeastern portion of the watershed because a significant portion is natural grassland (which possesses a deep rooting system and a long active lifecycle) with no significant irrigation development, relatively high moisture-capacity soils, such as the Natrustolls-Plevna soil association, and lower precipitation compared to the lower two-thirds of the watershed for the water-accounting period. Deep-drainage values in this area likely correspond to the actual ground-water recharge because the depth to the water table is generally shallow, in the range of 10-20 ft.

The distribution of actual evapotranspiration water loss is shown in fig. 33. Actual evapotranspiration is a complex function of climatic variables as reflected in the PE calculations, soil-moisture and soil-water capacity, z-table, and k-coefficients. The highest evapotranspiration losses are easily recognized to occur in combinations of high-moisture-capacity soils and irrigated crops, while the lowest evapotranspiration losses occur in nonirrigated cropland and low-soil-moisture-capacity areas.

The distribution of surface runoff is shown in fig. 34. Runoff is greatly affected by the amount, intensity, and frequency of precipitation, in addition to geomorphological factors. In the Greensburg-Bucklin climatic region, where the intensity and frequency of rainfall was higher than in other portions of the watershed (fig. 18), the largest surface runoff values of one inch or higher are observed. Also note that this region is mostly covered with dryland wheat with a shallow-rooting depth, which also contributes to higher runoff values given the appropriate precipitation conditions.

The lowest runoff values (.2-.5 inches) occur in the northeast portion of the watershed, which is covered to a large extent by grassland (with deeper rooting depths), nonirrigated crops, and relatively high soil-moisture capacities in combination with relatively low precipitation.

In general, the effect of irrigation is to significantly increase evapotranspiration and also increase deep drainage, as can be seen in figs. 20 and 21. For summer crops, such as sorghum and soybeans, as well as alfalfa, most of the irrigation amounts are spent in evapotranspiration activities, and negligible amounts for deep drainage. The effects of grasslands are reduced deep drainage and runoff and increased soil-moisture deficits compared to cropland acreages (fig. 19, 20, and 21). From the areal distribution of the various components of the water balance, we can conclude that single average values of hydrologic variables used in management practices are not realistic and that a spatial-discrimination attempt in managing water resources is in order.

Predictive capabilities A computerized water-balance procedure can be used to predict human and natural impacts on the hydrologic cycle. The hydrologic effects of vegetation changes, weather modification, extreme weather conditions, and so on can be readily estimated during the planning process. Thus, had the Rattlesnake basin been entirely covered by prairie grasses, as it probably was during predevelopment times, and the 1982-83 precipitation pattern and amount prevailed, the overall basin deep drainage would have been 1.13 inches, compared to 0.15 inches if alfalfa were planted exclusively in the basin. If the entire basin were planted with dryland wheat under 1982-83 precipitation conditions, the overall basin deep drainage would have been 5.1 inches. Such figures can be arrived at by multiplying the deep-drainage amounts for the corresponding crop and soil complex (Appendix III) by the planted area (Appendix IV), summing up these figures, and dividing by the area of interest (Appendix VI). Similarly the hydrologic effects of manipulating the proportion of various crops and the amounts of irrigation within any soil-association area can thus be assessed.

Provided that future precipitation patterns can be established, then, under known vegetation and land-use practices, various components of the water balance, such as deep drainage and surface runoff, can be readily predicted within the basin using the presented methodology. An example of the relative effects of an ~ 19% precipitation difference on the components of the water balance, keeping the precipitation time-pattern constant, is shown in fig. 23. This figure represents actual grassland data from the northeastern basin area which received 18.9 inches of precipitation and the rest of the watershed which received an average of 23.3 inches. Note the large increase in deep drainage in the higher precipitation region, especially in low-AWC soils, compared to the deep drainage in the lower precipitation region.

Additional assumptions Many assumptions are inherent in the simplification of complex problems such as simulating the water balance of the Rattlesnake watershed. The most important variables contributing to the water budget are believed to be accounted for in this study, and the various assumptions and simplifications made are believed to contribute only minor errors in comparison to the scale and totality of the problem. In addition to the simplifications and assumptions already mentioned in the "Versatile soil-moisture Budget-VB" section and in the irrigation and basinwide integration methodology subsections of the "Hydrologic budget implementation and synthesis" section, the following main assumptions also are made, or expanded here:

The rooting depths of most crops do not exceed 5 ft because most soil descriptions in Soil Conservation Survey soil manuals do not extend beyond that depth. The largest error from this assumption would probably be for alfalfa which may have roots extending to more than double that depth. A 5-ft rooting depth for alfalfa underestimates AE and in high precipitation areas may overestimate deep drainage. However, alfalfa represents only 5.1 % of the basin vegetation cover. Even at the modeled rooting depth of 5 ft, alfalfa is extremely efficient in extracting most of the available moisture capacity of the soil profile, thus leaving negligible amounts to drain below the modeled root zone. Only AE would be appreciably affected by the small rooting depth, the error being limited to the additional available-water capacity of the deeper soil profile.

In the calculations presented here, the basic soil unit is the soil series (soil type) and not the soil association. The various soils are modeled separately and the budget parameters are subsequently averaged into soil association budget parameters. The assumption is that the soils, as modeled, are not affected by surrounding soil series. This assumption is due to the nature of the VB procedure which can model only one soil type, one vegetative type, and one hydroclimatic regime at a time. The water budget calculates hydrologic variables in units of length over an unspecified area which needs to be estimated and integrated separately.

We reiterate here that the water-balance results presented are for an integrated system. For example, the water-balance parameters are calculated in relation to each other, but only within a particular soil type-vegetative cover complex. The soil combinations all are calculated separately and then merged together as areal averages. Similarly, the crop rotations are calculated separately and merged together to complete a full year as explained in Appendix I.

Natural growth or grassland is considered to be equivalent and is represented by brome grass. Since the natural state of the basin is prairie and the wooded areas are minimal, no significant problems are anticipated with this assumption.

The z-table chosen for the basin (curve F, fig. 16) simulates sandy soils, thus providing an index to soil-hydraulic conductivity. Soils with significant clay content would not release water as readily as sandy soils with the consequence that AE would be lower.

Variations in topographic elevation across the basin are not explicitly considered in this VB procedure. This is particularly troublesome in noncontributing watershed areas for surface runoff. The resulting VB runoff estimates from noncontributing areas are not taken into account assuming, based on actual observations, that the excess-water puddles created eventually become part of the evapotranspiration process. However, because the basin is flatland, the disadvantage of ignoring surface slope in the VB may not be significant.

Deep drainage below the modeled root zone is assumed to eventually be incorporated into the water table. As mentioned previously, this may be a reasonable assumption in cases of relatively shallow water table. However, drainage restrictions due to very shallow water table areas are not considered; here the water may not be able to drain below the rooting depth. This limitation may affect areas very close to flowing stream courses and marshlands.

VERIFICATION OF RESULTS

The validity of the estimates from the VB has been extensively verified by comparison with measured data, and by evaluating the efficiency of such estimates in explaining variations of observed crop yields (Baier and Robertson, 1968; Baier, 1972; Baier et al. 1976; Ravelo and Decker, 1979; Serilio and Brown, 1971; see further references in Baier et al, 1979, and Dyer and Mack 1984).

For the present study we compared runoff and deep drainage results predicted by the VB procedure with measured streamflow and groundwater recharge data for the Rattlesnake Watershed. The streamflow data at the Macksville, Zenith and Raymond gauging stations were plotted as daily hydrographs using the Surface II graphics system. The streamflow hydrographs were separated into baseflow and surface runoff components using standard graphical procedures (Linsley et al, 1982; Busby and Armentrout, 1965). Table 5 presents the results of this separation procedure for the 1983 water year (October 1, 1982 to September 30, 1983).

TABLE 5
Rattlesnake Creek streamflow hydrograph separation (1983 water year)

Gaging Station	Baseflow	Surface Runoff (10^6 ft^3 per year)	Total Streamflow
Macksville	256.258	131.414	387.672
Zenith	689.439	250.174	939.613
Raymond	919.900	335.107	1,255.007

Note that a large proportion of the Rattlesnake watershed does not contribute to surface runoff (fig. 4). Also note that the West, Middle, and East Forks of the Rattlesnake are ephemeral streams with quartz-dune-sand stream bottoms. Continuous flow of the Rattlesnake is not seen until after the three forks combine into the Rattlesnake main branch near the north edge of the Kiowa County line.

The surface runoff for the 1983 water year calculated from the stream hydrograph near the mouth of the creek (Raymond station) is 335.1 X 10^6 ft^3 (table 5). The total runoff calculated from the VB budget for the area of the basin contributing to surface runoff (from the Raymond station to the northern edge of the Kiowa County line, fig. 4) is 384.0 X 10^6 ft^3. This figure is calculated by multiplying the percentage area of each soil association contributing to surface runoff in each climatic zone by the composite VB-runoff estimate for that soil association. These products are then summed to arrive at the total runoff value for the contributing area of the watershed, as shown in Appendix VII. The resulting VB-runoff estimate is 12.7% higher than the hydrograph estimate. This is a satisfactory estimate given the approximate nature of both the hydrograph separation and the VB procedures. The surface runoff estimate for the abovementioned contributing-watershed area amounts to approximately 0.5 inch. Such an estimate is in accordance with average annual runoff values for that area published in the Kansas Water Atlas (Kansas Water Resources Board, 1967).

The Soil Conservation Service runoff-estimation method (U.S. Department of Agriculture, 1972) was also applied (Sophocleous and McAllister, 1985, unpublished typescript) for the surface-runoff-contributing area between the Raymond and Macksville streamgaging stations (234 mi^2). First, the contributing areas were determined. Then, the rangeland (grassland) and cropland areas within the contributing watershed area were determined, and their ratio was considered as an average value applicable to the soil association (the estimated ratio was 37% cropland, 63% rangeland for that portion of the watershed). Each soil group was then assigned a curve number depending on the ground cover and time of year (growing or dormant season). The daily precipitation for the 1983 water year was examined for storm events of 1 inch or more, assuming that events of less than 1 inch would not produce surface runoff. Each such storm event was used in calculating a resulting runoff value. Finally, these runoff values were added together to produce a composite total for the year. A runoff estimate of 0.42 inches was derived within the contributing area, using the average curve number procedure (U.S. Department of Agriculture, 1972). This estimate is comparable to the VB estimate of 0.5 inches.

While streamflow and runoff values represent integrated measurements, estimates of ground-water recharge from a number of sites within the watershed represent point measurements. In a concurrent study of natural ground-water recharge in the Great Bend aquifer (Sophocleous et al., in preparation; Sophocleous and Perry, 1984; 1985), five recharge sites, three of which are within the Rattlesnake Creek basin, were instrumented in the latter part of 1984 with recording precipitation gages, observation wells (some with continuous recorders), neutron access tubes, and tensiometers. More than a year's worth of data were collected on a weekly basis and recharge estimates for 1985 were made. Two of the sites are located in the northeastern portion of the watershed (site 1 at SESESE sec.13, T.25S., R.16W., and Site 2 at SWSWSE sec.36, T.23S., R.13W.), while a third site is located in the central portion of the basin (site 3 at NWNWNW sec. 7, T.21S., R.11W.).

Ground-water recharge at the sites was calculated as the residual term from the water balance equation (5) applied on a weekly basis,

$$R = PCP - AE - \Delta S \qquad (5)$$

where R is ground-water recharge, PCP and AE are the weekly precipitation and actual evapotranspiration, respectively, and ΔS is the change in moisture storage of the unsaturated zone over the weekly time interval.

Results from sites 1 and 3 for 1985 were of a "less than" or potential (or maximum) nature because of missing records due to instrument malfunctions, primarily related to the neutron probe employed. Thus, the estimated recharge for site 1 during 1985, based on field-measured data, was less than a maximum value of 6.0 inches, while the VB estimate (fig. 32) was 3.3 inches for grassland and 7.0 inches for irrigated cropland in the same area. Since the site-1 area is located within grassland (pasture near an irrigated field), the VB figure is within the range of the field measurement. The field-estimated recharge figure for site 2 during 1985 was 3.25 inches. The VB estimate of deep drainage (fig. 32) was 3.8 inches for dryland cropland in that vicinity and 4.7 inches for irrigated cropland in the same area. This VB estimate is in satisfactory agreement with the field measurements because site 2 is located in a nonirrigated cropland locality near an irrigated field. Finally, the 1985 field-estimated recharge for site 3 which is located in a nonirrigated cropland vicinity, is less than a maximum value of 8.6 inches, while the VB estimate for dryland cropland in that vicinity is 3.8 inches and for irrigated cropland is 4.7 inches. Also the timing of the predicted VB deep drainage generally coincide with the field-measured recharge events, which occur mainly during the spring season.

In general, all the estimated deep-drainage results are within the same order of magnitude as the measured ground-water-recharge amounts, indicating that the VB procedure performed satisfactorily in the basin, given the difficulties of recharge estimation. The field estimates of recharge and the VB deep-drainage estimates are not for the same year because recharge-related data are not available for years prior to 1985. The precipitation in the Rattlesnake watershed ranged from 19.0 to 23.5 inches during the VB accounting period of water-year 1983, while the precipitation at the three above-mentioned sites within the basin ranged from 21.5 to 29.0 inches during calendar-year 1985. The VB estimates represent areal averages over a soil association-plant cover complex, as opposed to the point values of onsite measurements. As Baier and Robertson (1966) stated ". . . it is doubtful whether spot readings of soil moisture, even if replicated, represent adequately the distribution of soil moisture in a manner that the time and space-integrating estimates from moisture budgets are expected to do." Although a difference between deep drainage and ground-water recharge exists, this difference may be negligible in this case because the depth to the water table at the measured sites was shallow, generally less than 25 ft, thus minimizing the additional loss of water as it percolates below the root zone towards the water table.

Finally, detailed weather data at the Sandyland station for 1982-83 were discovered in manual files at the station near the end of this study. These data provided an opportunity to compare the regression method for estimating potential evapotranspiration used in the VB procedure with the more elaborate Penman method. Fig. 35 shows a comparison of monthly PE estimates using both methods. The PE patterns are similar with a tendency towards PE underestimation by the VB procedure during the winter months and overestimation during the summer months. The total water-year PE estimates range within 10-13% of each other (fig. 35), thus providing an excellent comparison given the bare-minimum nature of the input data for PE estimation used in the present study.

CONCLUSIONS AND RECOMMENDATIONS

The validity and performance of the VB procedure for providing sufficiently accurate estimates of daily soil moisture on a zone by zone basis and for other applications of relatively small scale (field plot, farm size) has been extensively covered in the literature. The performance of the budget in combination with the integration methodology presented here also has been shown in this report to provide a suitable tool for regional estimates of various hydrologic variables from standard climatic, soil, and crop data for agricultural watersheds. We also demonstrated that because of the significant differences among irrigated and dryland croplands and grasslands, the spatial resolution of hydrologic variables within the basin into these three categories, as adopted in the present study, is a simple, intuitive, and realistic approach. Also the VB procedure employed in this study is simple to understand and use. Thus, the objective of this study to develop a sufficiently detailed and relatively simple hydrologic budget that was able to characterize the spatial distribution of the hydrologic components for the entire Rattlesnake basin, has been achieved.

For the Rattlesnake basin, precipitation is demonstrated to be the principal natural-water supply, while evapotranspiration is the major water-depletion process. Both these water-balance components dominate and control all other hydrologic variables such as runoff, deep drainage, and soil deficit. Compare, for example, the effect of precipitation on deep drainage, and the large difference in values of the ET component compared to the soil deficit, deep drainage, and runoff variables (fig. 23).

Soil factors, such as the available water capacity of soil profiles, play a dominant role in soil-moisture deficit development; the larger the AWC, the larger the resulting soil-moisture deficit, given appropriate and equal conditions (fig 19). Soil factors also significantly affect deep drainage; the lower the AWC the higher the deep drainage, everything else being equal (fig. 21).

Vegetation and land use (i.e. dryland or irrigated farming) play a significant role in the components of the water balance, especially in the ET process. Thus, evapotranspiration from irrigated alfalfa acreages is approximately triple that from wheat-fallow fields, and ET amounts from corn fields are approximately double that from wheat-fallow acreages. ET from grasslands is almost 30% higher than from dryland wheat-fallow fields. Most of the irrigation amounts for summer crops, such as sorghum and soybean, are spent in ET activities with negligible amounts for deep drainage. Deep drainage from irrigated wheat fields is significantly higher than from dryland wheat fields and minimal from alfalfa fields (fig. 27). Dryland wheat-soybean rotations and corn fields create significantly higher soil deficits compared to irrigated wheat-sorghum fields, assuming that farmers irrigate the appropriate amounts for each crop. Everything else being equal, the lowest runoff values were produced from prairie grasslands and alfalfa fields. We therefore conclude that the effects of vegetation and land use are too significant to be ignored, as sometimes is done by a number of hydrologists. Because of the significant role vegetation seems to play in water-balance studies, we also advocate that more research efforts into root distribution, soil-water root interaction, and generally the biological phase of water-balance computations are in order.

Ample room exists for improvements in the VB procedure, such as updating and improving the runoff function; providing a soil-water-movement rate aspect; incorporating surface slope and surface-water storage functions, interception storage, and free-water evaporation; accounting for depth to the water table; improving the snow budget, and so on. However, one should always strive not to lose one of the main advantages of the VB, namely that it is not a very involved procedure and therefore easy to use. Although a purely physical approach is often preferable, it is not usually possible, especially for large-scale problems, because hydraulic-conductivity and root-distribution functions, among others, are difficult to measure, spatially highly variable, and rarely available.

The methodology presented here can be used to predict human and natural impacts on the hydrologic cycle. We showed, for example, that decreasing the acreages of alfalfa and corn (the high water consumption crops) and increasing the winter wheat acreages in the basin would result in significant increases in deep drainage and ground-water recharge. Thus, we have demonstrated how vegetation changes may affect components of the hydrologic cycle and how such an approach can be used as a demonstration and predictive tool with obvious management capabilities.

We showed that the south-central portion of the watershed produced the highest amounts of deep drainage while the northeastern portion produced the least amount. The highest runoff values were in the southwestern portion of the watershed, while the lowest runoff amounts were produced in the northeastern portion of the watershed. Thus, it may be readily recognized that single average values of hydrologic variables used in management practices may not be realistic, and that some spatial distribution or zonation in managing water resources is in order.

Because of the dynamic nature of the hydrologic system, the results presented herein are not permanent and may change with land-use practices, vegetation changes, and especially hydroclimatic factors. Data were presented in this report indicating the magnitude of such changes to be expected. Also note that the results and conclusions presented here are specifically for the 1983 water year, and although the presented patterns are believed representative of the basin, care must be taken in extrapolating and overgeneralizing the results without due consideration to the dynamic nature of the water balance in the area.

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APPENDIX I: Rooting-depth procedure

For crop rotations in which two crops with different rooting depths are involved, such as the wheat-sorghum or wheat-soybean combinations, the following two procedures were adopted for simulating crop rotations.

i) If a date close to planting of the second deeper-rooted crop in the crop rotation (that is, within approximately a week) occurred in which the soil deficit was zero or close to zero, the simulation of the second crop started from that day, but the water-budget accounting was initiated from the original planting day. The budget accounting for the first crop continued until the planting of the second crop. In such cases, we assumed that the additional rooting-depth footage was at its maximum available water capacity (MAWC).

ii) Alternatively, if no date close to planting occurred in which the soil deficit was close to zero, the soil deficit was manipulated from the shallower to the deeper rooting depth as follows: the available capacity of the water-deficient shallower-rooting-depth profile was totaled and the ratios of available-water capacity (AWC) of each zone relative to the soil profile's total water capacity was calculated. The MAWC for the additional rooting-depth footage was then calculated. Assuming that this additional rooting-depth footage has the same percentage of AWC as the one in the last (6th) zone of the shallower rooting-depth profile, the total AWC of the additional rooting-depth footage was calculated and added to the shallower profile's total AWC. This total AWC finally was distributed over the six standard zones in the ratios of AWC found for the shallower profile. This second procedure was the one most frequently employed.

APPENDIX II

Crop Growth Stages and Crop Coefficients

			Soil Zone					
Plant	Starting Date of Crop Stage	Crop Stage	1	2	3	4	5	6
Prairie Grasses	82/10/01	Growth	.55	.19	.17	.08	.03	.01
	82/11/30	Dormancy	.50	.20	.10	.04	.02	.01
	83/03/01	Growth	.55	.19	.17	.08	.03	.01
Winter Wheat	82/10/01	Fallow	.40	.15	.12	.10	.02	.01
	82/10/17	Planting to emergence	.40	.15	.12	.10	.02	.01
	82/11/30	Dormancy	.40	.15	.12	.10	.02	.01
	83/03/01	Spring growth to jointing & heading	.17	.13	.10	.07	.04	.02
	83/05/01	Heading to soft-dough	.33	.15	.14	.12	.01	.05
	83/05/20	Soft dough to ripening & harvest	.22	.13	.12	.10	.06	.04
	83/06/15	Fallow (Post Harvest)	.40	.15	.12	.10	.02	.01
Corn	83/05/01	Planting	.40	.15	.12	.10	.02	.01
	83/05/11	Emergence	.40	.20	.13	.12	.03	.02
	83/08/05	Tasseling	.40	.25	.15	.12	.10	.03
	83/08/20	Silking	.40	.30	.20	.15	.10	.05
	83/09/30	Ear Emergence	.40	.30	.20	.15	.07	.03
Soybean	83/06/16	Planting	.20	.15	.15	.10		
	83/06/23	Emergence	.20	.20	.15	.10	.05	.05
	83/08/15	Flowering	.15	.15	.10	.10	.10	.05
	83/08/30	End of Flowering	.15	.15	.20	.20	.15	.10
	83/09/15	Maturity	.10	.15	.20	.15	.10	.10
Sorghum	83/06/16	Planting	.14	.05	.04	.03	.01	.00
	83/06/23	Post planting	.30	.15	.09	.08	.02	.01
	83/08/15	Heading	.37	.23	.13	.11	.09	.03
	83/08/30	Blossom	.20	.16	.10	.08	.05	.02
	83/09/15	Hard Dough	.07	.06	.03	.02	.01	.01
	82/10/01	Full Cover	.50	.25	.25	.20	.18	.12
	82/11/20	Dormancy	.50	.20	.10	.04	.02	.01
	83/03/01	Spring Growth	.50	.20	.15	.12	.08	.05
	83/04/01	Full Cover	.50	.25	.23	.22	.15	.10

	83/04/09	1st cut & early growth	.50	.22	.18	.15	.15	.10
Alfalfa	83/05/20	Full cover	.50	.25	.25	.20	.18	.12
	83/06/10	2nd cut & early growth	.45	.25	.20	.20	.20	.15
	83/07/10	Full cover	.50	.25	.25	.20	.18	.12
	83/08/01	3rd cut & early growth	.45	.25	.20	.20	.20	.15
	83/09/05	Full cover	.50	.25	.25	.20	.18	.12
	83/09/26	4th cut & early growth	.45	.25	.20	.20	.20	.15

APPENDIX III

PRECIPITATION AND IRRIGATION (INCHES)

GRASS	WHEAT	IRR. WHEAT	WHEAT TO SORGHUM	IRR. WHEAT TO SORGHUM	WHEAT TO SOYBEANS	IRR. WHEAT TO SOYBEANS	IRR. CORN	FALLOW TO IRR. SORGHUM OR IRR SOYBEANS	IRR ALFALFA	ALFALFA		
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	CFT	
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	DT	
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	NaPl	HUD-HUD
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	PT	
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	PC	
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	NF	
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	NC	
18.88	18.88	24.88	18.88	37.38	18.88	36.94	33.88	31.38	42.38	18.88	BF	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	35.58	46.58	23.08	PC	HUD-TROU
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	35.58	46.58	23.08	NaPl	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	35.58	46.58	23.08	PT	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	35.58	46.58	23.08	NF	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	35.58	46.58	23.08	NC	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	34.58	46.58	23.08	PT	GR-TROU
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	34.58	46.58	23.08	APC	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	34.58	46.58	23.08	NC	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	34.58	46.58	23.08	ZHW	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	34.58	46.58	23.08	FL	
23.08	23.08	29.08	23.08	41.58	23.08	41.14	38.08	34.58	46.58	23.08	NF	
23.52	23.52	29.52	23.52	41.52	23.52	41.08	38.52	35.02	47.02	23.52	APC	GR-BUCK
23.52	23.52	29.52	23.52	41.52	23.52	41.08	38.52	35.02	47.02	23.52	H	
23.52	23.52	29.52	23.52	41.52	23.52	41.08	38.52	35.02	47.02	23.52	HU	
23.52	23.52	29.52	23.52	41.52	23.52	41.08	38.52	35.02	47.02	23.52	PT	

APPENDIX III

DRAINAGE (INCHES)

GRASS	WHEAT	IRR. WHEAT	WHEAT TO SORGHUM	IRR. WHEAT TO SORGHUM	WHEAT TO SOYBEANS	IRR. WHEAT TO SOYBEANS	IRR. CORN	FALLOW TO IRR. SORGHUM OR IRR SOYBEANS	IRR ALFALFA	ALFALFA		
.00	2.67	7.83	2.77	7.88	2.73	7.93	3.23	1.96	.00	.00	CFT	
1.54	4.05	8.88	4.16	8.93	4.11	8.98	4.61	3.78	.52	.31	DT	
.07	2.74	7.85	2.84	7.90	2.79	7.22	3.29	1.96	.00	.00	NaPl	HUD-HUD
1.28	3.97	8.78	4.07	8.83	4.02	8.87	4.60	3.64	.28	.04	PT	
.22	3.07	7.94	3.17	7.99	3.12	8.04	3.64	2.37	.00	.00	PC	
.00	2.72	7.84	2.83	7.90	2.78	7.95	3.25	1.95	.00	.00	NF	
.00	2.79	7.85	2.89	7.90	2.84	7.95	3.31	2.01	.00	.00	NC	
.00	2.57	7.83	2.68	7.88	2.63	7.93	3.13	1.83	.00	.00	BF	
.91	5.72	10.86	5.78	11.13	5.70	10.80	5.11	5.11	.00	.00	PC	HUD-TROU
.35	5.27	10.32	5.33	10.56	5.14	10.23	4.52	4.46	.00	.00	NaPl	
3.05	6.90	12.01	6.99	12.30	6.86	11.96	6.79	6.71	1.16	.91	PT	
.18	5.24	10.16	5.33	10.45	5.20	10.12	4.37	4.32	.00	.00	NF	
.24	5.30	10.18	5.38	10.47	5.25	10.14	4.42	4.39	.00	.00	NC	
3.29	7.05	12.24	7.11	12.55	7.10	12.19	7.01	6.59	1.33	.91	PT	GR-TROU
2.38	6.66	11.75	6.66	12.02	6.71	11.69	6.54	6.09	.71	.41	APC	
.46	5.62	10.67	5.88	10.99	5.67	10.63	5.23	5.20	.00	.00	NC	
.77	5.62	10.71	5.68	10.99	5.67	10.65	4.30	4.62	.00	.00	ZHW	
.11	5.48	10.52	5.53	10.11	5.53	10.47	4.79	4.41	.00	.00	FL	
.38	5.58	10.63	5.63	10.70	5.63	10.59	4.88	5.11	.00	.00	NF	
3.76	8.17	13.18	7.77	13.08	8.22	13.13	7.99	7.73	.00	.00	APC	GR-BUCK
.78	6.11	11.30	6.16	11.20	6.16	11.25	5.45	5.45	.00	.00	H	
.33	5.99	11.25	6.04	11.15	6.16	11.20	5.58	5.33	.00	.00	HU	
4.74	8.46	13.34	8.51	13.24	8.51	13.29	8.65	8.16	.52	.10	PT	

Cont'd

APPENDIX III

WATER-BALANCE VARIABLES IN INCHES

ACTUAL EVAPORATION (INCHES)

GRASS	WHEAT	IRR. WHEAT	WHEAT TO SORGHUM	IRR. WHEAT TO SORGHUM	WHEAT TO SOYBEANS	IRR. WHEAT TO SOYBEANS	IRR. CORN	FALLOW TO IRR. SORGHUM OR IRR SOYBEANS	IRR ALFALFA	ALFALFA		
24.28	18.99	19.83	20.65	30.56	23.23	33.50	37.68	33.41	47.98	24.46	CFT	
18.30	15.12	16.17	15.83	26.65	16.56	27.84	31.10	26.50	42.95	19.79	DT	
24.11	18.76	19.46	19.85	30.32	22.30	32.69	36.15	31.21	47.32	23.82	NaCl	HUD-HUD
19.43	15.51	16.44	16.41	27.10	17.26	28.44	31.83	28.09	43.43	20.28	PT	
22.09	17.54	18.28	18.79	29.09	20.19	30.91	34.71	31.37	45.54	22.02	PC	
23.89	18.97	19.63	20.50	30.48	22.78	33.13	37.58	33.40	47.32	23.82	NF	
23.55	18.78	19.46	20.24	30.25	22.27	32.69	36.10	33.06	46.99	23.49	NC	
24.75	19.24	19.85	21.05	30.95	23.93	34.09	38.70	34.77	48.58	25.06	BF	
25.07	18.77	19.47	20.44	29.77	21.96	32.70	37.10	30.32	49.14	26.08	PC	HUD-TROU
27.14	19.97	20.63	21.61	31.07	25.43	34.43	39.68	31.89	50.58	27.77	NaCl	
21.68	16.64	17.51	17.88	27.97	18.98	29.60	33.40	27.70	46.21	23.53	PT	
27.29	20.13	20.81	21.43	31.08	24.28	34.56	39.93	32.05	50.90	27.77	NF	
26.89	19.93	20.62	21.43	30.84	23.83	34.19	39.48	31.76	50.58	27.45	NC	
21.45	16.41	17.26	17.30	27.64	18.32	29.35	33.19	29.15	46.06	23.55	PT	GR-TROU
22.90	16.79	17.98	17.84	28.16	20.10	30.28	34.41	30.26	47.24	24.56	APC	
26.78	19.59	20.24	20.97	30.33	23.40	33.76	39.11	34.57	50.77	27.57	NC	
26.52	19.56	20.19	20.88	30.29	23.40	33.64	38.89	34.40	50.77	27.57	ZHW	
28.36	20.94	20.75	21.91	31.14	25.24	35.06	40.81	35.92	52.33	29.21	FL	
27.18	19.78	20.41	21.22	30.54	23.88	34.09	39.54	34.92	51.11	27.90	NF	
22.80	16.35	17.26	17.19	27.23	18.50	29.35	33.56	29.00	47.15	25.38	APC	GR-BUCK
27.19	19.28	19.99	20.72	29.98	23.74	33.82	39.65	34.29	50.87	29.11	H	
27.65	19.92	20.57	21.41	30.65	24.51	34.54	40.18	35.08	51.23	29.45	HU	
20.40	15.44	16.46	16.04	26.64	17.52	29.59	32.77	28.01	46.22	24.77	PT	

APPENDIX III

SOIL DEFICIT (INCHES)

GRASS	WHEAT	IRR. WHEAT	WHEAT TO SORGHUM	IRR. WHEAT TO SORGHUM	WHEAT TO SOYBEANS	IRR. WHEAT TO SOYBEANS	IRR. CORN	FALLOW TO IRR. SORGHUM OR IRR SOYBEANS	IRR ALFALFA	ALFALFA		
5.63	3.28	3.33	4.90	2.28	7.53	6.07	6.35	5.00	6.30	6.20	CFT	
1.59	1.37	1.42	2.18	.11	2.90	2.00	1.96	.61	1.80	1.90	DT	
5.42	3.16	3.21	4.17	2.18	6.55	4.47	4.96	2.37	5.70	5.50	NaPl	HUD-HUD
2.52	1.60	1.65	2.52	.40	3.34	1.90	2.44	1.74	2.10	2.00	PT	
3.89	2.43	2.48	3.72	1.36	5.11	3.66	4.06	3.61	3.80	3.70	PC	
5.45	3.33	3.38	4.78	2.21	7.13	5.22	6.28	5.04	5.70	5.50	NF	
5.10	3.17	3.22	4.60	2.03	6.70	4.86	4.59	4.86	5.30	5.20	NC	
6.24	3.43	3.48	5.13	2.55	8.12	6.22	7.25	5.66	6.90	6.80	BF	
3.59	2.40	2.45	3.72	.53	5.45	3.55	4.07	.86	3.90	3.70	PC	HUD-TROU
5.19	3.06	3.15	4.71	1.41	8.65	4.97	6.11	1.70	5.70	5.50	NaPl	
2.38	1.60	1.65	2.60	.00	3.70	1.78	2.24	.00	2.10	2.10	PT	
5.13	3.20	3.25	4.70	1.26	7.58	4.84	6.13	1.56	5.70	5.50	NF	
4.80	3.07	3.12	4.50	1.15	7.22	4.63	5.70	1.36	5.40	5.20	NC	
2.44	1.66	1.71	2.76	.28	3.42	1.72	2.32	1.84	2.20	2.20	PT	GR-TROU
2.88	1.93	1.98	3.02	.00	3.95	2.15	2.79	2.34	2.70	2.60	APC	
4.90	3.07	3.12	4.50	1.06	6.90	4.54	5.80	4.74	5.60	5.30	NC	
4.99	3.12	3.17	4.44	.29	6.94	3.72	5.82	4.48	5.60	5.30	ZHW	
6.10	3.54	3.52	5.30	1.76	8.57	5.74	7.40	6.04	7.10	7.00	FL	
5.20	3.23	3.25	4.70	1.24	7.33	4.84	6.20	5.07	5.90	5.70	NF	
2.77	1.95	2.00	2.54	.01	4.08	2.56	2.85	2.57	2.70	2.70	APC	GR-BUCK
5.40	3.20	3.25	4.50	1.36	7.70	5.64	7.10	5.74	6.60	6.60	H	
5.67	3.73	3.78	5.13	1.99	8.41	6.26	7.81	6.36	7.00	7.20	HU	
2.46	1.48	1.53	2.32	.00	3.46	2.34	2.62	2.14	2.10	2.10	PT	

APPENDIX III

RUNOFF (INCHES)

GRASS	WHEAT	IRR. WHEAT	WHEAT TO SORGHUM	IRR. WHEAT TO SORGHUM	WHEAT TO SOYBEANS	IRR. WHEAT TO SOYBEANS	IRR. CORN	FALLOW TO IRR. SORGHUM OR IRR SOYBEANS	IRR ALFALFA	ALFALFA		
.26	.26	.47	.27	.65	.28	.56	.35	.43	.51	.38	CFT	
.48	.89	1.02	.90	1.19	.91	1.10	.97	1.06	.55	.43	DT	
.27	.29	.53	.30	.71	.31	.61	.38	.46	.51	.38	NaPl	HUD-HUD
.51	.75	1.01	.76	1.18	.77	1.09	.83	.91	.55	.43	PT	
.26	.46	.86	.47	1.03	.48	.94	.54	.62	.52	.40	PC	
.26	.26	.49	.27	.66	.28	.57	.35	.43	.51	.38	NF	
.26	.26	.53	.27	.70	.28	.61	.35	.43	.51	.38	NC	
.26	.26	.41	.27	.58	.28	.49	.35	.43	.51	.38	BF	
.50	.85	1.02	.84	1.80	.84	1.78	1.01	.84	1.16	.59	PC	HUD-TROU
.57	.72	1.00	.73	1.12	.69	1.02	.91	.66	1.18	.64	NaPl	
.54	1.00	1.04	1.00	1.74	1.00	1.69	1.08	.98	1.08	.53	PT	
.55	.70	1.10	.67	1.17	.67	1.07	.89	.62	1.18	.64	NF	
.55	.70	1.14	.67	1.21	.67	1.11	.89	.63	1.18	.64	NC	
.63	1.06	1.09	1.07	1.19	1.08	1.08	1.16	1.09	1.15	.60	PT	GR-TROU
.52	.97	1.14	.98	1.23	.99	1.12	1.10	.99	1.20	.63	APC	
.57	.77	1.13	.78	1.20	.79	1.09	.96	.73	1.22	.66	NC	
.58	.75	1.10	.76	1.20	.77	1.09	.93	.72	1.22	.66	ZHW	
.59	.70	1.13	.71	1.22	.72	1.11	.90	.65	1.23	.71	FL	
.57	.75	1.13	.76	1.20	.77	1.09	.99	.70	1.22	.66	NF	
.60	.65	.84	.69	.96	.70	.73	.79	.75	2.35	.62	APC	GR-BUCK
.75	1.06	1.27	1.07	1.43	1.08	1.36	1.36	.79	2.51	.86	H	
.93	1.06	1.27	1.07	1.38	1.08	1.36	1.43	.79	2.54	1.03	HU	
.59	.83	1.04	.84	1.14	.85	1.08	.90	.88	2.23	.61	PT	

Cont'd

APPENDIX IV — WATER BALANCE VARIABLES IN ACREFEET

CROP									ROW TOTALS (ACRE-FEET)			
GRASS	IRRIGATED WHEAT	FALLOW TO IRRIGATED SORGHUM	FALLOW TO IRRIGATED CORN	IRRIGATED WHEAT TO IRRIGATED SORGHUM	DRYLAND WHEAT	DRYLAND WHEAT TO SORGHUM	IRRIGATED ALFALFA	DRYLAND ALFALFA	TOTAL	PARAMETER		
2476.80	.00	.00	.00	.00	5574.40	1388.80	.00	281.60	9721.60	AREA	CFT	HUDSON - HUDSON
3901.33	.00	.00	.00	.00	8769.60	2189.33	.00	444.80	15305.39	PCP		
1163.20	.00	.00	.00	.00	1523.73	568.53	.00	146.13	3401.24	SD		
5017.07	.00	.00	.00	.00	8820.80	2394.67	.00	576.00	16809.01	AE		
.00	.00	.00	.00	.00	1240.00	321.07	.00	.00	1561.46	DR		
53.87	.00	.00	.00	.00	120.53	31.47	.00	9.07	214.76	RN		
48249.60	57.60	140.80	198.40	115.20	2860.80	716.80	121.60	147.20	52607.99	AREA	DT	
75914.63	124.90	361.60	563.73	362.67	4497.07	1122.67	438.40	228.27	83613.88	PCP		
6393.07	6.93	6.93	32.53	19.73	328.40	129.60	16.67	22.93	6957.17	SD		
73582.38	81.07	305.07	517.33	273.07	3601.60	941.33	444.27	238.93	79986.12	AE		
6192.00	44.27	43.73	76.80	88.00	964.80	247.47	5.33	3.73	7666.35	DR		
1930.13	5.33	12.27	16.00	10.67	212.27	53.33	5.87	5.33	2250.71	RN		
37952.00	.00	.00	.00	.00	.00	.00	.00	.00	37952.00	AREA	NaPl	
59710.93	.00	.00	.00	.00	.00	.00	.00	.00	59710.93	PCP		
17141.86	.00	.00	.00	.00	.00	.00	.00	.00	17141.65	SD		
76251.75	.00	.00	.00	.00	.00	.00	.00	.00	76251.75	AE		
221.33	.00	.00	.00	.00	.00	.00	.00	.00	221.39	DR		
853.87	.00	.00	.00	.00	.00	.00	.00	.00	853.92	RN		
15884.80	326.40	748.80	1081.60	640.00	9228.80	2304.00	672.00	467.20	31353.60	AREA	PT	
24992.00	677.33	1962.67	3061.33	1968.53	14518.93	3625.07	2380.80	736.53	53922.66	PCP		
3336.00	44.80	108.80	220.27	101.33	1230.40	483.73	117.87	77.87	5721.49	SD		
25720.00	447.47	1757.33	2876.27	1515.20	11927.46	3150.93	2440.00	790.93	50625.06	AE		
1694.40	238.93	227.73	415.47	472.53	3052.80	781.33	15.47	1.60	6901.01	DR		
675.20	27.73	57.07	75.20	58.13	576.53	146.13	30.93	16.53	1662.94	RN		
8006.40	2528.00	5804.80	8384.00	4947.20	74560.00	18617.60	5216.00	3782.40	131846.37	AREA	PC	
12595.20	5237.33	15179.20	23672.54	15221.33	117312.50	29290.13	18412.27	5949.33	242869.75	PCP		
2595.20	522.13	1746.13	2836.80	1508.27	15099.20	5771.20	1651.20	1165.87	32895.31	SD		
14736.54	3848.00	15174.40	24252.26	12737.07	108986.12	29150.40	19785.06	6939.20	235608.50	AE		
146.67	1671.47	1146.67	2543.47	3313.07	19075.73	4917.87	.00	.00	32814.50	DR		
173.33	180.80	299.73	377.07	387.20	2858.13	729.07	226.13	125.87	5358.40	RN		
1350.40	844.80	1945.60	2809.60	1657.60	16595.20	4147.20	1747.20	844.80	31942.38	AREA	NF	
2129.60	1753.60	5082.67	7926.40	5097.07	26114.66	6520.00	6165.33	1324.27	62113.07	PCP		
614.93	238.40	816.53	1469.33	720.00	4605.87	1650.67	829.33	385.60	11330.51	SD		
2694.40	1383.47	5409.60	8792.00	4571.20	26238.93	7079.46	6883.73	1670.93	64724.27	AE		
.00	552.53	315.73	760.53	1097.07	3762.13	977.07	.00	.00	7465.28	DR		
29.33	34.67	69.87	82.13	78.40	359.47	93.33	74.13	26.67	847.76	RN		
1030.40	1088.00	2502.40	3609.60	2131.20	23923.20	5971.20	2246.40	1216.00	43718.40	AREA	NC	
1618.13	2254.93	6536.00	10193.07	6554.13	37642.66	9398.40	7928.00	1908.80	84033.56	PCP		
437.33	291.73	1012.27	1380.80	862.40	6320.53	2289.60	991.47	525.87	14111.78	SD		
2018.67	1763.73	6885.87	10860.80	5800.00	37443.20	10075.20	8790.40	2374.93	86012.81	AE		
.00	711.47	418.67	995.73	1410.67	5562.67	1438.40	.00	.00	10537.76	DR		
22.40	48.00	89.60	105.07	108.27	518.40	134.40	95.47	38.40	1160.03	RN		
217.60	96.00	224.00	320.00	192.00	4998.40	1248.00	198.40	256.00	7750.40	AREA	BF	
338.13	201.07	581.87	907.73	583.47	7862.93	1963.20	706.13	398.93	13542.82	PCP		
111.47	28.27	105.07	194.13	98.13	1428.27	533.33	115.20	143.47	2757.73	SD		
443.20	160.00	644.80	1036.80	538.67	8012.80	2188.80	809.07	529.07	14363.63	AE		
.00	62.93	34.13	83.73	125.33	1070.40	278.93	.00	.00	1655.26	DR		
4.80	3.20	8.00	9.60	8.00	108.27	28.27	8.53	8.00	185.93	RN		
1625.60	736.00	1696.00	2451.20	1446.40	15456.00	3859.20	1523.20	780.80	29574.39	AREA	PC	HUDSON - TROUSDALE
3124.27	1787.20	5025.07	7768.53	4949.87	29724.80	7421.33	5908.80	1507.73	67217.06	PCP		
485.87	150.40	121.60	830.40	427.20	3091.20	1196.27	494.93	241.60	7038.93	SD		
3393.60	1196.80	4282.13	7568.53	3934.40	24173.86	6572.80	6233.60	1703.47	59058.13	AE		
123.20	667.73	721.60	1042.67	1299.20	7366.93	1858.67	.00	.00	13079.57	DR		
67.73	62.93	118.40	205.87	214.40	1094.93	269.87	147.20	38.40	2219.71	RN		
12608.00	.00	.00	.00	.00	.00	.00	.00	.00	12608.00	AREA	NaPl	
24249.59	.00	.00	.00	.00	.00	.00	.00	.00	24249.39	PCP		
5452.80	.00	.00	.00	.00	.00	.00	.00	.00	5452.96	SD		
28515.19	.00	.00	.00	.00	.00	.00	.00	.00	28515.09	AE		
367.47	.00	.00	.00	.00	.00	.00	.00	.00	367.73	DR		
598.93	.00	.00	.00	.00	.00	.00	.00	.00	598.88	RN		
16678.40	217.60	499.20	723.20	428.80	3801.60	947.20	448.00	192.00	23936.00	AREA	PT	
32072.54	528.00	1483.73	2293.87	1461.33	7312.00	1825.60	1744.53	370.67	49092.36	PCP		
3307.20	29.87	.00	134.93	63.47	506.67	205.87	78.40	33.60	4360.36	SD		
30126.93	317.87	1155.20	2011.73	1051.73	5272.00	1414.40	1730.67	378.13	43458.19	AE		
4238.40	218.13	280.00	409.07	425.07	2186.13	553.07	43.20	14.40	8366.98	DR		
750.40	18.67	41.07	65.07	60.27	316.80	78.93	40.53	8.53	1380.11	RN		
723.20	422.40	972.80	1401.60	825.60	12422.40	3104.00	870.40	627.20	21369.60	AREA	NF	
1396.27	1025.07	2881.60	4454.40	2838.40	23887.99	5964.27	3388.27	1211.73	47046.87	PCP		
310.40	114.67	126.40	717.33	333.87	3312.00	1214.40	414.40	288.53	6832.00	SD		
1650.67	733.33	2595.73	4670.93	2384.00	20834.66	5537.60	3702.40	1457.60	43567.41	AE		
10.67	357.87	349.87	510.93	698.13	5423.46	1377.60	.00	.00	8728.91	DR		
33.07	38.93	50.13	104.00	73.60	724.27	173.33	85.87	33.60	1317.24	RN		
2035.20	940.80	2163.20	3129.60	1843.20	22073.60	5510.40	1945.60	1120.00	40761.60	AREA	NC	
3917.33	2284.27	6422.93	9929.07	6326.40	42452.26	10599.46	7552.00	2153.07	91636.81	PCP		
814.93	245.33	245.33	1486.40	712.00	5646.93	2066.67	875.73	485.33	12577.49	SD		
4564.27	1619.73	5733.33	10294.40	5257.60	36658.13	9841.60	8200.53	2560.53	84730.13	AE		
40.53	799.47	792.53	1152.53	1559.47	9748.27	2470.93	.00	.00	16563.95	DR		
93.33	89.60	113.60	232.00	170.67	1287.47	307.73	191.47	59.73	2545.64	RN		
37382.40	51.20	3532.80	3264.00	3488.00	11097.60	1440.00	3033.60	576.00	63865.61	AREA	PT	GREENSBURG - TROUSDALE
71894.94	129.60	12235.73	10356.80	10060.27	21340.79	2774.93	11786.13	1109.87	141689.06	PCP		
7600.53	7.47	82.13	630.93	535.47	1534.93	411.20	556.80	105.60	11465.55	SD		
66817.63	76.80	8133.87	9027.20	8480.53	15173.33	2202.67	11654.40	1132.27	122698.69	AE		
10248.53	54.40	3693.33	1906.67	1917.33	6518.93	853.87	336.53	43.73	25572.59	DR		
1962.67	4.80	350.40	315.73	317.33	980.27	129.60	291.20	28.80	4379.93	RN		
5529.60	166.40	11136.00	10291.20	11008.00	50496.00	6566.40	9574.40	2624.00	107392.00	AREA	APC	
10637.87	409.07	38580.79	32656.53	31721.06	97116.25	12627.20	37162.66	5051.20	265962.69	PCP		
1327.47	27.73	.00	2392.53	2146.67	8121.07	2161.07	2154.13	569.07	18899.67	SD		
10554.66	252.80	26129.06	29509.33	27758.39	70649.06	10996.80	37689.59	5374.93	218914.12	AE		
1097.07	165.33	11153.07	5608.53	5586.67	28024.00	3670.93	566.40	89.60	55961.06	DR		
239.47	16.00	1141.33	943.47	908.27	4081.60	541.87	957.33	138.13	8966.93	RN		
243.20	64.00	4345.60	4019.20	4294.40	20627.20	2681.60	3737.60	1075.20	41087.99	AREA	NC	
473.60	159.47	15057.60	12745.60	12380.27	39670.93	5158.40	14504.00	2063.47	102213.31	PCP		
100.80	17.07	384.00	1941.33	1697.07	5276.80	1541.87	1744.00	473.60	13176.37	SD		
549.33	110.93	10983.46	13090.13	12377.07	33672.54	5229.87	15809.06	2464.53	94286.94	AE		
9.60	58.67	3979.73	1750.40	1861.87	9659.73	1267.20	.00	.00	18587.25	DR		
11.73	6.40	434.67	321.07	261.33	1323.73	176.53	379.73	59.20	2974.10	RN		
32.00	.00	166.40	153.60	166.40	2572.80	332.80	147.20	134.40	3705.60	AREA	ZHW	
59.20	6.40	585.60	495.47	481.60	4948.80	643.20	563.73	257.60	8040.96	PCP		
12.80	.53	4.27	75.73	62.40	668.80	193.60	67.73	59.20	1144.96	SD		
67.73	4.27	426.67	506.13	478.93	4193.60	652.27	614.40	307.20	7251.89	AE		
2.13	2.13	154.67	56.00	64.53	1204.80	157.87	.00	.00	1642.31	DR		
1.60	.00	17.07	12.27	10.13	161.07	21.33	14.93	7.47	245.14	RN		
179.20	38.40	2342.40	2163.20	2316.80	15244.80	1984.00	2016.00	793.60	27078.41	AREA	FL	
349.87	85.87	8114.13	6868.27	6671.46	29320.53	3812.27	7816.00	1524.80	64563.73	PCP		
92.27	10.67	343.47	1334.93	1165.33	4497.07	1415.47	1191.47	462.40	10512.96	SD		
430.40	61.33	6076.80	7360.53	6930.13	26601.60	4169.07	8780.80	1930.13	62340.79	AE		
1.60	30.93	1972.80	864.00	850.67	6961.60	913.60	.00	.00	11595.63	DR		
9.07	3.20	237.87	162.13	125.33	889.07	118.93	206.40	46.93	1799.60	RN		
179.20	12.80	780.80	723.20	774.40	14784.00	1920.00	672.00	768.00	20614.41	AREA	NF	
339.73	28.80	2704.53	2289.60	2224.00	28433.59	3697.07	2605.33	1478.93	43801.17	PCP		
76.27	3.20	80.53	372.80	325.87	3979.20	1174.40	330.13	365.33	6707.79	SD		
400.00	20.27	1986.67	2377.07	2245.87	24368.53	3825.07	2858.67	1787.73	39869.28	AE		
5.33	10.67	696.00	293.33	328.53	6874.13	901.87	.00	.00	9110.29	DR		
8.53	1.07	77.87	59.73	44.80	923.73	123.20	68.27	42.13	1349.94	RN		
2796.80	582.40	3833.60	2188.80	4864.00	17088.00	6041.60	2041.60	377.60	39814.39	AREA	APC	GREENSBURG - BUCKLIN
5479.46	1428.27	13269.33	7022.40	14187.20	33497.60	11841.60	7989.87	737.07	95453.31	PCP		
645.33	96.53	3.20	519.47	1041.07	2777.07	2054.40	458.67	84.80	7680.80	SD		
5312.00	835.20	8702.40	6117.87	11748.27	23285.87	9314.13	8011.73	795.73	74123.75	AE		
876.27	637.87	4180.27	1456.53	3131.73	11635.73	4138.67	.00	.00	26056.54	DR		
139.73	40.53	306.67	144.00	304.00	925.87	352.53	399.47	19.20	2632.03	RN		
1689.60	140.80	915.20	518.40	1158.40	13414.41	4742.40	486.40	294.40	23360.01	AREA	H	
3316.80	339.73	3156.80	1670.93	3375.47	26296.54	9296.00	1900.80	578.67	49932.36	PCP		
761.60	37.33	103.47	307.73	553.07	3577.60	3043.20	266.67	162.67	8813.92	SD		
3834.67	230.40	2279.47	1719.47	3305.07	21556.26	9382.93	2056.53	716.27	45081.01	AE		
109.87	130.13	851.73	236.27	525.33	6831.46	2434.67	.00	.00	11119.36	DR		
105.60	14.40	108.80	59.20	76.27	1185.07	426.67	101.33	21.33	2098.88	RN		
9158.40	499.20	3283.20	1875.20	4166.40	67520.00	23865.59	1747.20	1484.80	113600.00	AREA	HV	
17947.20	1224.00	11370.13	6017.07	12156.80	132335.44	46781.32	6946.40	2912.53	237590.81	PCP		
4326.40	156.80	545.07	1220.27	2208.00	20986.66	16727.46	1019.20	891.73	48081.22	SD		
21098.67	852.80	8393.60	6276.80	12177.60	112080.00	48750.93	7459.20	3646.93	220735.37	AE		
251.73	466.67	3053.33	871.47	1850.13	33702.93	12252.27	.00	.00	52448.64	DR		
709.87	52.80	378.13	223.47	274.13	5964.27	2148.27	369.60	127.47	10247.41	RN		
11475.20	128.00	838.40	480.00	1062.40	864.00	307.20	448.00	19.20	15622.39	AREA	PT	
22491.20	312.53	2905.60	1537.60	3106.67	1687.47	596.27	1749.33	37.33	34423.68	PCP		
2352.53	16.00	.00	104.53	189.87	106.13	88.00	78.40	3.20	2938.37	SD		
19507.73	174.40	1864.00	1308.27	2484.80	1107.73	444.27	1719.47	38.93	28649.54	AE		
4532.80	141.33	926.40	345.07	723.73	606.93	216.00	19.20	.00	7511.84	DR		
564.27	11.20	80.00	35.73	77.87	59.73	21.33	83.20	1.07	934.00	RN		

OK. Oct 8 '86
New calculation

APPENDIX V

WATER-BALANCE MAP VALUES (INCHES)

		NATURAL GROWTH					NON-IRRIGATED VALUES					IRRIGATED VALUES				
	SOIL ASSOC.	PCP	SD	AC	DR	RN	PCP	SD	AC	DR	RN	PCP	SD	AC	DR	RN
	CFT	18.88	5.63	24.28	.00	.26	18.88	3.70	19.52	2.59	.27	.00	.00	.00	.00	.00
	DT	18.88	1.59	18.30	1.54	.48	18.88	1.55	15.44	3.93	.87	34.71	1.59	30.40	4.84	.94
	NaPl	18.88	5.42	24.11	.07	.27	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	PT	18.88	2.52	19.43	1.28	.51	18.88	1.79	15.87	3.84	.74	34.71	2.05	31.20	4.73	.86
	PC	18.88	3.89	22.09	.22	.26	18.88	2.73	17.95	2.97	.46	34.71	3.69	33.85	3.87	.66
	NF	18.88	5.45	23.89	.00	.26	18.88	3.69	19.45	2.64	.27	34.71	5.43	36.06	3.63	.45
	NC	18.88	5.10	23.55	.00	.26	18.88	3.52	19.24	2.70	.27	34.71	4.71	35.36	3.67	.46
	BF	18.88	6.24	24.75	.00	.26	18.88	3.89	19.81	2.49	.27	34.71	6.29	37.15	3.57	.43
MUD-TROY	PC	23.08	3.59	25.07	.91	.50	23.08	2.70	19.38	5.51	.84	38.91	3.10	35.50	5.71	1.15
	NaPl	23.08	5.19	27.14	.35	.57	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	PT	23.08	2.38	21.68	3.05	.54	23.08	1.81	17.15	6.68	.98	38.91	1.59	32.46	7.12	1.17
	NF	23.08	5.13	27.29	.18	.55	23.08	3.58	20.68	5.05	.69	38.91	4.55	37.57	5.11	.94
	NC	23.08	4.80	26.89	.24	.55	23.08	3.43	20.51	5.11	.69	38.91	4.26	37.22	5.15	.95
GR-TROY	PT	23.08	2.44	21.45	3.29	.63	23.08	1.80	16.82	6.79	1.04	39.98	1.63	33.53	7.09	1.15
	APC	23.08	2.88	22.90	2.38	.52	23.08	2.08	17.25	6.39	.96	39.98	1.91	34.52	6.57	1.13
	NC	23.08	4.90	26.78	.46	.57	23.08	3.33	20.09	5.40	.77	39.98	4.22	38.18	5.58	1.02
	ZHW	23.08	4.99	26.52	.77	.58	23.08	3.36	20.06	5.38	.75	39.98	3.95	38.07	5.20	1.01
	FL	23.08	6.10	28.36	.11	.59	23.08	3.89	21.41	5.24	.70	39.98	5.47	39.52	5.03	1.00
	NF	23.08	5.20	27.18	.38	.57	23.08	3.50	20.30	5.34	.75	39.98	4.52	38.51	5.39	1.02
GR-BUCK	APC	23.52	2.77	22.80	3.76	.60	23.52	2.11	16.71	7.94	.66	39.01	1.88	31.47	8.36	1.06
	N	23.52	5.40	27.19	.78	.75	23.52	3.59	19.81	6.03	1.06	39.01	4.74	35.82	6.51	1.34
	HU	23.52	5.67	27.65	.33	.93	23.52	4.15	20.46	5.91	1.06	39.01	5.34	36.46	6.47	1.35
	PT	23.52	2.46	20.40	4.74	.59	23.52	1.71	15.74	8.34	.83	39.01	1.58	30.65	8.75	1.17

APPENDIX VI

Prediction Table

Climatic Zone	Soil	Area (acres)	NATIVE GRASSES		ALFALFA		WINTER WHEAT	
			Deep Drainage (in)	Deep Drainage (acrefeet)	Deep Drainage (in)	Deep Drainage (acrefeet)	Deep Drainage (in)	Deep Drainage (acrefeet)
HUD-HUD	CFT	9,722	0.00	--	0.00	--	2.67	2,163
	DT	52,608	1.54	6,750	0.31	1359	4.05	17,755
	Na-Pl	37,952	0.07	221	0.00	--	2.74	8,666
	PT	31,354	1.28	3,345	0.04	105	3.97	10,373
	PC	131,846	0.22	2,417	0.00	--	3.07	33,731
	NF	31,942	0.00	--	0.00	--	2.72	7,240
	NC	43,718	0.00	--	0.00	--	2.79	10,164
	BF	7,750	0.00	--	0.00	--	2.57	1,660
HUD-TROU	PC	29,574	0.91	2,243	0.00	--	5.72	14,097
	Na-Pl	12,608	0.35	368	0.00	--	5.27	5,537
	PT	23,936	3.05	6,084	0.91	1815	6.90	13,763
	NF	21,370	0.18	321	0.00	--	5.24	9,331
	NC	40,762	0.24	815	0.00	--	5.30	18,003
GR-TROU	PT	63,866	3.29	17,510	0.91	4843	7.05	37,521
	APC	107,392	2.38	21,299	0.41	3669	6.66	59,603
	NC	41,088	0.46	1,575	0.00	--	5.62	19,243
	ZHW	3,706	0.77	238	0.00	--	5.62	1,735
	FL	27,078	0.11	248	0.00	--	5.48	12,366
	NF	20,614	0.38	653	0.00	--	5.58	9,586
	APC	39,814	3.76	12,475	0.00	--	8.17	27,107

R-BUCK	Hol	23,360	0.78	1518	0.00	--	6.11	11,894
	HU	113,600	0.33	3,124	0.00	--	5.99	56,705
	PT	15,622	4.74	6,171	0.10	130	8.46	11,014
		931,283		87,374		11,921		399,257
		(1455.13 mi^2)		(1.13 in)		(0.15 in)		(5.14 in)

APPENDIX VII

Surface runoff calculations

(1)	(2)	(3)	(4)	(5)	(6)
		Contributing Area		VB runoff estimate for entire soil assoc. (acre feet)	VB runoff estimate for contributing area col. (5) X col. (3) (acre feet)
limatic Zone	Soil Association	Soil Assoc. Percentage	Area (acres)		
UD-HUD	CFT	88	8,561	215	189
	DT	49	25,778	2251	1103
	Na-Pl	98	37,193	854	837
	PT	1	314	1663	17
	PC	4	5,274	5358	214
	NF	82	26,188	848	695
	NC	21	9,180	1160	244
	BF	71	5,498	186	132
UD-TROU	PC	15	4,435	2220	333
	Na-Pl	100	12,608	599	599
	PT	8	1,915	1380	110
	NF	51	10,902	1317	672
	NC	42	17,123	2546	1069
R-TROU	PT	16	10,220	4380	701
	APC	6	6,444	8967	538
	NC	42	17,257	2974	1249
	ZHW	46	1,708	245	113
	FL	0	--		
	NF	0	--		
OTAL			200,598		8815 acre feet 3.84×10^8 ft^3 0.527 in

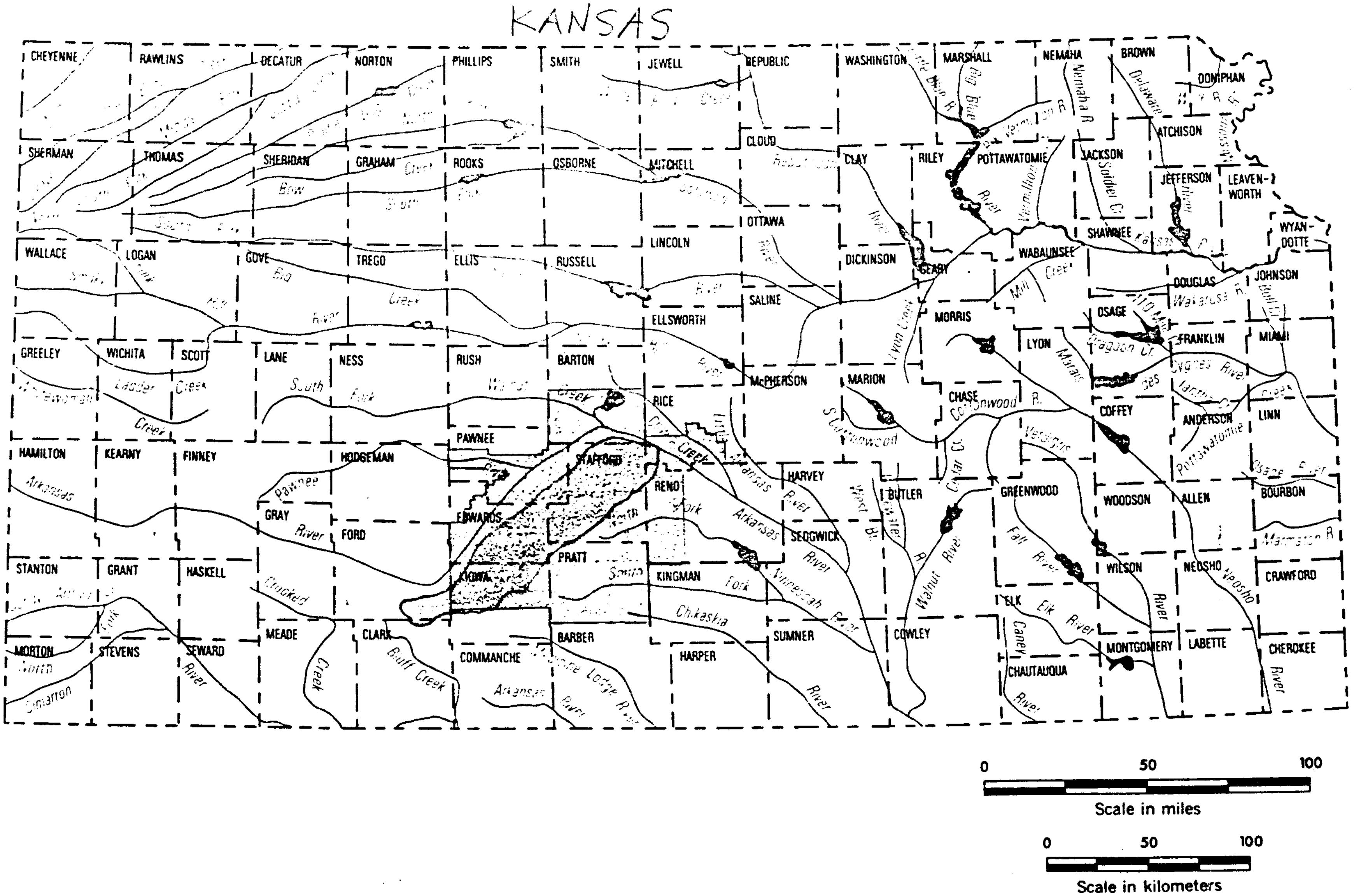


Fig. 1 Rattlesnake watershed location map

FIG. ~~1~~ 2

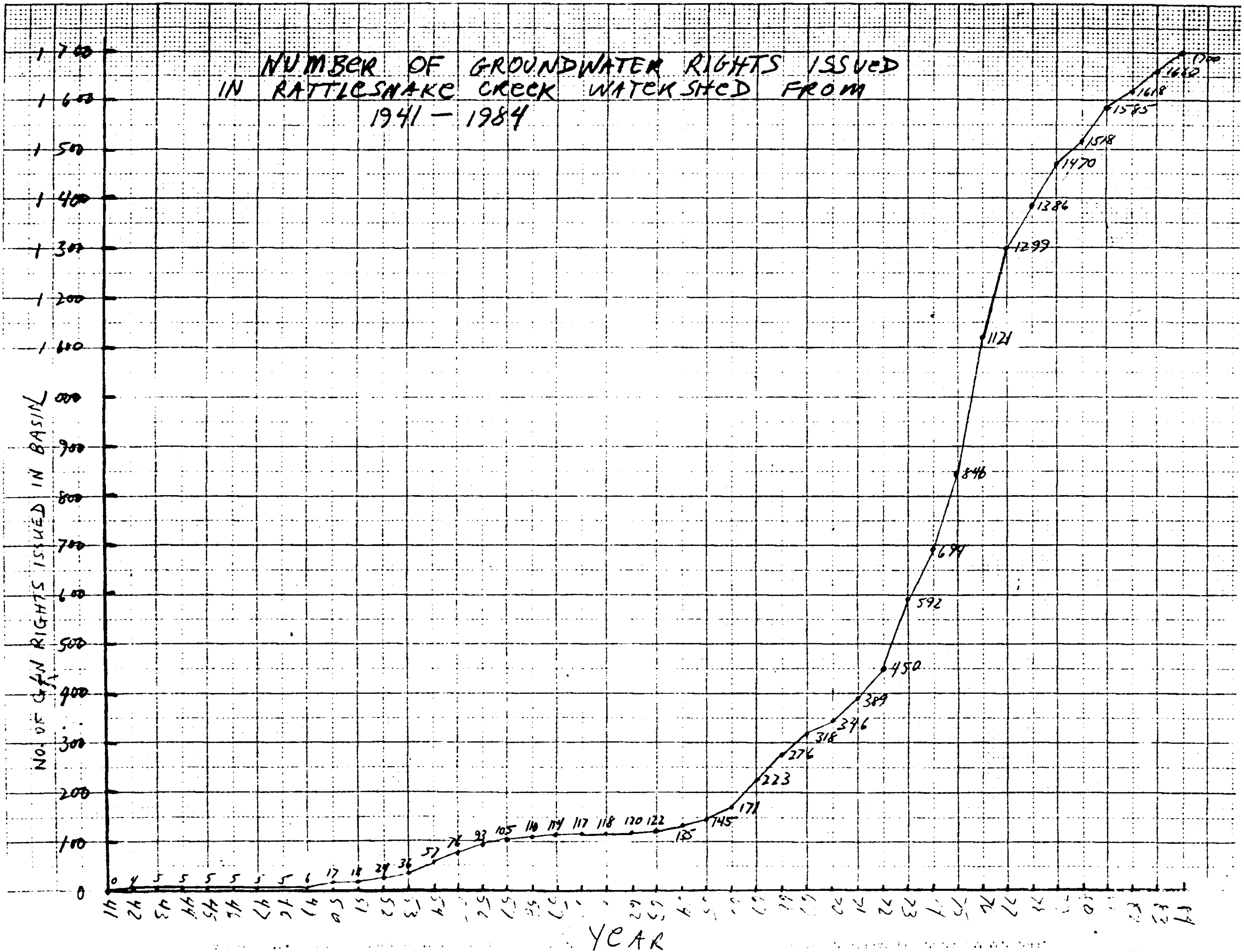

NUMBER OF GROUNDWATER RIGHTS ISSUED IN RATTLESNAKE CREEK WATERSHED FROM 1941 – 1984

FIG 2 Number of ground-water rights issued in Rattlesnake Creek watershed

Fig 23

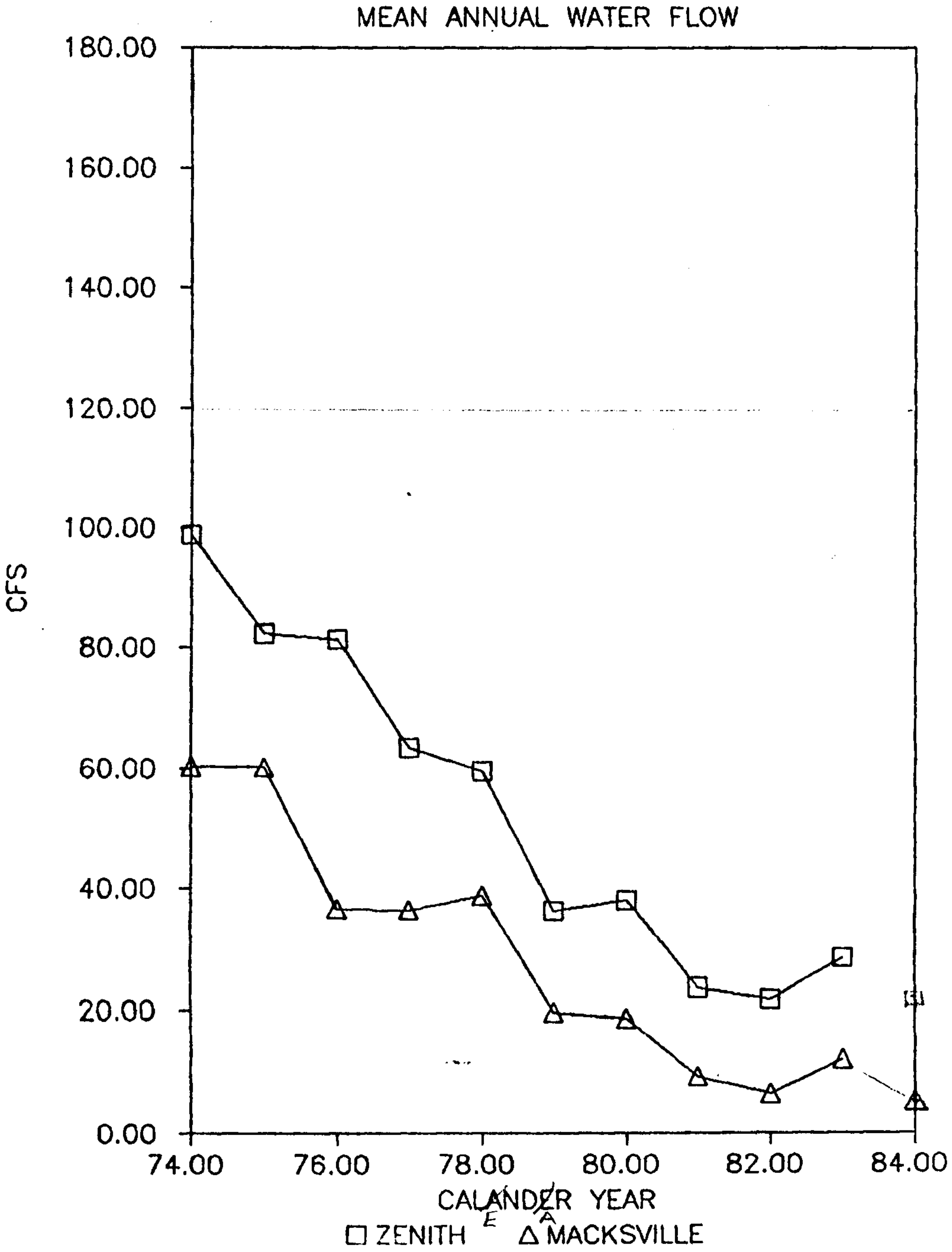
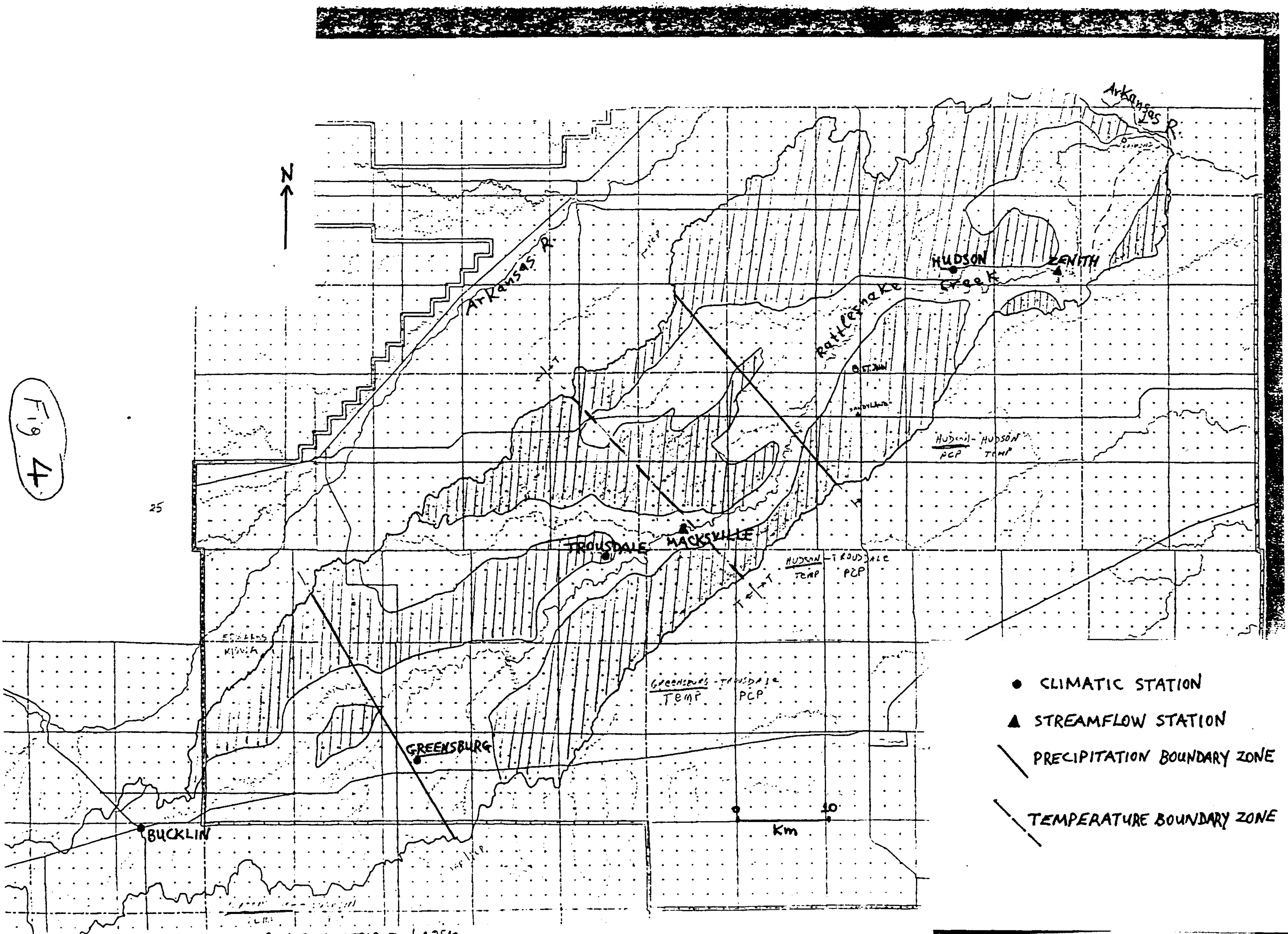


Fig 3 Mean annual flow on Rattlesnake Creek, 1974-1984.

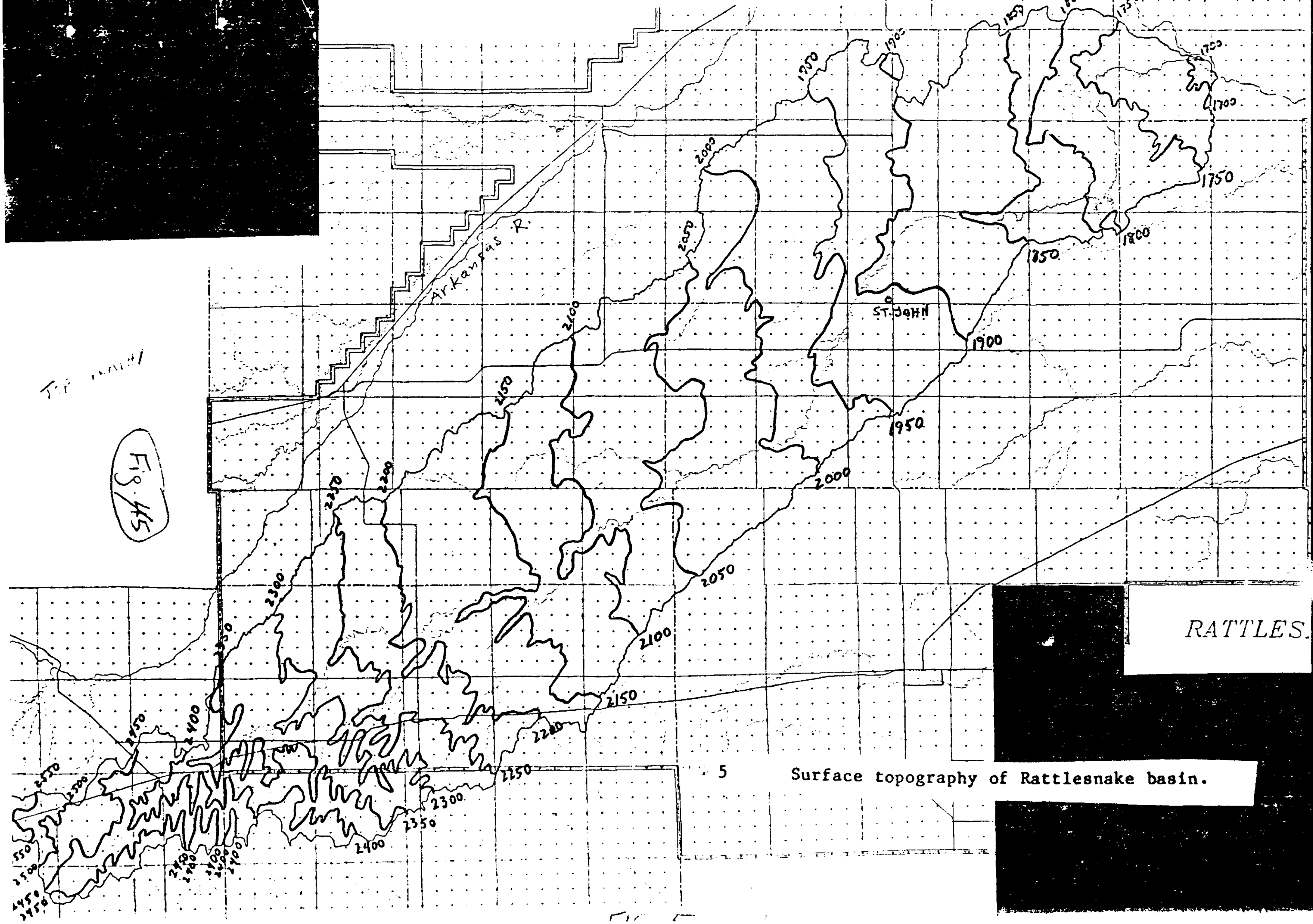
Fig 4



SURFACE RUNOFF CONTRIBUTION AREAS
▨ = non-contributing
☐ = contributing

FIG. 4 Surface-drainage map and weather stations of Rattlesnake watershed.

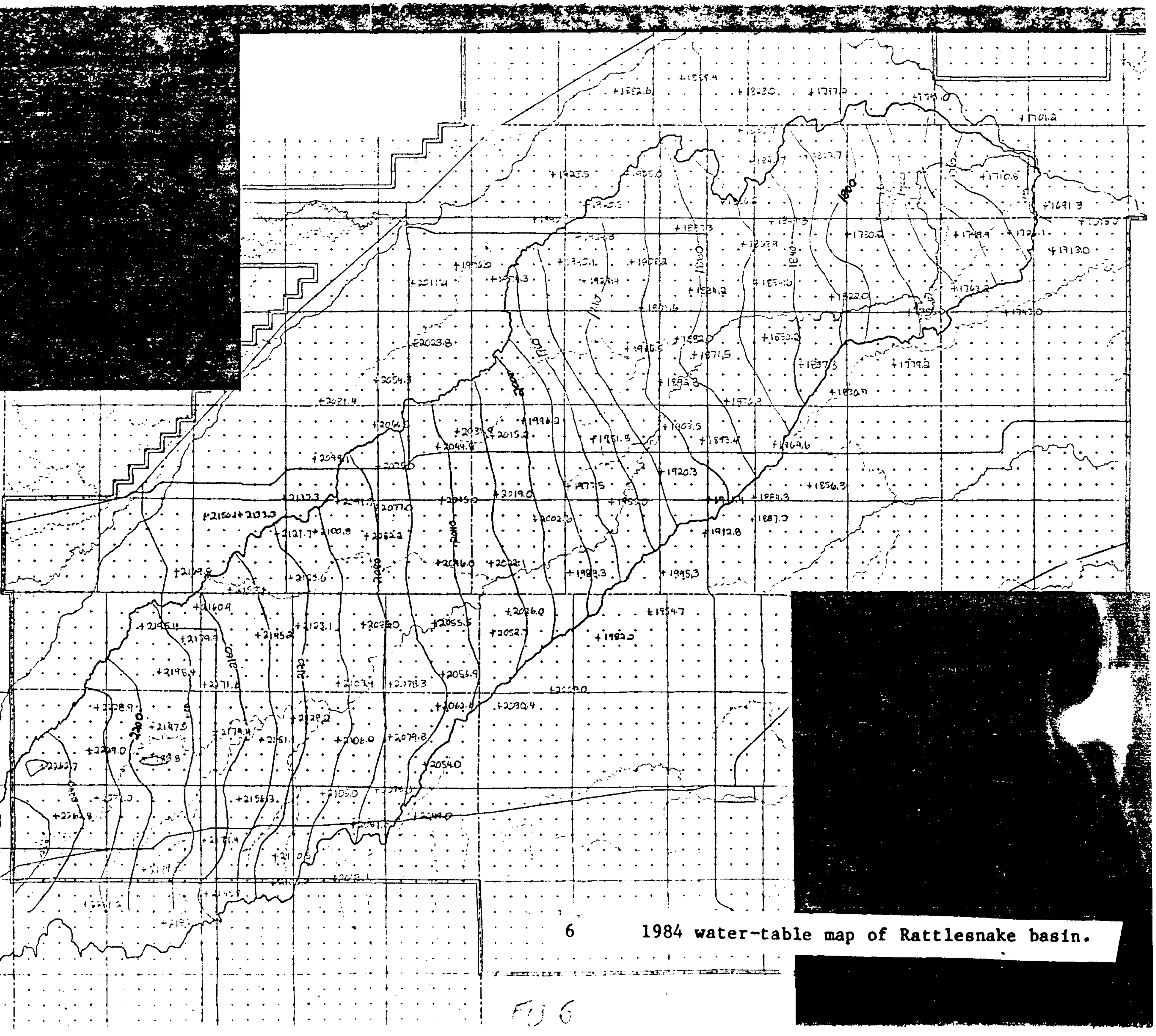
Fig. 45



5 Surface topography of Rattlesnake basin.

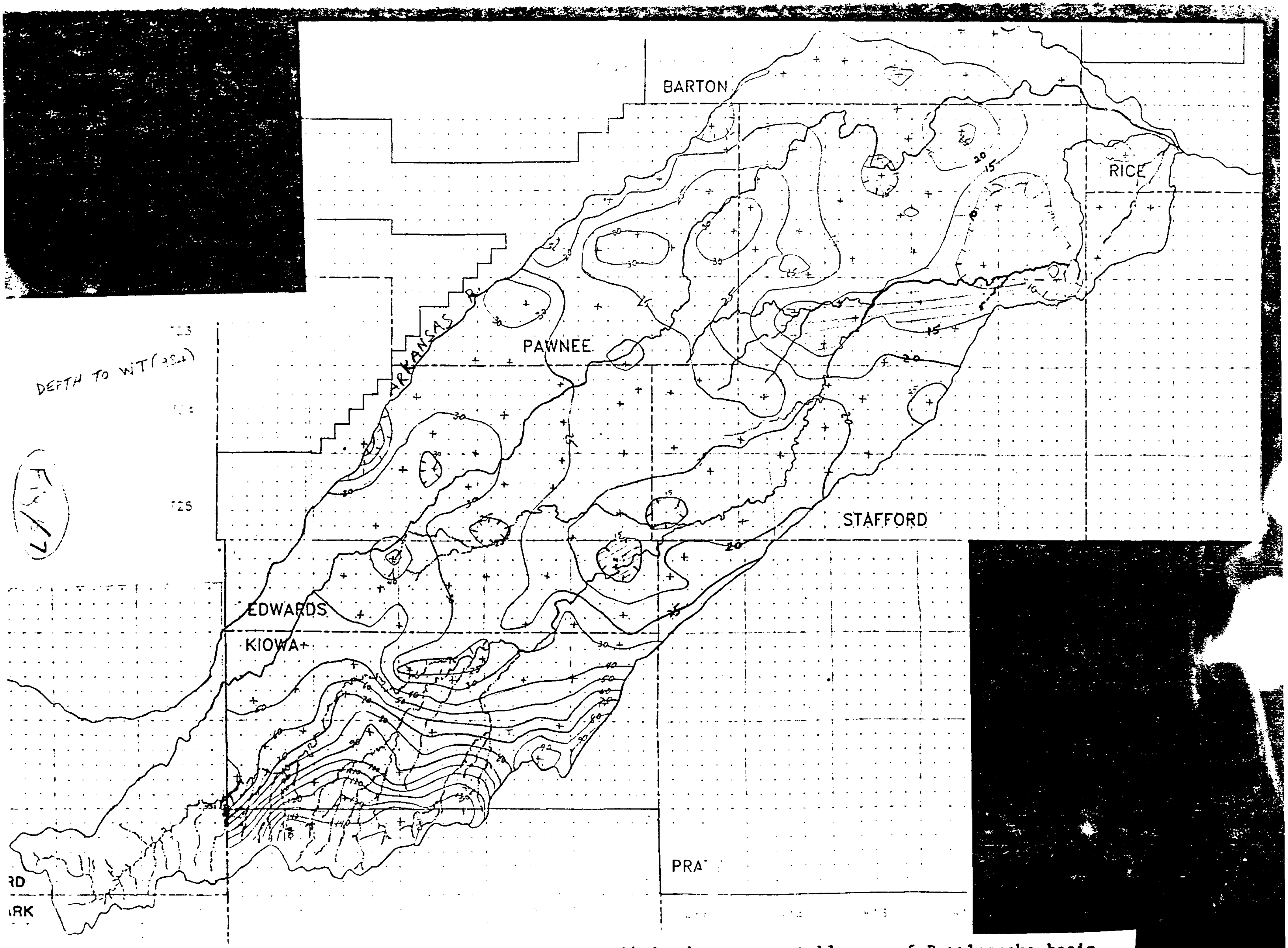
1984 WT

FIG 6



6 1984 water-table map of Rattlesnake basin.

FIG 6



DEPTH TO WT (1984)

Fig 17

Fig. 7 1984 depth-to-water-table map of Rattlesnake basin.

8 1944-1984 water-table-change map of Rattlesnake

Fig. 8

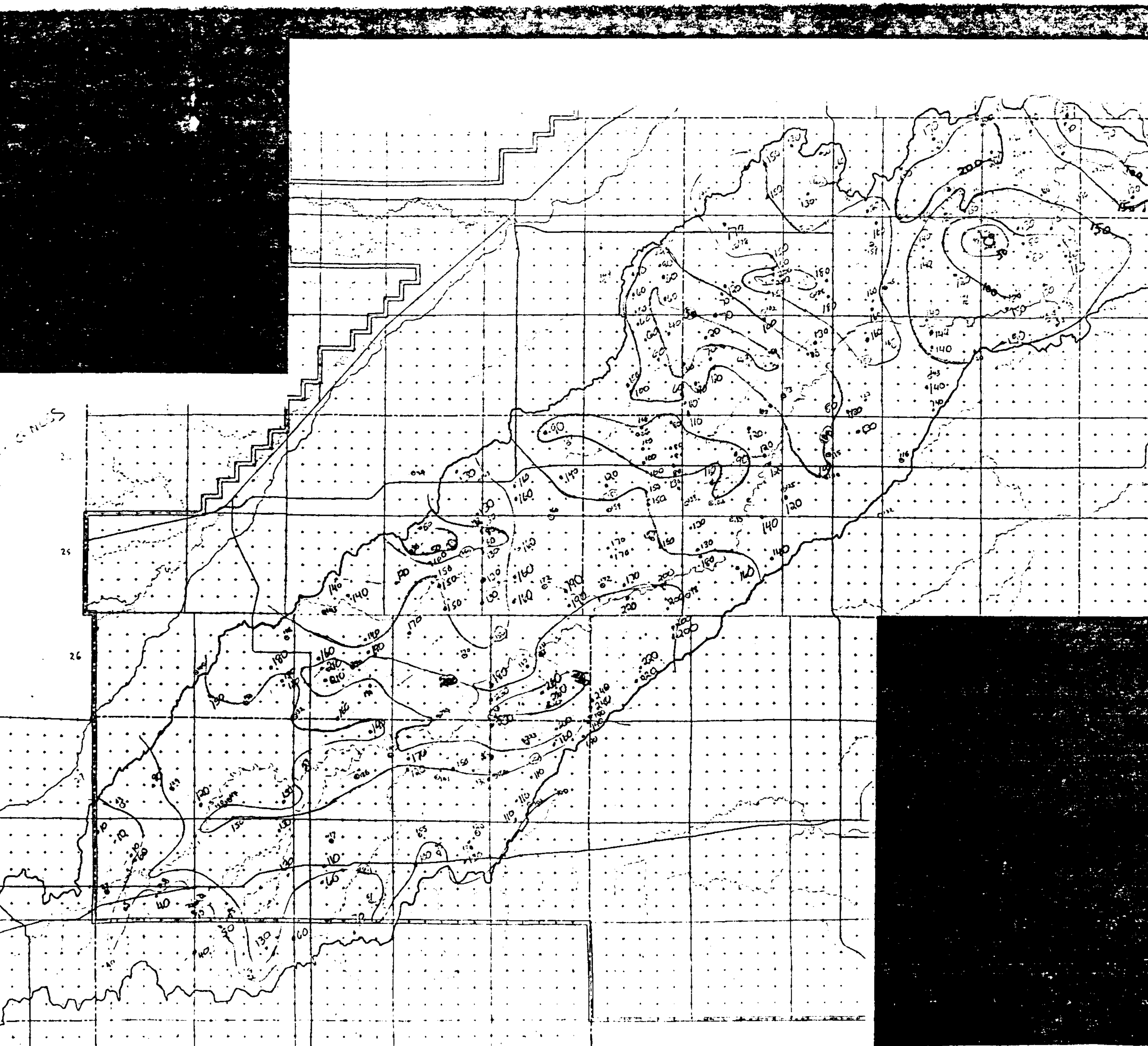
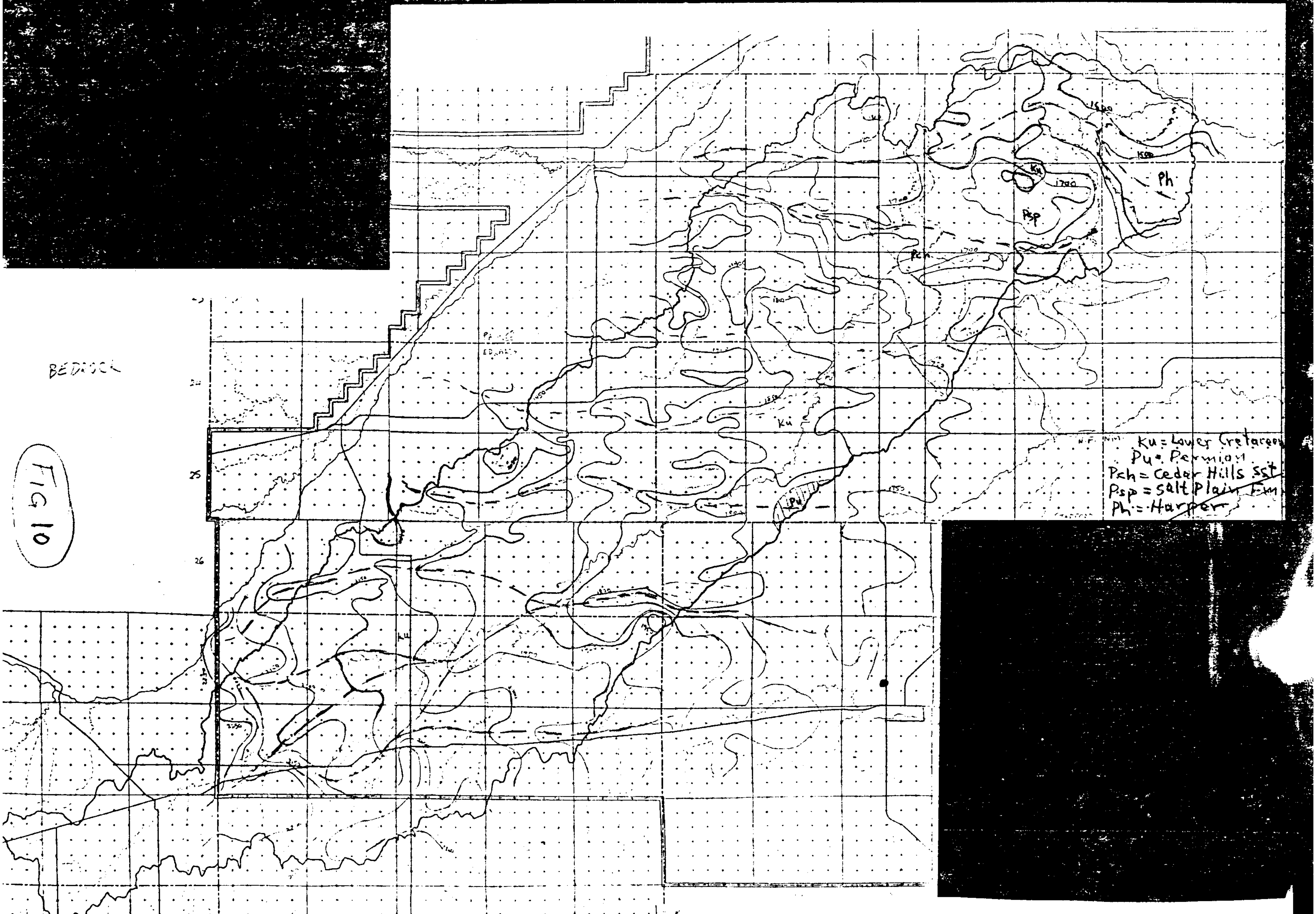


FIG9 Saturated thickness map of the Rattles

FIG 10

BEDROCK



10 Bedrock map of the Rattlesnake basin.

--- bedrock channels

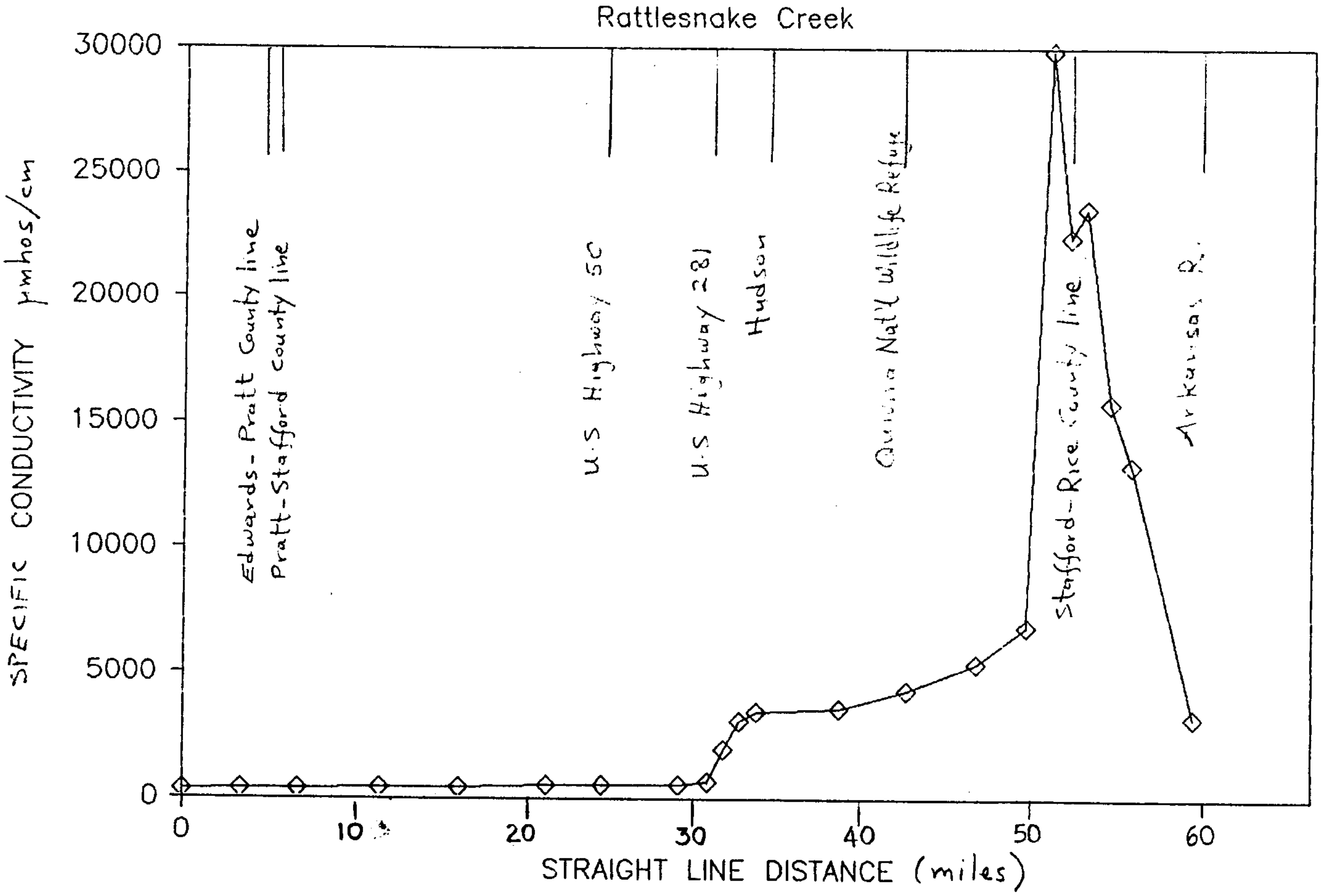


Fig. 11 Specific conductance survey along Rattlesnake Creek.

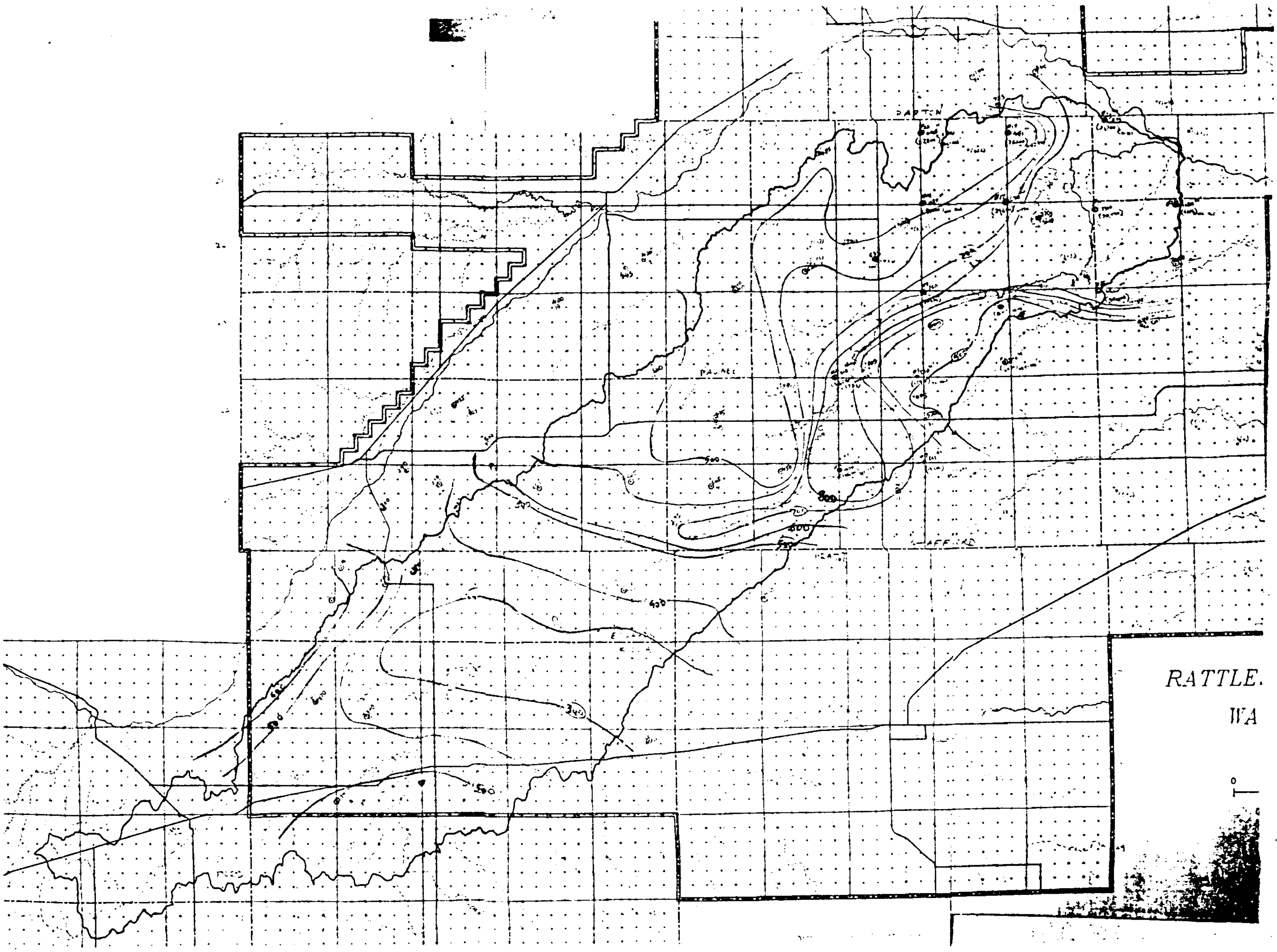


FIG. 12 Ground water quality map of Rattlesnake basin.

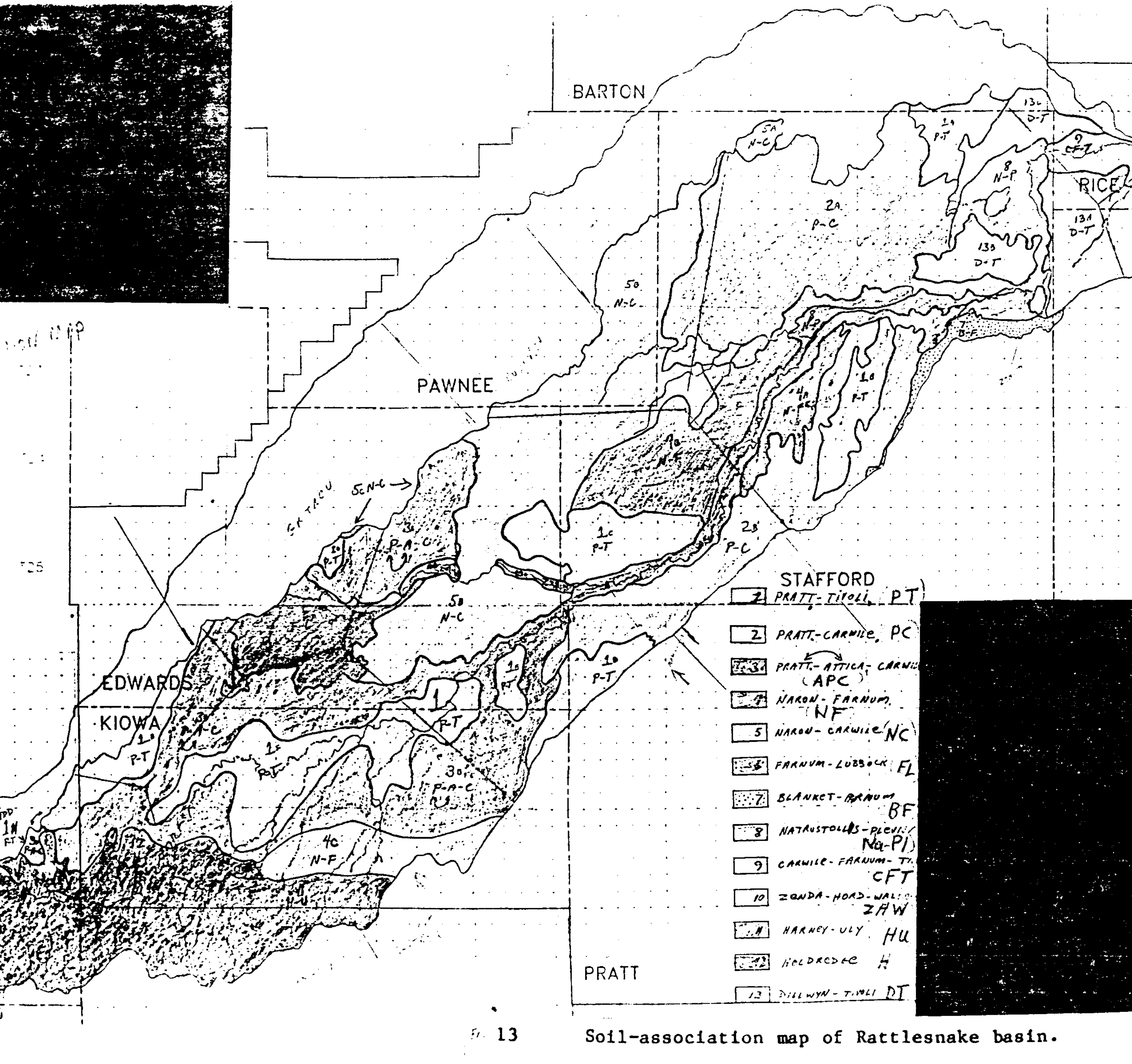
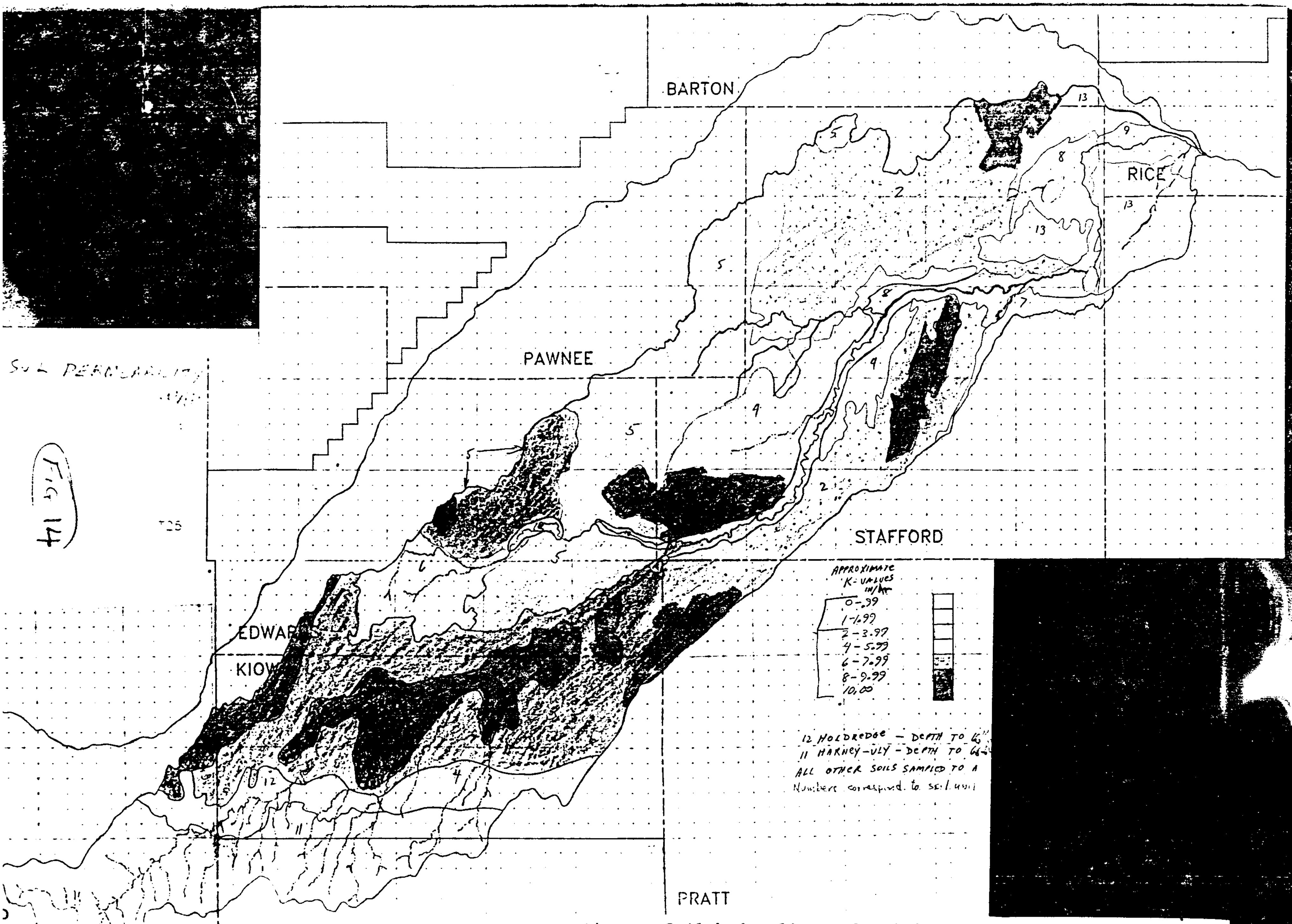


Fig. 13 Soil-association map of Rattlesnake basin.

Soil Permeability

Fig 14



14 Soil hydraulic-conductivity map of Rattlesnake basin.

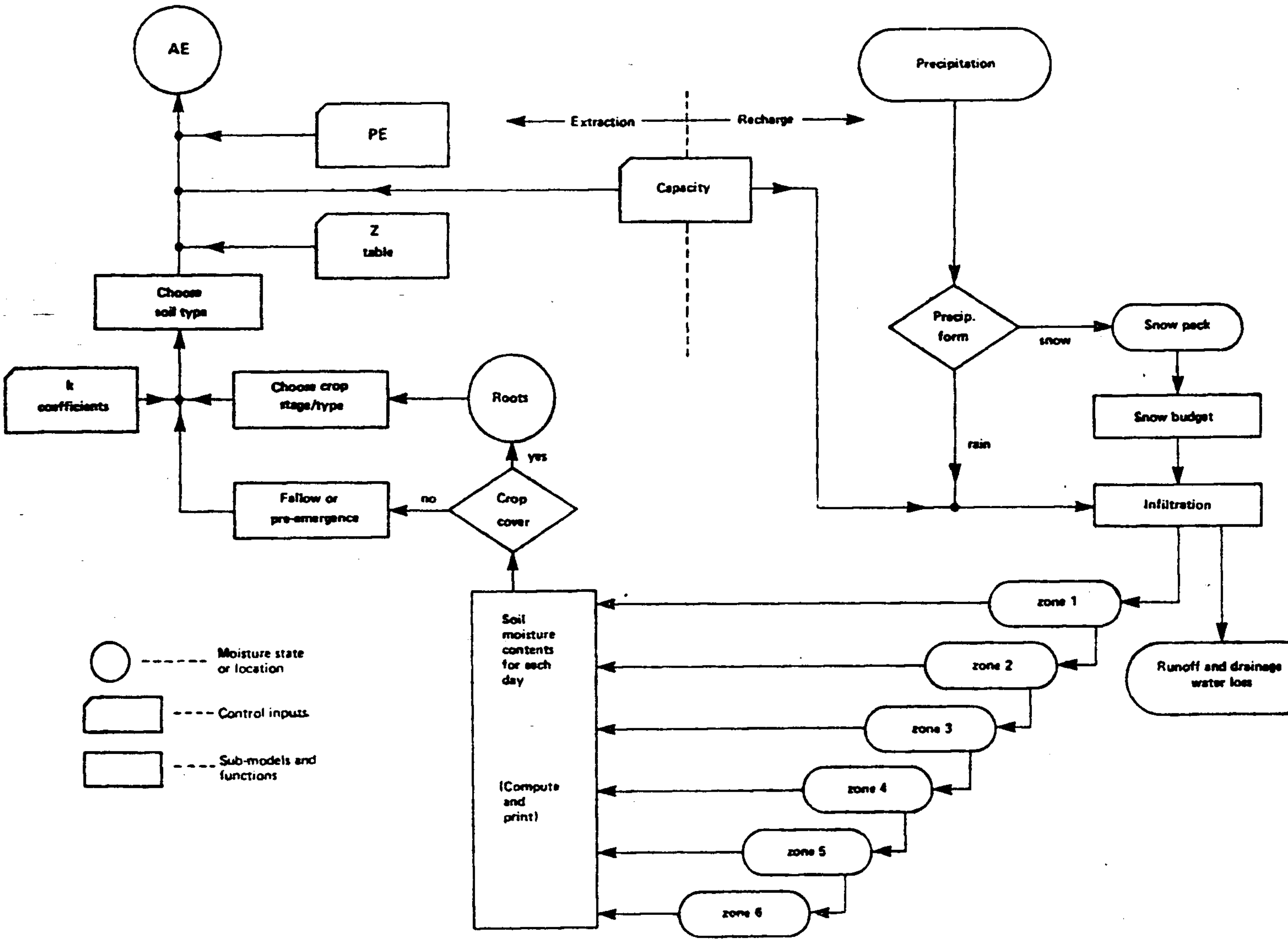


Fig. IV 15 Versatile Budget flow chart.

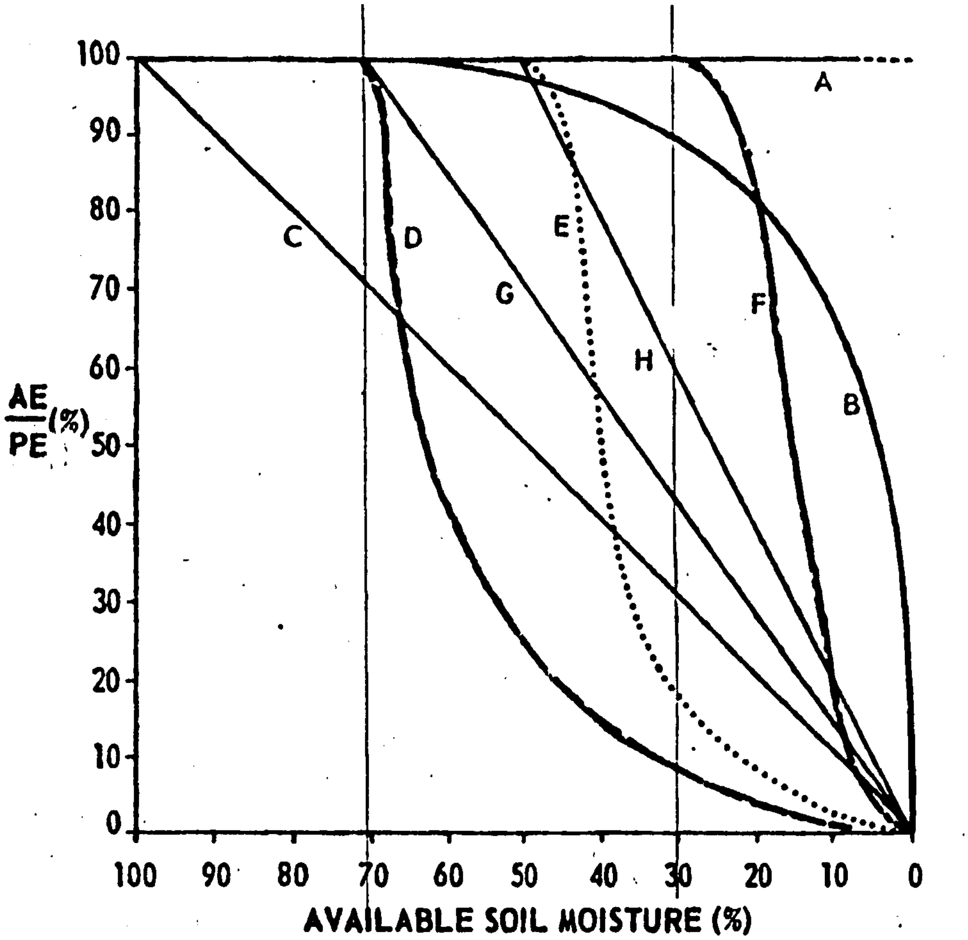
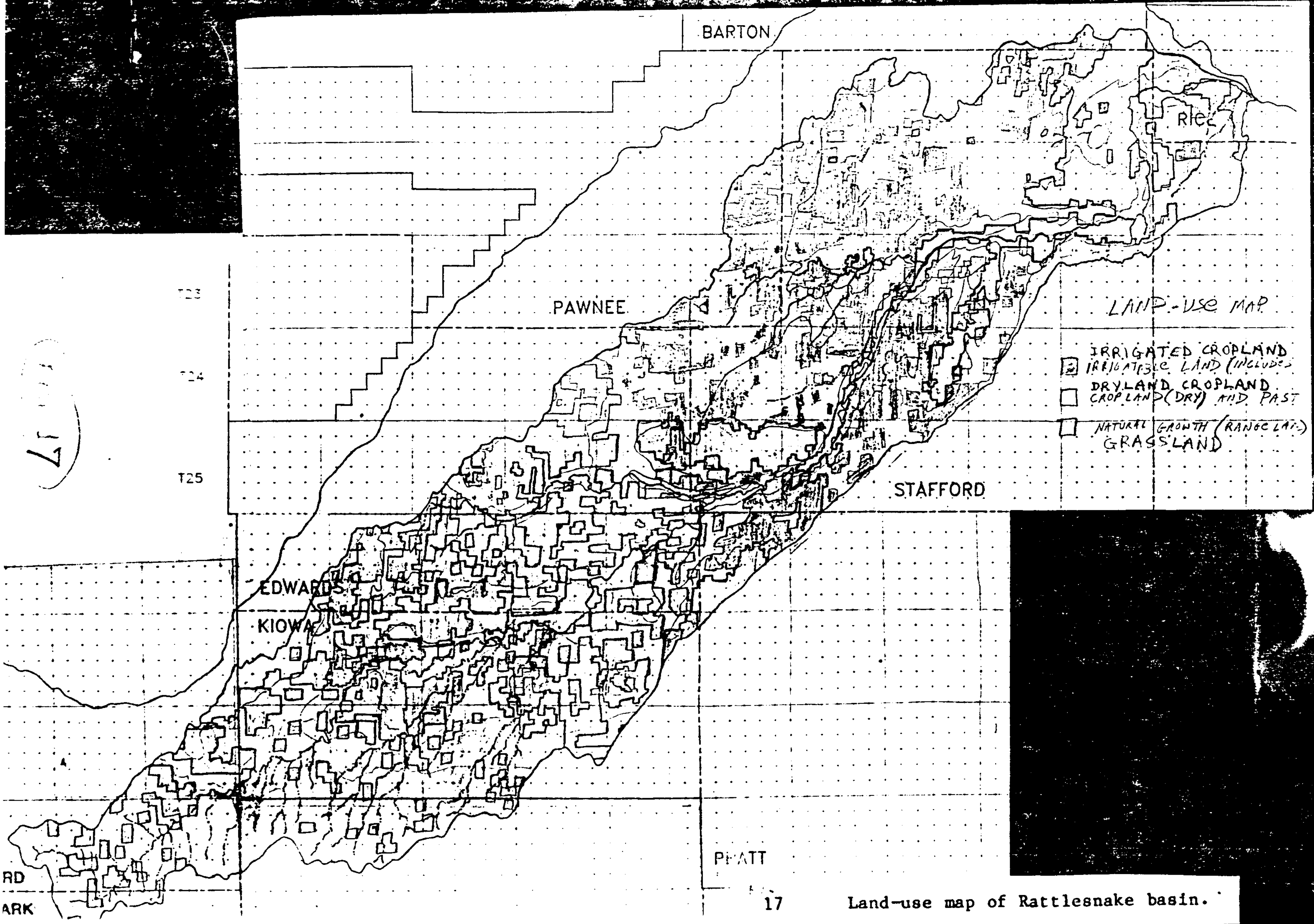


FIG 16 Various proposals for relationships between AE:PE ratio and available soil moisture.



17 Land-use map of Rattlesnake basin.

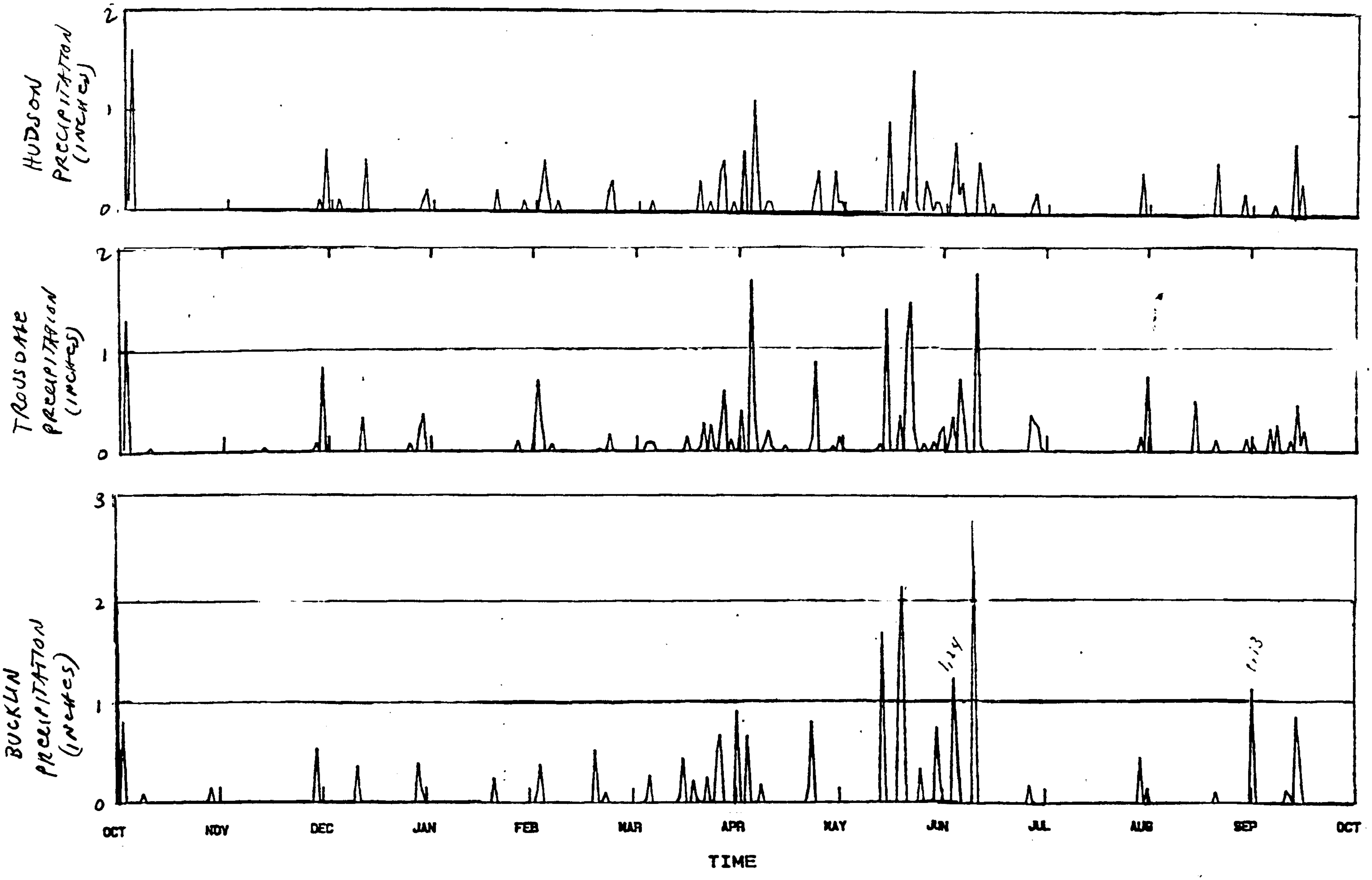
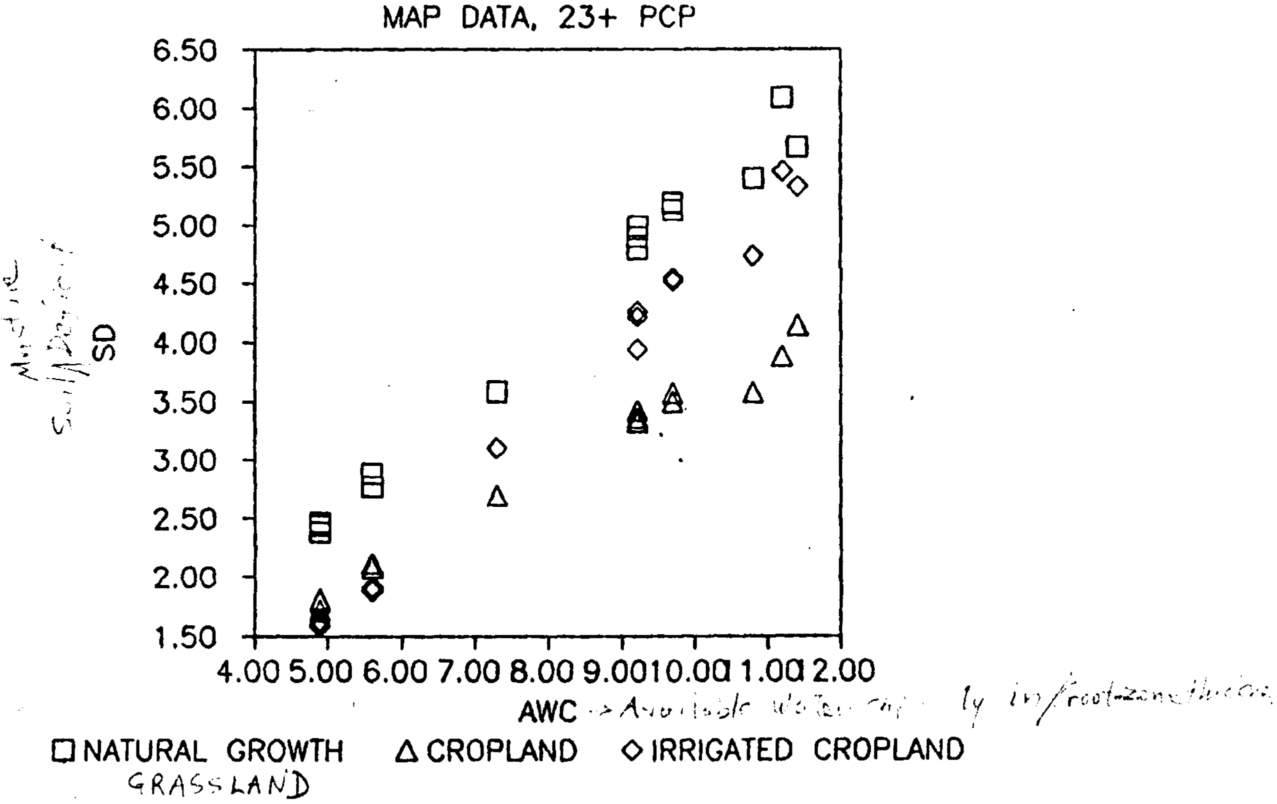


Fig. 18 Precipitation patterns at three stations in Rattlesnake basin (1983 water year).

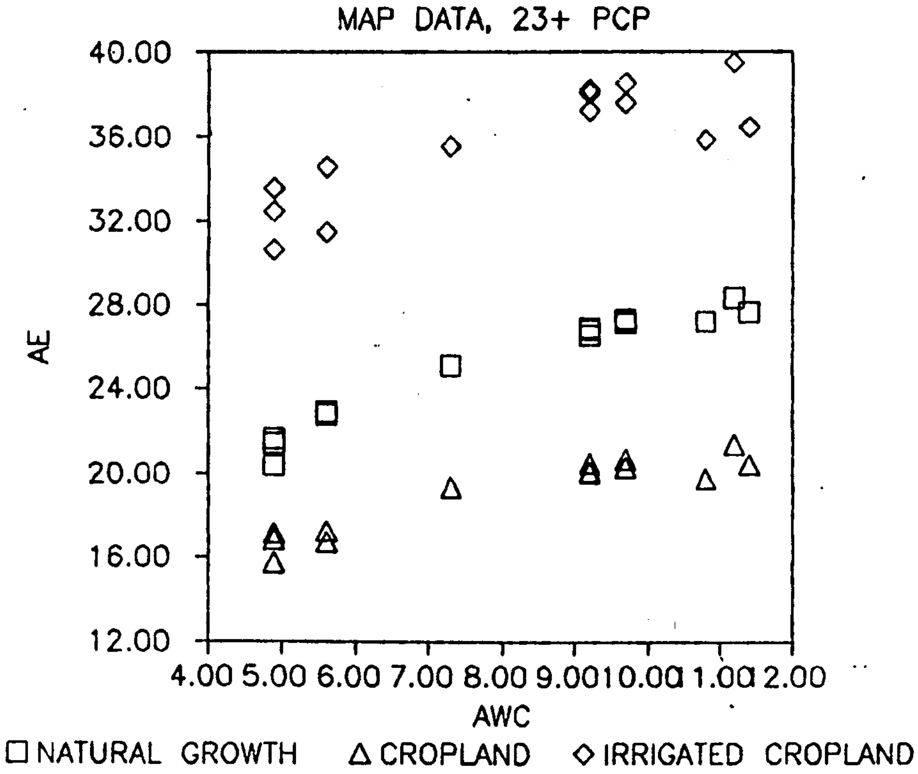
19

FIG #6 New [illegible]



F[illegible] 19 Soil deficit versus available water capacity for grassland, dryland, and irrigated cropland for Rattlesnake basin portion covered by Bucklin and Trousdale precipitation stations.

FIG. ~~17~~ 20 New alfalfa



20 Actual evapotranspiration versus available water capacity for grassland, dryland, and irrigated cropland for Rattlesnake basin portion covered by Bucklin and Trousdale precipitation stations.

21

Fig 18

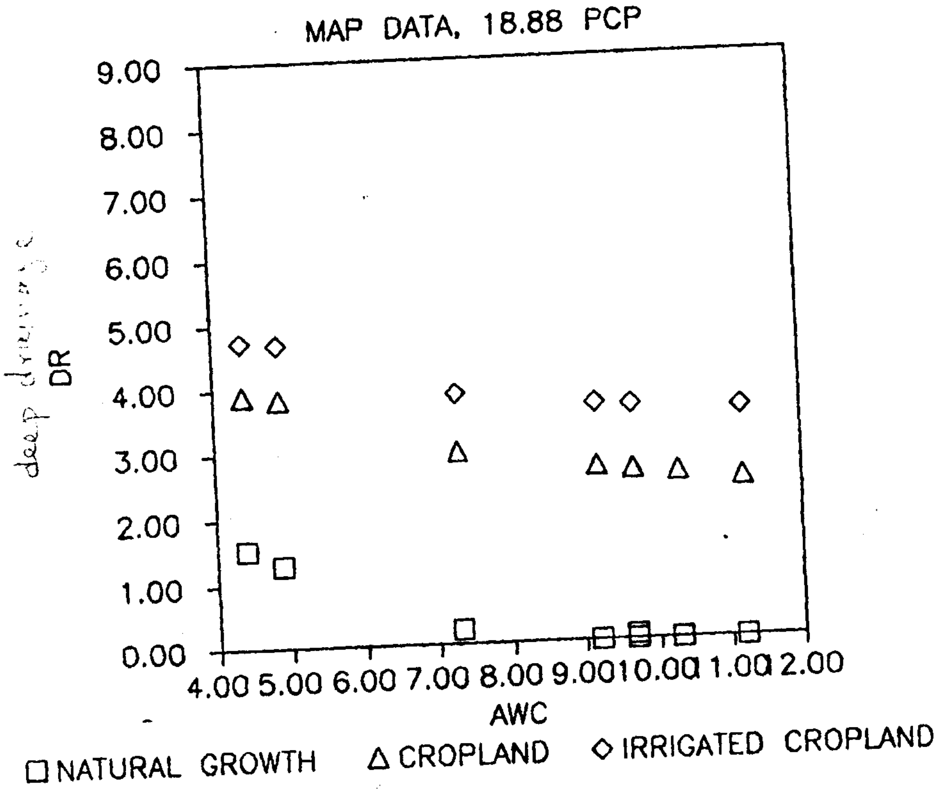


Fig 21 Deep drainage versus available water capacity for grassland, dryland, and irrigated cropland for Rattlesnake basin portion covered by Bucklin and Trousdale precipitation stations for Hudson climatic region of Rattlesnake basin.

FIG ~~19~~ 22.. New alfalfa

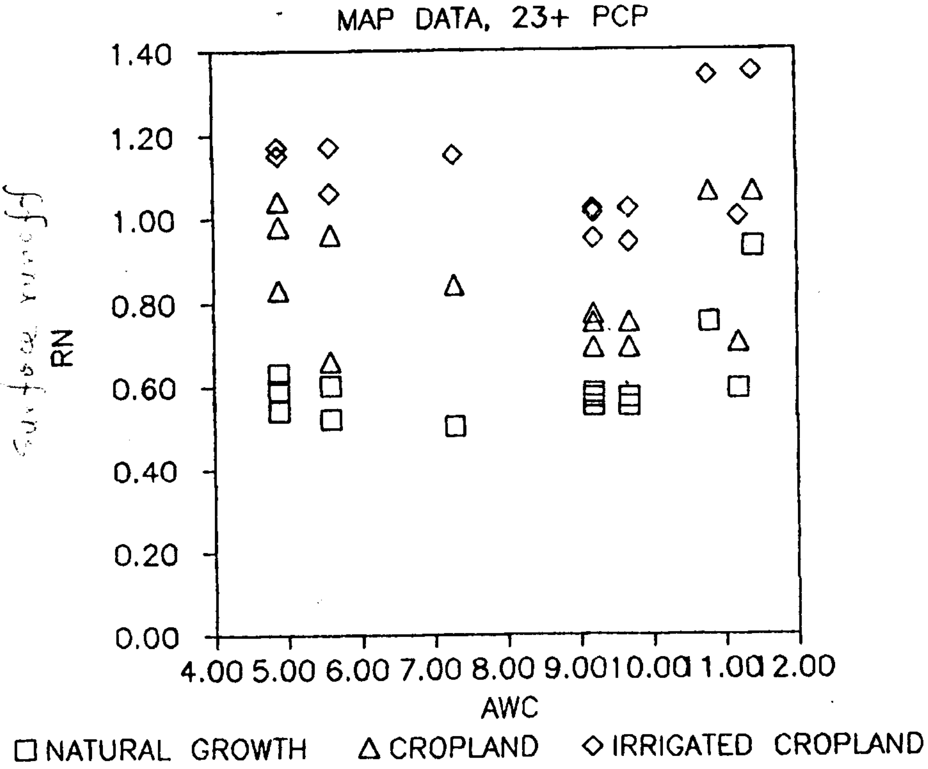


Fig
22 Surface runoff versus available water capacity for grassland, dryland, and irrigated cropland for Rattlesnake basin portion covered by Bucklin and Trousdale precipitation stations.

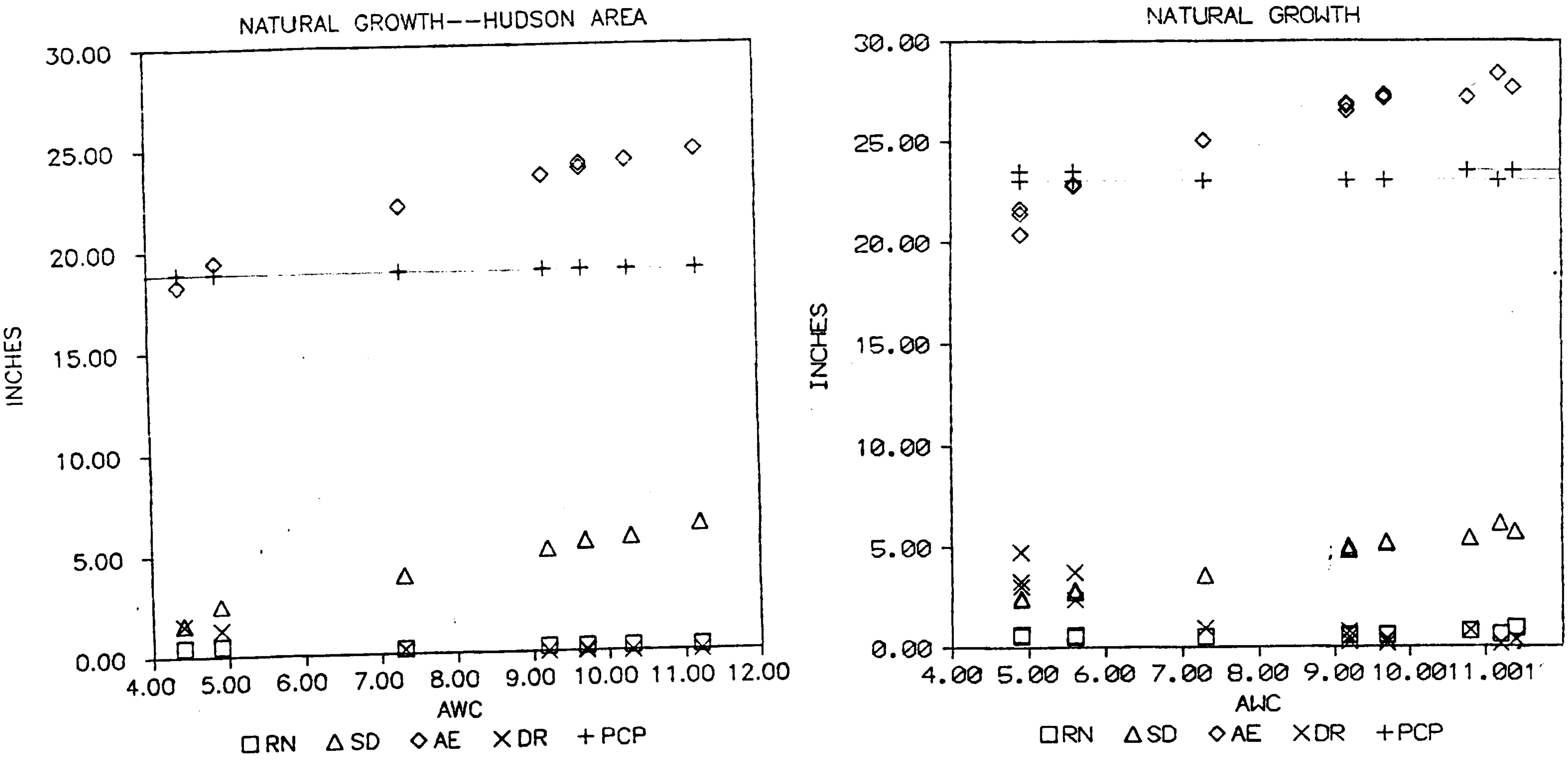


FIG 23 Grassland water-balance components for Hudson climatic region and the rest of Rattlesnake basin.

24
Fig. 2~~5~~

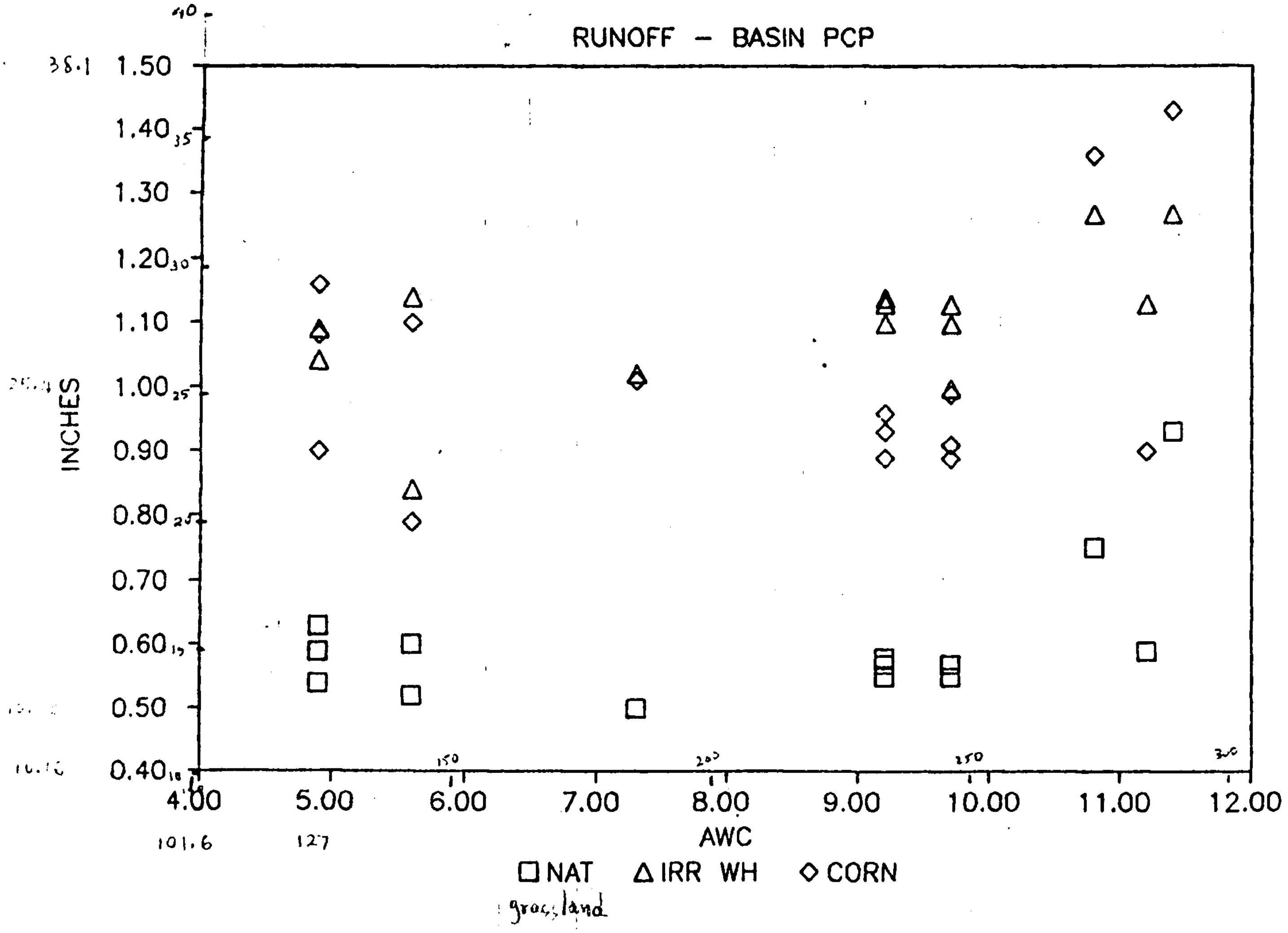


Fig 24 Effects of vegetation on surface runoff in Rattlesnake basin portion covered by Trousdale and Bucklin precipitation stations.

FIG ~~22~~ 25 new alfalf.

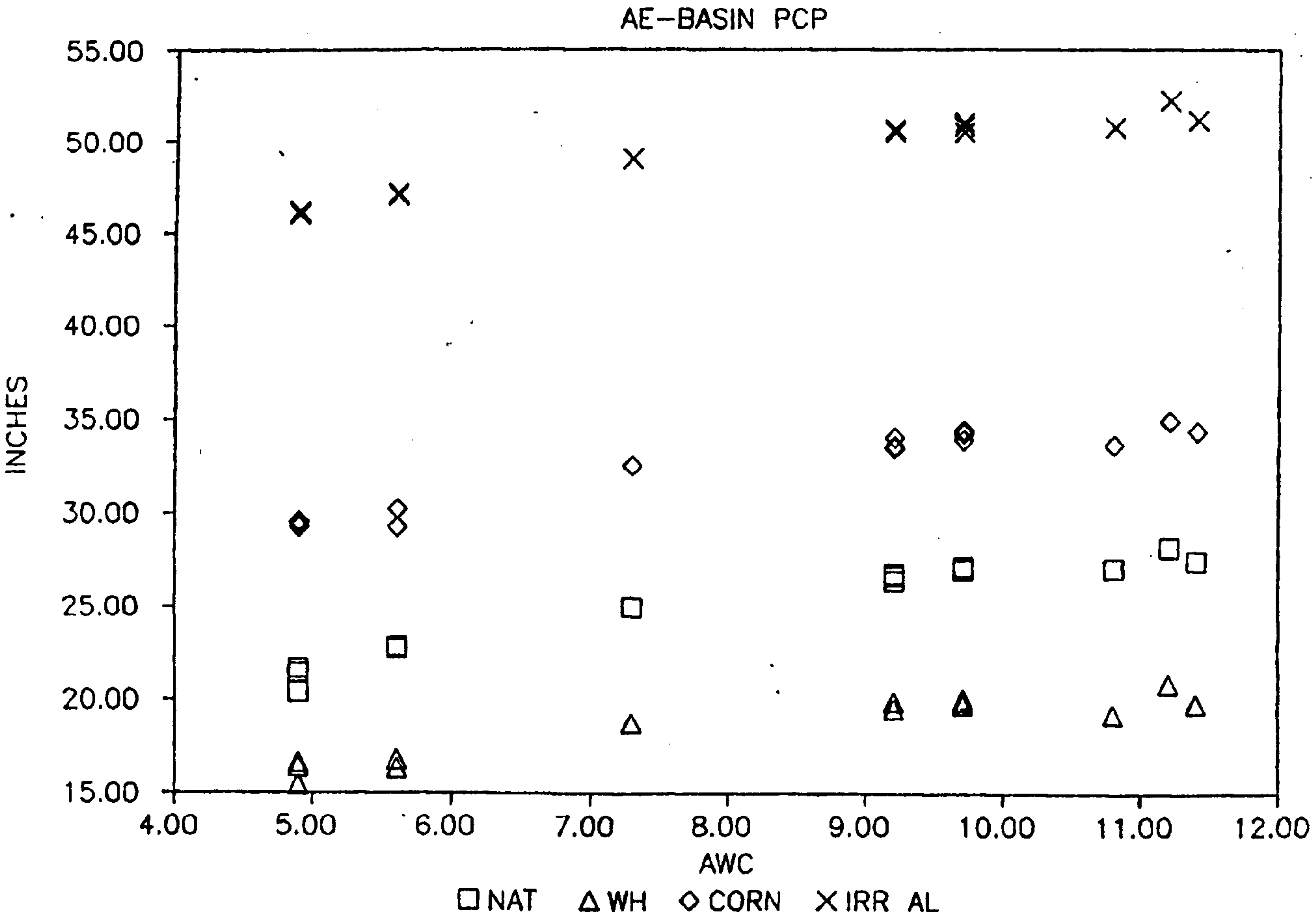


FIG
25 Effects of vegetation on actual evapotranspiration in Rattlesnake basin portion covered by Trousdale and Bucklin precipitation stations.

Fig 26

OCT 6 PT [illegible]

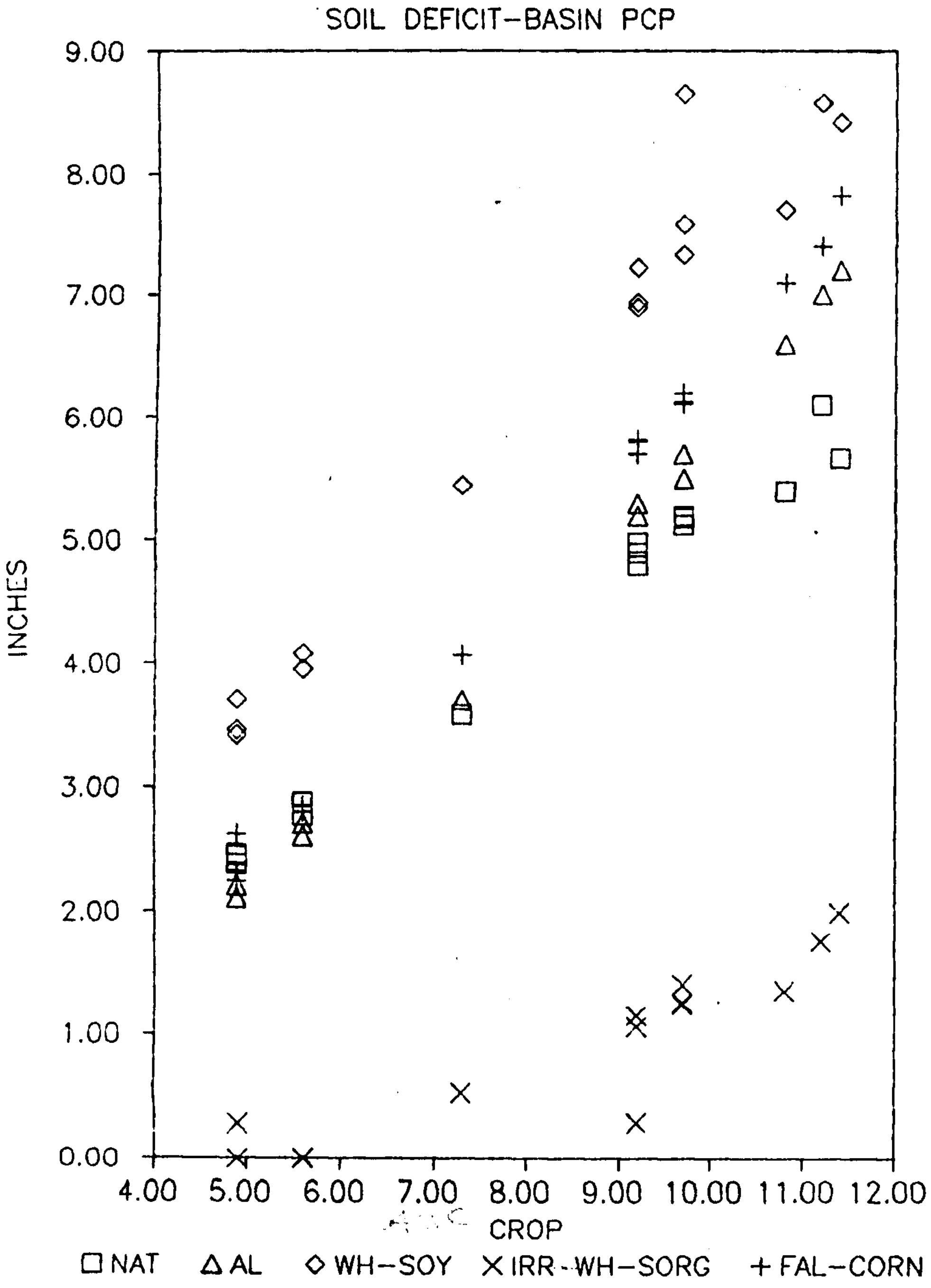
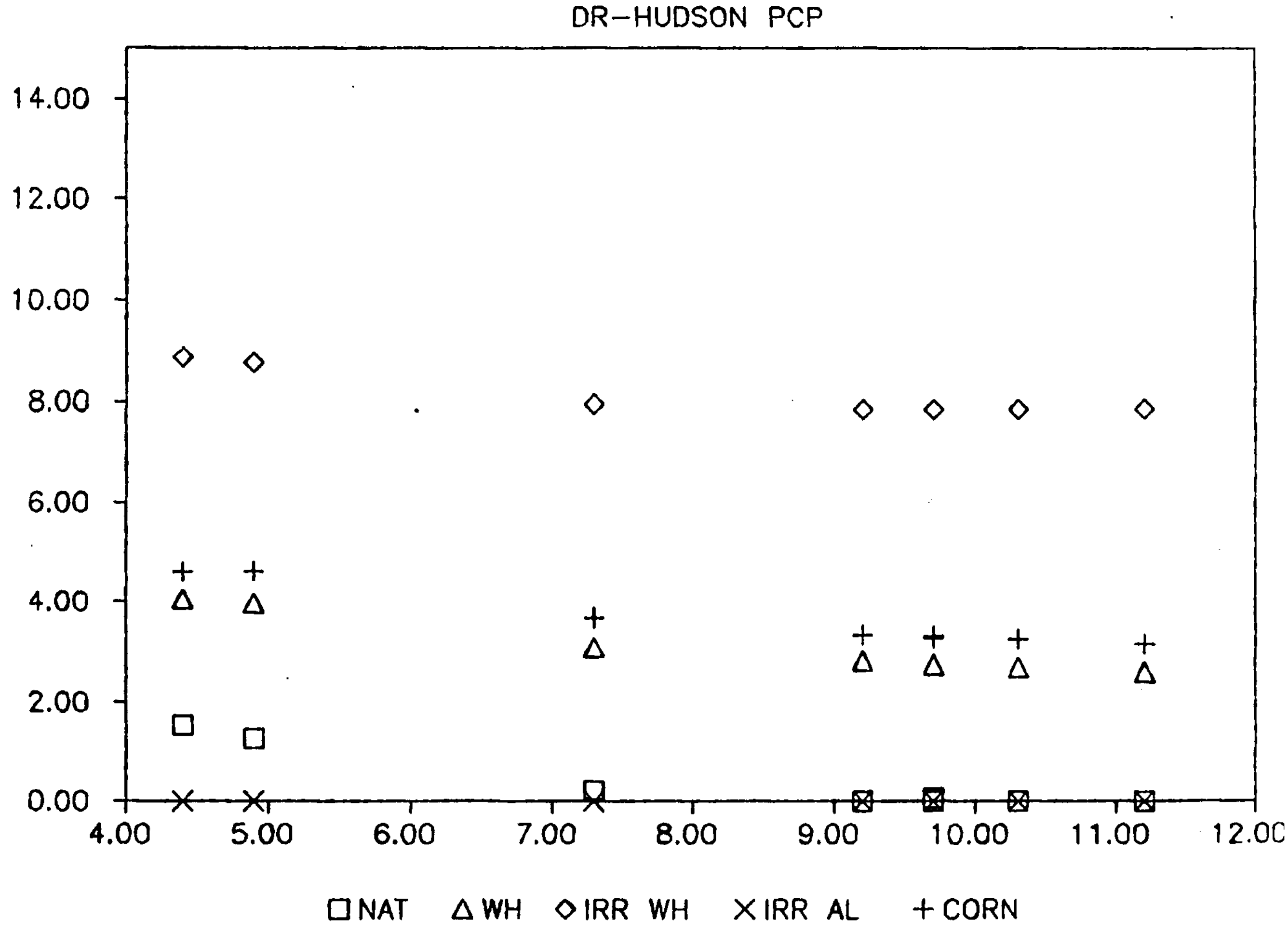


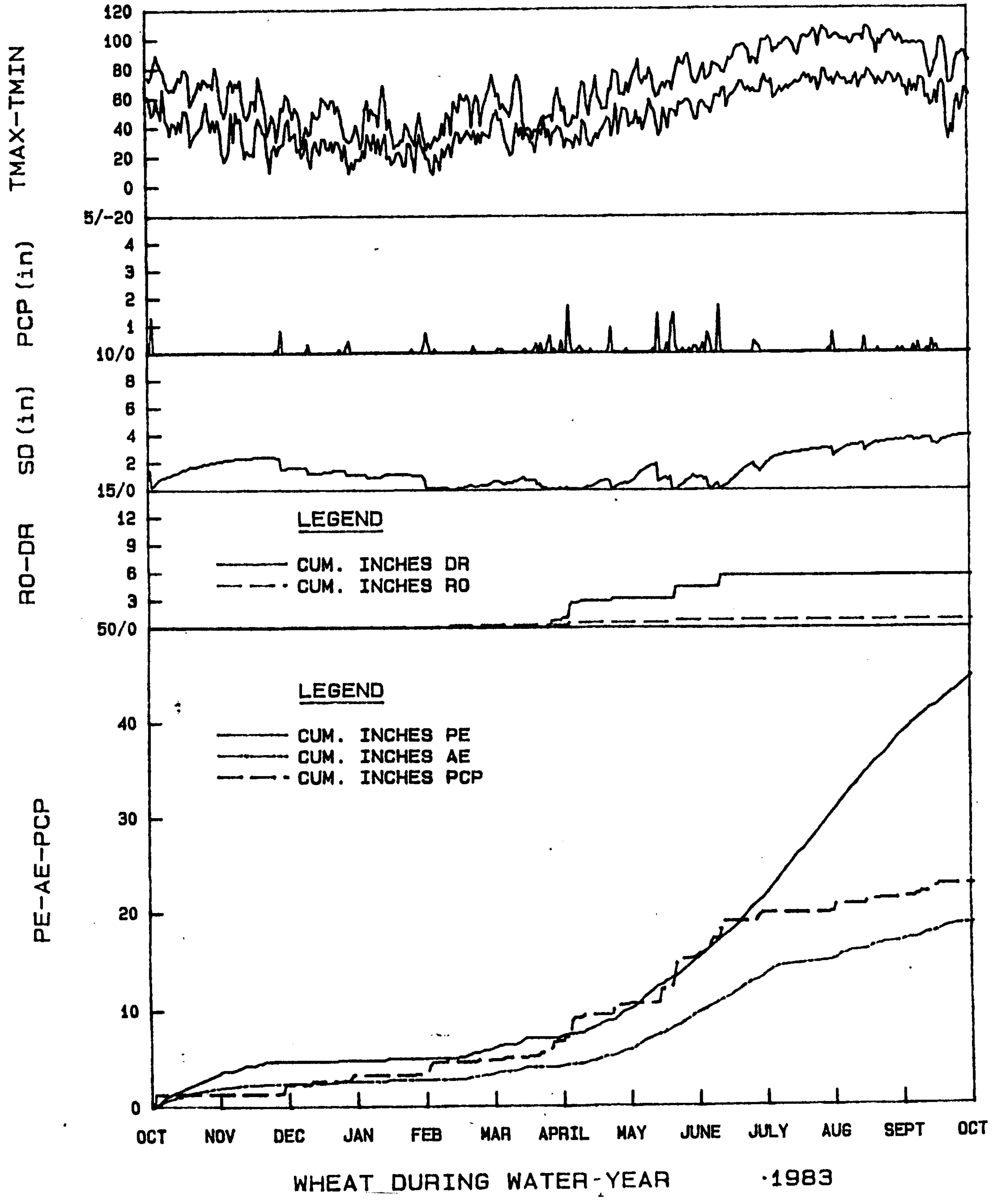
Fig 26 **Effects of vegetation on soil deficit in Rattlesnake basin portion covered by Trousdale and Bucklin precipitation stations.**

Fig 27



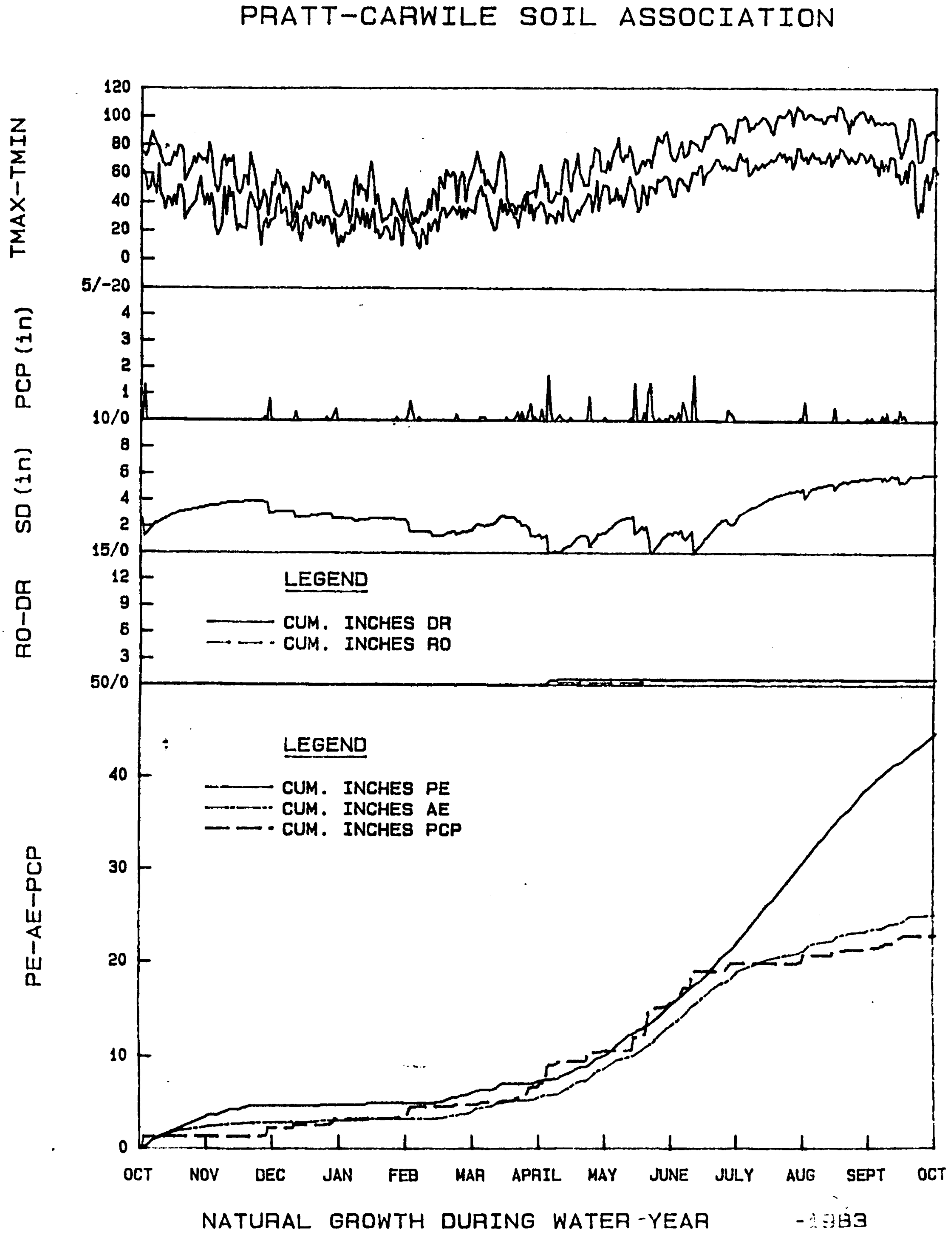
27 **Effects of vegetation on deep drainage in Hudson climatic region of Rattlesnake basin.**

PRATT-CARWILE SOIL ASSOCIATION



28 Time patterns of water-balance components for dryland wheat-fallow rotation in Rat nake basin.

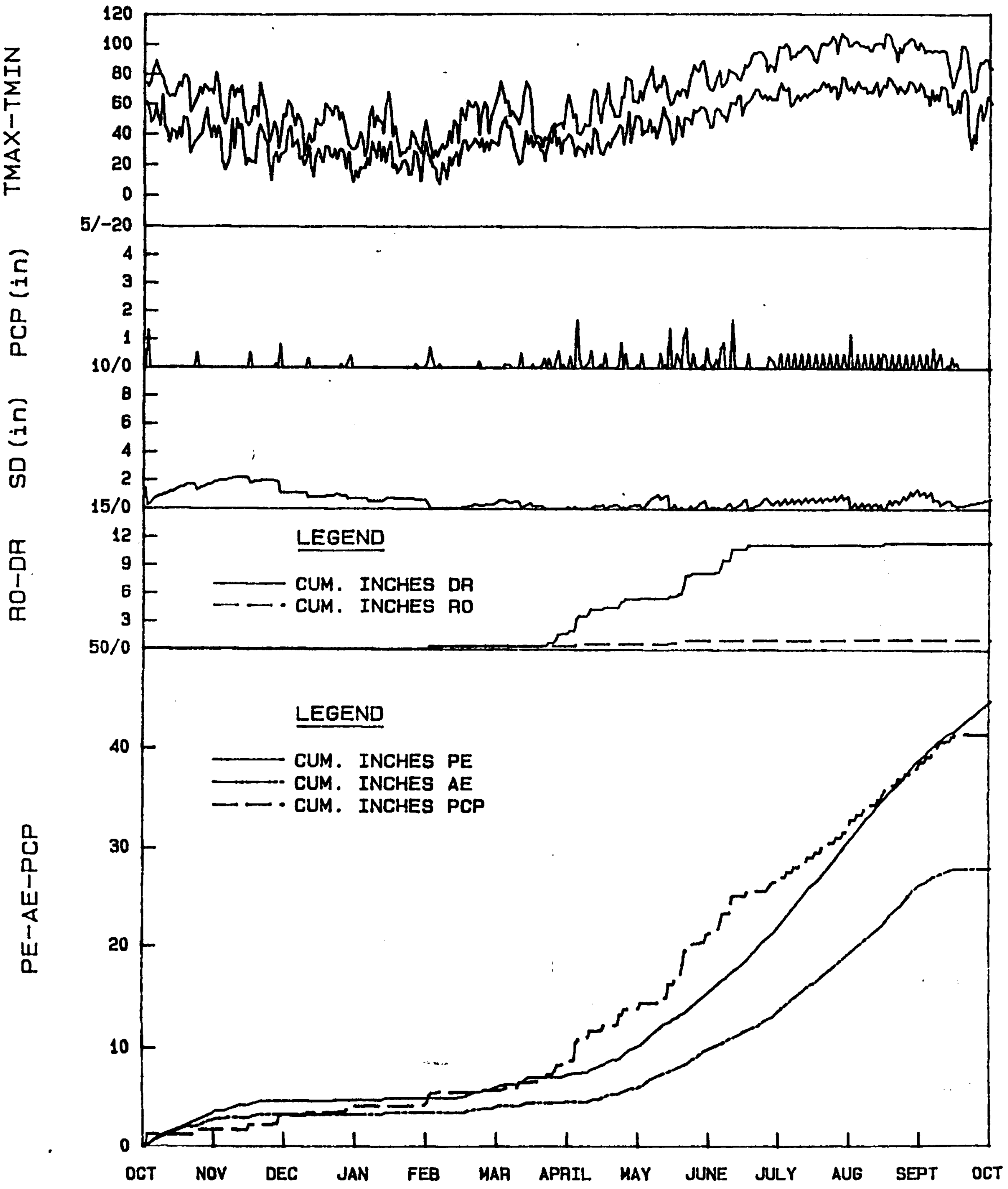
Fig. 29



29 Time patterns water-balance components for natural growth in

FIG 30 (New)

PRATT-CARWILE SOIL ASSOCIATION



IRRIGATED WHEAT-SORGHUM WATER YEAR 1983

FIG 30 Time patterns water-balance components for irrigated wheat-sorghum rotation in snake basin.

FIG 31

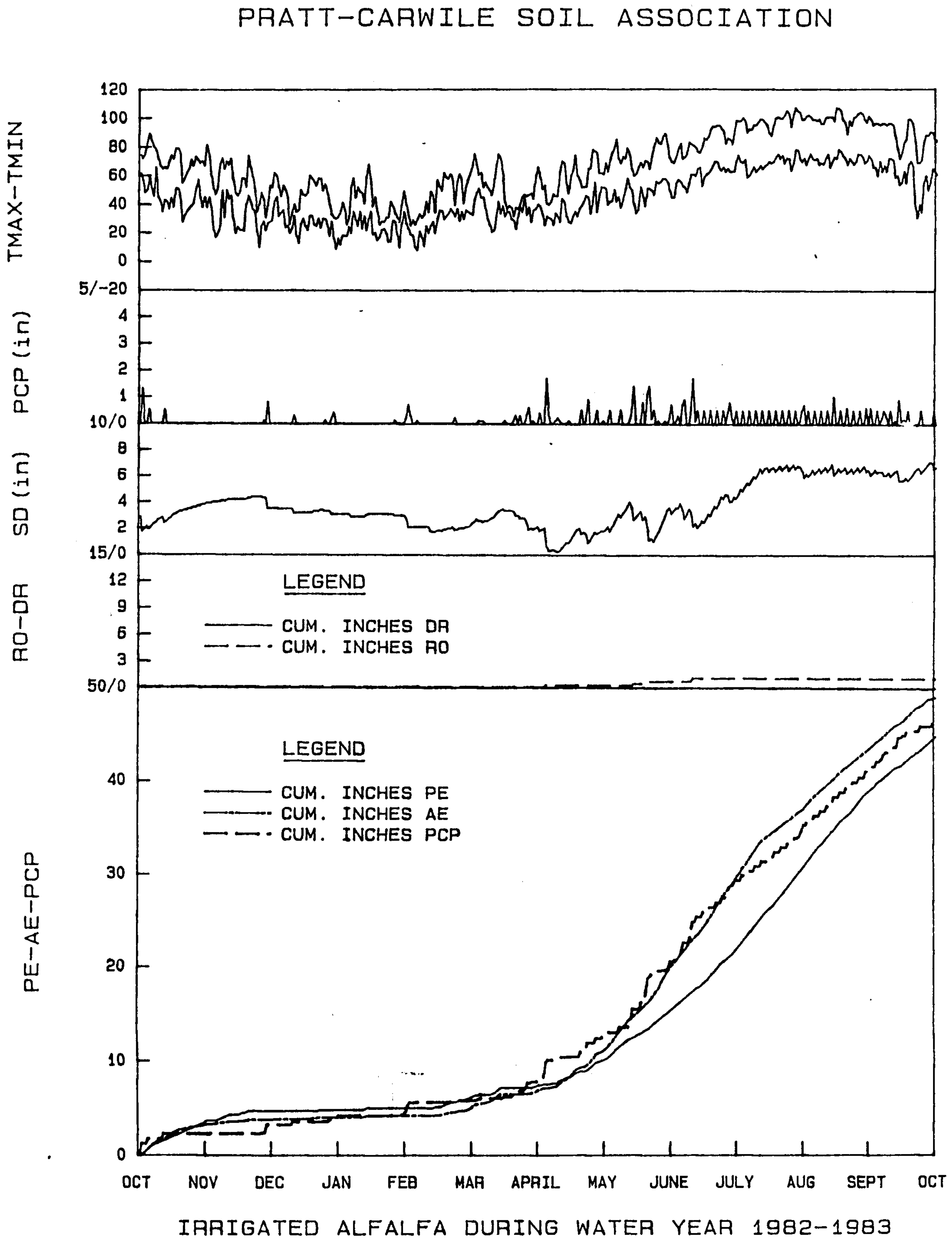
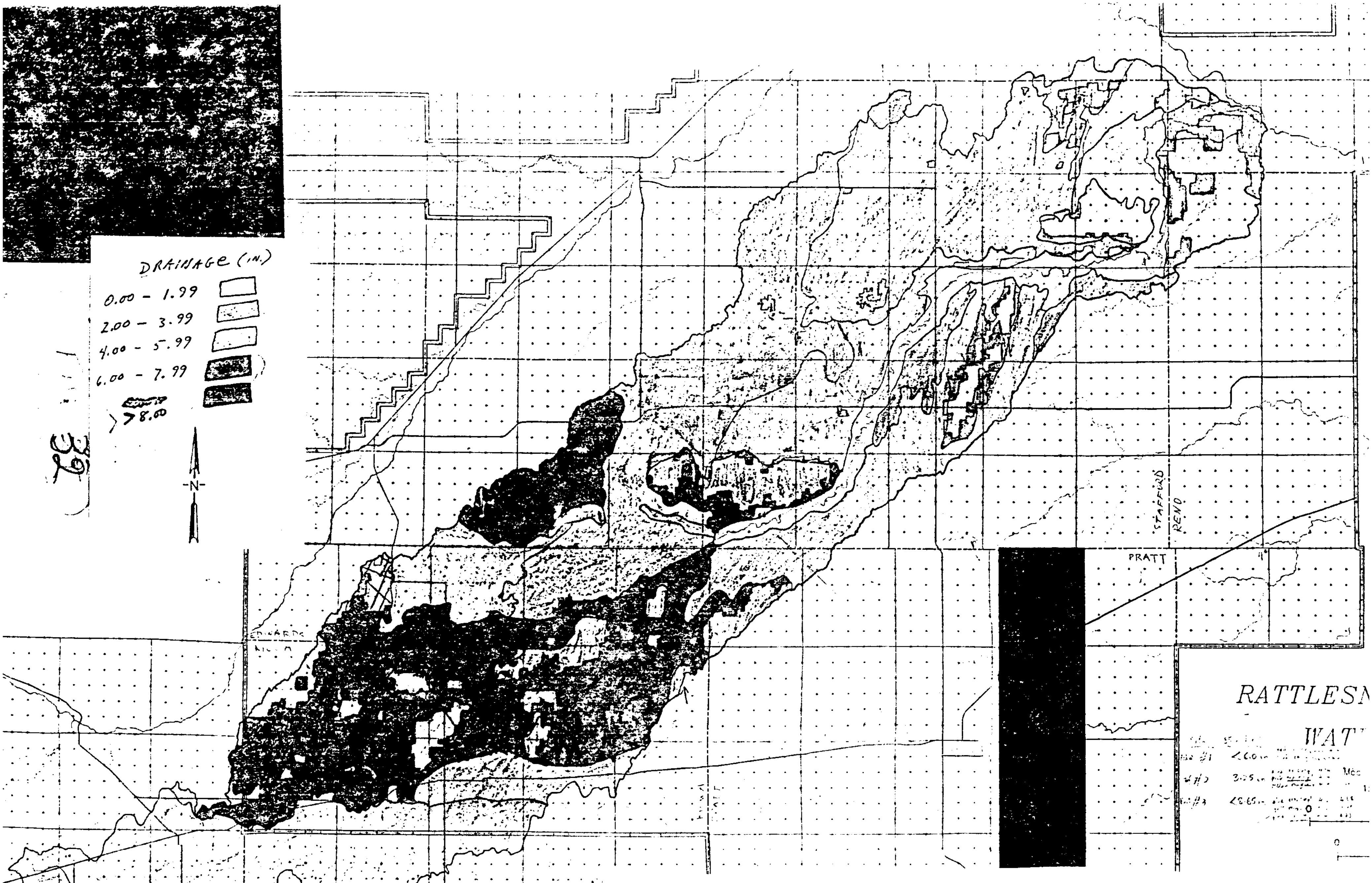
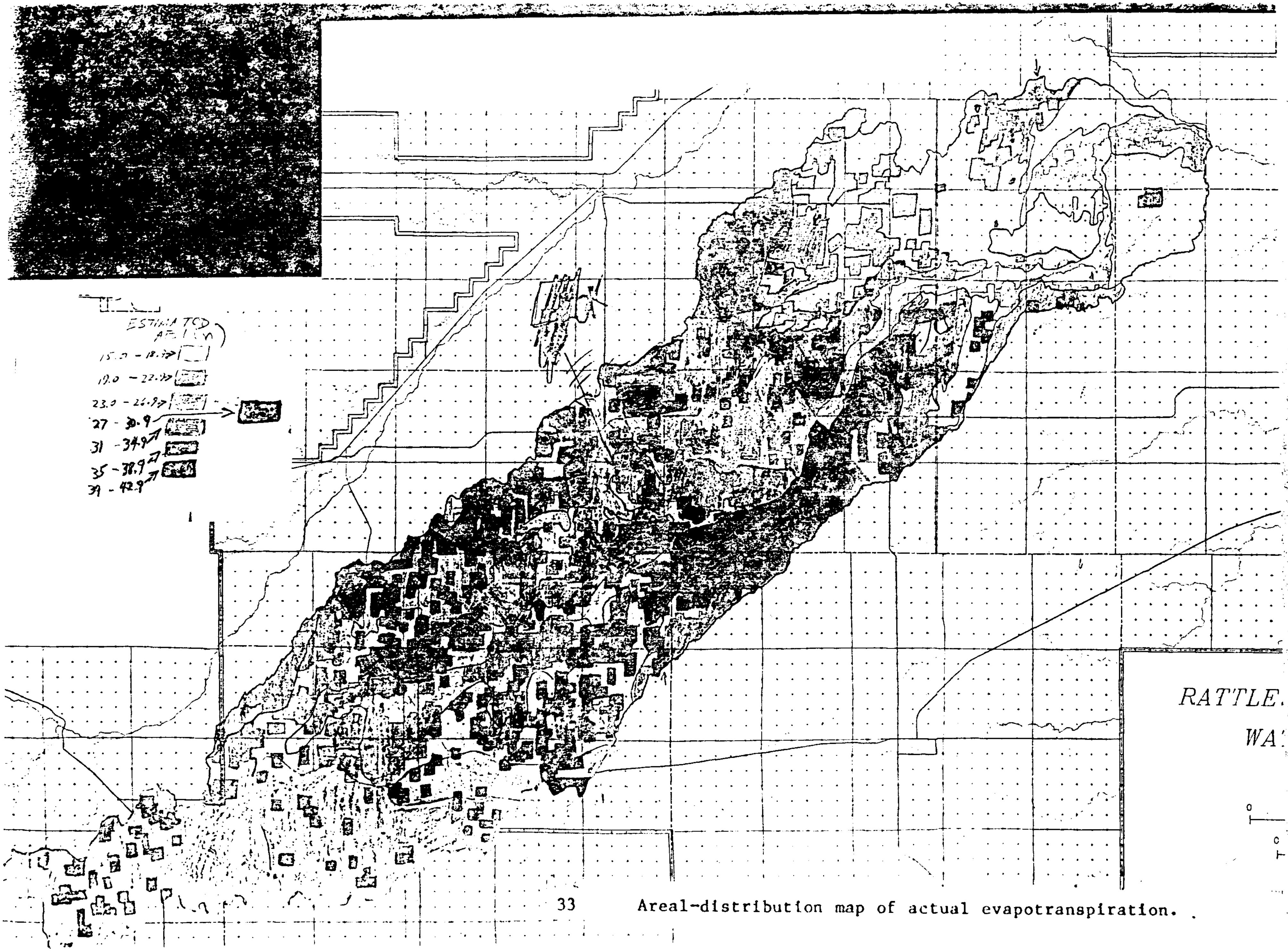


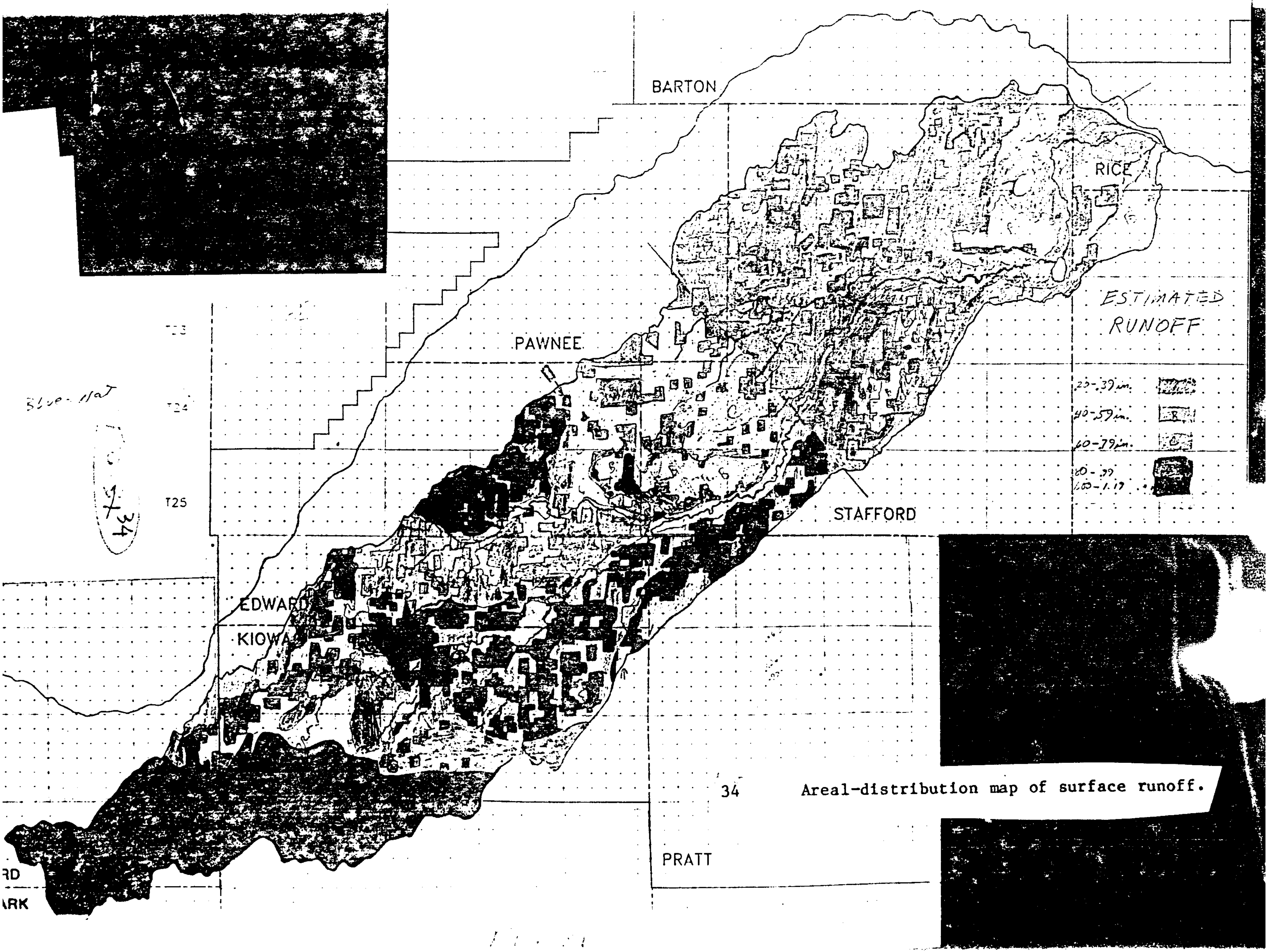
Fig 31 Time patterns of water-balance components for irrigated alfalfa in Rattl[illegible]e basin.



Areal-distribution map of deep drainage.



33 Areal-distribution map of actual evapotranspiration.



34 Areal-distribution map of surface runoff.

Fig. ~~32~~ 35

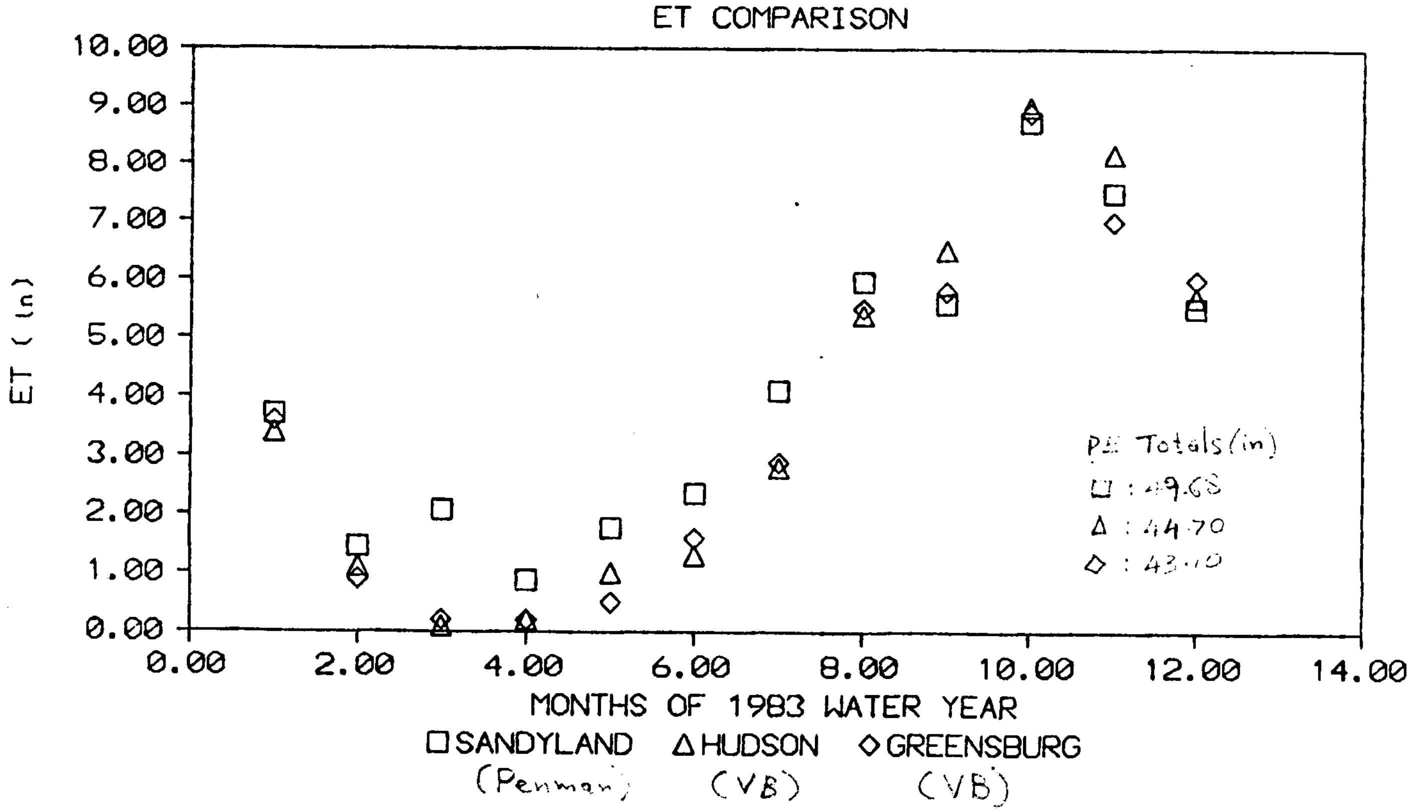


FIG. 35 Comparison of potential-evapotranspiration estimates using Penman and Versatile Budget procedures.