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Comparative Evaluation of Methods for Distributing Naturalized Streamflows from Gauge to Ungauged Sites

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TECHNICAL REPORT

COMPARATIVE EVALUATION OF METHODS FOR DISTRIBUTING NATURALIZED STREAMFLOWS FROM GAGED TO UNGAGED SITES

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INTRODUCTION

Scope of the Report

Senate Bill 1, Article VII of the 75th Texas Legislature directs the Texas Natural Resource Conservation Commission (TNRCC) to develop water availability models for the 22 river basins of the state, excluding the Rio Grande. Models for six river basins are to be completed by December 1999, and the 16 others completed by December 2001. The Water Availability Modeling (WAM) Project is being conducted collaboratively by the TNRCC, Texas Water Development Board (TWDB), Texas Parks and Wildlife Department (TPWD), consulting firms, and university research entities, in coordination with the water management community. The WAM system being developed includes databases and database management tools, a geographic information system, user interfaces, and the *Water Rights Analysis Package (WRAP)* simulation model and associated data files (TNRCC 1998). The study documented by this report was performed in conjunction with the Water Availability Modeling (WAM) Project.

The investigation documented by this report consists of identifying, developing, and evaluating alternative approaches for estimating sequences of monthly naturalized streamflows at ungaged sites based on known naturalized flows at gaged locations. The ultimate product of the study is a recommended set of flow distribution methodologies for incorporation into the *Water Rights Analysis Package* (*WRAP)* model (Wurbs 1999). The objectives of the investigation are:

- To analyze relationships between flows from different subwatersheds of river basins and the watershed characteristics governing these relationships

- To evaluate alternative methodologies and associated parameters for transposing flows from gaged to ungaged locations

- To develop a recommended set of procedures for transposing flows from gaged to ungaged locations for incorporation into *WRAP*

A literature review was performed. Meetings were held with personnel of the TNRCC, Texas Water Development Board, Texas Parks and Wildlife Department, University of Texas Center for Research in Water Resources, U.S. Geological Survey, USDA Agricultural Research Service, Texas Agricultural Experiment Station, and several consulting firms. Flow distribution approaches were identified and evaluated. Available naturalized flows at selected gaging stations in the Brazos and the San Jacinto River Basins were used to investigate relationships between flows at different locations and to evaluate alternative methods for distributing flows. Streamflow data from the Sulphur River Basin were later used to supplement initial analyses.

The following general approaches for estimating naturalized flows at ungaged sites are addressed to various degrees of detail.

- distribution of flows in proportion to drainage area
- flow distribution equation with ratios for various watershed parameters

- adaptation of the NRCS curve number method
- use of stream gage records to develop regression equations relating flows to watershed characteristics
- use of recorded data at gaging stations to develop precipitation-runoff relationships
- watershed (precipitation-runoff) computer models such as the Soil and Water Assessment Tool (SWAT)

Recommendations regarding adoption of a set of procedures for the TNRCC Water Availability Modeling (WAM) system are presented in the *Chapter 7 Summary and Conclusions*.

Role of Streamflow Distribution in Water Availability Modeling

Methods for developing naturalized streamflow data are addressed from the perspective of a water availability modeling process consisting of two phases (TNRCC 1997):

1. development of monthly naturalized streamflow sequences covering the hydrologic period-of-analysis at the locations of reservoirs, diversions, instream flow requirements, and other pertinent sites

2. simulation of the water rights/reservoir/river system, for the input sequences of naturalized flows, to determine reliability indices, unappropriated flows, and related information

Naturalized or unregulated flows represent natural historical hydrology without the effects of reservoirs and human water use. The process of estimating monthly naturalized streamflows consists of three phases:

1. adjusting recorded flows at selected gaging stations to remove the effects of historical water management/use

2. filling in gaps and extending record lengths to cover a common hydrologic period-of-analysis at all the gage sites

3. distributing the naturalized flows at the gaging stations to pertinent ungaged sites of actual or proposed water rights

This report focuses on the third phase, transferring naturalized flows from gaged to ungaged locations.

The problem addressed by this study is that of estimating flows for ungaged subwatersheds. Sequences of naturalized monthly flows covering a several decade hydrologic period-of-record will be available at the location of stream gaging stations. These flows are used to estimate the corresponding flow sequences at the ungaged locations of actual and proposed water rights. For some river basins, the number of relevant ungaged sites may be many times greater than the number of gaging stations. The relative significance of sites may vary. More sophisticated methods may be adopted for developing flows for selected key ungaged locations, while simpler methods are applied to determine flows for numerous other sites. In some cases, the flows computed at selected locations using more sophisticated approaches may in turn be distributed to other sites using simpler techniques.

An illustrative hypothetical river basin is shown in Figure 1.1. Naturalized monthly flow sequences at ungaged locations 1 through 12 in the figure are to be determined, given the corresponding flows at gaging stations A-E.

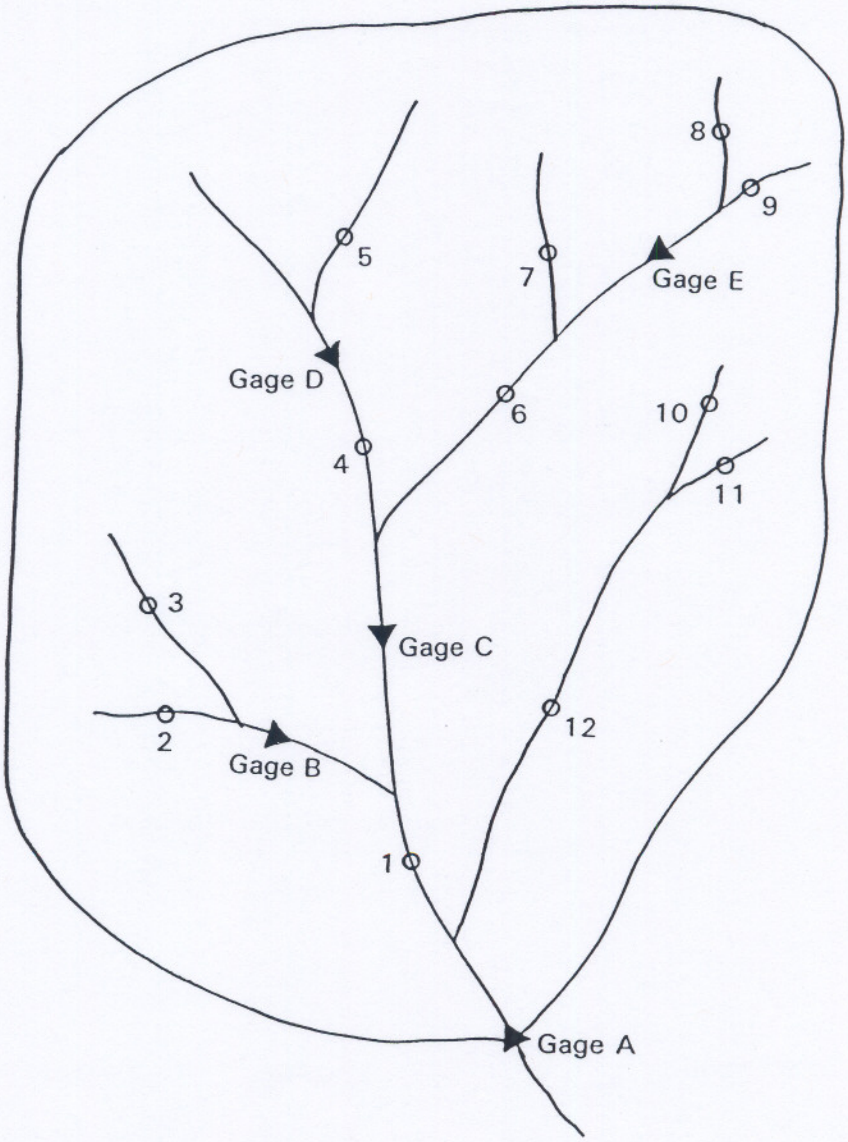


Figure 1.1 Hypothetical River Basin

Flows at Numerous Water Rights Sites

The TNRCC (1997) notes the number of water rights in each of the 22 river basins in Texas excluding the Rio Grande, with a total of 5,310 rights. Most of the appropriated water is associated with a relatively few larger water rights. Since the larger diversion and storage rights are typically located on major streams reasonably near gaging stations, the role of naturalized flows at ungaged sites is associated largely with the numerous smaller rights. Of course, some of the larger rights are also located some distance from gaging stations. There are a few hundred stream gaging stations in Texas with adequate record lengths for use in developing naturalized monthly flow sequences.

As previously noted, the water availability modeling process consists of two phases: (1) the methodology for developing naturalized flows and (2) the river/reservoir/rights system water allocation model. However, the two phases are interconnected. One data management consideration is whether to incorporate some of the naturalized flow distribution computations into the river/reservoir/rights system simulation model or to develop the complete set of naturalized flows independently of the model. For one of the larger basins with several hundred water rights sites, a naturalized flow database might include flows at 20 to 30 stream gage locations and perhaps 10 to 40 other key locations. The flows at several hundred other locations would then be synthesized from flows in the database during execution of the *WRAP* reservoir/river/rights system water allocation model. The size of the naturalized flow databases may be greatly reduced by incorporating the naturalized flow distribution in the river/reservoir/rights system simulation software as a user-option that would typically be applied for the numerous smaller rights.

The Brazos, San Jacinto, and Sulphur Basins, respectively, provide examples of the range of larger and smaller major river basins. These and other major river basins of the state are shown in Figure 1.2. For the 1,200 rights in the Brazos River Basin, which include storage in 600 reservoirs, 42 percent of the annual diversion volume and 62 percent of the conservation storage capacity are associated with 12 reservoirs managed by the Brazos River Authority and U.S. Army Corps of Engineers (Wurbs *et al.* 1994). These and other rights accounting for much of the remaining permitted water use and storage capacity in the Brazos Basin are located reasonably near stream gaging stations. Over 1,000 other smaller rights are scattered throughout the basin.

A recent update of the San Jacinto River Basin water availability model using *WRAP* involved 108 rights, of which 78 include reservoir storage (TNRCC 1996). San Jacinto River Authority and City of Houston rights associated with Lakes Houston and Conroe account for 94 percent of the total diversion volume and 93 percent of the storage capacity in the basin. The model was formulated with 1940-1980 sequences of naturalized flows input for 22 selected control points. Flows were distributed to several other sites within the model by simply applying drainage area ratios.

The Texas portion of the Sulphur River Basin has 54 existing water rights and two major reservoirs, Wright Patman Lake and Jim Chapman Lake, along with 27 other impoundments with a storage capacity of greater than 200 acre-feet. A study of the Sulphur Basin performed for the

TNRCC by R. J. Brandes Company (1999) used naturalized flows at 6 gaging stations covering a 1940-1996 period-of-analysis. Flows at the other sites were estimated from flows at the six gaged sites.

Figure 1.2 River Basins in Texas

Reproduction of Relevant Streamflow Characteristics

Although future streamflows are of concern rather than the past, the future is unknown. Thus, historical hydrology is used as being representative of flow characteristics to be expected in the future. In synthesizing flows for ungaged watersheds, accuracy in estimating the actual flow for any particular month in the past is typically not important as long as relevant statistical characteristics of the long-term historical naturalized flows are adequately captured. Achieving accuracy in the flow-duration (flow-frequency) relationship is particularly important. Capturing the likelihood of long-duration droughts represented by sequencing of many months of flows is also important.

Methods that relate flows at ungaged sites to the corresponding flows at gaged sites will typically tend to result in the estimated flows at ungaged sites being more closely correlated to the gaged site than is actually the case in reality. For example, estimating flows at ungaged site 5 in Figure 1.1 by applying a drainage area ratio to the flows at gaging station D will result in an absolute correlation. In the computations, a low flow at station D will always result in a correspondingly low flow at site 5. In reality, a lower-than-average flow at gage D could occur in the same month as a higher-than-average flow at site 5. This over-correlation between locations is probably acceptable as long as the flow-duration relationship at site 5 is reasonably accurate.

Uncertainties

The task of developing sequences of naturalized flows for ungaged watersheds necessarily involves uncertainties and inaccuracies. Major areas of uncertainty affecting the accuracy of flow estimates include the following.

- Precipitation, streamflow, and other hydrologic variables are highly stochastic and vary greatly both temporally and spatially.

- Rainfall intensities vary drastically over short distances. An intense storm may be concentrated over a particular subwatershed while neighboring subwatersheds receive little or no rainfall. Rain gages are much too sparsely located to capture the spatial variability of rainfall events with a high degree of accuracy.

- Watersheds may be highly nonhomogeneous with soils, vegetation, land use, topography, and other characteristics changing significantly over short distances.

- Watershed characteristics are difficult to accurately measure.

- Changes over time in land use and other watershed characteristics are typically not reflected in the process of naturalizing gaged flows.

- The hydrologic processes that transform rainfall to streamflow, such as infiltration, surface storage/flow, subsurface storage/flow, and evapotranspiration, are complex. Watershed modeling requires major simplifications and approximations.

- Streamflow includes both base flow and surface runoff. Accurately accounting for the separate base flow component, from subsurface sources, and the surface runoff, from recent rainfall, is difficult.

- Channel losses and other interactions between subsurface flows and streamflows are complex.

- Inaccuracies and uncertainties are inherent in all recorded data including gaged streamflows, gaged rainfall, and data used to naturalize gaged streamflows such as reservoir storage, evaporation rates, and water use.

CHAPTER 2
LITERATURE REVIEW

Although the published literature on watershed hydrology is voluminous, there is remarkably little work reported on the specific topic of developing sequences of naturalized monthly flows at ungaged locations based upon corresponding flows at gaging stations. While the monthly flow distribution problem of concern here is not addressed directly, the hydrology literature does focus in depth on related topics such as:

- watershed processes through which precipitation is partitioned into hydrologic abstractions and streamflow
- methods for estimating flood peaks and/or volumes associated with specified annual exceedance frequencies
- watershed modeling methods for developing flood hydrographs from precipitation input
- watershed modeling methods for synthesizing long-term streamflow sequences from precipitation input
- stochastic hydrology techniques for synthesizing sequences of flows that reproduce selected statistical characteristics of observed flows
- flood-flow and low-flow frequency analysis methods and flow-duration curves at gaged sites

The hydrologic processes affecting streamflow and an array of associated modeling/analysis methods are addressed by numerous hydrology books including Linsley et al. (1982), Chow et al. (1988), Shaw (1988), Ponce (1989), Brooks et al. (1991), Singh (1992), Maidment (1993), Dingman (1994), Newson (1994), Viessman and Lewis (1996), and McCuen (1998), as well as thousands of journal and conference papers, agency reports, and other references. However, the problem of relating monthly flow sequences at ungaged sites to the corresponding flows at gaged locations is essentially ignored in the literature. Regression analyses and watershed (precipitation-runoff) modeling are two subjects addressed extensively in the hydrology books cited above and other references, which are particularly relevant to developing sequences of flows for ungaged watersheds. However, although these methods have been applied extensively to other types of hydrologic analyses as discussed below, very few applications deal directly with the problem of distributing monthly flow sequences from gaged watersheds to ungaged subwatersheds.

Investigation of data management software, data sources, and databases is a key aspect of the methodology development effort. Data management systems are an important consideration in applying any of the methods for developing naturalized streamflows. Thus, data management systems are reviewed in the last section of this chapter.

Regression Relationships

Standard statistical methods for regression and correlation analyses and associated significance tests are covered in many statistics books such as Milton and Arnold (1995) and

Kottegoda and Rosso (1997) as well as the previously cited hydrology books. A common form of regression equation is

$$Y \;=\; a\, x_1^b\, x_2^c\, x_3^d \ldots x_n^m \qquad (2\text{-}1)$$

where the dependent (response) variable Y is expressed as a function of independent (explanatory) variables x_i. The regression coefficients (a, b, c, d, ... , m, n) are determined based on least squares regression or other analyses of observed data. Other general forms of the regression equation may be used as well. The investigations cited in the next paragraph illustrate the application of statistical techniques to extensive databases of field data to test the significance of the alternative independent variables being considered, to develop multiple-variable regression models, and to analyze the expected accuracy of the regression models.

The U.S Geological Survey (USGS) is particularly notable of the many entities that have modeled hydrologic characteristics of watersheds using regression equations. For example, Driver and Tasker (1990) present a set of regression equations for estimating runoff volumes and loads of 11 water quality constituents from urban watersheds for individual storm events and for annual means. The dependent (response) variables predicted by the regression equations are runoff volumes and loads of the 11 water quality constituents. The independent (explanatory) variables include rainfall depth and duration; 2-year recurrence interval 24-hour rainfall intensity; watershed area; watershed percent impervious; percent commercial, industrial, residential, and nonurban land use; temperature; and population density. Different regression equations were developed for different regions of the nation.

Kircher et al. (1985) applied regression techniques to estimate streamflow characteristics for natural streams in western Colorado. Mean annual discharge, mean monthly discharge, and peak discharge are predicted as a function of drainage area, mean annual precipitation, mean basin elevation, and mean basin slope.

Flood flow prediction accounts for most of the work reported in the literature in developing regression equations relating hydrologic variables to watershed parameters. Jennings et al. (1994) present regression equations for predicting peak flood flows associated with specified exceedance probabilities, for rural and urban watersheds in various regions of the nation. Independent variables in the regression equations include watershed area, percent impervious, watershed slope, channel slope, mean annual precipitation, and other watershed parameters. Asquith and Slade (1997) present regional regression equations for peak flood flow associated with specified exceedance probabilities for natural (unregulated rural) watersheds in Texas. Devulapalli (1995) provides regression equations for flood volume-duration-frequency relationships for small ungaged rural watersheds in different regions of Texas that are based on watershed parameters including drainage area, slope, and an index precipitation depth. Xin et al. (1997) compare regression methods and other methods for predicting flood flows from ungaged watersheds.

A reasonably in-depth literature review revealed only one journal paper that focuses specifically on methods for transferring sequences of monthly flows from gaged to ungaged sites. Gan et al. (1991) investigated the use of various forms of regression equations for relating concurrent monthly flows from neighboring watersheds. In the regression analyses, monthly flows were related to the following watershed parameters: drainage area, mean annual precipitation, and percent of watershed covered with forest. Gan et al. (1991) conclude that:

> "*The transposition of monthly streamflow data from a gauged catchment to an ungauged catchment is a difficult exercise, whereby great accuracy is not to be expected. The relationship between the concurrent streamflows of two hydrologically similar catchments is essentially a linear one. It is sufficiently accurate if expressed as $Y=BX$ where X and Y represent concurrent monthly discharges. ... Even if B is well estimated, the individual transposed flows may still be much in error as the regression line only represents an average relationship between the flows of two catchments.*"

Watershed Models

Much of the work reported in the literature related to the watershed characteristics that govern streamflow deals with hydrologic modeling. Watershed models simulate the hydrologic processes by which precipitation is converted to streamflow. The watershed is the system being modeled; precipitation is the input; and hydrologic abstractions and runoff are the computed output. Simplified techniques such as the rational formula, which is widely used in drainage design, compute only the peak flood flow associated with a specified annual exceedance probability. Computer models of watershed hydrology incorporate an array of water balance accounting techniques representing the various hydrologic processes. Some watershed models consider only water quantities; others include sediment transport and water quality processes.

Precipitation-Runoff Processes

Some precipitation is loss through the natural hydrologic processes of interception, depression storage, infiltration, evaporation, and transpiration. The remaining precipitation flows overland and through the soil, collects as flow in swales and small channels, and eventually becomes runoff to streams. Groundwater also contributes to streamflow, largely independently of the particular precipitation-runoff event. Contaminants enter the water during the runoff processes. Various pollutant transport and transformation processes occur within the hydrologic processes. Land use, drainage improvements, storage facilities, and other development activities significantly affect the processes by which precipitation is converted to streamflow. Snowfall and snowmelt as well as rainfall are important in many areas. Numerous hydrology textbooks such as those previously cited cover the fundamentals of watershed (precipitation-runoff) processes and modeling thereof.

Watershed modeling involves computing flow rates and sometimes contaminant concentrations or loads, over time, at the watershed outlet (or multiple subwatershed outlets) for specified precipitation input. Larger watersheds are typically divided into a number of smaller more hydrologically homogeneous subwatersheds for modeling purposes. The runoff from the individual subwatersheds is routed through stream reaches and combined at appropriate locations. Runoff from subwatersheds may also be routed through water control facilities and temporarily stored in reservoirs.

Generalized Watershed Models

Singh (1995) describes 27 of the many major generalized watershed modeling packages which among others include the Hydrologic Engineering Center's *HEC-1 Flood Hydrograph Package*, U.S. Geological Survey's *Precipitation-Runoff Modeling System (PRMS)*, National Weather Service's *River Forecast System*, USACE North Pacific Division's *Streamflow Synthesis and Reservoir Regulation (SSARR)*, Danish Hydraulic Institute's *Systeme Hydrologique Europeen (MIKE SHE)*, Environmental Protection Agency's *Stormwater Management Model (SWMM)* and *Hydrologic Simulation Program-Fortran (HSPF)*, and Agricultural Research Service's *SWRRB*, *EPIC*, *CREAMS*, and *GLEAMS*. Several generalized watershed simulation models are described below.

Watershed models can be categorized as single-event or continuous. Single-event models are designed to simulate individual storm events and have no capabilities for the soil infiltration capacity and other watershed abstraction capacities to be replenished during extended dry periods. Continuous models simulate long periods of time which include multiple precipitation events separated by significant dry periods with no precipitation. Some models can be used optionally in either single-event or continuous modes. Most single-event watershed models are designed for quantity-only applications and contain no features for modeling water quality. Most (but not all) continuous models provide capabilities for analyzing water quality as well as quantity.

HEC-1 and HEC-HMS

The HEC-1 Flood Hydrograph Package (Hydrologic Engineering Center 1998) is probably the most widely used of the numerous available watershed models. The recently developed HEC Hydrologic Modeling System (HEC-HMS) incorporates most of the modeling capabilities of HEC-1 in a windows-based environment (Hydrologic Engineering Center 1998). HEC-HMS is intended to eventually replace HEC-1. HEC-1 and HEC-HMS simulate individual flood events. They have no water quality capabilities. The generalized watershed simulation models provide an extensive package of optional computational methods. Precipitation-runoff modeling represents the central focus of the package, but other related modeling capabilities are provided as well. In addition to the basic watershed modeling capabilities, the modeling package includes several other optional features involving: partially automated parameter calibration, multiplan-multiflood analysis, dam safety analysis, economic flood damage analysis, and flood control system optimization.

A HEC-1 or HEC-HMS precipitation-runoff modeling application typically involves dividing a watershed into a number of subwatersheds. Precipitation-runoff is simulated for each subwatershed. The models provide flexible options for developing and/or inputting precipitation data, which may reflect snowfall and snowmelt as well as rainfall. Precipitation volumes are converted to direct runoff volumes using one of the following optional methods: NRCS curve number method; initial and uniform loss rate; exponential loss rate function; Holtan loss rate function; or Green and Ampt relationship. Runoff hydrographs are computed from the incremental runoff volumes using either the unit hydrograph or kinematic routing options. An unit hydrograph may be input to HEC-1. Alternatively, the model includes options for developing synthetic unit hydrographs using either the Soil Conservation Service, Synder, or Clark methods. Watershed modeling also involves routing hydrographs through stream reaches and reservoirs. HEC-1 uses hydrologic storage routing for reservoirs. The following channel routing options are provided: Muskingum, Muskingum-Cunge, modified Puls, working R and D, average lag, and kinematic wave.

HSPF

The Hydrological Simulation Program - Fortran (HSPF) is documented by Johanson et al. (1984). HSPF provides relatively sophisticated capabilities for continuous simulation of a broad range of hydrologic and water quality processes. The model is oriented more toward agricultural and other non-urban watersheds, but urban watersheds can also be simulated. HSPF consists of a set of modules arranged in a hierarchical framework built around a time series data management system. The various simulation and utility modules can be invoked individually or in various combinations. The structured design of the model facilitates users adding their own modules, if they so desire.

HSPF simulates watershed hydrology and water quality for both conventional and toxic organic pollutants. Input data include time histories of rainfall, temperature, and solar radiation; and information regarding land-surface characteristics, such as land-use patterns, soil properties, and land-management practices. The result of the simulation of a subwatershed is a hydrograph and pollutographs. The model predicts flow rates, sediment loads, and nutrient and pesticide concentrations. The subwatershed runoff characteristics are then used by the model to simulate instream processes to determine hydrographs and pollutographs at all pertinent locations in the watershed. HSPF allows integrated simulation of land and soil contaminant runoff processes with instream hydraulic and sediment-chemical interactions.

MIKE SHE

The Danish Hydraulic Institute's *MIKE SHE* stems from the Systeme Hydroloqique Europeen (SHE) developed by a consortium of three European organizations. *MIKE SHE* simulates water flow, water quality, and sediment transport in rural watersheds. The generalized model is particularly notable for its comprehensive inclusion of all major hydrological processes occurring in the land phase of the hydrologic cycle including both surface and ground water processes. *MIKE SHE* has been widely applied throughout the world in a variety of different types of applications.

Agricultural Research Service Models

The U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) has developed a number of models for simulating hydrologic and water quality processes in rural watersheds. The Soil and Water Assessment Tool (SWAT) is the model applied in the analyses reported in Chapter 6 of this report. SWAT builds upon the Simulator for Water Resources in Rural Basins (SWRRB) developed by the ARS Grassland, Soil, and Water Research Laboratory in Temple, Texas. SWRRB is designed to predict the effect of various types of watershed management practices on water and sediment yields in ungaged agricultural watersheds (Arnold *et al.* 1990). The major processes reflected in the model include precipitation, surface runoff, percolation, lateral subsurface flow, evapotranspiration, pond and reservoir evaporation, erosion and sedimentation, soil temperature, crop growth, and irrigation. Many years of daily flows may be determined for inputted or computed precipitation data. Precipitation may be either inputted or developed by the model as a Markov process using inputted probabilities. A watershed may be divided into as many as ten subwatersheds. The soil profile can be divided into as many as ten layers. The hydrologic computations are based on the water balance equation. The NRCS curve number method is used to compute runoff volumes. Sediment yield is determined using the modified universal soil loss equation and a sediment routing model.

The Simulator for Water Resources in Rural Basins - Water Quality (SWRRB-WQ) was developed by adding water quality modeling capabilities to SWRRB. SWRRB-WQ simulates weather, hydrology, erosion, sediment yield, nitrogen and phosphorus cycling and movement, pesticide fate and movement, crop growth and management, pond and reservoir management, and other processes. SWRRB-WQ has been used by the Agricultural Research Service, Soil Conservation Service, Environmental Protection Agency, and other agencies to assess the effects of land management on off-site water quantity and quality, pollution of coastal bays and estuaries, reservoir sedimentation, and registration of pesticides.

SWRRB-WQ was developed by modifying and expanding the earlier CREAMS model. The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model simulates hydrology, erosion, nutrients, and pesticides from field-size areas. SWRRB expands CREAMS for applicability to larger, more complex watersheds. The recently developed Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model was designed to replace the earlier CREAMS model. GLEAMS simulates the effects of weather, soils, tillage practices, and pesticide and nutrient management on movement of nutrients, pesticides, and pesticide degradation products to ground and surface waters. GLEAMS is a continuous, field-scale model that permits assessment of the effects of variable topography and slope within the field. The model is used by the USDA, other government agencies, and agricultural chemical companies to assess the environmental effects of alternative management practices and pesticide products.

Soil and Water Assessment Tool (SWAT)

The recently developed Soil and Water Assessment Tool (SWAT) is designed to extend the capabilities of SWRRB-WQ to large complex rural river basins (Arnold et al. 1996). SWAT, like SWRRB, was developed at the ARS Grassland, Soil, and Water Research Laboratory in Temple, Texas. This research facility also houses the Blackland Research Center of the Texas Agricultural Experiment Station (TAES) of the Texas A&M University System. Watershed modeling research programs have been a joint partnership of the ARS and TAES. Natural Resource Conservation Service (NRCS) personnel also participate in the research programs at the facility in Temple.

SWAT reflects changes to SWRRB-WQ involving: (1) expanding the model to allow simultaneous computations on several hundred subwatersheds and (2) adding components to simulate lateral flow, ground water flow, reach routing transmission losses, and sediment and chemical movement through ponds, reservoirs, streams, and valleys. SWAT is a spatially distributed watershed model that uses a daily time step for simulation periods that may exceed 100 years. Major components of the model include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, ground water and lateral flow, and agricultural management. SWAT has been combined with geographical information systems and relational databases. A unique aspect of the development and application of SWAT has been the focus on linking the watershed simulation model to a number of GIS databases that include precipitation and other weather data, soils, land use, and agricultural data (Srinivasan and Arnold 1994). SWAT has been run primarily on workstations under the UNIX operating system, but MS-DOS and Windows based microcomputer versions are also available.

SWAT has been used for various river basin modeling applications. It is presently being used in the HUMUS (Hydrologic Unit Model for the United States) project which entails national and regional water assessments for all the major river basins of the United States.

Data Management Systems

Data management software systems for compilation, storage, retrieval, editing, mathematical computations, analysis, and tabular/graphical display of voluminous data are a central foundation of the entire water availability modeling process. Data management is a key aspect of the streamflow naturalization methodologies being investigated.

Available data management software may be categorized as follows.

- spreadsheet/graphics/database packages such as Excel, Quattro Pro, and Lotus 1-2-3
- commercially available database management systems such as Oracle
- water resources data management systems such as HECDSS
- geographic information systems (GIS) such as Arc/Info and ArcView

These different types of data management software are briefly discussed below.

Spreadsheet Programs

Excel, Quattro Pro, and Lotus 1-2-3 are among the most popular of the numerous spreadsheet/graphics/database packages available on the market (Wurbs 1995). Spreadsheet programs are widely-used, polished, inexpensive commercial products. They provide the advantage of applying the same familiar software to many different applications. A particular application can be addressed using software that is already being used in the office for other purposes as well. Spreadsheet software provides extensive computational and data management capabilities. However, application of spreadsheet programs grows awkward as the volume of data increases. The programs discussed next are designed to handle large databases.

Commercial Database Management Systems

Thuraisingham (1997) defines data management systems as systems that manage data, extract meaningful information from the data, and make use of the information extracted. These systems are widely used in business and government. Most of the popular database management systems are classified as being relational because each database file is considered as a two-dimensional table, and related files are linked via connection fields. The voluminous literature on database management technology includes books by Simovici and Tenney (1995), Zaniolo et al. (1997), and Thuraisingham (1997) covering fundamental theory and applications.

Many relational database system products are marketed by various companies including Oracle Corporation, Ingres Corporation, IBM, Digital Equipment Corporation, Hewlett Packard, Informix, and Sybase, Inc. Particularly notable are the numerous products for database management, server technology, and applications developed by the Oracle Corporation. Oracle's Oracle7 Server is extensively used in business, industry, and government. The Oracle7 relational database management system is a set of software products to support various functions including query processing, online transaction processing, data warehousing, workgroup management, and internet access.

Oracle7, ObjectStore (an object-oriented system marketed by Object Design Inc.), Illustra (an object-relational system marketed by Informix Inc.), and other competing products are large-scale more-expensive database management systems used by large organizations. Less expensive, smaller-scale systems for personal computers include Paradox and dBASE, available from Borland International, and Access from Microsoft.

These generalized database management systems tend to be oriented toward business applications involving extensive text information as well as numbers. Water resources data typically involve numerous large blocks of numbers. The data management systems discussed below were designed specifically for water resources applications with the intent of being more efficient for these applications than the generalized commercial systems cited above.

Water Resources Data Management Systems

Software systems have been developed by the water agencies specifically for water resources related data management and analysis applications. Two particularly notable packages are described below. HECDSS and ANNIE were developed by the Hydrologic Engineering Center and U.S. Geological Survey, respectively.

HECDSS. - The Hydrologic Engineering Center (HEC) Data Storage System (DSS) is one of a number of widely-used computer programs available from the HEC of the U.S. Army Corps of Engineers (Hydrologic Engineering Center 1995). The public domain software may be downloaded from the HEC website (http://www.wrc-hec.usace.army.mil) and is also distributed by various vendors. HECDSS is widely used by water agencies and consulting firms for a variety of different types of applications.

HECDSS database management capabilities are oriented particularly toward voluminous sets of time series data. HECDSS uses a block of sequential data as the basic unit of storage. The basic concept underlying the HECDSS is the organization of data into records of continuous, applications-related elements, as opposed to individually addressable data items. This approach is more efficient for water resources applications than that of a conventional database system because it avoids the processing and storage overhead required to assemble an equivalent record from a conventional system. HECDSS is available for desktop computers, and the FORTRAN77 programs have also been compiled and executed on various minicomputer and mainframe systems.

HECDSS provides capabilities to: (1) store and maintain data in a centralized location, (2) provide input to and store output from application programs, (3) transfer data between application programs, (4) mathematically manipulate data, and (5) display the data in graphs and tables. The user may interact with the database through: (1) utilities that allow entry, editing, and display of information, (2) application programs that read from and write to the data base, and (3) library routines that can be incorporated in any program to access data base information. HECDSS does not presently have a graphical user interface. However, the California Department of Water Resources is currently sponsoring development of a graphical user interface in conjunction with adopting HECDSS for use by state and local agencies in California.

A variety of utility programs are included in HECDSS for entering data into a database file. Some are designed for entering data from other databases such as the U.S. Geological Survey WATSTORE system and National Weather Service climatic databases. Several HEC application programs have been interfaced with DSS, allowing users to retrieve data for analysis or store results in a DSS file. This provides the user the capability of displaying and analyzing application program results by using the DSS utility programs. A set of FORTRAN subroutines are available which can be used to link application programs with HECDSS (Hydrologic Engineering Center 1990). HECDSS also provides means for mathematically manipulating data in a variety of ways. Normal arithmetic operations and many mathematical functions are provided. Various statistical analyses can be performed. Missing data can be synthesized. Hydrologic routing of streamflows can be performed.

Application of HECDSS capabilities specifically for developing naturalized streamflows is illustrated by a recent major water availability/allocation study for the Alabama-Coosa-Tallapoosa (ACT) and Apalachicola-Chattahoochee-Flint (ACF) River Basins in Georgia, Alabama, and Florida (U.S. Army Corps of Engineers 1997). Participants in this several-year, several million dollar water availability modeling effort included several agencies of the three states, several local water management entities, several consulting firms including Camp, Dresser & McKee Inc., and several Corps of Engineers offices.

ANNIE. - ANNIE is a computer program for interactive hydrologic analyses and data management, which was developed by the U.S. Geological Survey (Lumb et al. 1990). ANNIE contains a set of procedures to organize, manipulate, and analyze data needed for hydrologic modeling and analysis. The user interactively performs tasks related to data management, tabular and graphical presentation, statistical analysis, and input preparation for hydrologic models. ANNIE stores data in a binary, direct-access file with a specified structure, which is called a Watershed Data Management (WDM) file. The WDM file provides users with a common database for many applications, thus eliminating the need to reformat data from one application to another. ANNIE and/or the WRM file format are currently used with a number of U.S. Geological Survey and Environmental Protection Agency hydrologic and water quality models. ANNIE is written in FORTRAN and designed for portability to mainframe computers, minicomputers, and microcomputers.

ANNIE provides capabilities to create a Watershed Data Management (WDM) file, transport data to and from the WDM file, and adjust and manipulate the data. The data can be tabulated in various presentation formats. ANNIE graphics capabilities includes time series plots, X-Y plots, and probability plots. The plots can meet USGS publication standards. ANNIE provides a number of statistical analysis capabilities including flow-duration, frequency, error, and trend analyses. The ANNIE library of routines has also been used to create custom programs for use in developing input files for specific hydrologic, hydraulic, or water quality simulation programs.

ANNIE-IDE.- The ANNIE Interaction Development Environment (ANNIE-IDE) was created by the Environmental Protection Agency to provide a consistent methodology for building interactive interfaces for environmental computer programs and data bases (Kittle, Hummel, Imhoff 1989). ANNIE-IDE incorporates a number of routines and methods from ANNIE. ANNIE-IDE is a set of tools for developing user interfaces for simulation models and pre-and post-processor programs. The ANNIE-IDE system provides the program developer with a set of subroutines which may be incorporated into a model to perform one or more of the following operations: (1) display text on the monitor screen, (2) display static and/or dynamic menus, (3) prompt the user to input or edit values in a one- or two- dimensional array, (4) open a file to store or retrieve information, and (5) display context-sensitive help, instructions, and model parameter information.

Geographic Information Systems

A geographic information system (GIS) is a set of computer-based tools for capturing, storing, processing, combining, manipulating, analyzing, and displaying data which are spatially referenced to the earth. Thus, GIS is a special case of data management/analysis dealing specifically with spatial or geographical data. GIS technology dates back to the 1960's and has evolved into a major discipline in recent years. Groups monitoring the GIS industry estimate the total value of hardware, software, and services conducted by the private, government, educational, and other sectors that handle spatial data to be about $6 billion per year (Clark 1997). The voluminous GIS literature includes recent books by Antenucci et al. (1991), Maquire et al. (1991), Goodchild et al. (1993), Demers (1997), and Clarke (1997).

Applications of GIS technology vary widely. In general, geographic information systems provide cartographic, data management, analytical, and polygon processing capabilities. Cartographic capability allows accurate maps and engineering drawings to be produced efficiently. This capability includes digitizing, graphic display generation, interactive graphic manipulation, and plotting. Data management capabilities involve the efficient storage and retrieval of both graphic and nongraphic data, including nongraphic attributes linked to graphic images. Data management includes selecting data and producing graphics and reports on the basis of attribute values. Analytical capabilities involve various mathematical computations and analyses. Polygon processing consists of overlaying sets of data. For example, soil type data may be overlain on land use data to construct polygons having specified combinations of soil type and land use.

In some cases, customized GIS software has been developed for a particular governmental organization or private company and its own particular applications. However, many generalized GIS software packages are available which provide a variety of capabilities for a broad range of applications. The following eight GIS packages account for the majority of applications (Clark 1997):

- Arc/Info marketed by the Environmental Systems Research Institute (ESRI) (http://www.ersi.com)
- ArcView also marketed by ERSI
- Atlas*GIS originally marketed by Strategic Mapping Incorporated and later sold to Claritas which in turn was purchased in 1996 by ESRI (http://www.stratmap.com)
- Geographical Resources Analysis Support System (GRASS) which is public domain software developed by the U.S. Army Corps of Engineers (USACE) Construction Engineering Research Laboratory (CERL) (http://www.cecer.army.mil)
- IDRISI developed, distributed, and supported by the Clark University Graduate School of Geography
- MapInfo marketed by MapInfo Corporation (http://www.mapinfo.com)
- Maptitude marketed by the Caliper Corporation (http://www.caliper.com)
- Microstation MGE marketed by Intergraph Corp. (http://www.intergraph.com/infrastructure)

ARC/INFO. - Arc/Info is one of the earliest and still most widely used of the available generalized GIS software packages. ESRI marketing literature indicates that the company has over 100,000 customers in 120 countries that use its various products. Clarke (1997) states that over 30,000 people are using Arc/Info at over 7,000 organizations worldwide. The software is used by federal, state, and local government agencies, businesses, utilities, and universities for applications in planning, cartography, transportation, research, telecommunications, oil and gas, forestry, environmental management, hydrology, and many other disciplines.

Early versions of Arc/Info were developed for use on Sun workstations with the Unix operating system, but versions are currently available for implementation on a wide range of computer systems, including higher-end microcomputers, most workstation systems, and various mainframe computers. Significant effort is required to become proficient with the software. An array of manuals, references, training materials, and courses are available to assist users.

As the name suggests, Arc/Info is comprised of two components, ARC and INFO. ARC is a system for working with map coordinate data representing geographic features. INFO is database management system for attribute data. ARC/INFO is a set of tools for creating, analyzing, displaying, and managing computerized maps in vector format. The vector approach for storing data is used. Geometric features of a map are represented by points, lines (an arc or set of arcs), and polygons (planes enclosed by arcs). For example, a river basin application might involve representation of precipitation and streamflow gages as points, streams as arcs, subwatershed boundaries as arcs, and subwatersheds as polygons. The associated attribute data might include stream reach lengths, subwatershed areas, soil types, and land use.

The Arc/Info system provides a broad range of optional capabilities for data management and analysis. A macro language is provided for developing customized applications. Data can be edited, checked, and manipulated in various ways. Data can be displayed in a variety of graphic and textual formats. Analytical tools are available for modeling networks, including the computational tasks of routing, allocation, and districting. Routing determines the optimum paths for the movement of resources (such as vehicles, water, electricity, or pulses of communication) through a network (comprised of roads, pipes, or telephone lines). Allocation involves finding the nearest center for each link in the network that best serves the network (such as finding the closest fire station from each street within a city). Districting involves aggregation of areas bounded by certain networks, such as dividing a city into districts bounded by selected streets. Attribute data can then be displayed by district.

ArcView. - ArcView is desktop-computer GIS software package that is easier to learn and use than Arc/Info but does not have the full capabilities of Arc/Info. ERSI developed both ArcView and Arc/Info, and there is compatibility between the two systems. ArcView is oriented more toward map display than database management. ArcView provides capabilities for storing, modifying, querying, analyzing, and displaying information about geographic space. An intuitive graphical user interface facilitates data display and viewing. The software includes features for spatial and tabular queries, *hot links* to other programs, and various types of graphics.

HEC-PREPRO. - HEC-PREPRO is a GIS preprocessor for the USACE Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS). The GIS preprocessor was developed by Professor David R. Maidment, University of Texas Center for Research in Water Resources, under contract with the HEC. A draft HEC-PREPRO user's guide and reference manual (Hydrologic Engineering Center 1997) is available from Dr. Maidment's web site:

http://civil.ce.utexas.edu/prof/maidment/gishydro/ferdi/research/hecprepro/uguide/uguide.html

as well as from the HEC. HEC-PREPRO is written in Arc/Info's Arc Macro Language (AML).

As previously discussed, the Hydrologic Modeling System (HEC-HMS) was recently developed by the Hydrologic Engineering Center in conjunction with their NexGen project to incorporate advances in computer technology into HEC generalized models (Hydrologic Engineering Center 1997). The HEC-HMS is a watershed (precipitation-runoff) modeling package for simulating flood events. It is the NexGen version of the widely used HEC-1 Flood Hydrograph Package. HEC-PREPRO converts watershed data from Arc/Info databases into a format for input to HEC-HMS. Input to HEC-PREPRO consists of GIS stream coverage, subbasin coverage, and an elevation grid which is translated by the program into a schematic data structure for input to HEC-HMS.

Available Major Databases

The Texas Natural Resources Information System (TNRIS) is the state's clearinghouse and referral center for natural resources data (http://www.tnris.state.tx.us). The TNRIS was established by the Texas Legislature in 1968 as the Texas Water-Oriented Data Bank and in 1972 was designated the TNRIS. The TNRIS is an operational section of the Texas Water Development Board. Its policies and guidelines are set by an interagency task force composed of representatives from 16 of the state's natural resource agencies and the Office of the Governor. Funding is provided by the legislature through the TWDB. TNRIS is a clearinghouse for data developed by the federal and state agencies and other entities. In addition to providing information regarding data availability, the TNRIS maintains a library of data that can be accessed directly. TNRIS operates a geographic information system primarily for support of participating agency mapping requirements.

THE TNRIS web site (http://www.tnris.state.tx.us) provides information regarding numerous databases. Several of the databases that are particularly pertinent to the task of distributing naturalized streamflows from gaged to ungaged sites are cited as follows. These databases are commonly used in conjunction with geographic information systems.

Watershed areas can be determined by a GIS using Digital Elevation Models (DEM) developed by the U.S. Geological Survey (USGS). DEM data files are digital representations of cartographic information in a raster form. A grid of terrain elevations are provided. The data files are produced by the USGS as part of its National Mapping Program and are sold in 7.5-minute, 15-minute, 2-arc-second (also known as 30-minute), and 1-degree units. The extent of available coverage of regions of the United States varies between the different scales.

Land Use and Land Cover (LULC) data are also developed by the USGS as part of the National Mapping Program. LULC data files describe the vegetation, water, natural surface, and cultural features of the land surface. The LULC mapping program is designed so that the standard topographic maps of a scale 1:250,000 can be used for compilation and organization of the land use and land cover data. LULC data are available for most of the contiguous United States and Hawaii. All LULC features are delineated by curved or straight lines that depict the actual boundaries of an area, commonly referred to as a polygon. These polygons have a minimum size of 10 acres or 4 hectares. Each polygon represents a homogeneous element in the mapping scheme that is labeled with an integer or attribute code. The arcs and nodes are further defined by a x,y point or string of points that provide the direction and location for the polygon. This relationship may be defined by the labeled area within the polygon or outside of it. Such positional data can be manipulated to meet a variety of user needs by reprojecting the data or re-scaling them. The LULC data are available in two different formats: (1) as a part of the Geographic Information Retrieval and Analysis System (GIRAS) and (2) in the Composite Theme Grid (CTG) format which is grid cell oriented instead of polygonal.

The State Soil Geographic (STATSGO) database was developed by the Natural Resource Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA). STATSGO is a general soil association map developed in conjunction with the National Cooperative Soil Survey Program administered by the NRCS. STATSGO consists of a broad based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale mapped. The soil maps for STATSGO are compiled by generalizing more detailed soil survey maps. Where more detailed soil survey maps are not available, data on geology, topography, vegetation, and climate are assembled, together with Land Remote Sensing Satellite (LANDSAT) images. Soils of like areas are studied, and the probable classification and extent of the soils are determined. STATSGO was designed for regional, multi-county, river basin, state, and multi-state resource planning and management.

CHAPTER 3
WATERSHED CHARACTERISTICS

The primary watershed characteristics governing streamflow may be outlined as follows.

- precipitation characteristics
- watershed area
- watershed characteristics affecting hydrologic abstractions and runoff volumes
    - land cover (land use and vegetation)
    - soils
    - antecedent moisture conditions
- topographic characteristics primarily affecting runoff response time
    - watershed shape
    - stream tributary configuration
    - watershed slope
    - stream channel slope
- watershed characteristics affecting subsurface base flow
    - soils
    - vegetation
    - soil moisture
    - channel bed materials
    - stream channel length
    - geology
    - groundwater table

Different precipitation and watershed characteristics affect different aspects of the streamflow hydrograph as discussed below.

Precipitation Characteristics

Precipitation is the source of surface and subsurface water. Whether the precipitation is in the form of snowfall or rainfall significantly affects streamflow characteristics, but precipitation in Texas is usually rainfall. For a given rain storm, intensities vary greatly both temporally and spatially. A storm may be centered over a particular subbasin and miss an adjacent subbasin, and then vice versa for the next rainfall event.

In distributing naturalized monthly streamflows from a gaging station to various ungaged locations in a river basin, if accuracy in predicting flow for particular historical months (say June 1967) is the primary concern, then knowing the precipitation falling in that month over each subwatershed would be important. However, if only the long-term characteristics of streamflows are of concern, knowing the long-term mean precipitation for each subbasin is probably adequate for representing differences in precipitation in the distribution of streamflows.

For many water availability modeling situations, the differences in mean annual precipitation may be insignificant for relevant closely spaced locations in a river basin. However, there will be applications in which the mean precipitation for an ungaged subbasin will be significantly different than the gaged watershed from which streamflows are being transferred. Although seasonal patterns of precipitation may vary between regions, annual means are still the key characteristic to be considered in distributing flows to different sites within a river basin.

Watershed Area

Drainage areas clearly affect the streamflows from various subbasins in a river basin. Drainage area is a key parameter in essentially all techniques for estimating discharge hydrographs, daily or monthly volumes, peak flows, or other flow characteristics at ungaged sites. Drainage area is logically considered to be a primary watershed characteristic to be incorporated in methods for transposing monthly naturalized flows from gaged watersheds to ungaged subwatersheds.

Other Watershed Characteristics Governing Surface Runoff

The watershed characteristics governing the hydrologic processes that partition precipitation into hydrologic abstractions (surface storage, infiltration, soil moisture, and evapotranspiration) and streamflow can be categorized as follows.

- watershed characteristics affecting runoff volumes
    - land cover
    - soils
    - antecedent moisture conditions
- topographic characteristics primarily affecting runoff response time
    - watershed shape and slope
    - stream tributary configuration and channel slopes

The tremendous amount of work reported in the literature on the subject of watershed modeling provides insight into the relevance of various watershed characteristics in estimating streamflows. The Hydrologic Engineering Center's *Hydrologic Modeling System (HEC-HMS)* and its predecessor *HEC-1* are used as an example here because either version of the HEC modeling package provides a comprehensive array of alternative widely-accepted hydrologic analysis methods (Hydrologic Engineering Center 1998).

In *HEC-1*, *HEC-HMS*, and the various other single rainfall event watershed models, the precipitation-runoff process is represented in three phases.

Phase 1: For each subbasin, precipitation is transformed to runoff volumes by subtracting hydrologic abstractions.

Phase 2: For each subbasin, runoff volumes are converted to discharge hydrographs.

Phase 3: Flows are routed through stream reaches, and hydrographs from different subbasins are combined.

The phase 2 and 3 computations are performed after completion of phase 1 and have no affect on runoff volumes. The single-event models provide a detailed simulation of the watershed response to a rain storm that results in flows rates at computational time steps of several minutes to a few hours. Thus, the entire hydrograph for the several-hours to several-days rainfall-runoff event is precisely defined. Continuous models like the *Soil and Water Assessment Tool (SWAT)* compute daily runoff volumes without needing to define the instantaneous flow rates within a day. Thus, the phase 2 computations noted above are not performed. Likewise, in dealing with naturalized monthly flows, the phase 2 and 3 processes are of little or no concern.

The point here is that watershed characteristics associated with phase 1 are important in distributing monthly naturalized flows from gaged to ungaged sites, but the watershed characteristics associated with phase 2 are of relative little importance. The collective experience in watershed modeling indicates that:

- Watershed characteristics affecting runoff volumes such as antecedent moisture conditions, land cover, and soils, are very relevant to the problem of estimating monthly flow sequences for ungaged locations.

- Topographic characteristics primarily affecting runoff response time, such as watershed shape, stream tributary configuration, and watershed and channel slopes, are much less relevant.

The HEC-1/HEC-HMS options for determining the direct runoff volumes to result from precipitation include the Natural Resource Conservation Service (NRCS) curve number, Green and Ampt, and Holtan methods which incorporate parameters representing physical characteristics of the watershed and the exponential and initial/uniform methods which are completely empirical requiring calibration studies. Drainage area is a key parameter in all the methods. The other parameters associated with the relevant three methods are indicated in Table 3.1.

Table 3.1 Watershed Runoff Volume Parameters in HEC-1 Options

Method	Watershed Parameters	Watershed Characteristics
NRCS Curve Number	curve number	land cover, soil type antecedent moisture
Green and Ampt	hydraulic conductivity effective porosity suction head	soil characteristics antecedent moisture
Holtan	growth index percolation rate	vegetation soil type

An array of options are incorporated in HEC-1 and HEC-HMS to convert runoff volumes to discharge hydrographs. The watershed parameters incorporated in the three alternative synthetic unit hydrograph methods, in addition to drainage area, are as follows.

NRCS Method	lag time which is a function of watershed slope, basin hydraulic length, and curve number
Synder Method	lag time which is a function of storage coefficients, basin hydraulic length, and distance to basin centroid
Clark Method	storage coefficient, time of concentration, and time-area relationship

These parameters are related primarily to the time required for the rainfall to run off the watershed and reach the outlet. The topographic characteristics of the basin govern the runoff response time and shape the discharge hydrograph but do not affect runoff volumes in the model. These types of topographic parameters are important in predicting instantaneous peak flood flow rates but are much less important in determining daily or monthly flow volumes.

Watershed Characteristics Affecting Base Flow

Base flow entering the stream from subsurface water is perhaps the most complex aspect of streamflow to characterize. Fortunately, to a large extent, base flow can be expected to vary between locations in roughly about the same proportion as surface runoff. Thus, flow distribution methods that deal with total flows, without separating surface runoff and base flow, are probably adequate in most cases, but may present problems in some watersheds. Base flow depends upon various surface and subsurface characteristics of the watershed including:

- the relationship between the groundwater table and stream channel bottom elevations
- geologic conditions affecting the flow through the saturated zone
- soil characteristics and moisture conditions affecting flow through the unsaturated zone
- stream length and width and channel bed materials
- vegetation in the watershed and along the streambanks affecting transpiration losses

There have been two general strategies for separating base flow from surface runoff. One approach includes various empirical, largely judgmental methods of analyzing observed hydrographs at gaging stations. The other approach involves comprehensive water accounting algorithms built into watershed computer models.

Key Watershed Characteristics for Transferring Flows from Gaged to Ungaged Sites

Based upon the considerations outlined in the previous paragraphs, the most relevant watershed characteristics to be incorporated into approaches for distributing naturalized monthly streamflows from gaged to ungaged watersheds are as follows.

1. drainage area
2. soil type and land cover which may be combined into a NRCS curve number
3. mean precipitation
4. antecedent moisture condition which may also be reflected in the curve number

CHAPTER 4
METHODS FOR DISTRIBUTING FLOWS FROM GAGED TO UNGAGED SITES

Chapter 1, page 1 includes a list of general approaches for estimating monthly naturalized streamflows for ungaged subwatersheds based upon naturalized flows at gaging stations. The following discussion of alternative methods is organized based on the categorization of general approaches reflected in that list.

Distribution of Flows in Proportion to Drainage Area

Application of drainage area ratios is the simplest and perhaps most widely used method for distributing flows from gaged to ungaged sites. This has been the predominant method adopted in water availability modeling studies conducted by the TNRCC and its predecessor agencies.

The streamflow per unit area of watershed is assumed constant. The monthly naturalized flow Q_{ungaged} at the ungaged site is related to the corresponding naturalized flow at the gage Q_{gage} by the ratio of drainage areas A_{ungaged} and A_{gage} above the gaging station and ungaged site.

$$Q_{ungaged} = Q_{gage}\left(\frac{A_{ungaged}}{A_{gage}}\right) \tag{4-1}$$

In Figure 1.1, the flow each month at site 5 is estimated as a function of flow at gage D as follows.

$$Q_5 = Q_D\left(\frac{A_5}{A_D}\right)$$

The flows at site 12 could be estimated similarly as a function of total flows at gage A. Alternatively, the flows at site 12 could be estimated as a function of the incremental local flows at gage A computed as

$$\mathrm{Q_{incremental}} = \mathrm{Q_A} - \mathrm{Q_B} - \mathrm{Q_C}$$

$$\mathrm{A_{incremenatal}} = \mathrm{A_A} - \mathrm{A_B} - \mathrm{A_C}$$

$$Q_{12} = Q_{incremental}\left(\frac{A_{12}}{A_{incremental}}\right)$$

Flows at site 1 may be estimated by an area-weighted averaging of flows at gages A, B, and C.

Alternatively, flows could be estimated as a nonlinear function of drainage area ratio as follows

$$Q_{ungaged} \quad = \quad Q_{gage}\left(\frac{A_{ungaged}}{A_{gage}}\right)^{N} \qquad (4\text{-}2)$$

with the exponent N being determined from empirical analyses of gaged flows at many different gaging stations.

Although the drainage ratio approach is logical and has been widely applied, the literature review has uncovered no work dealing specifically with evaluating the validity of using drainage area ratios to distribute flows. An evaluation of the drainage area ratio approach is included in the analyses of available naturalized flows at selected gaging stations in the Brazos, San Jacinto, and Sulphur River Basins reported in Chapters 5 and 6. The drainage area is also a key parameter in all the other approaches considered in this investigation.

Flow Distribution Equation with Watershed Parameter Ratios

Murthy et al. (1975) describe early water availability modeling concepts developed by the Texas Water Rights Commission (a predecessor of the TNRCC) and application to the Guadalupe River Basin. The following equation is presented for distributing storm runoff to the subwatersheds between gaging stations:

$$SWRF_i \quad = \quad SRF_j\left(\frac{a_i}{A_j}\right)^{C1}\left(\frac{dd_i}{DD_j}\right)^{C2}\left(\frac{cn_i}{CN_j}\right)^{C3}\left(\frac{rdc_i}{RDC_j}\right)^{C4} \qquad (4\text{-}3)$$

where $SWRF_i$ and SRF_j are the runoff from subwatershed i and watershed j, respectively; a_i and A_j are the drainage areas of subwatershed i and watershed j; dd_i and DD_j are drainage densities; cn_i and CN_j are hydrologic characteristic numbers; and rdc_i and RDC_j are rainfall distribution coefficients for ungaged subwatershed i and gaged watershed j. The drainage density (dd and DD) is defined as the total length of main stream and tributaries per unit drainage area. The hydrologic characteristic number (cn and CN) is determined based on soil characteristics and land use in the watershed. Rainfall distribution coefficients are computed from monthly rainfall records and their probability distributions. Murthy et al. (1975) do not explain how the exponents C1, C2, C3, and C4 are determined. Presumably, estimates could be developed based on analyses of flows at multiple gaging stations.

If C2, C3, and C4 are zero, Equation 4-3 reduces to Equation 4-2. Although the parameters in Equation 4-3 and perhaps others were investigated during the water availability modeling studies conducted by the Texas Water Rights Commission, Texas Department of Water Resources, and Texas Water Commission during the 1970's and 1980's, the drainage area ratio was the predominant parameter used to distribute flows.

The drainage area (A) and curve number (CN) are parameters for both Equation 4-3 and the adaptation of the NRCS curve number method (Equation 4-4) described next. With the drainage density and rainfall distribution coefficient ratios set equal to one, Equation 4-3 reduces to the following.

$$SWRF_i \;=\; SRF_j \left(\frac{a_i}{A_j}\right)^{C1} \left(\frac{cn_i}{CN_j}\right)^{C3}$$

A simple exercise was performed in conjunction with the present investigation to compare this equation with the NRCS curve number method. The exponent *C1* was set equal to one, consistent with the NRCS equation, and an attempt was made to determine a value for *C3* that would result in the equations providing similar results. However, the above equation is fundamentally different from the NRCS curve number equation and will yield significantly different results if the curve numbers for the gaged and ungaged watersheds are significantly different. The equation above provides a linear relationship between the flows at the gaged and ungaged sites. The adaptation of the NRCS curve number provides a nonlinear relationship between flows at the different sites. The nonlinearity is significant.

The approach presented next is considered to be preferable to the use of Equation 4-3 since the form of the NRCS equation is more realistic, and it has been used in many different types of applications. The use of drainage density ratios are not incorporated in the NRCS method. However, drainage densities are somewhat arbitrary to estimate because of difficulties in determining the distance to extend the tributary stream length measurements. The approach outlined below incorporates mean precipitation in a more straight-forward manner than the rainfall coefficient in Equation 4-3.

NRCS Curve Number Method Adaptation

The Natural Resource Conservation Service (NRCS) curve number (CN) method is based on the following relationship between rainfall depth, P in inches, and runoff depth, Q in inches.

$$Q \;=\; \frac{(P-0.2S)^2}{P+0.8S} \qquad where \quad S=\frac{1{,}000}{CN}-10 \qquad (4\text{-}4)$$

$$Q = 0 \quad \text{if } P < 0.2S$$

P and *Q* in inches must be multiplied by the watershed area to obtain volumes. The potential maximum retention, *S* in inches, represents an upper limit on the amount of water that can be abstracted by the watershed through surface storage, infiltration, and other hydrologic abstractions. For convenience, *S* is expressed in terms of a curve number *CN*, which is a dimensionless watershed parameter ranging from 0 to 100. A *CN* of 100 represents a limiting condition of a perfectly impervious watershed with zero retention and thus all the rainfall becoming runoff. A *CN* of zero conceptually represents the other extreme with the watershed abstracting all rainfall with no runoff regardless of the rainfall amount.

The watershed parameter *CN* can be determined from empirical information, such as that reproduced as Table 4.1, developed by the NRCS as a function of watershed soil type, land cover/use/condition, and antecedent moisture condition.

Table 4.1 Watershed Curve Numbers (McCuen 1998)

Land Use Description	Average % impervious	Curve Numbers for Hydrologic Soil Group A	B	C	D
Fully developed urban areas[a] (vegetation established)					
Lawns, open spaces, parks, golf courses, cemeteries, etc.					
Good condition; grass cover on 75% or more of the area		39	61	74	80
Fair condition; grass cover on 50% to 75% of the area		49	69	79	84
Poor condition; grass cover on 50% or less of the area		68	79	86	89
Paved parking lots, roofs, driveways, etc.		98	98	98	98
Streets and roads					
Paved with curbs and storm sewers		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89
Paved with open ditches		83	89	92	93
Commercial and business areas	85	89	92	94	95
Industrial districts	72	81	88	91	93
Row houses, town houses, and residential with lots sizes 1/8 acre or less	65	77	85	90	92
Residential: average lot size					
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acre	12	46	65	77	82
Developing urban areas[c] (no vegetation established)					
Newly graded area		77	86	91	94
Western desert urban areas					
Natural desert landscaping (pervious area only)[f]		63	77	85	88
Artificial desert landscaping		96	96	96	96

Land Use Description	Treatment or Practice[d]	Hydrologic Condition	Curve Numbers for Hydrologic Soil Group A	B	C	D
Cultivated agricultural land						
Fallow	Straight row or bare soil		77	86	91	94
	Conservation tillage	Poor	76	85	90	93
	Conservation tillage	Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Conservation tillage	Poor	71	80	87	90
	Conservation tillage	Good	64	75	82	85
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured and	Poor	69	78	83	87
	conservation tillage	Good	64	74	81	85
	Contoured and terraces	Poor	66	74	80	82
	Contoured and terraces	Good	62	71	78	81
	Contoured and terraces	Poor	65	73	79	81
	and conservation tillage	Good	61	70	77	80
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Conservation tillage	Poor	64	75	83	86
	Conservation tillage	Good	60	72	80	84
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured and	Poor	62	73	81	84
	conservation tillage	Good	60	72	80	83
	Contoured and terraces	Poor	61	72	79	82
	Contoured and terraces	Good	59	70	78	81
	Contoured and terraces	Poor	60	71	78	81
	and conservation tillage	Good	58	69	77	80
Close-seeded legumes rotations meadows[e]	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured and terraces	Poor	63	73	80	83
	Contoured and terraces	Good	51	67	76	80
Noncultivated agricultural land						
Pasture or range	No mechanical treatment	Poor	68	79	86	89
	No mechanical treatment	Fair	49	69	79	84
	No mechanical treatment	Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow		—	30	58	71	78
Forestland—grass or orchards—evergreen deciduous		Poor	55	73	82	86
		Fair	44	65	76	82
		Good	32	58	72	79
Brush		Poor	48	67	77	83
		Fair	35	56	70	77
		Good	30	48	65	73
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		—	59	74	82	86
Forest-range						
Herbaceous		Poor		80	87	93
		Fair		71	81	89
		Good		62	74	85
Oak-aspen		Poor		66	74	79
		Fair		48	57	63
		Good		30	41	48

The soil groups and hydrologic conditions in Table 4.1 are based upon standard NRCS classification procedures. The NRCS has classified soils throughout the United States in county soils surveys and soils databases. Soils are categorized as follows.

Group A: deep sand; deep loess; aggregated silts (infiltration 0.30-0.45 inch/hour)
Group B: shallow loess; sandy loam (infiltration 0.15-0.30 inch/hour)
Group C: clay loams; shallow sandy loam; soils low in organic content; soils usually high in clay (infiltration 0.05-0.15 inch/hour)
Group D: soils that swell significantly when wet; heavy plastic clays; certain saline soils (infiltration 0-0.15 inch/hour)

Hydrologic condition is defined as follows.

Poor: heavily grazed or regularly burned areas with less than 50% of the ground surface protected by plant cover or tree canopy.
Fair: moderate with 50 to 75% of the ground surface protected by vegetation.
Good: heavy or dense cover with more than 75% of the ground surface protected by vegetation.

The *CN* values in Table 4.1 are for average antecedent moisture conditions. The NRCS procedures also allow adjustments for either wet or dry antecedent conditions.

For a watershed with subareas of different soil types and land cover, a composite *CN* is determined by weighting the *CN's* for the different subareas in proportion to land area associated with each.

$$\text{composite CN} = \text{CN}_1(\%\text{ area }1) + \text{CN}_2(\%\text{ area }2) + \ldots + \text{CN}_N(\%\text{ area }N) \qquad (4\text{-}5)$$

The curve number *CN* method dates back to the 1950's and is based on extensive field tests conducted by the Soil Conservation Service (renamed Natural Resource Conservation Service). The method is described by the Soil Conservation Service (1985), a number of hydrology textbooks including McCuen (1998), and numerous other references. Ponce and Hawkins (1996) review the important role played by the method and its strengths and weaknesses. The standard references all reproduce the tables of empirical information, such as Table 4.1, developed by the NRCS to facilitate estimation of the *CN* as a function of watershed characteristics. The technique is widely used by water agencies, consulting firms, and universities in the United States and abroad. The *CN* method has been widely applied largely because it is easy to use, empirical information including soils and land use databases are available for estimating the single parameter *CN*, and it is supported by a major federal agency. The *CN* method has been widely criticized due to its over simplicity.

The CN method was developed to compute the total runoff volume *Q* given the total depth *P* for a rain storm. The original motivation in the 1950's was to develop a technique for evaluating the impact of agricultural activities on runoff volumes. However, the method has since been applied to a much broader range of urban and agricultural watershed modeling situations than originally envisioned. The HEC-1 Flood Hydrograph Package and HEC-HMS Hydrologic Modeling System apply the CN equation to obtain the runoff from each small time increment of rainfall during a rainfall event (Hydrologic Engineering Center 1998). The Soil and Water Assessment Tool (SWAT) applies the CN equation to obtain the runoff from daily rainfall amounts. The CN method is incorporated in various other complex computer models and simple manual computation procedures.

The present research includes an investigation of the validity of applying the CN method to transfer monthly flows from gaged to ungaged locations. Although the method was developed to determine the runoff from single storm events, it might also be a reasonable approximation for monthly values. Observations of gaged data indicate that the runoff volume associated with a particular precipitation depth tends to vary greatly between storm events. The CN number method, like other approaches discussed here, estimates the mean runoff associated with a particular precipitation depth and may be significantly in error for a particular rainfall event. Golding (1997) notes that the fit of measured data to the CN relationship improves with aggregation such that estimating monthly runoff from monthly rainfall has less scatter than for daily values. Although the original CN method does not include base flow, the procedure for distributing naturalized flows outlined below distributes all of the flow including base flow in the same proportion as runoff.

The following proposed procedure for distributing monthly naturalized flows at one or more gaging stations to an ungaged site is an adaptation of the CN relationship. The required data consists of monthly naturalized flows at the gaging station and drainage areas A and watershed curve numbers CN for both the gage location and the ungaged site. The CN can be estimated using standard procedures either manually or from GIS-based databases of soil type and land use. Likewise, the drainage areas can be determined either manually or by GIS. Optionally, the long-term mean precipitation M may be input for both the watershed and subwatershed for the precipitation adjustment outlined in step 3. The following computations are performed for each month.

Step 1: The flow at the gage, in acre-feet/month, is divided by the drainage area A_{gage} and multiplied by a unit conversion factor to convert to an equivalent depth Q_{gage} in inches.

Step 2: Q_{gage} is input to the curve number equation (Equation 4-4) to obtain P_{gage} in inches. An iterative method is required to solve Equation 4-4 for P. This approximation for precipitation depth is assumed to be applicable to the ungaged subwatershed as well as the gaged watershed. Base flow is being distributed along with storm runoff, all in the same proportion.

Step 3: If the long-term mean precipitation varies between the watershed and subwatershed, the precipitation depth may optionally be adjusted by multiplying P_{gage} by the ratio of the long-term mean precipitation depth of the subwatershed to that of the watershed to obtain a $P_{ungaged}$ adjusted in proportion to mean precipitation.

$$adjusted\ P_{ungaged} = P_{gage}\left(\frac{M_{ungaged}}{M_{gage}}\right) \tag{4-6}$$

where $M_{ungaged}$ and M_{gaged} are the mean precipitation for the ungaged subwatershed and gaged watershed. Otherwise, $P_{ungaged}$ is assumed equal to P_{gage}.

Step 4: $P_{ungaged}$ is input into Equation 4-4 to obtain $Q_{ungaged}$ in inches. $Q_{ungaged}$ in inches is multiplied by $A_{ungaged}$ and a unit conversion factor to convert to flow in acre-feet/month.

Regression of Flows at Gages with Watershed Parameters

The TNRCC (1997) presents a set of three alternative methodologies proposed by the USGS for developing naturalized monthly flows at ungaged sites. The USGS has identified 76 stream gages in Texas with at least a 40 year period-of-record of unregulated/nonurbanized flow data and an additional 354 stations with between 5 and 40 years of unregulated/nonurbanized flow data. The objective is to devise a scheme for relating flows at ungaged sites to the flows at these gages based upon measurable characteristics of the gaged and ungaged watersheds such as drainage area, major channel length and slope, and a basin shape factor defined as the ratio of the major channel length to the mean basin width.

A database of naturalized monthly flows at the gages would be developed by (1) naturalizing the gaged flows by adjustments to remove the effects of human water use and (2) extending flows at gages with short records by regressing with flows at gages with longer records. A database of the watershed characteristics for each gage would also be developed.

The first alternative USGS procedure outlined by the TNRCC (1997) would be based on a regression study to develop a set of equations to relate flows at ungaged locations to those at selected gages based on watershed characteristics. The second alternative procedure would be based on relating flow duration-curves at ungaged sites to the flow-duration curves at selected gages based on watershed characteristics. The third procedure is based on incorporating short-term flow measurements at the otherwise ungaged sites into the analyses.

Rainfall-Runoff Relationships

Linsley et al. (1982) and other hydrology books review the practice of developing relations between precipitation and runoff using recorded data from precipitation and streamflow gages, for a monthly, seasonal, or annual time interval. Annual data typically exhibit less scatter than monthly data. The general form of the relationship is illustrated by the annual precipitation-runoff relation reproduced as Figure 4.1 for the 4,460 mile^2 (11,550 km^2) watershed of the Merrimack River above Lawrence, Massachusetts.

Runoff volume expressed as an equivalent depth covering the watershed area represents the measured flow volumes for the selected time interval at a streamflow gage. Precipitation is typically determined by spatially averaging the records of several precipitation gages in the watershed above the streamflow gage. Gaged precipitation depths, in inches or millimeters, are related to runoff volume as a depth equivalent in inches or mm. Standard regression techniques may be used to express the relationship as an equation. The precipitation-runoff relationship for gaged watersheds is assumed to be applicable to other ungaged watersheds. Precipitation estimates for a subwatershed with no stream gage are combined with the precipitation-runoff relationship to obtain the runoff depth which is then combined with the subwatershed drainage area to obtain the volume in acre-feet or other units for the ungaged site.

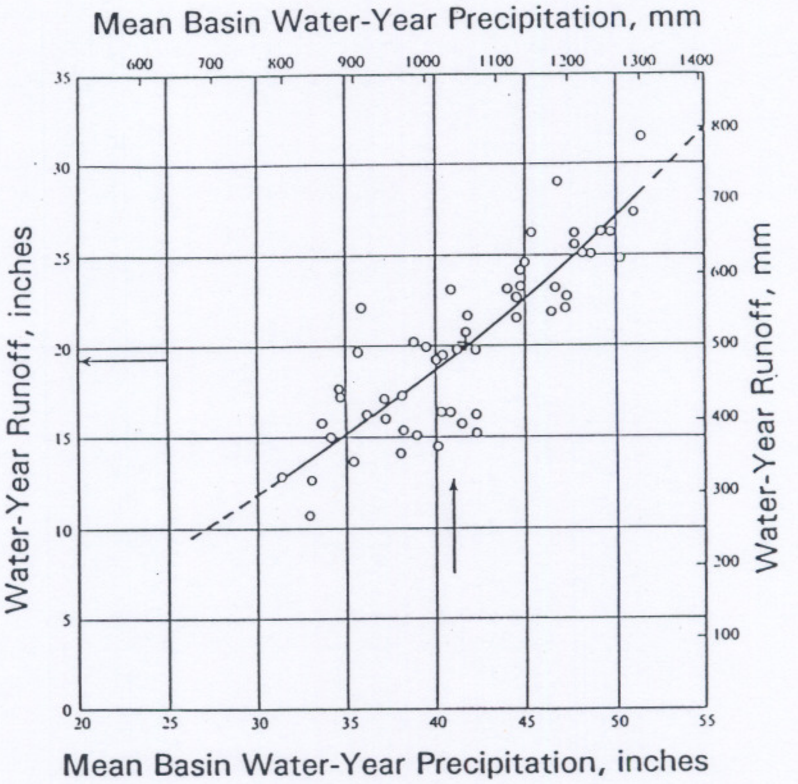


Figure 4.1 Relationship Between Annual Precipitation and Runoff for the Merrimack River Basin (Linsley et al. 1982)

Reed, Maidment, and Patoux (1997) used a precipitation-runoff relationship in developing the runoff portion of a water balance for the state of Texas. This study included constructing independent models for an atmospheric water balance, a soil water balance, and a surface water balance. The surface water balance resulted in gage-calibrated maps of mean annual runoff and evaporation for the entire state on a 500 meters grid. A rainfall-runoff relationship was used to estimate runoff in ungaged areas.

Variations of the procedure adopted by Reed, Maidment, and Patoux (1997) may be adapted to various applications. The general procedure for determining runoff from ungaged subwatersheds of a larger gaged watershed based on spatial variations in precipitation is as follows.

- A curve of annual rainfall depth, in millimeters, versus runoff volume as a depth equivalent, in mm, is developed using recorded streamflow and rainfall measurements for numerous watersheds throughout the state.

- Recorded precipitation at appropriate gages is spatially averaged to estimate the precipitation for a subwatershed. This precipitation depth is combined with the precipitation-runoff relationship to estimate runoff for ungaged areas.

- Flow accumulation computations proceed from upstream to downstream. The runoff volume as an equivalent depth in mm from each additional incremental drainage area is determined as noted above. The cumulative volume in m^3 is determined by converting the runoff depths of upstream subareas to m^3 and summing.

- At the stream gaging station at the outlet of the overall watershed the runoff volume estimated using the generalized annual precipitation-runoff curve is compared to the runoff measured at the gage. The difference between gaged and estimated is treated as a correction to be distributed back throughout the subareas of the watershed.

The use of precipitation-runoff relationships to distribute flows from gaged to ungaged locations allows the flows to vary between locations in response to spatial variations in precipitation as estimated by recorded measurements at multiple precipitation gages. However, this procedure by itself does not reflect differences in subwatershed characteristics other than drainage area and precipitation.

Computer Models of Watershed Hydrology

As previously discussed, generalized watershed models are available that compute sequences of daily or monthly streamflows for given precipitation input. The practicality of adopting the *Soil and Water Assessment Tool (SWAT)* or other hydrologic simulation models for developing naturalized monthly flows for ungaged watersheds is investigated as a part of this study.

As discussed in Chapter 2, water accounting routines are incorporated in watershed models to simulation surface storage, surface runoff, infiltration, soil moisture, evapotranspiration, groundwater storage/flow, and streamflow. A river basin is divided into subbasins and flows computed at all pertinent locations.

Computer models simulating river basin hydrology have advantages and disadvantages relative to the simpler methods previously discussed. Watershed (precipitation-runoff) models contribute to a greater understanding of the hydrologic processes governing streamflows in the basin. Models also provide capabilities for dealing with complexities such as subsurface/surface water interactions. However, a watershed modeling study requires considerable expertise, time, and effort. More input data is needed. Additional sophistication reflected in a watershed model may not necessarily result in significant improvements in the accuracy of naturalized flow estimates.

A variety of alternative strategies could be formulated for applying a watershed model to develop naturalized flows. The conventional approach for applying a model involves the following tasks.

1. Sequences of recorded daily precipitation depths at all relevant precipitation gaging stations are provided as model input.
2. The river basin is divided into subbasins to obtain flows at all pertinent locations. Initial values for the parameters are estimated for all subbasins and stream routing reaches.
3. A calibration study is performed in which parameters are iteratively adjusted until the computed flows reasonably match the observed flows at stream gaging stations.
4. The calibrated model is executed with given precipitation input to obtain sequences of daily flows at all pertinent locations. The daily flows are aggregated to obtain monthly flows.

A simpler flow distribution approach was investigated in this study (Chapter 6) that still incorporates the capabilities provided by a watershed simulation model. This approach involves applying SWAT with options requiring minimal input to develop relationships (regression equations) between flows at gaged and ungaged locations. The regression equations are then combined with the known naturalized flows at the gage to obtain flows at the ungaged site.

The watershed of Figure 1.1 is used to illustrate this general approach. Period-of-analysis sequences of daily rainfall observations at one or more precipitation gages are provided as input. Alternatively, the synthetic rainfall generation option in SWAT could be used with only one gage from the precipitation station database for simplicity. GIS is used to delineate drainage areas. As discussed in Chapter 5, the required weather data and watershed parameters are obtained from existing databases through the SWAT/GIS Interface. SWAT performs computations using a daily time step with results aggregated to monthly values. Model output would include naturalized monthly streamflows at the five gaging stations and 12 ungaged sites shown in Figure 1.1. These flows will be approximate and will not match the already known naturalized flows at the five gages. However, the flows should represent spatial consistency such that they would be adequate for developing relationships between gaged and ungaged locations. For each of the 12 ungaged sites, the SWAT computed sequence of monthly flows for that site are regressed with the corresponding flows at the next downstream gage, using standard least squares regression techniques. The regression equation will likely be of the form

$$Q_{ungaged} = a + b\,Q_{gage}^{C}$$

where the coefficients a, b, and c are determined by applying least squares regression analysis to the SWAT output and will be different for each site. The already known naturalized monthly flows at the gage (not those computed with SWAT) are then substituted into the regression equation for Q_{gage} to obtain flows for the ungaged site $Q_{ungaged}$.

CHAPTER 5
ANALYSES OF NATURALIZED FLOWS AT SELECTED GAGING STATIONS

Chapters 5 and 6 summarize the results of analyses of naturalized monthly streamflows at selected gaging stations in the Brazos, San Jacinto, and Suphur River Basins. Analyses for the stations in the Brazos and San Jacinto Basins were included in the initial (June 1998) draft of this report. Since that time, the R. J. Brandes Company under contract with the TNRCC has modeled the Texas portion of the Sulphur River Basin. The analyses presented in Chapters 5 and 6 have been extended to include several gaging stations in the Sulphur River Basin using data from the TNRCC/Brandes study.

The relationships between flows from different subwatersheds of a river basin are investigated, and alternative methods for transferring flows are tested. Chapter 5 describes the naturalized monthly flow data adopted for the study and presents the results of analyses comparing flows at the different gaging stations. The following techniques are applied:

- scatter plots of flows at one location versus flows at another location
- standard correlation and regression analysis methods
- comparison of ratios of flows at pairs of locations

Understanding the degree of correlation and the relationships between the flows at different locations is fundamental to formulating methods for distributing flows from gaged to ungaged sites and evaluating their validity.

The naturalized flows described in Chapter 5 are used in Chapter 6 in a comparative evaluation of alternative approaches outlined in Chapter 4 for transferring flows. Analyses reported in Chapter 6 involve computing naturalized flows at locations for which the flows are known and then comparing the computed flows with the known flows.

Description of River Basins and Streamflow Data

The location and size of the Brazos and San Jacinto River Basins and the Texas portion of the Sulphur River Basin relative to other major basins in Texas are shown by the map of Figure 1.2. A map of the Brazos and San Jacinto Basins is provided as Figure 5.1.

Brazos River Basin

The Brazos River Basin encompasses an area of 45,600 miles^2, with about 43,000 miles^2 in Texas and the remainder in New Mexico. Approximately 9,750 mile^2 in the northwestern portion of the basin, including all the area in New Mexico and a portion of the area in Texas, are non-contributing to downstream flows. The basin encompasses about 16 percent of the land area of Texas. Mean annual precipitation varies from about 16 inches in the northwestern (upstream) end of the basin to over 50 inches in the lower basin near the Gulf of Mexico. In its upper reaches in the arid plains of West Texas, the Brazos River is a salty intermittent stream. Toward the coast, it is a rolling river flowing through hardwood bottoms, pastures, and cultivated fields. The

Little River and Navasota River watersheds are in the more humid lower half of the Brazos Basin and consist of pastures, forests, agricultural fields, and small cities.

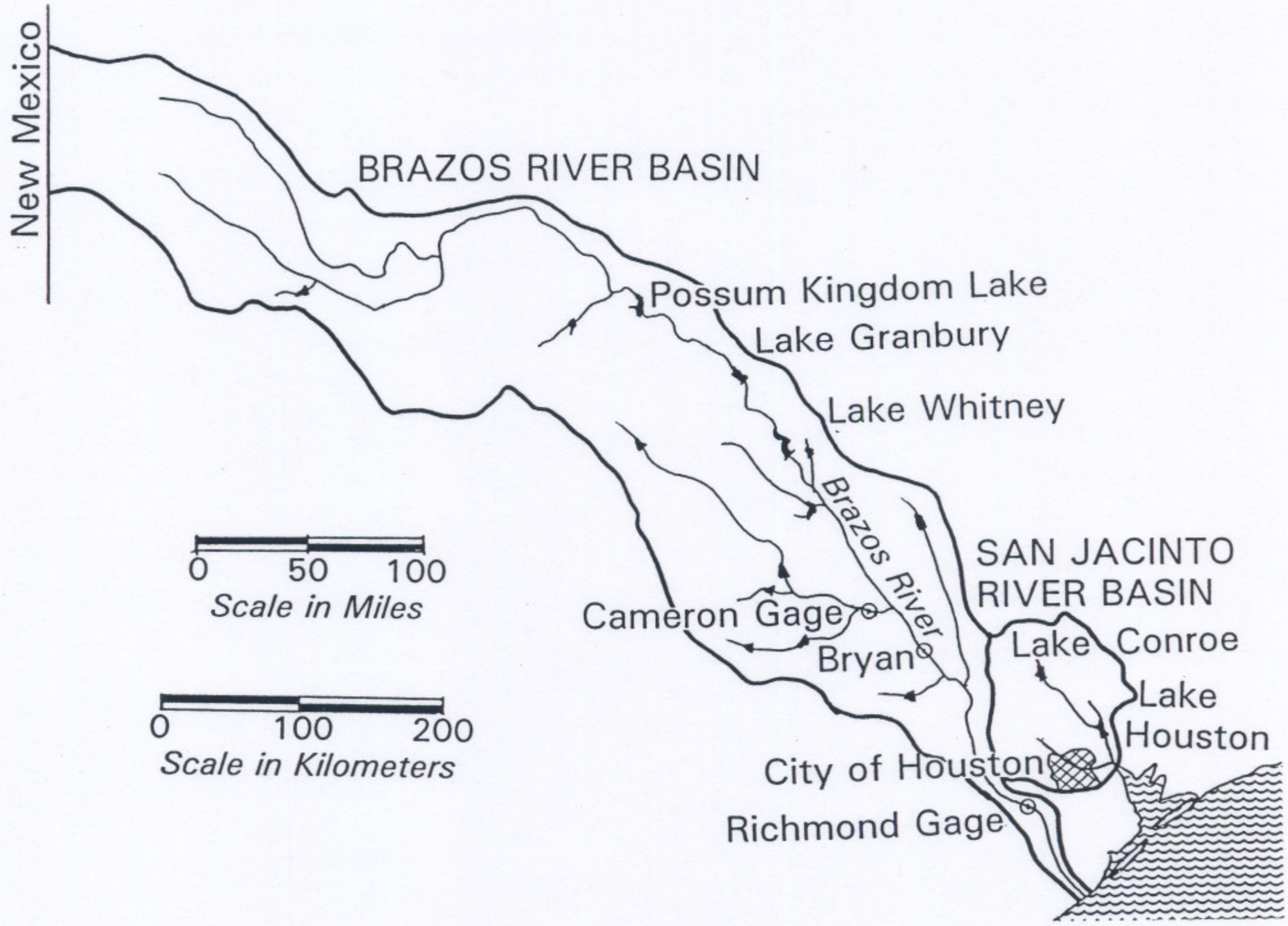


Figure 5.1 Brazos and San Jacinto River Basins

Texas Department of Water Resources (TDWR) Report 244 (Doughtery 1980) describes 141 stream gaging stations in the Brazos River Basin. Most are maintained by the U.S. Geological Survey (USGS). Naturalized monthly flows at the 15 USGS stream gaging stations shown in Table 5.1 and Figure 5.2 were adopted for this study. The 15 stations are divided into three groups for purposes of the analyses presented in this report. Stations 1 through 7 are located on various tributaries in the Little River subbasin and have drainage areas ranging from 248 to 7,065 mile^2. Stations 8 and 9 on the Navasota River have drainage areas of 968 and 1,454 mile^2. Stations 10 through 15 on the main-stem Brazos River have very large drainage areas varying from 23,810 to 45,010 mile^2.

The naturalized flow data used in this investigation were developed in conjunction with a water availability modeling study performed by the Texas Department of Water Resources (1981). Naturalized flows for the period 1940-1976 were developed by the TDWR by adjusting gaged flows to remove the effects of reservoir storage and diversions for beneficial use. The naturalization process included adjustments for about 40 major water supply reservoirs, many smaller storage facilities, over 400 Soil Conservation Service flood retarding dams, and numerous diversions and return flows. As indicated by Table 5.1, the period-of-record for several of the stations does not completely cover the period 1940-1976. The TDWR extended the records as necessary by regressing flows at these stations with flows at nearby gaging stations, using the MOSS-IV computer program (Beard 1973).

The Texas Water Commission (TWC), the TDWR's successor, provided the 1940-1976 naturalized flows at 23 USGS gaging stations developed by the TDWR (1981) to researchers at Texas A&M University (TAMU) for use in the study documented by Wurbs *et al.* (1988). Wurbs *et al.* (1988) developed an alternative set of monthly unregulated flow sequences covering the period 1900-1984. Gaged flows were adjusted to remove the effects of 21 of the largest water supply reservoirs. Flows at the Richmond gage were further adjusted to remove the effects of diversions through the Brazos River Authority Canal A and Richmond Irrigation Company Canal. The TAMU and TWC data sets were compared and found to be very similar, indicating that the few larger reservoirs considered in the TAMU study account for most of the adjustments reflected in the much more detailed TDWR/TWC flow naturalization process.

Gaged monthly flows at the Richmond and Waco gages on the Brazos River (stations 15 and 13) and Cameron gage (station 7) on the Little River are plotted in Figures 5.3, 5.4, and 5.5. Flow-duration curves for 1940-1976 monthly flows at these three stations are compared in Figures 5.6 - 5.8. Annual gaged, TAMU unregulated, and TWC naturalized flows are compared in Tables 5.2, 5.3, and 5.4. Again, the Texas Water Commission (TWC) naturalized flows are the USGS gaged flows adjusted by the TDWR (TWC predecessor) as described above. The TAMU regulated flows are USGS gaged flows adjusted by Wurbs et al. (1988).

Annual precipitation for the watersheds of the Richmond, Bryan, Waco, and Cameron gages are tabulated in Table 5.5. (Wurbs et al. 1988). The precipitation depths are estimated by averaging recorded amounts at 8 precipitation gages for the Little River watershed above the Cameron gage (station 7) and 28 and 41 precipitation gages, respectively, for the Brazos River watersheds above the Waco and Richmond gages (stations 12 and 15). The periods-of-record vary between gages, and the means for each year reflect the gage records available for that year. Figures 5.9, 5.10, and 5.11 are plots of 1940-1976 annual precipitation versus naturalized streamflow. The plots illustrate the scatter typical of rainfall versus runoff data. Monthly data tend to have greater scatter than aggregated annual means.

Table 5.1 Selected Streamflow Gaging Stations in the Brazos River Basin

Station	Stream	Nearest City	USGS Gage Number	Drainage Area (mile^2)	Mean Flow (ac-ft/yr)	Mean Flow (inches/yr)	Portion of 1940-1976 Covered by Period of Record
	Little River Subbasin						
1	Leon River	Hasse	08099500	1,261	114,800	1.71	1940-1976
2	Leon River	Belton	08102500	3,542	518,300	2.74	1940-1976
3	Lampasas River	Youngsport	08104000	1,240	210,200	3.18	1940-1976
4	Lampasas River	Belton	08104100	1,321	261,200	3.71	Feb 1963 – Dec 1976
5	N. Fork San Gabriel	Georgetown	08104700	248	69,600	5.26	Jul 1968 – Dec 1976
6	San Grabriel River	Laneport	08105700	738	189,600	4.82	Aug 1965 – Dec 1976
7	Little River	Cameron	08106500	7,065	1,328,500	3.53	1940-1976
	Navasota Subbasin						
8	Navasota River	Easterly	08110500	968	319,500	6.19	1940-1976
9	Navasota River	Bryan	08111000	1,454	391,000	5.04	Jan 1951 – Dec 1976
	Mainstream						
10	Brazos River	Palo Pinto	08089000	23,810	861,500	0.68	1940-1976
11	Brazos River	Aquilla	08093100	27,240	1,756,000	1.21	1940-1976
12	Brazos River	Waco	08096500	29,570	1,934,000	1.23	1940-1976
13	Brazos River	Bryan	08109000	39,520	4,007,000	1.90	1940-1976
14	Brazos River	Hempstead	08111500	43,880	5,344,000	2.28	1940-1976
15	Brazos River	Richmond	08114000	45,010	6,401,000	2.67	1940-1976

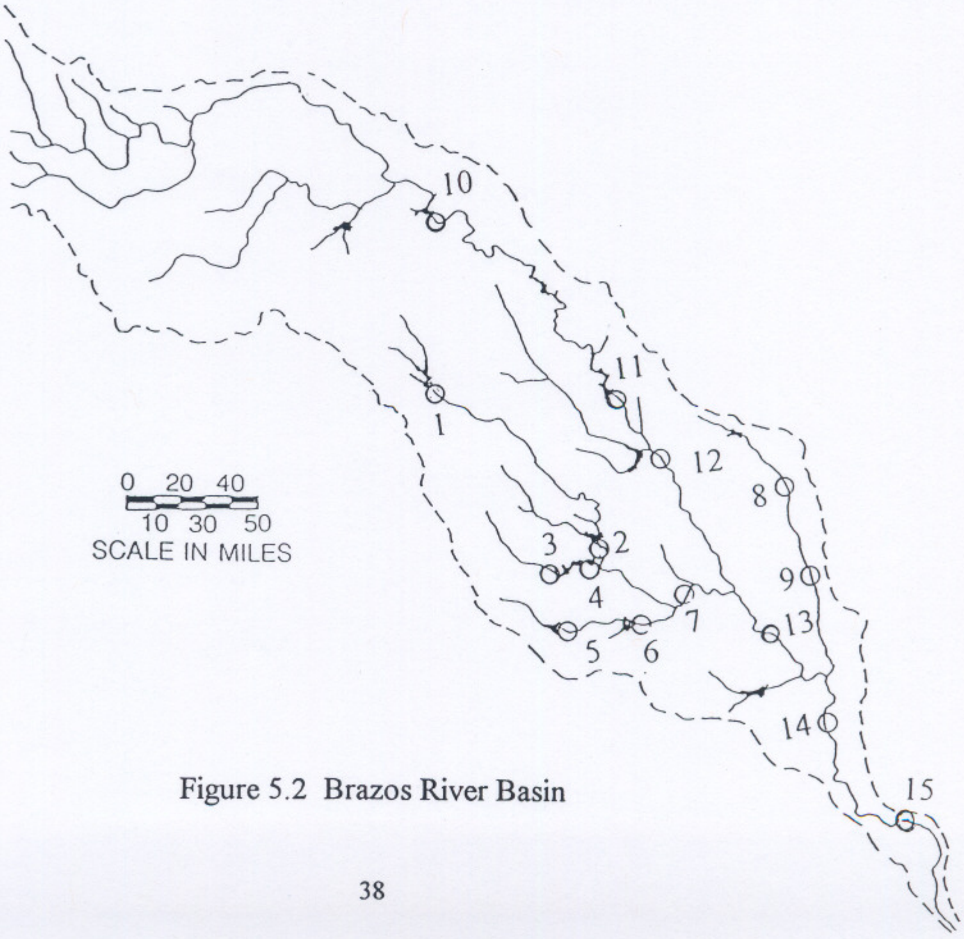


Figure 5.2 Brazos River Basin

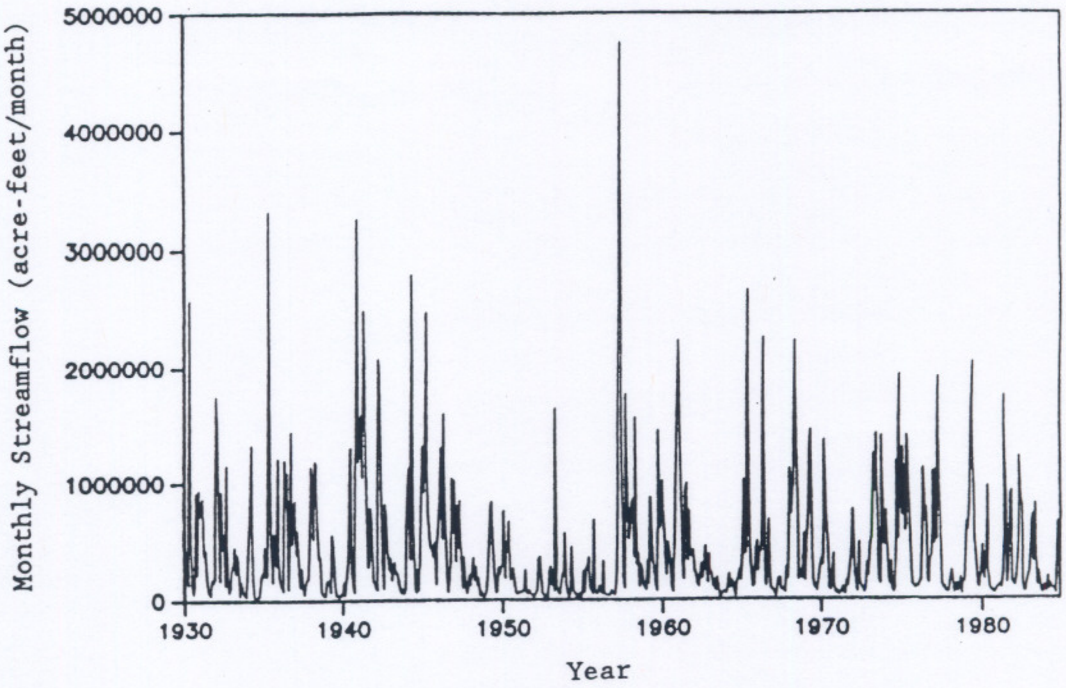


Figure 5.3 Monthly Gaged Streamflow Hydrograph
at Richmond Gage on Brazos River (Station 15)

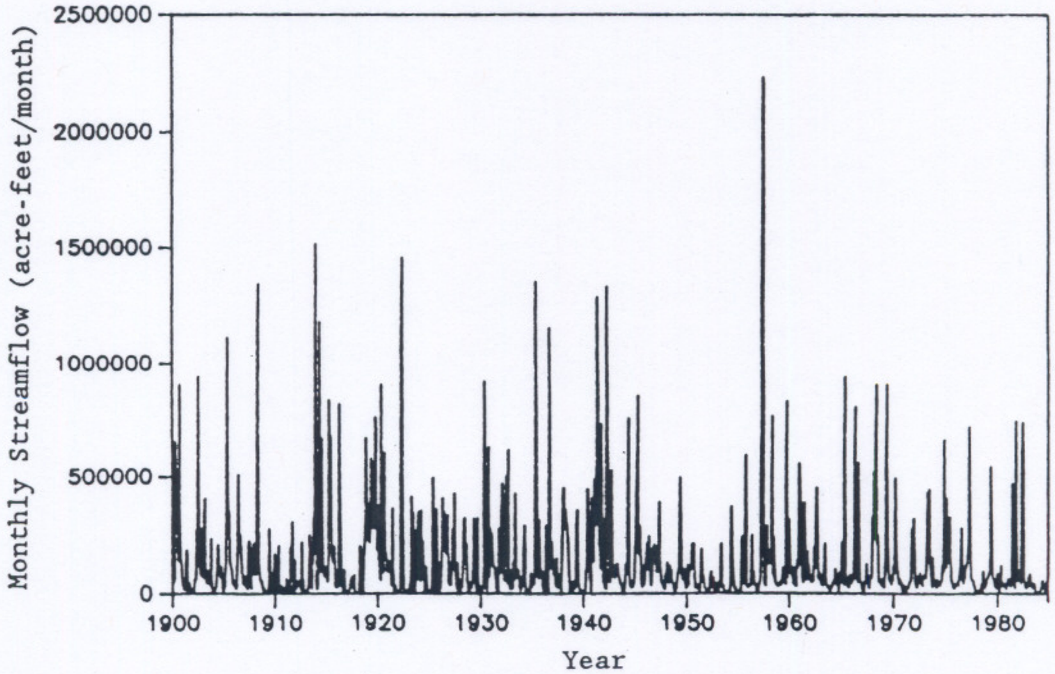


Figure 5.4 Monthly Gaged Streamflow Hydrograph
at Waco Gage on Brazos River (Station 12)

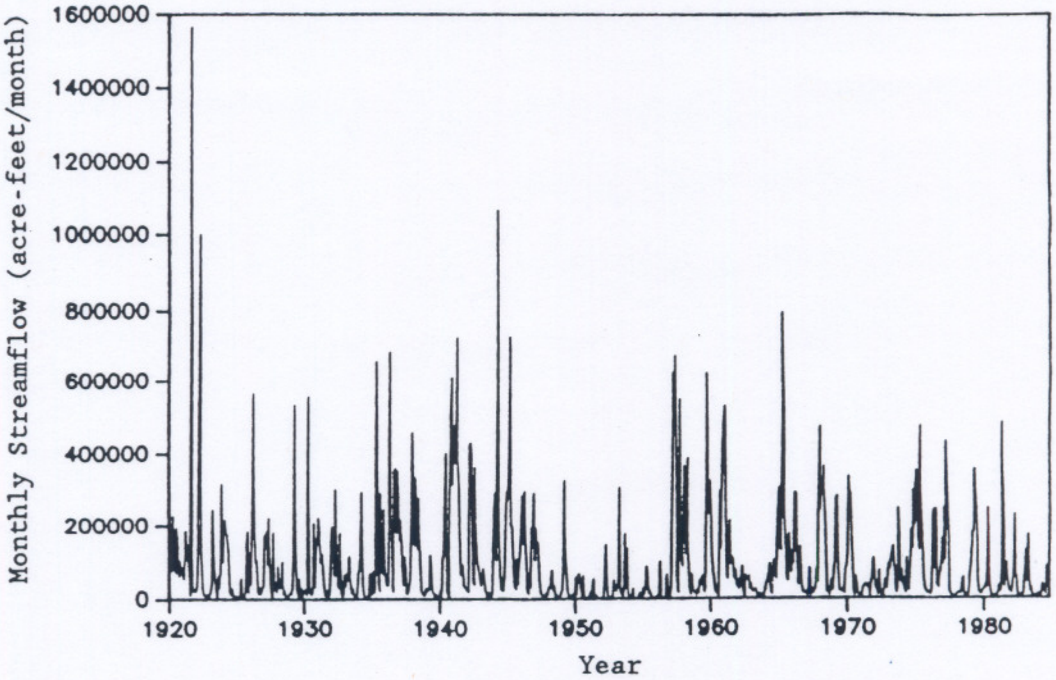


Figure 5.5 Monthly Gaged Streamflow Hydrograph
at Cameron Gage on Little River (Station 7)

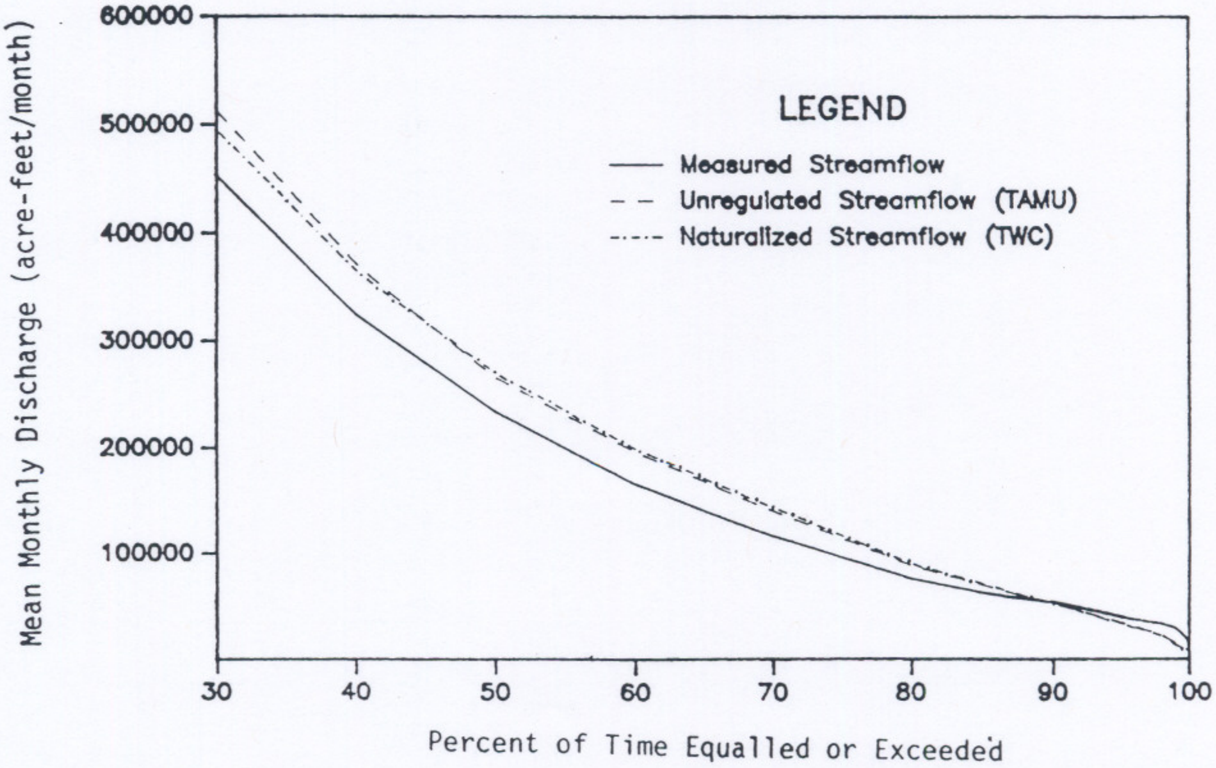


Figure 5.6 Flow-Duration Curves at Richmond Gage on Brazos River (Station 15)

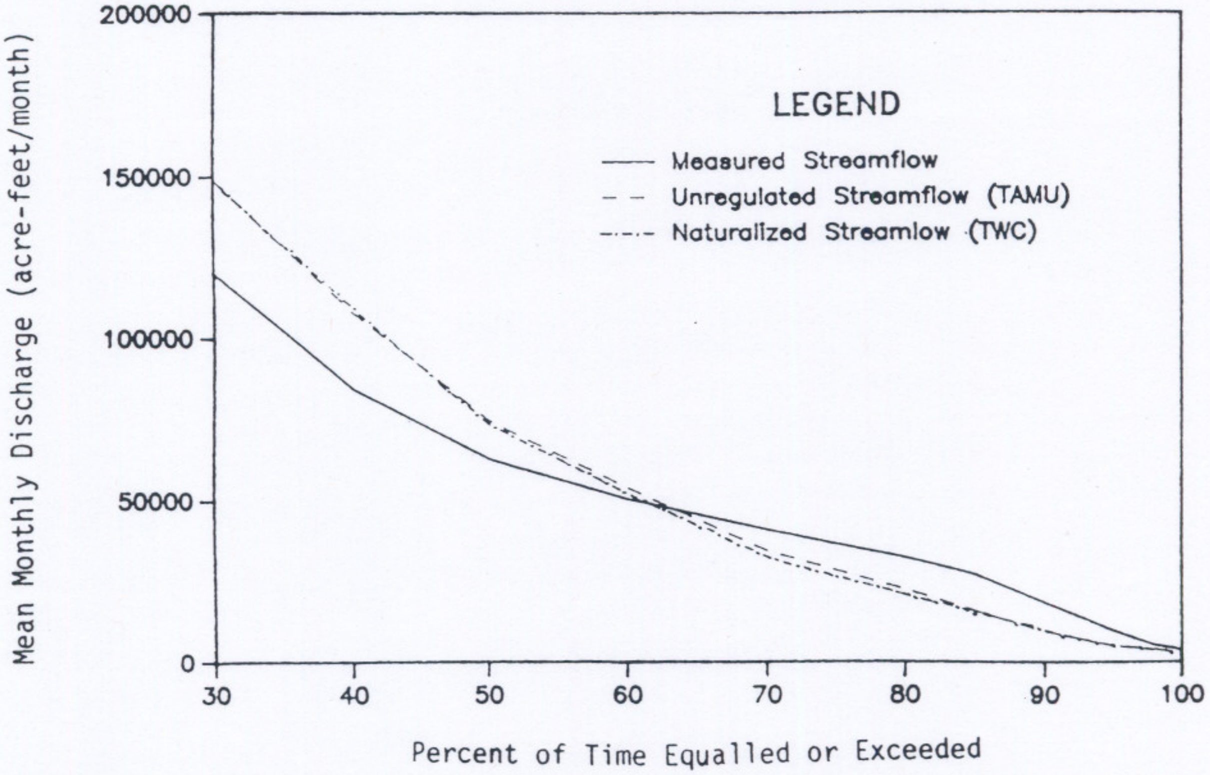


Figure 5.7 Flow-Duration Curves at Waco Gage on Brazos River (Station 12)

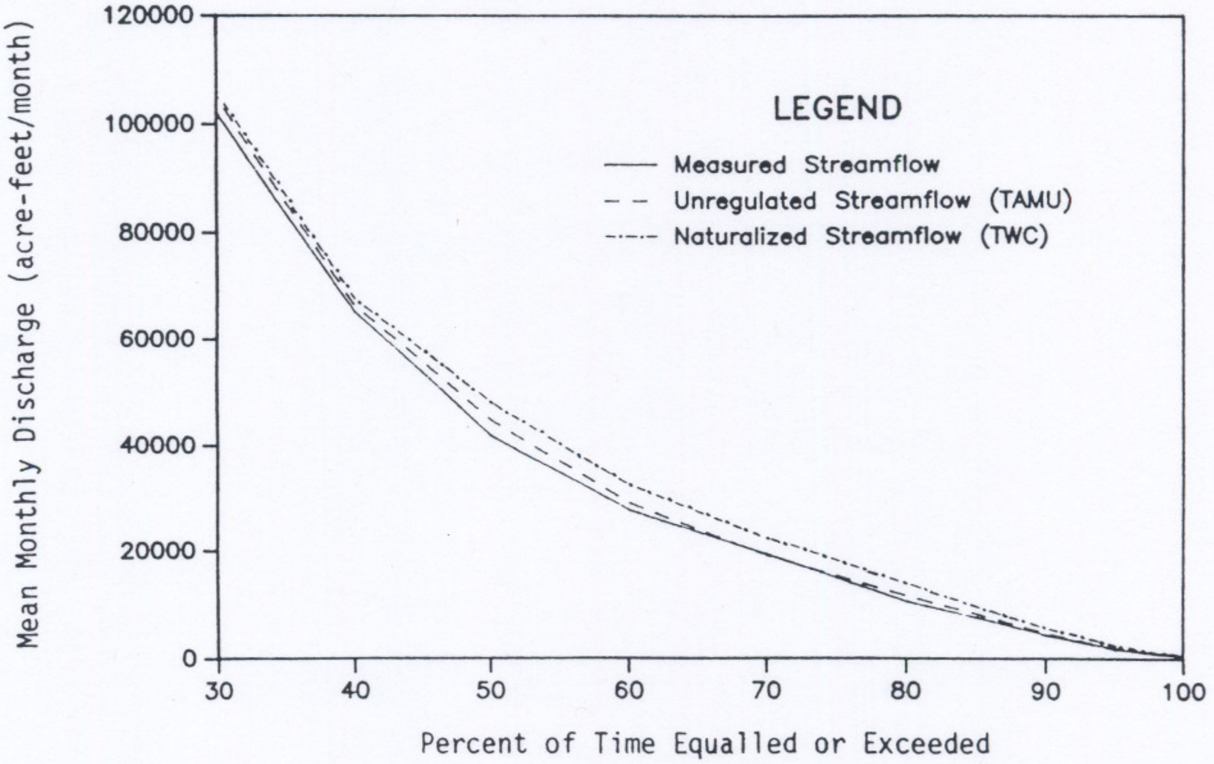


Figure 5.8 Flow-Duration Curves at Cameron Gage on Little River (Station 7)

Table 5.2 Comparison of Annual Flows at Richmond Gage (Station 15)
(Wurbs et al. 1988)

	Annual Flow in acre-feet			Percent of Gaged	
Year	Gaged	TAMU Unregulated	TWC Naturalized	TAMU Unregulated	TWC Naturalized
1940	7,758,910	7,410,388	7,851,618	95.5	101.2
1941	13,910,500	14,346,378	13,806,657	103.1	99.3
1942	8,296,710	8,505,618	8,517,257	102.5	102.7
1943	2,108,960	2,106,135	1,984,736	99.9	94.1
1944	8,600,480	8,878,290	8,901,381	103.2	103.5
1945	9,659,400	10,058,334	10,075,109	103.7	104.0
1946	8,227,090	8,886,366	8,406,103	108.0	102.8
1947	4,781,200	5,381,676	4,877,188	112.6	102.0
1948	1,697,900	1,892,009	1,873,102	111.4	110.3
1949	4,023,710	4,064,956	4,322,245	101.0	107.4
1950	3,670,770	4,426,907	3,960,416	121.0	107.9
1951	891,910	1,042,432	996,828	116.9	111.8
1952	1,446,990	1,648,562	1,612,838	112.4	110.0
1953	3,668,980	4,419,181	4,606,973	120.4	126.1
1954	1,127,660	1,418,617	1,362,354	126.0	121.0
1955	2,236,590	2,802,870	2,986,883	125.3	134.0
1956	960,020	842,231	898,582	88.0	93.6
1957	14,209,420	13,825,945	14,984,783	97.3	106.0
1958	5,756,700	5,909,958	5,932,483	103.1	103.1
1959	5,447,250	5,836,004	5,875,656	107.1	108.1
1960	6,857,140	7,110,624	7,158,404	104.1	104.4
1961	9,693,800	9,901,227	10,018,645	102.1	103.4
1962	2,941,700	3,590,161	3,381,734	122.0	115.1
1963	1,353,000	1,551,270	1,698,264	115.1	126.0
1964	1,659,280	2,057,165	2,209,970	124.1	133.2
1965	7,861,000	8,860,428	8,630,871	114.0	110.8
1966	5,822,080	6,331,361	6,412,548	108.4	110.1
1967	1,381,440	1,794,160	1,963,592	130.1	142.1
1968	10,009,900	11,030,169	11,074,102,	110.2	111.0
1969	5,524,730	6,285,600	6,405,007	114.1	116.0
1970	4,711,890	5,083,781	5,019,975	108.1	107.0
1971	2,073,450	3,420,179	3,342,931	165.1	161.2
1972	2,370,460	3,058,040	3,001,706	129.0	127.0
1973	8,566,400	9,078,366	9,113,881	106.1	106.4
1974	6,601,540	7,524,022	7,823,188	114.1	119.0
1975	7,084,590	7,093,489	7,280,038	100.1	103.1
1976	5,701,000	6,308,629	6,400,579	111.1	112.3

Table 5.3 Comparison of Annual Flows at Waco Gage (Station 12)
(Wurbs et al. 1988)

	Annual Flow in Acre-feet			Percent of Gaged	
		TAMU	TWC	TAMU	TWC
Year	Gaged	Unregulated	Naturalized	Unregulated	Naturalized
1940	2,003,570	2,036,267	2,038,918	102.0	102.1
1941	4,965,660	5,732,670	5,700,425	115.4	115.1
1942	3,831,550	3,943,540	3,973,631	103.0	104.0
1943	738,920	500,669	512,290	68.1	69.3
1944	1,472,020	1,651,409	1,681,202	112.2	114.2
1945	2,835,030	3,075,364	3,103,807	109.1	110.1
1946	1,808,160	1,885,563	1,909,210	104.3	106.1
1947	1,361,740	1,338,830	1,349,068	98.3	99.1
1948	737,470	787,502	795,028	107.1	108.1
1949	1,540,300	1,647,823	1,707,407	107.1	111.0
1950	1,197,430	1,352,578	1,363,694	113.1	114.1
1951	610,680	582,360	589,597	95.4	97.0
1952	412,650	430,742	434,409	104.4	105.3
1953	432,510	1,224,589	1,232,289	283.1	285.0
1954	761,420	814,349	836,368	107.1	110.0
1955	1,424,510	1,798,487	1,864,593	126.3	131.1
1956	649,280	453,840	476,796	70.1	73.4
1957	6,151,850	6,657,818	6,726,271	108.2	109.3
1958	1,864,540	1,899,938	1,926,859	102.1	103.3
1959	1,572,870	1,832,874	1,871,637	117.0	119.1
1960	1,459,370	1,604,427	1,631,701	110.0	112.0
1961	2,639,660	2,783,641	2,830,387	105.5	107.2
1962	1,627,110	1,858,597	1,889,101	114.2	116.1
1963	670,760	684,175	750,999	102.1	112.1
1964	582,220	817,981	875,277	140.5	150.3
1965	1,680,290	2,192,212	2,227,415	130.5	133.1
1966	2,139,400	2,485,294	2,529,568	116.2	118.2
1967	626,760	863,368	921,764	138.1	147.1
1968	3,006,640	3,357,044	3,372,471	112.1	112.2
1969	1,936,150	2,492,019	2,524,598	129.0	130.4
1970	1,311,110	1,533,267	1,395,099	117.0	106.4
1971	1,042,860	2,092,884	1,864,536	201.1	179.1
1972	802,910	1,283,166	1,157,339	160.0	144.0
1973	1,911,350	2,122,328	2,076,896	111.0	109.1
1974	1,339,000	1,918,892	2,043,226	143.3	153.1
1975	1,721,810	1,816,234	1,898,435	105.5	110.3
1976	1,057,090	1,504,459	1,464,606	142.3	139.1

Table 5.4 Comparison of Annual Flows at Cameron Gage (Station 7)
(Wurbs et al. 1988)

	Annual Flow in Acre-feet			Percent of Gaged	
Year	Gaged	TAMU Unregulated	TWC Naturalized	TAMU Unregulated	TWC Naturalized
1940	2,054,350	2,054,350	2,054,956	100.0	100.0
1941	3,280,800	3,280,800	3,282,135	100.0	100.0
1942	2,150,180	2,150,180	2,154,788	100.0	100.2
1943	389,420	389,420	391,832	100.0	101.0
1944	2,584,280	2,584,280	2,589,675	100.0	100.2
1945	2,443,240	2,443,240	2,449,115	100.0	100.2
1946	1,689,000	1,689,000	1,693,990	100.0	100.3
1947	998,350	998,350	1,002,645	100.0	100.4
1948	261,030	261,030	266,762	100.0	102.2
1949	712,810	712,810	721,383	100.0	101.2
1950	363,350	363,350	367,954	100.0	101.3
1951	133,230	133,230	138,330	100.0	104.0
1952	327,952	327,952	333,429	100.0	102.1
1953	835,610	835,610	861,193	100.0	103.1
1954	73,087	92,731	98,454	127.1	135.0
1955	274,780	467,077	489,028	170.1	178.1
1956	216,220	216,685	232,191	100.2	107.4
1957	3,244,730	3,363,659	3,384,816	104.1	104.3
1958	1,614,040	1,635,853	1,645,774	101.4	102.1
1959	1,450,690	1,479,590	1,510,125	102.1	103.5
1960	1,740,640	1,764,633	1,778,414	101.4	102.2
1961	2,385,510	2,407,549	2,423,227	101.0	102.1
1962	547,420	586,013	605,643	107.0	111.0
1963	201,030	257,833	299,717	128.3	149.1
1964	647,770	711,644	757,591	110.1	117.1
1965	2,905,700	2,930,402	2,973,446	101.1	102.3
1966	1,331,540	1,366,925	1,409,473	103.1	106.1
1967	379,370	390,906	463,129	103.0	122.1
1968	2,284,140	2,609,875	2,673,668	114.3	117.1
1969	1,012,770	1,103,290	1,156,140	109.0	114.2
1970	1,424,410	1,464,031	1,513,251	103.1	106.2
1971	427,860	612,031	733,555	143.0	171.4
1972	378,960	455,173	502,654	120.1	132.6
1973	1,142,550	1,341,895	1,388,700	117.4	122.0
1974	1,188,100	1,460,675	1,534,861	123.0	129.2
1975	2,061,360	1,906,154	1,962,568	92.5	95.2
1976	1,195,070	1,284,759	1,324,026	108.1	111.1

Table 5.5 Annual Precipitation for Watersheds in the Brazos River Basin
(Wurbs et al. 1988)

(INCHES)

	Watershed Above Stream Gage At			
Year	Waco	Cameron	Bryan	Richmond
1900	37.42	35.47	38.88	41.83
1901	17.83	15.80	17.76	18.23
1902	33.53	27.97	34.16	35.83
1903	27.54	31.55	30.38	31.59
1904	28.20	32.44	29.44	30.74
1905	44.03	37.13	44.10	44.74
1906	34.90	28.62	33.47	33.58
1907	30.22	32.42	33.16	35.01
1908	35.79	32.61	36.05	36.41
1909	21.89	21.18	22.84	23.31
1910	18.38	21.72	20.69	21.02
1911	27.99	25.38	27.57	28.75
1912	22.32	22.65	23.03	23.54
1913	32.75	39.76	35.10	36.25
1914	36.42	35.04	36.70	37.69
1915	31.67	27.00	31.51	31.92
1916	23.09	25.38	23.94	24.36
1917	14.86	15.03	15.35	15.51
1918	23.46	23.21	24.29	24.76
1919	39.70	44.58	41.81	44.02
1920	32.91	35.70	34.00	35.01
1921	21.06	25.36	23.81	25.53
1922	24.79	32.25	28.33	29.80
1923	31.98	35.11	33.46	35.39
1924	18.83	20.83	20.16	21.08
1925	21.23	22.33	21.59	22.49
1926	32.91	32.68	33.89	34.99
1927	22.24	28.91	25.08	25.89
1928	22.79	26.15	24.04	24.69
1929	22.44	26.88	24.47	26.04
1930	25.00	29.41	26.85	27.44
1931	23.74	31.49	25.67	26.20
1932	33.96	37.80	35.31	35.43
1933	21.07	25.00	22.32	23.01
1934	16.47	23.75	19.47	20.94
1935	31.15	36.33	33.49	34.58
1936	25.67	35.89	28.73	29.34
1937	22.56	28.99	25.03	25.34
1938	24.55	30.67	26.42	26.94
1939	20.34	26.09	22.15	22.30
1940	25.87	41.81	30.81	31.87
1941	43.53	37.80	42.33	43.41
1942	28.89	39.62	31.75	32.03
1943	17.10	21.53	18,85	19.81
1944	29.08	38.15	32.89	33.64
1945	25.16	37.61	29.53	30,95
1946	26.32	35.86	29.39	30.89
1947	21.82	20.66	22.58	23.58
1948	16.70	21.99	18.47	18.72
1949	29.10	32.57	30.06	31.57
1950	24.12	25.17	24.37	24.68
1951	18.50	22.91	19.67	20.41
1952	18.25	24.60	20.73	21.72
1953	21.03	30.75	24.33	25.32
1954	15.97	16.19	16.24	16.45
1955	22.90	28.08	24.76	25.11
1956	12.35	17.70	13.99	14.44
1957	36.65	46.15	39.88	40.40
1958	25.00	32.22	27.28	27.87
1959	28.09	34.09	30.72	31.66
1960	26.25	33.81	28.88	30.18
1961	30.54	36.08	32.47	33.53
1962	26.35	27.11	26.77	27.13
1963	20.78	20.33	20.65	20.79
1964	22.31	31.91	25.16	25.74
1965	25.75	35.32	29.48	30.45
1966	24.29	28.76	26.31	26.73
1967	22.83	28.10	24.75	24.97
1968	29.41	39.97	32.93	34.24
1969	31.49	29.49	31.30	31.56
1970	19.14	28.66	21.98	22.89
1971	27.61	31.27	29.04	29.28
1972	25.70	24.86	25.88	26.38
1973	28.72	33.78	31.56	32.19
1974	28.47	34.18	30.68	31.09
1975	24.49	28.67	26.18	26.59
1976	26.09	33.43	28.90	28.61
1977	20.51	22.80	21.86	22.15
1978	23.16	25.89	24.29	24.77
1979	26.68	35.06	29.83	30.87
1980	23.40	27.50	24.42	24.84
1981	27.98	30.56	29.81	30.61
1982	27.63	28.61	28.26	28.64
1983	22.52	23.81	23.93	24.51
1984	24.52	27.21	26.11	26.45
1900-1984 mean	25.89	29.64	27.58	28.37
1940-1984 mean	24.96	30.06	26.89	27.55

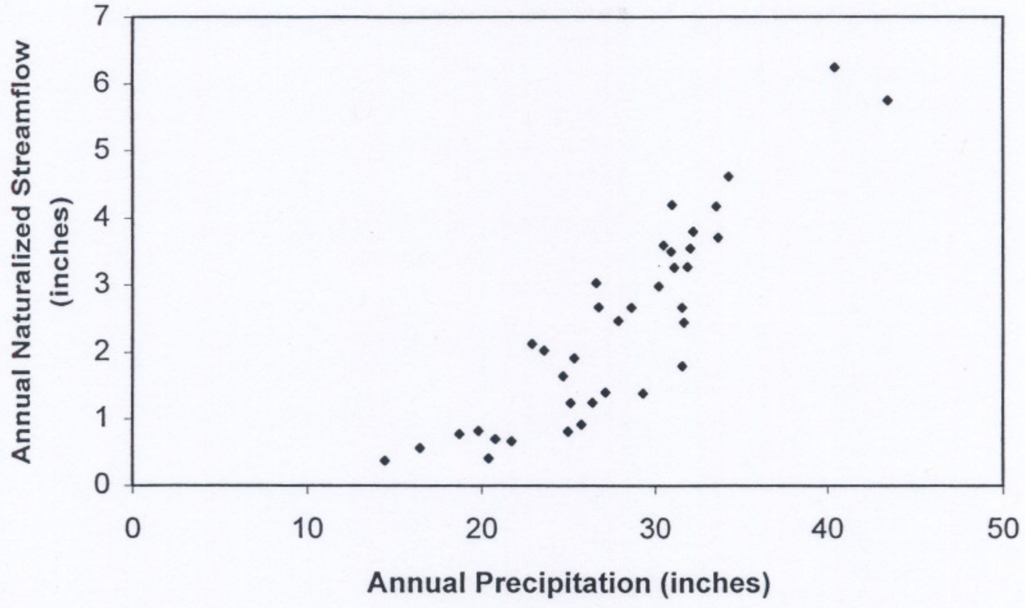


Figure 5.9 Annual Precipitation-Runoff Relationship for the Watershed above the Richmond Gage on the Brazos River (Station 15)

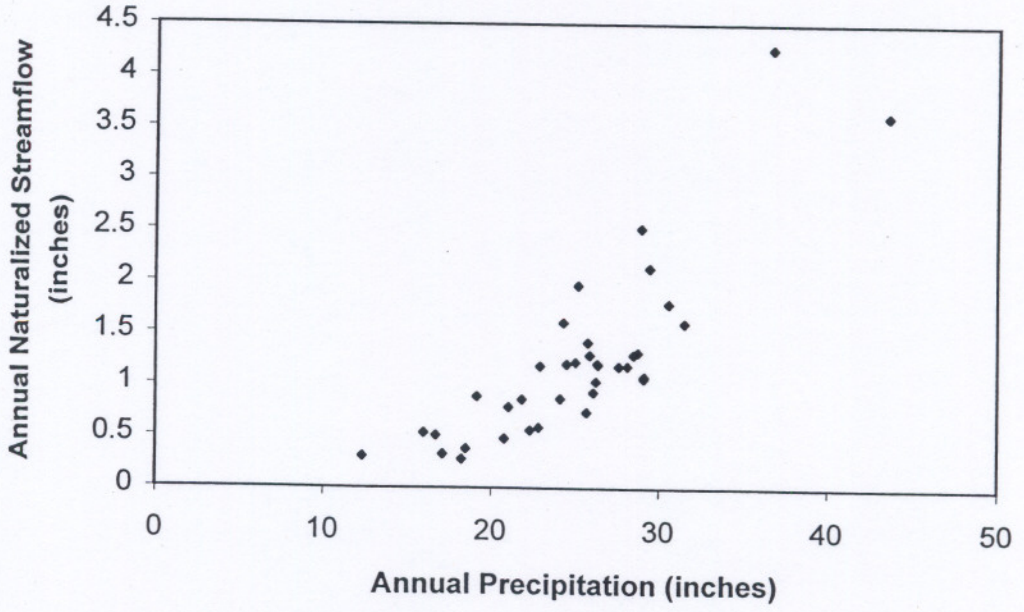


Figure 5.10 Annual Precipitation-Runoff Relationship for the Watershed above the Waco Gage on the Brazos River (Station 12)

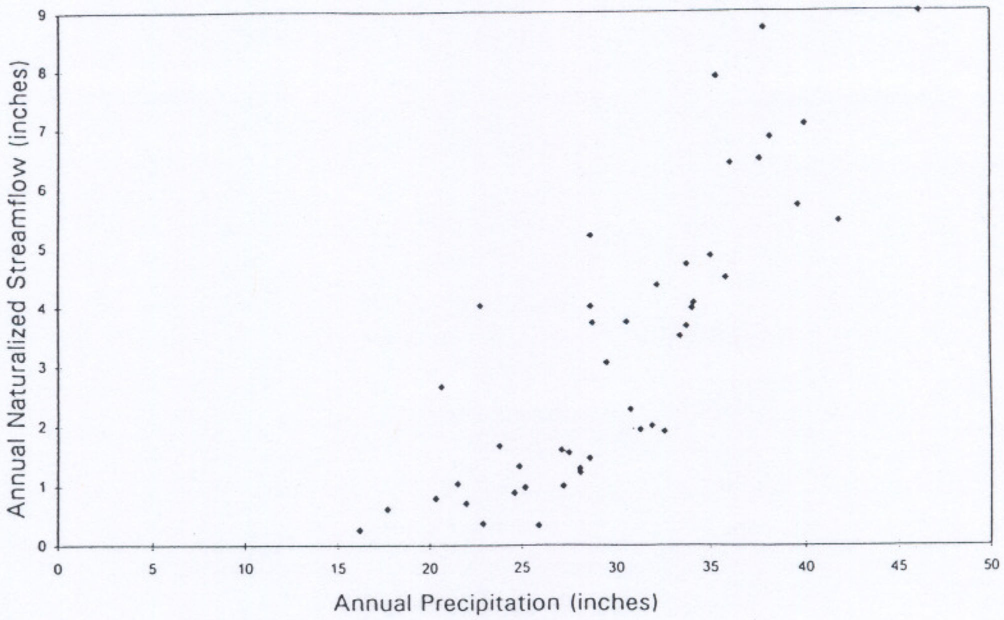


Figure 5.11 Annual Precipitation-Runoff Relationship for the Watershed above the Cameron Gage on the Little River (Station 7)

San Jacinto River Basin

As indicated by Figure 5.12, the two principal drainage systems of the San Jacinto River Basin are the watersheds of the San Jacinto River and Buffalo Bayou which flow into the Houston Ship Channel which flows into Galveston Bay. The total basin drainage area of 3,900 square miles includes 2,900 and 1,000 square miles in the San Jacinto River and Buffalo Bayou subbasins, respectively. The City of Houston lies within the Buffalo Bayou watershed. Naturalized monthly flows at the 12 USGS stream gaging stations shown in Figure 5.12 and Table 5.6 are used in this study. The combined watershed area of the stream gages adopted in the study is 2,730 square miles.

The naturalized flow data adopted for this investigation were developed in conjunction with a water availability modeling study performed by the Texas Department of Water Resources (1983). Naturalized flows for the period 1940-1980 were developed by the TDWR by adjusting gaged flows to remove the effects of reservoir storage and diversions for beneficial use. As indicated by Table 5.6, the period-of-record for several of the stations do not completely cover the period 1940-1980. The TDWR extended the records as necessary by regressing flows at these stations with flows at nearby gaging stations. The water availability model was later updated by the Texas Natural Resource Conservation Commission (1996). The 1996 San Jacinto Basin water availability model update incorporated the same 1940-1980 naturalized flows at the stations listed in Table 5.6. The station numbers adopted here (first column of Table 5.6) correspond to the watershed identifiers assigned by the 1983 TDWR report and control points used in the 1996 TNRCC report. Drainage areas and the means of the 1940-1980 naturalized flows at each station are shown in Table 5.6.

Figure 5.12 San Jacinto River Basin

Table 5.6 Selected Streamflow Gaging Stations in the San Jacinto Basin

Station	Stream	Nearest City	USGS Gage Number	Drainage Area (mile^2)	Mean Flow (ac-ft/yr)	Mean Flow (inches/yr)	Portion of 1940-1980 Covered by Period of Record
1	West Fork San Jacinto	Conroe	8068000	809	370,000	8.6	1940-1980
2	Spring Creek	Spring	8068520	419	158,000	7.1	1940-1980
3	Cypress Creek	Westfield	8069000	285	121,000	8.0	Jul 1944 - 1980
4	East Fork San Jacinto	Cleveland	8070000	325	163,000	9.4	1940-1980
5	Peach Creek	Splendora	8071000	117	55,200	8.8	Oct 1943 - 1980
6	Caney Creek	Splendora	8070500	105	55,600	9.9	Jan 1944 - 1980
8	Greens Bayou	Houston	8076000	72.7	43,500	11.2	Oct 1952 - 1980
9	Buffalo Bayou	Addicks	8073500	293	163,000	10.4	Aug 1945 - 1980
10	Buffalo Bayou	Houston	8074000	358	216,000	11.3	1940-1980
11	White Bayou	Houston	8074500	84.7	59,900	13.3	1940-1980
12	Brays Bayou	Houston	8075000	88.4	88,100	18.7	1940-1980
13	Sims Bayou	Houston	8075500	64.0	54,500	16.0	Oct 1952 - 1980

Sulphur River Basin

The Sulphur River flows from northeast Texas into Arkansas where it confluences with the Red River, which is a tributary of the Mississippi River. The Texas portion of the Sulphur River Basin encompasses 3,600 square miles and has an average annual precipitation ranging from 40 inches in the west to 47 inches at the state line. Basin population increased from 154,000 in 1980 to 162,000 in 1990. The largest cities in the basin are Texarkana (1990 population of Texas side of 32,000) and Sulphur Springs (population 14,000). The city of Paris (25,000) lies on the divide between the Sulphur and Red River Basins. Permitted diversion rights are for 185,057 ac-ft/yr municipal, 165,875 ac-ft/yr industrial, 26,635 ac-ft/yr irrigation, and 863 ac-ft/yr other uses. A total conservation storage capacity of 750,000 acre-feet is contained in 29 impoundments with capacities greater than 200 ac-ft each. Lakes Wright Patman, Chapman, and Sulphur Springs account for about 95 percent of this total storage capacity (R. J. Brandes Company 1999).

The basin is rural in nature, predominately pasture and agricultural land. The western part of the basin is mainly open rolling prairies with small tracts of woodlands. The eastern portion is typically forested, with a smaller amount of cropland and pasture. Since the 1940's, land use has changed from primarily cropland, mostly cotton, to a predominance of pastureland.

The R. J Brandes Company performed a water availability modeling study for the Sulphur River Basin, under contract with the TNRCC, using the *WRAP* model (R. J. Brandes Company 1999). The investigation included developing 1940-1996 sequences of naturalized monthly flows at six USGS stream gaging stations. The five stations shown in Figure 5.13 and Table 5.7 were adopted for the present study.

Table 5.7 Selected Streamflow Gaging Stations in the Sulphur Basin

Station	Stream	Nearest City	USGS Gage Number	Drainage Area (mile^2)	Mean Flow (ac-ft/yr)	Mean Flow (inches/yr)	Portion of 1940-1996 Covered by Period of Record
A	South Sulphur River	Cooper	7342500	541	320,670	11.1	Jun 1942-Sep 1991
B	North Sulphur River	Cooper	7343000	311	175,270	10.6	Oct 1949-Dec 1996
C	Sulphur River	Talco	7343200	1,380	952,520	12.9	Oct 1956-Dec 1996
D	White Oak Creek	Talco	7343500	546	387,050	13.3	Jan 1940-Nov 1949
E	Sulphur River	Darden	7344000	2,850	1,983,620	13.1	Jan 1940-Dec 1956

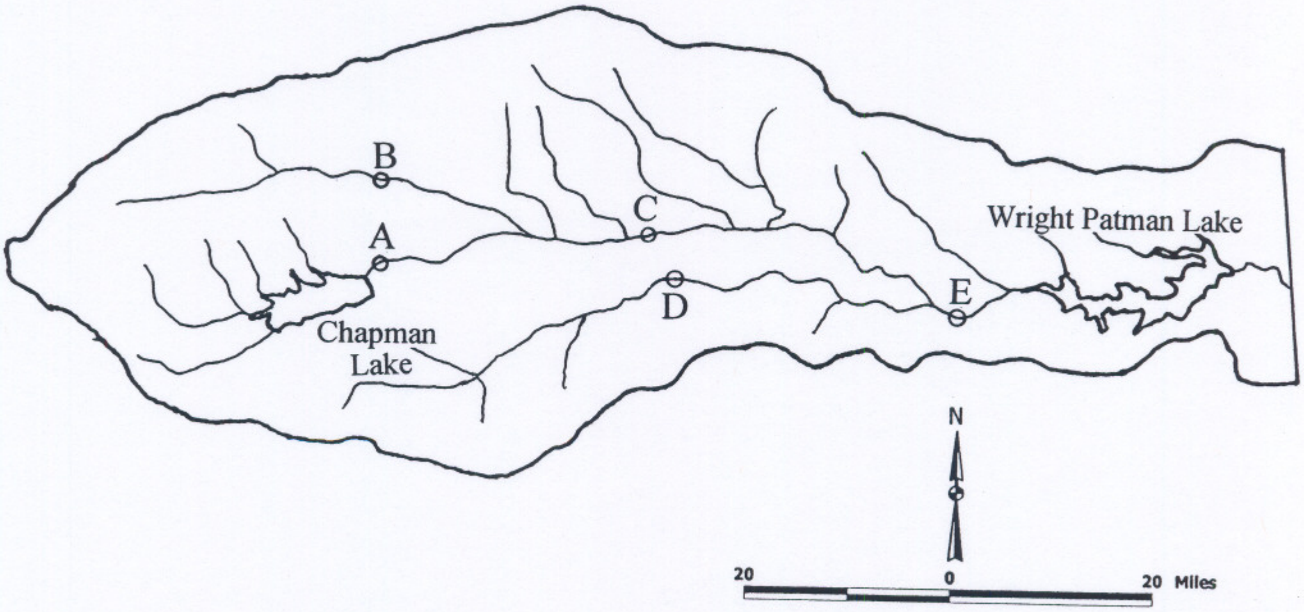


Figure 5.13 Sulphur River Basin

Scope of the Analyses to Compare Concurrent Flows at Different Locations

The remainder of Chapter 5 presents the results of analyses to determine how closely the naturalized monthly flows from the different subwatersheds are related and the form of the relationships. Graphs are plotted, and least squares linear regression/correlation techniques are applied to evaluate relationships between the flows at different locations.

Pairing of Brazos River Basin Stations

As indicated in Table 5.1, the 15 stations in the Brazos River Basin are divided into three groups.

- *Stations 1-7 on the Little River and its Tributaries:* Stations 1 through 6 are located on various tributaries above station 7 on the Little River. Flows at each of stations 1-6 are compared with flows at station 7. Flows at adjacent stations on the same tributaries are also compared.
- *Stations 8 and 9 on the Navasota River*
- *Stations 10-15 on the Brazos River:* Flows at stations 10, 11, 12, 13, and 14 on the Brazos River are compared with flows at station 15, which is the most downstream station on the Brazos River. Each of the stations on the main-stem Brazos River is also paired with the adjacent station located immediately upstream.

The portion of the 1940-1976 period covered by the period-of-record at each gaging station is shown in Table 5.1. In the original development of the sequences of naturalized flows, the Texas Department of Water Resources (1981) extended records as necessary to cover the period 1940-1976 by regression techniques using flows at other gages with complete longer records. In the present investigation, the comparisons of flows at pairs of stations include the flows covering the portion of the period 1940-1976 that is covered in the period-of-record of both gaging stations. Thus, all of the naturalized flows used in the study are gaged flows adjusted to remove the effects of historical water management.

Pairing of San Jacinto River Basin Stations

The following comparisons are presented for the 12 stations in the San Jacinto Basin shown in Figure 5.12.

- comparison of flows at each of the 12 gaging stations with the combined total flows
- comparison of flows at pairs of gaging stations for adjacent subwatersheds
- comparison of flows at stations 9 and 10 on Buffalo Bayou

Station 9, which is located upstream of station 10, is the only station for which another station is located downstream. The combined total flow for each month consists of the summation of flows at all of the stations except station 9. This represents the flow from the entire 2,730 mile^2 watershed above the stations.

The period-of-record at each gaging station is shown in Table 5.6. The Texas Department of Water Resources (1983) extended records as necessary to cover the period 1940-1980 by regression techniques using flows at other gages with complete longer records. In the present investigation, the comparisons of flows at each station with the concurrent total combined flows include all flows covering the period 1940-1980 including those synthesized to extend records. A set of plots and correlation/regression statistics are presented for adjacent-station concurrent flows that include only the months included in the period-of-record for both gaging stations, shown in Table 5.6, thus excluding flows previously synthesized by the TDWR to extend records.

Pairing of Sulphur River Basin Stations

The following comparisons are presented for the five stations in the Sulphur Basin shown in Figure 5.13.

- comparsion of flows at stations A and B with station C
- comparison of flows at station D with station E
- comparison of flows at stations B with station A

Station C is downstream of stations A and B. Station D is upstream of station E. Stations A and B are at the outlets of adjacent subwatersheds. The portions of the period 1940-1996 covered by the gage record at each station are shown in Table 5.7. Again, only flows for the common portions of the periods-of-record are used, so that all of the naturalized flows used in the study are gaged flows adjusted to remove the effects of historical water management.

Plots Relating Concurrent Flows at Different Locations

Hydrographs of annual naturalized flows at stations in the Brazos Basin are compared in Figures 5.14 through 5.16. The flows at the 7 stations in the Little River watershed are compared in Figure 5.14. Flows at the two stations on the Navasota River are compared in Figure 5.15. The hydrographs for the main-stem Brazos River are plotted in Figure 5.16. Annual flows for stations for two example stations in the San Jacinto Basin are compared with the total combined flows in Figure 5.17. Flows at the two stations on Buffalo Bayou are plotted in Figure 5.18.

Concurrent Monthly Flows at Pairs of Stations in the Brazos River Basin

Concurrent 1940-76 monthly naturalized flows at pairs of stations in the Brazos River Basin are plotted in Figures 5.19 through 5.37. In Figures 5.19-5.24, flows at each of the stations in the Little River watershed above station 7 are related to the corresponding flows at station 7. In Figures 5.25-5.27, flows at pairs of stations on the same tributaries (Leon, Lampases, and San Gabriel Rivers) in the Little River watershed are compared. The flows at the two stations on the Navasoto River are plotted in Figure 5.28. The flows at the stations on the Brazos River are plotted against the flow at station 15, the most downstream station, in Figures 5.29-5.33. Concurrent flows at adjacent stations on the Brazos River are plotted in Figures 5.34-5.37.

From the perspective of fitting curves through the data, the plots of Figures 5.19-5.37 generally indicate that the relationships are essentially linear. Linear regression and correlation coefficients associated with these data are presented in the next section.

There is significant scatter in the plotted data. In general, the correlation between flows at subwatershed versus watershed outlets depends largely on the differences in the drainage areas between the two stations being compared. For example, the Figure 5.19 plot of concurrent 1940-1976 monthly flows at stations 1 and 7, with drainage areas of 1,260 and 7,060 mile^2, respectively, show little correlation. The flows at stations 2 and 7 (3,540 versus 7,060 mile^2) in Figure 5.20 are much more closely correlated. Concurrent flows at stations 14 and 15 (43,880 versus 45,010 mile^2) plot almost as a straight line in Figure 5.33.

Concurrent Monthly Flows at Pairs of Stations in the San Jacinto River Basin

Regression plots of naturalized monthly flows at pairs of stations in the San Jacinto River Basin are presented in Figures 5.38-5.60. Correlation and regression analyses are presented in the next section. The plots for all of the pairs of stations also indicate essentially linear regression relationships.

The combined flows from the total 2,730 mile^2 watershed above the 12 stations in the San Jacinto Basin are computed by summing the flows at the individual stations. The flows at each station are compared with the total combined flows in Figures 5.38-5.49. The relationship between individual station flows and the combined flows exhibits significant scatter at all of the stations. However, the flows at stations 1, 2, 3, 4, 5 and 6 in the predominately rural San Jacinto River subbasin are more closely correlated to combined flows than are the relationships for the flows at stations 8, 9, 10, 11, 12, and 13 in the urban and urbanizing Buffalo Bayou subbasin.

The concurrent flows at adjacent stations for each month are plotted in Figures 5.50-5.60. Only the months included in the gaging station period-of-record shown in Table 5.6 are included in the adjacent-station plots of Figures 5.50-5.60. The monthly flows for the entire period 1940-1980 are included in the combined-flow plots of Figures 5.38-5.49. The adjacent-station plots also exhibit considerable scatter. The closest correlation is between flows at stations 9 and 10. Station 9 is located above station 10 on the same stream. These are the only two stations in the San Jacinto Basin located on the same tributary.

Concurrent Monthly Flows at Pairs of Stations in the Sulphur River Basin

The flows at A and B are compared with C and the flow at D is compared with E in Figures 5.61-5.63. The flow at B is also compared with the flow of A Figure 5.64. These plots show an essentially linear trend with much scatter similar to the plots for the stations in the San Jacinto and the Brazos Basins.

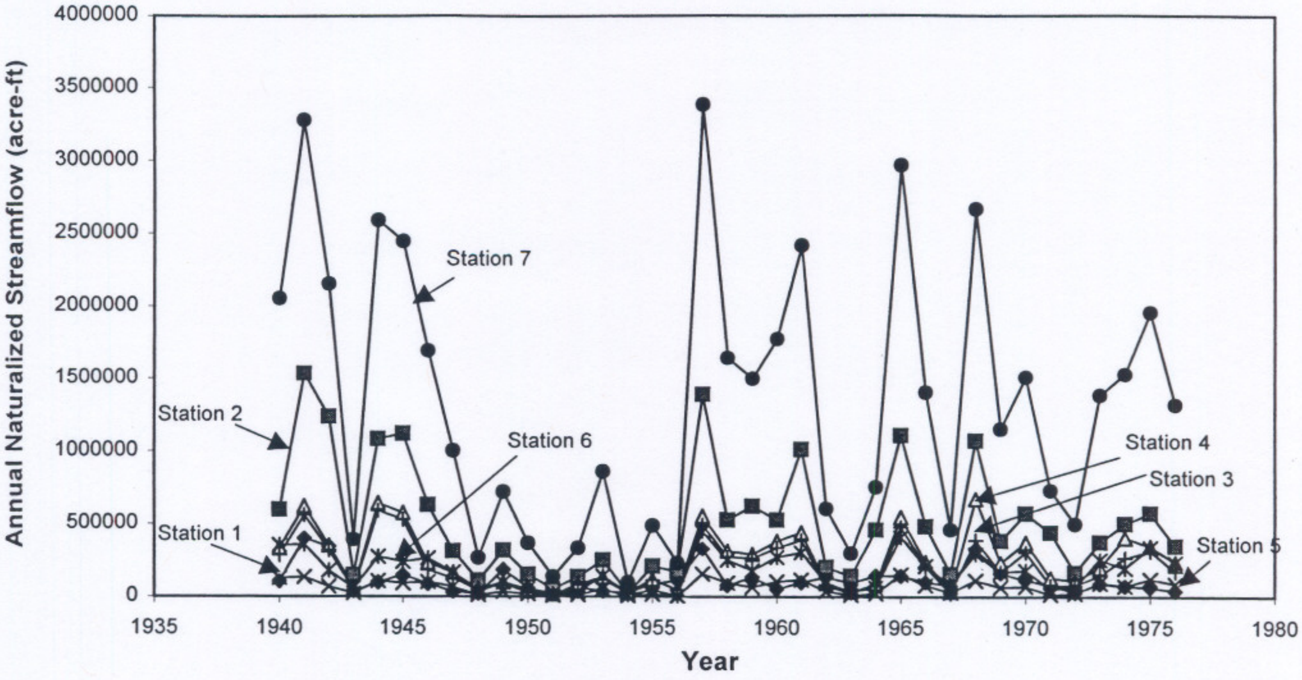


Figure 5.14 Annual Flow Hydrographs for Stations in the Little River Watershed

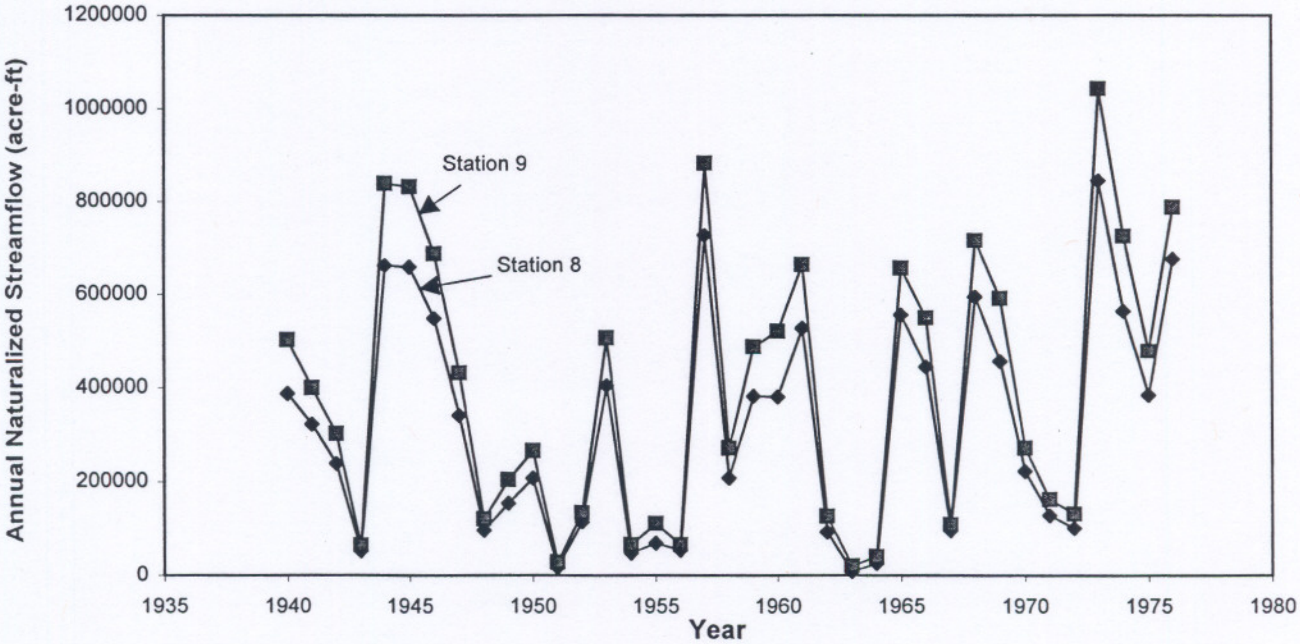


Figure 5.15 Annual Flow Hydrographs for Stations on the Navasota River

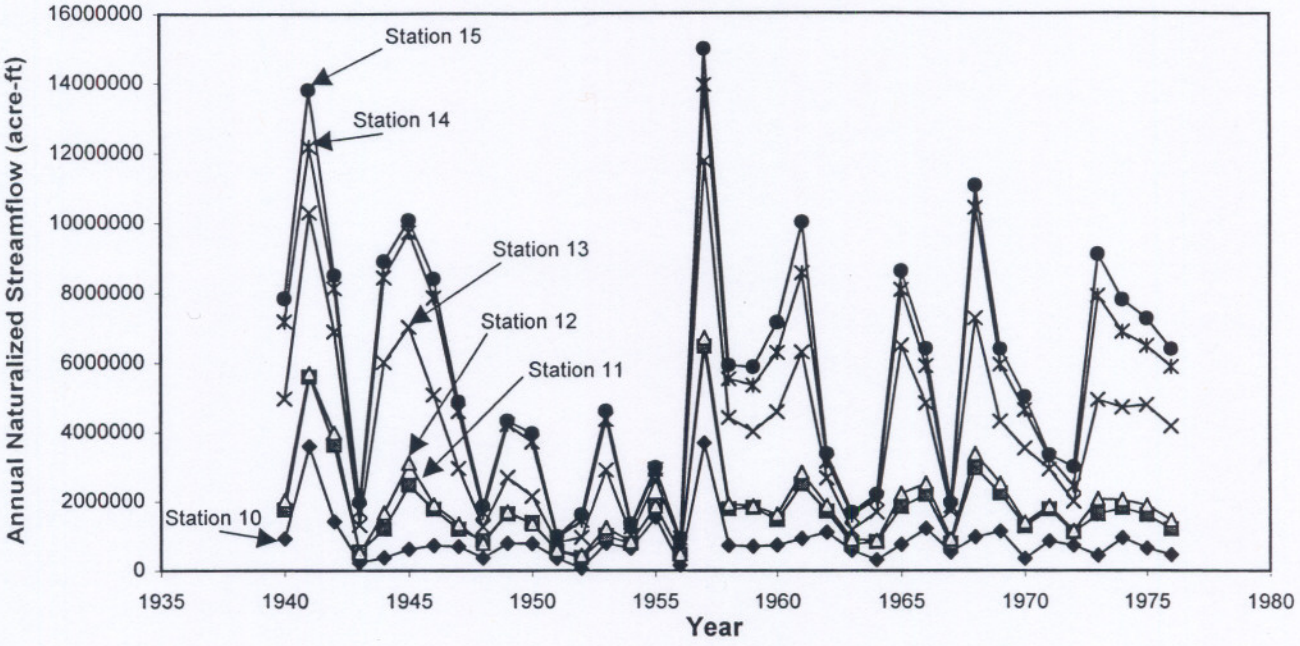


Figure 5.16 Annual Flow Hydrographs for Stations on the Brazos River

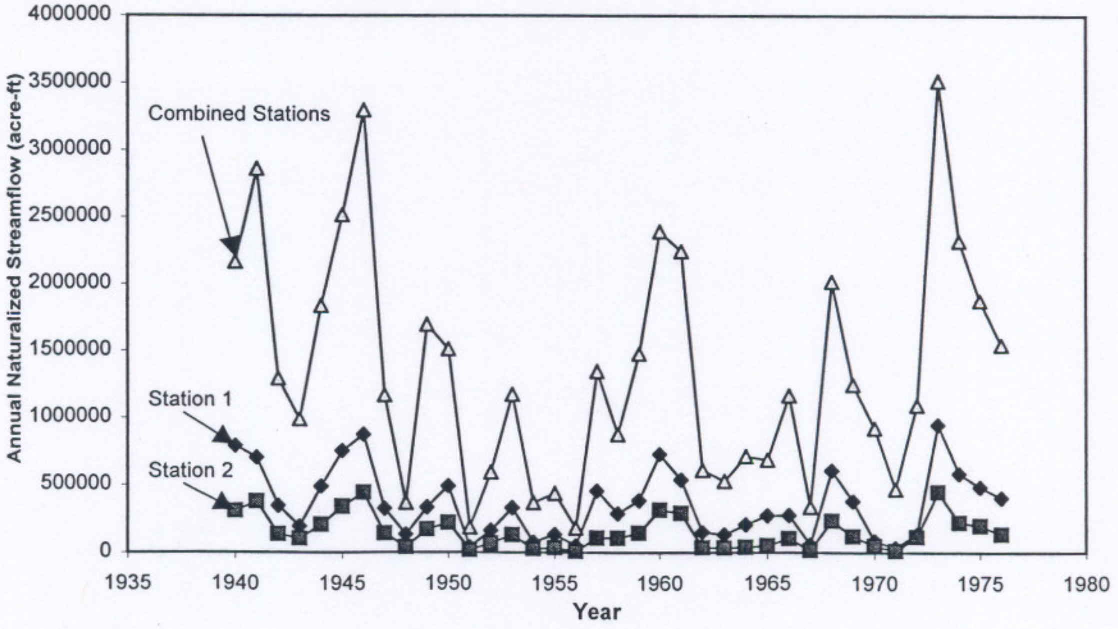


Figure 5.17 Annual Flow Hydrographs for Stations in the San Jacinto River Basin

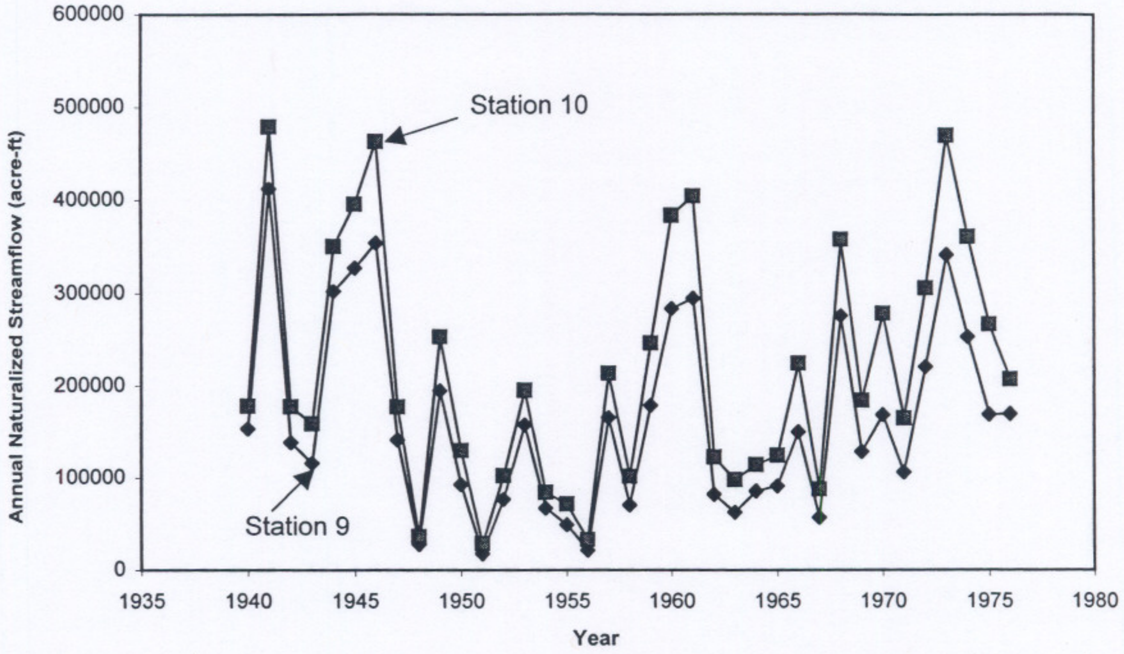


Figure 5.18 Annual Flow Hydrographs for Stations on Buffalo Bayou

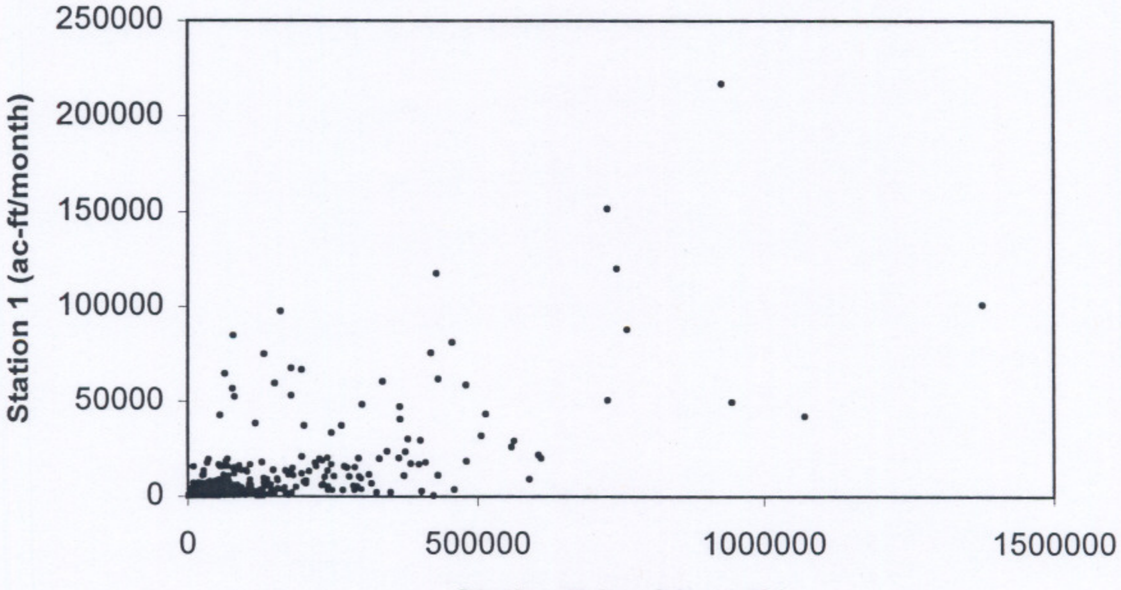


Figure 5.19 Monthly Flows at Station 1 versus Station 7
in the Little River Watershed

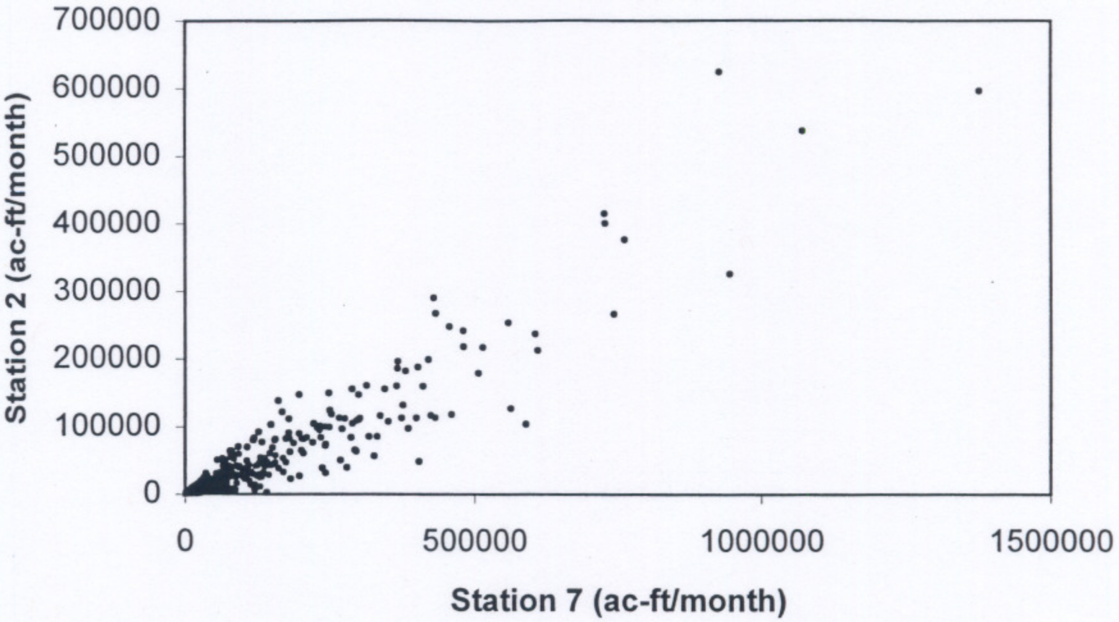


Figure 5.20 Monthly Flows at Station 2 versus Station 7
in the Little River Watershed

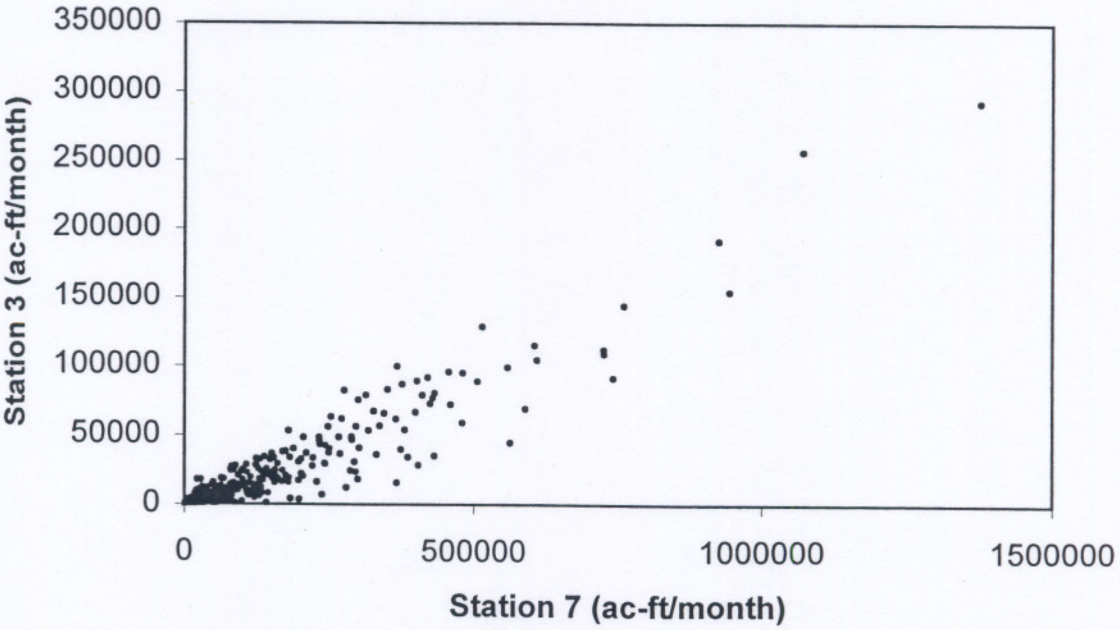


Figure 5.21 Monthly Flows at Station 3 versus Station 7
in the Little River Watershed

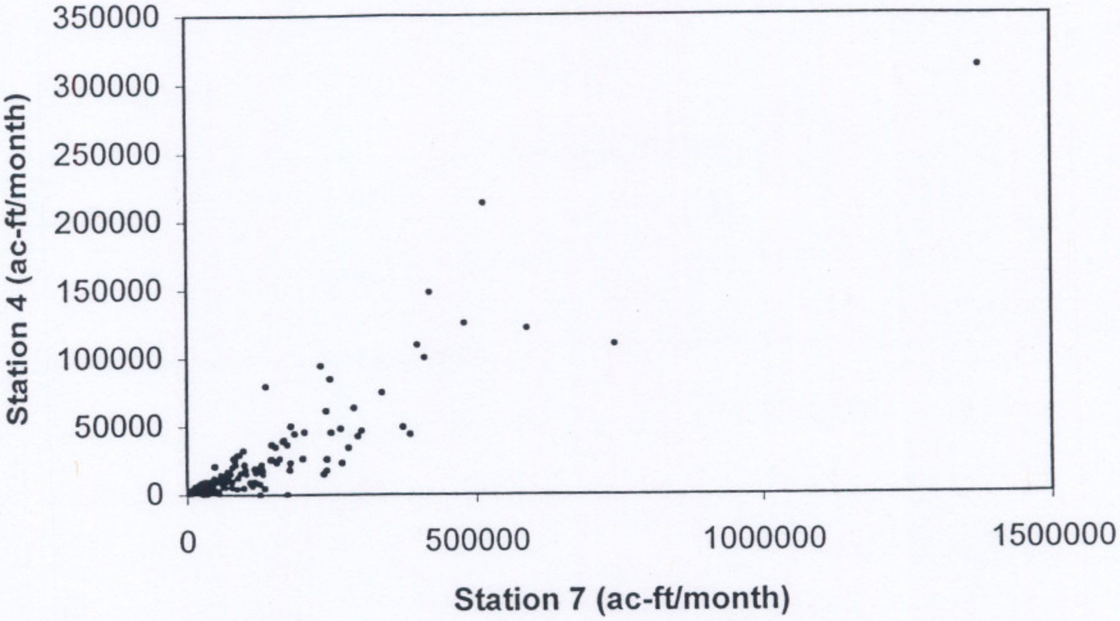


Figure 5.22 Monthly Flows at Station 4 versus Station 7 in the Little River Watershed

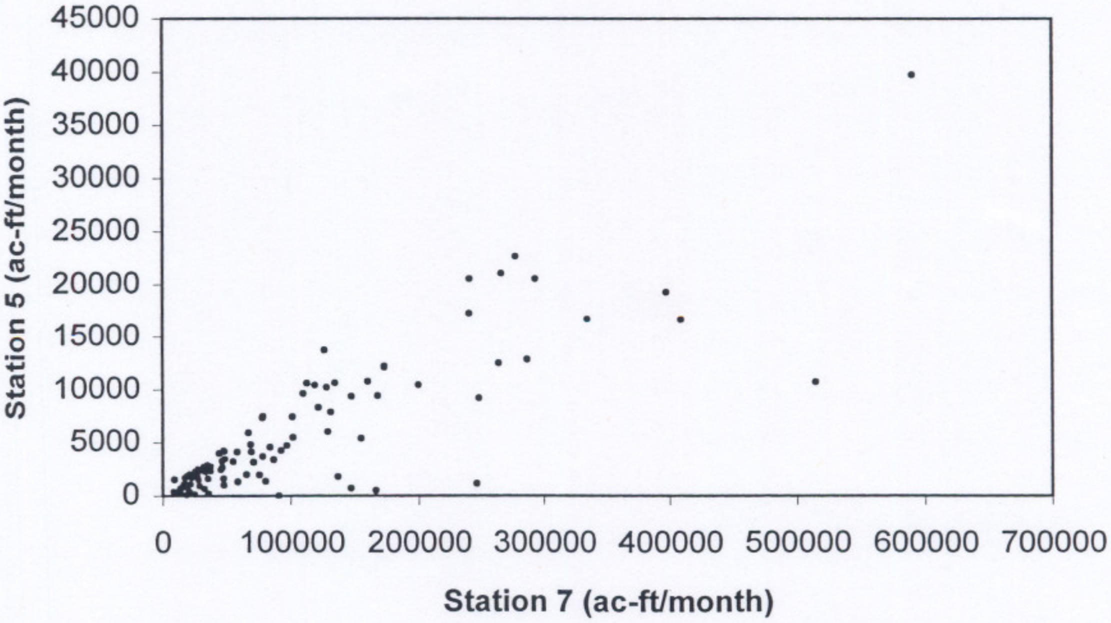


Figure 5.23 Monthly Flows at Station 5 versus Station 7 in the Little River Watershed

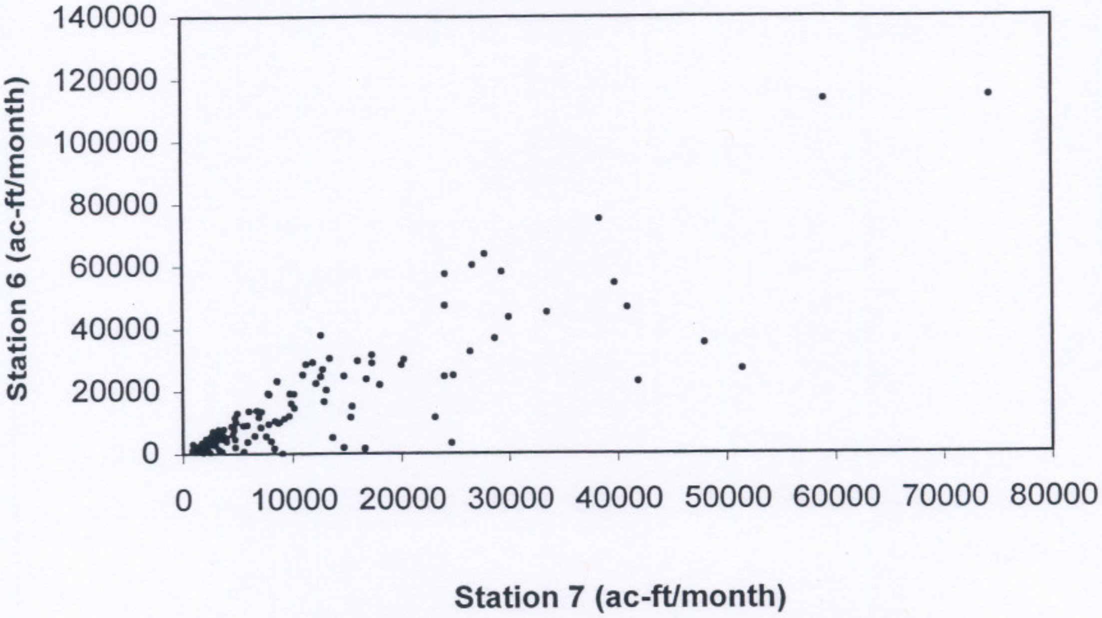


Figure 5.24 Monthly Flows at Station 6 versus Station 7
in the Little River Watershed

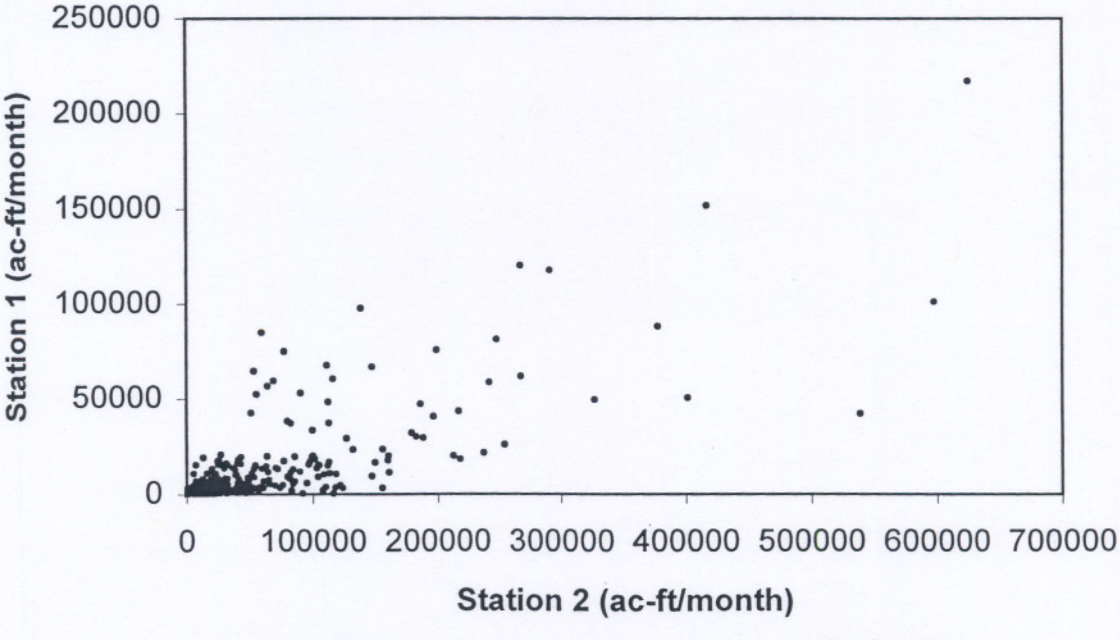


Figure 5.25 Monthly Flows at Station 1 versus Station 2
on the Leon River

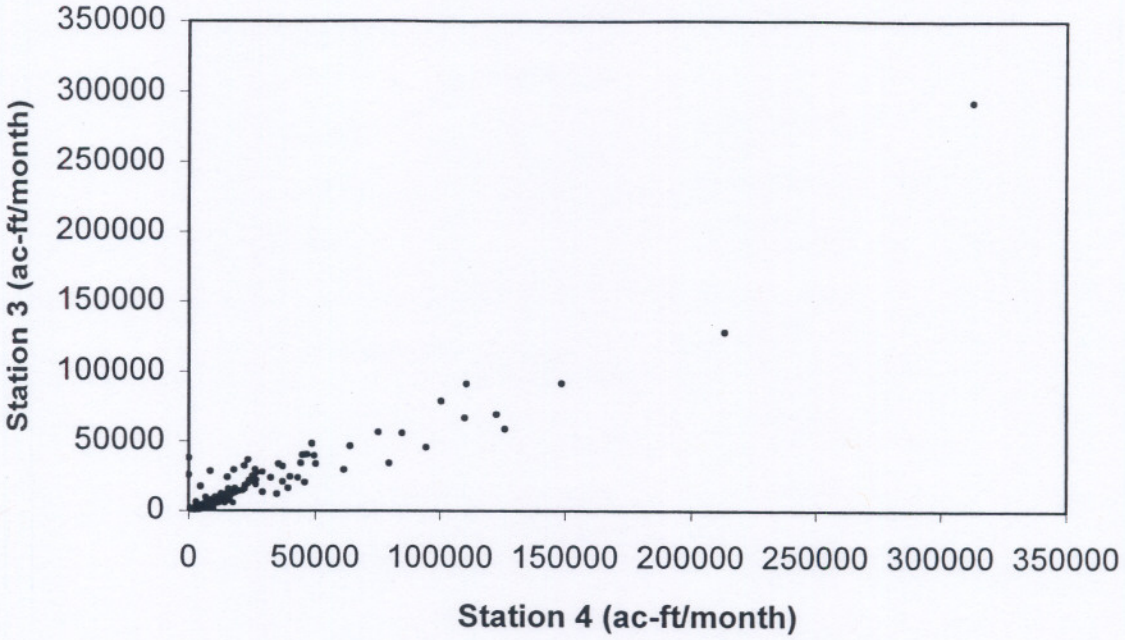


Figure 5.26 Monthly Flows at Station 3 versus Station 4 on the Lampases River

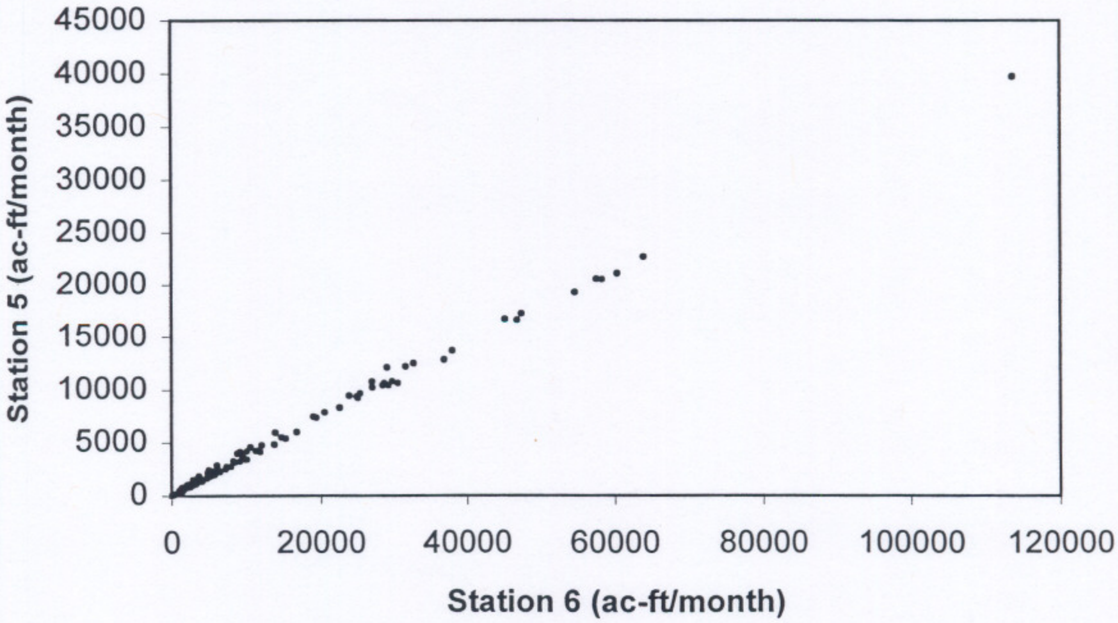


Figure 5.27 Monthly Flows at Station 5 versus Station 6 on the San Gabriel River

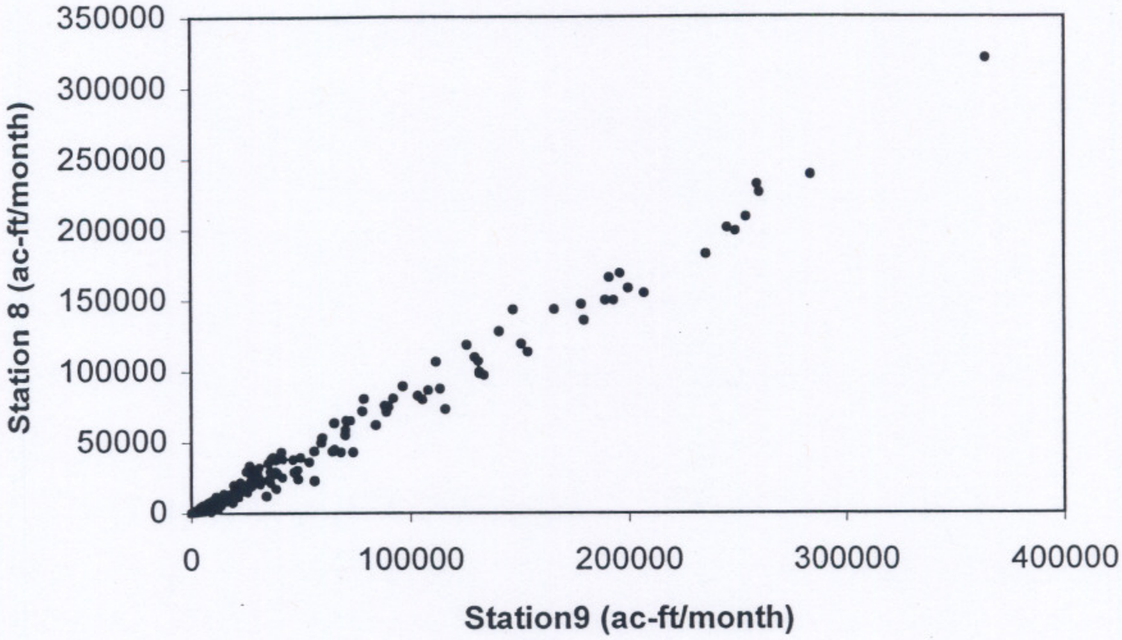


Figure 5.28 Monthly Flows at Station 8 versus Station 9 on the Navasota River

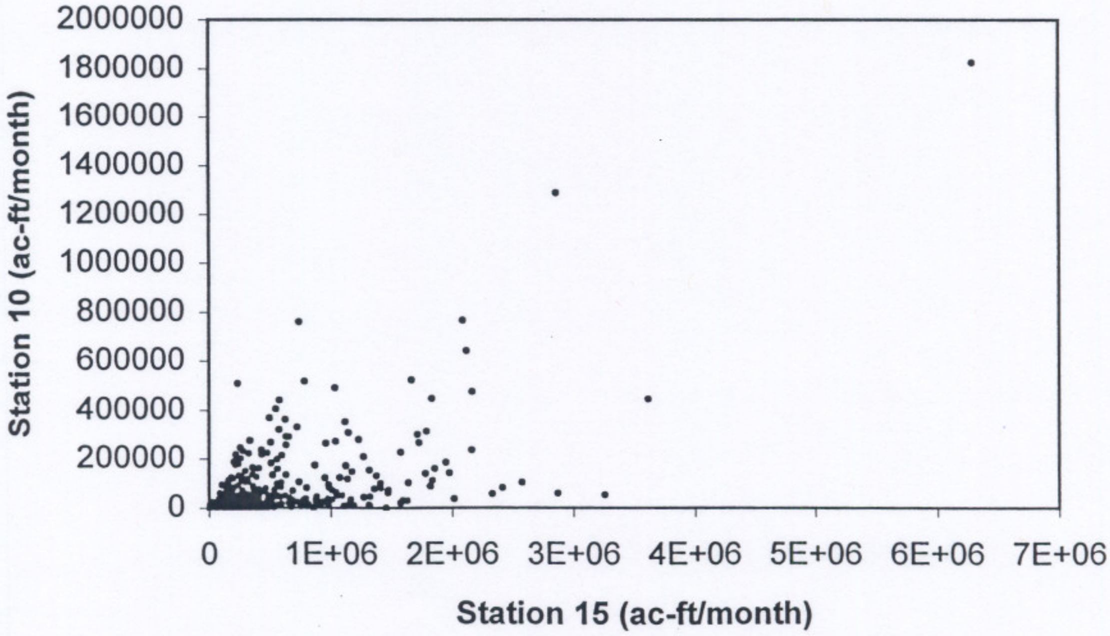


Figure 5.29 Monthly Flows at Station 10 versus Station 15 on the Brazos River

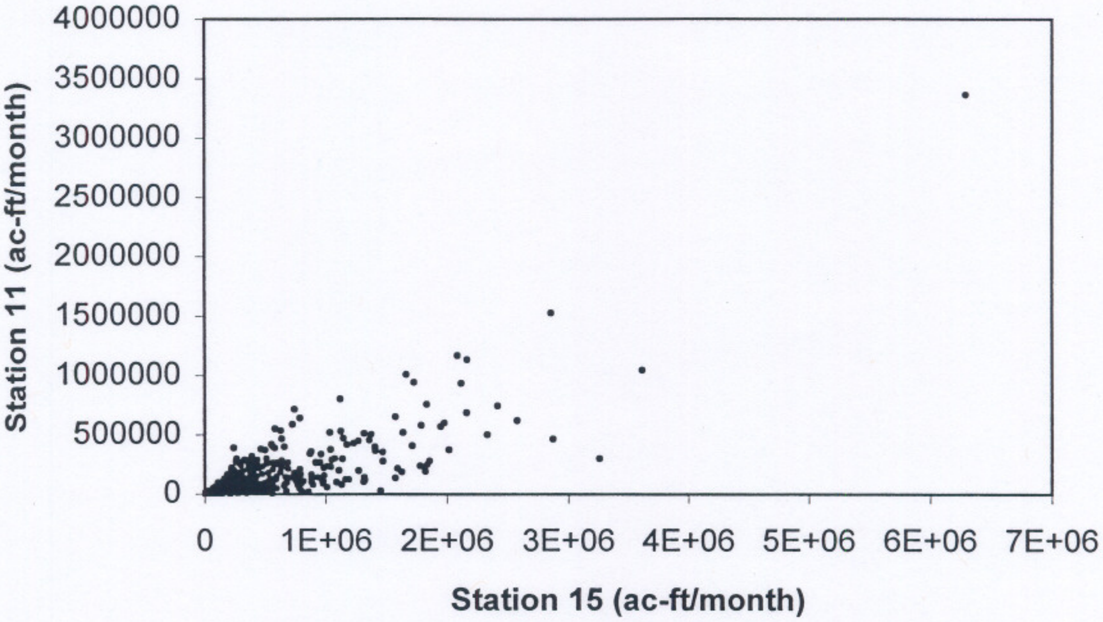


Figure 5.30 Monthly Flows at Station 11 versus Station 15
on the Brazos River

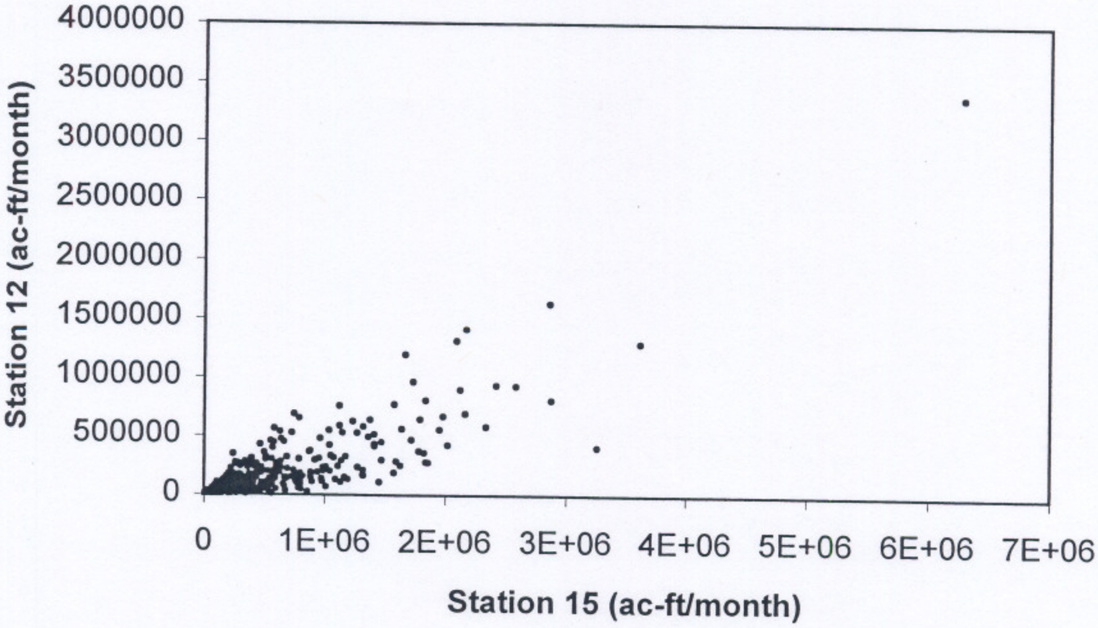


Figure 5.31 Monthly Flows at Station 12 versus Station 15
on the Brazos River

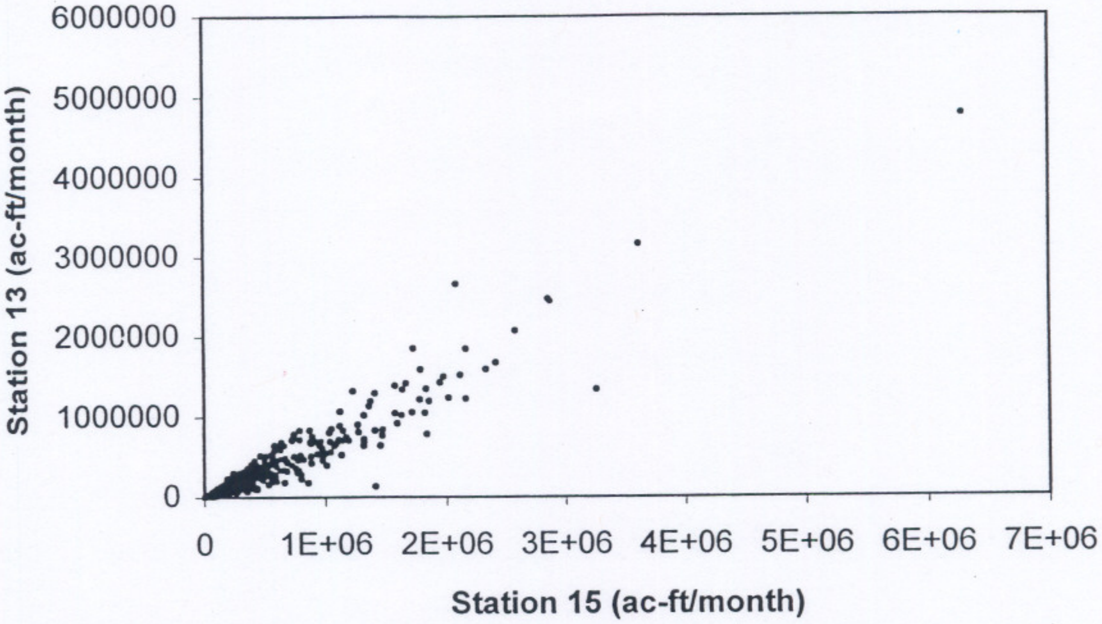


Figure 5.32 Monthly Flows at Station 13 versus Station 15 on the Brazos River

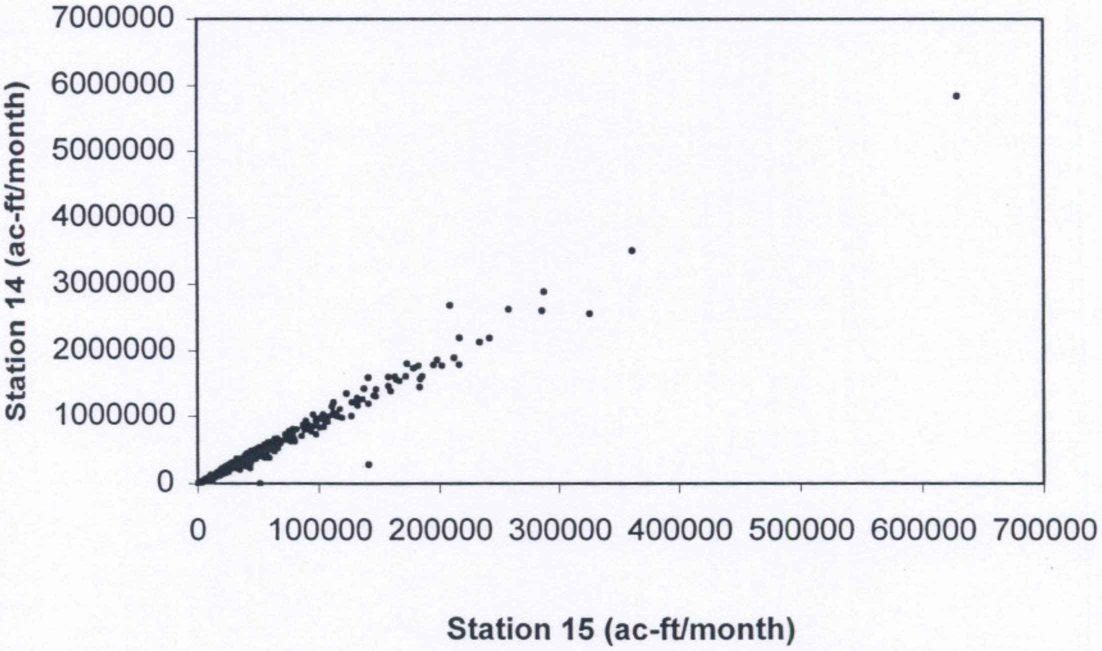


Figure 5.33 Monthly Flows at Station 14 versus Station 15 on the Brazos River

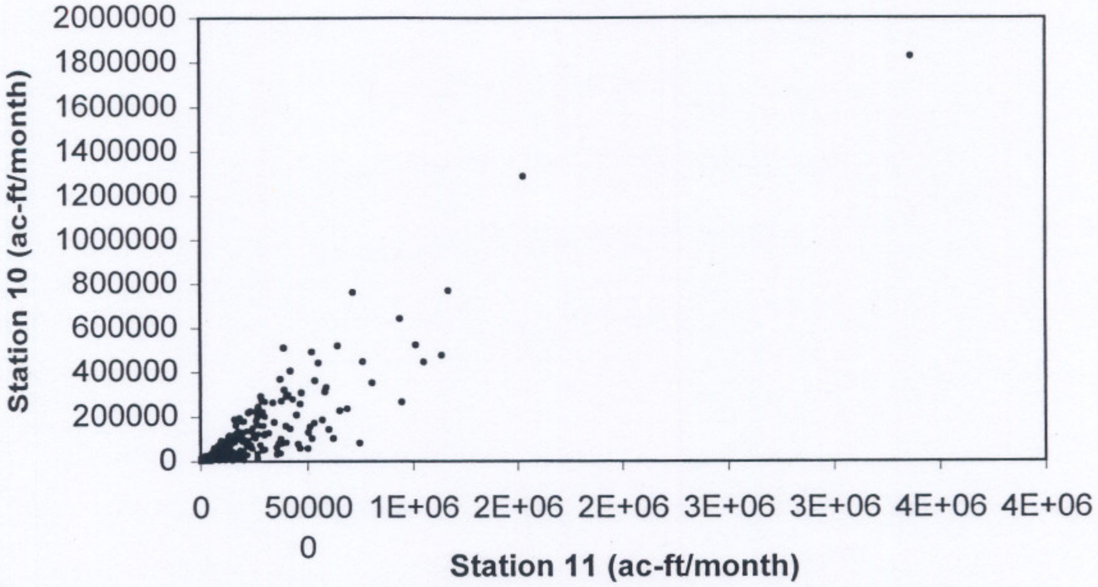


Figure 5.34 Monthly Flows at Station 10 versus Station 11
on the Brazos River

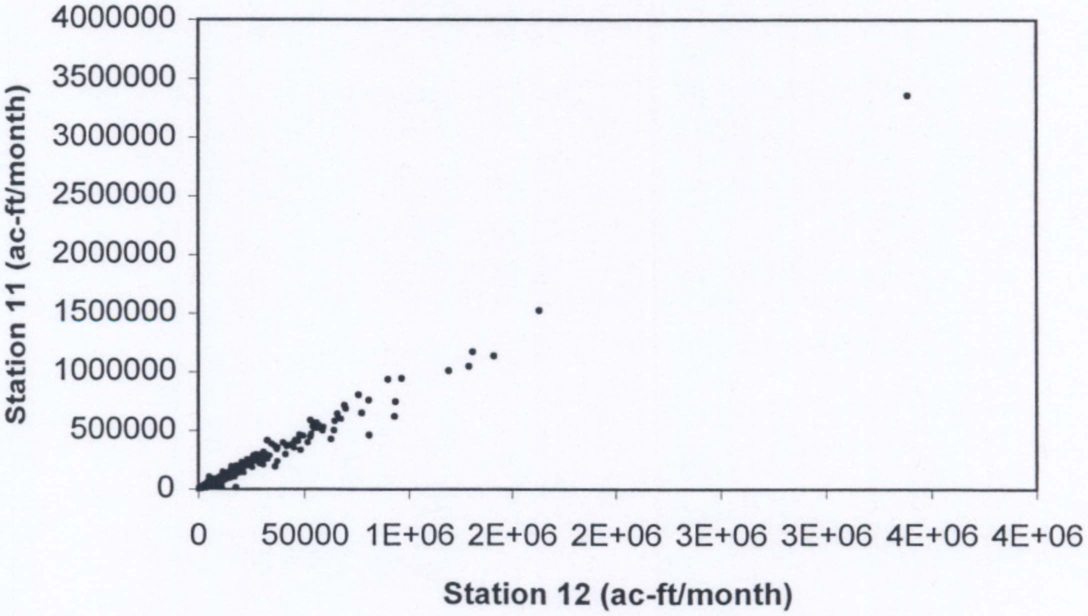


Figure 5.35 Monthly Flows at Station 11 versus Station 12
on the Brazos River

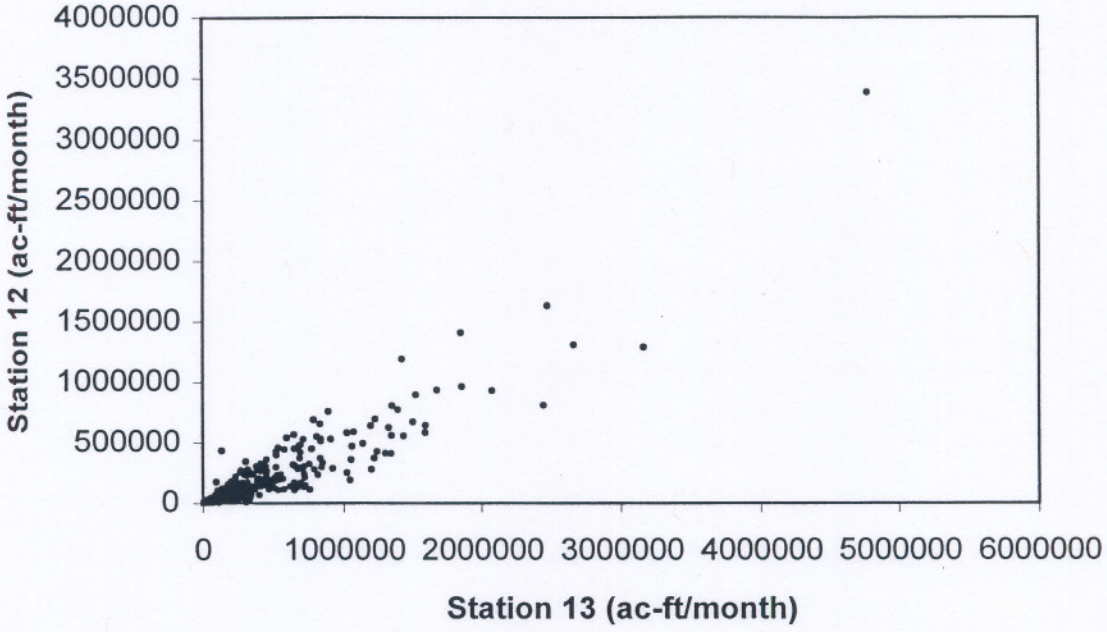


Figure 5.36 Monthly Flows at Station 12 versus Station 13 on the Brazos River

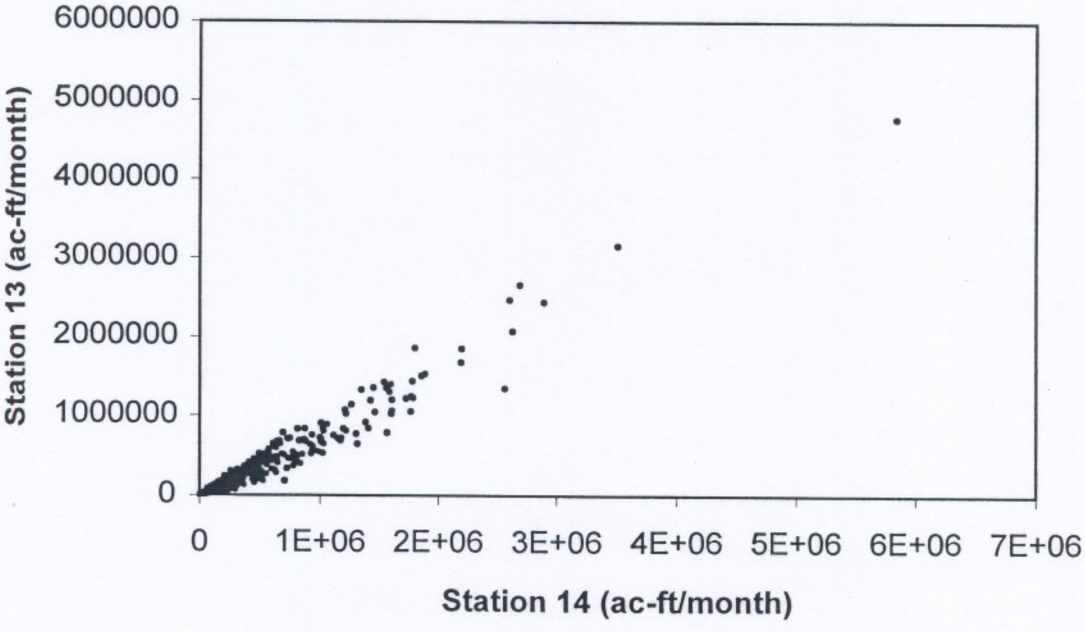


Figure 5.37 Monthly Flows at Station 13 versus Station 14 on the Brazos River

Figure 5.38. Station 1 vs Combined

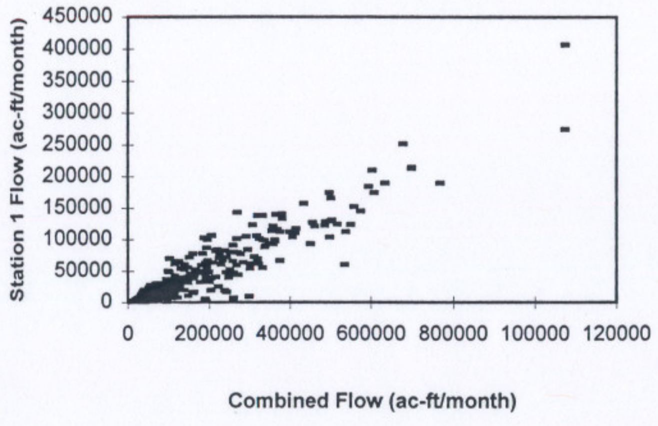


Figure 5.39. Station 2 vs Combined

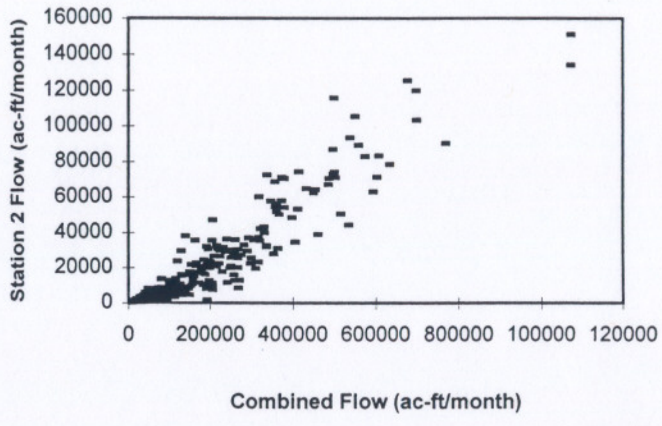


Figure 5.40. Station 3 vs Combined

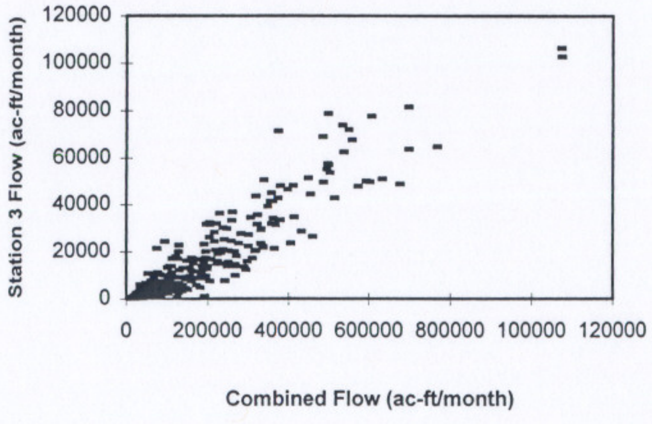


Figure 5.41. Station 4 vs Combined

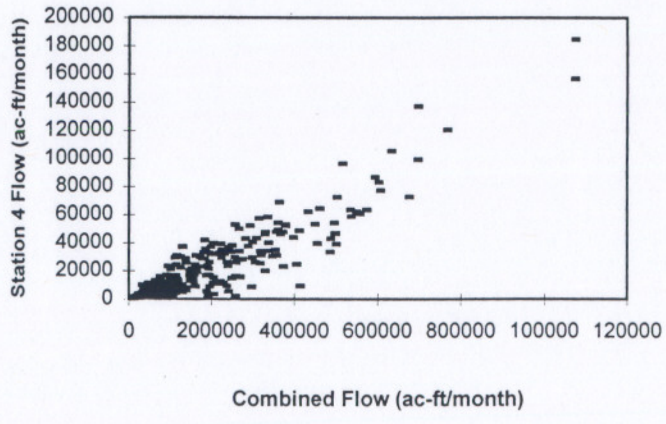


Figure 5.42. Station 5 vs Combined

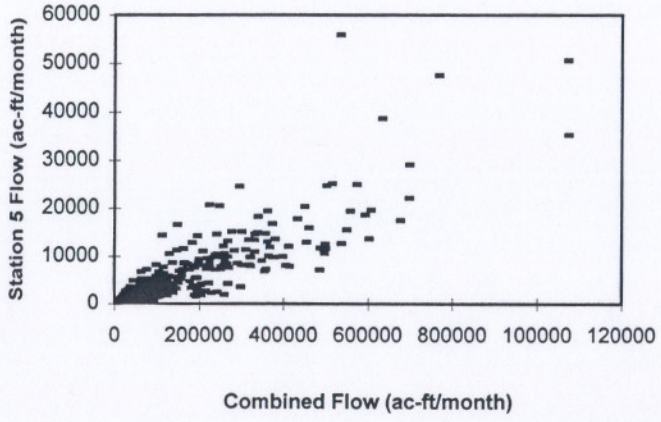


Figure 5.43. Station 6 vs Combined

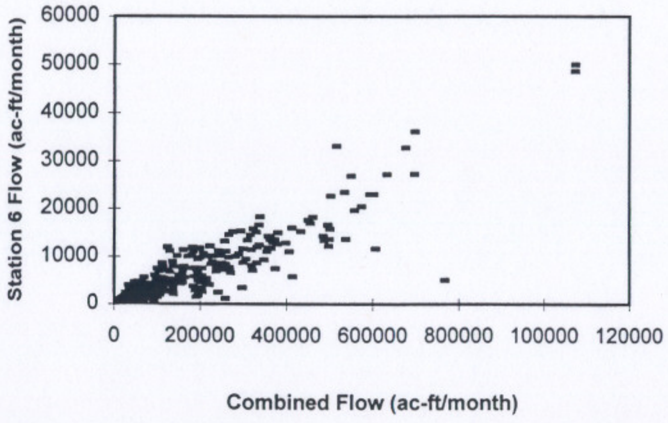


Figure 5.44. Station 8 vs Combined

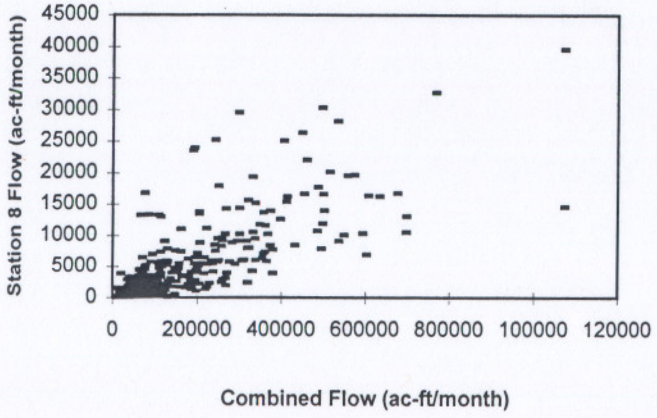


Figure 5.45. Station 9 vs Combined

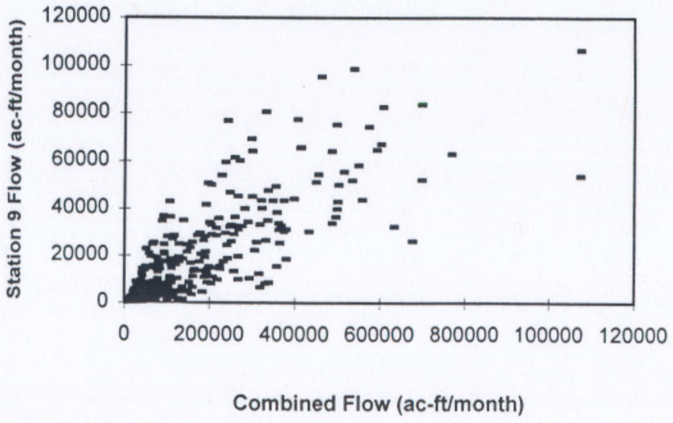


Figure 5.46. Station 10 vs Combined

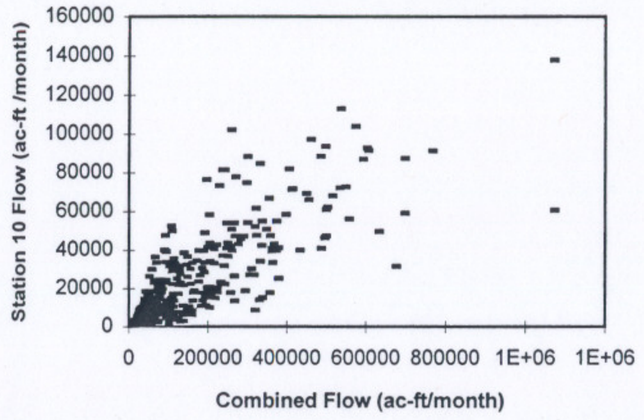


Figure 5.47. Station 11 vs Combined

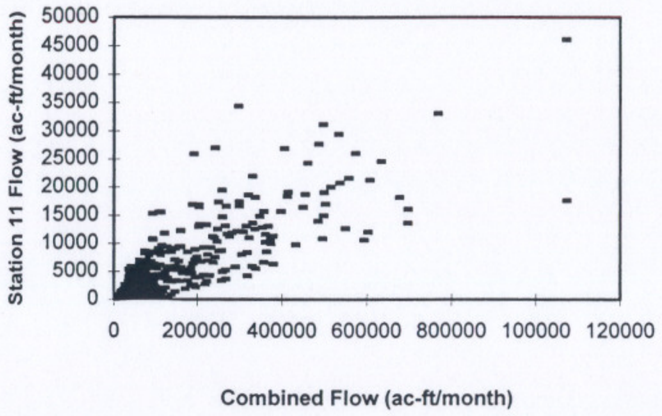


Figure 5.48. Station 12 vs Combined

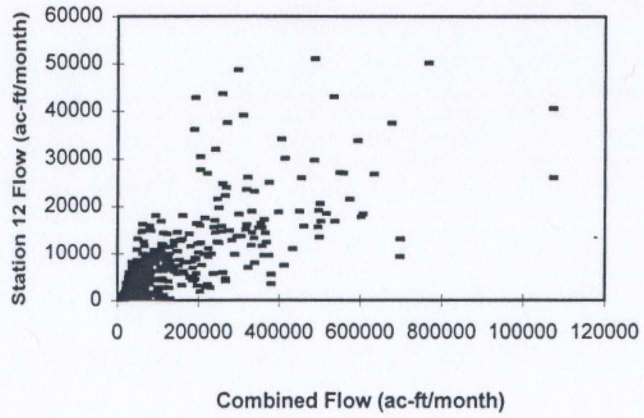
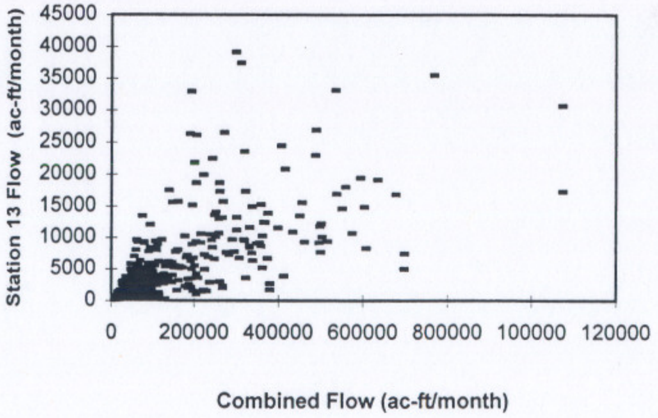


Figure 5.49. Station 13 vs Combined



Concurrent Monthly Flows at Stations in the San Jacinto Basin

Figure 5.50. Station 5 vs Station 4

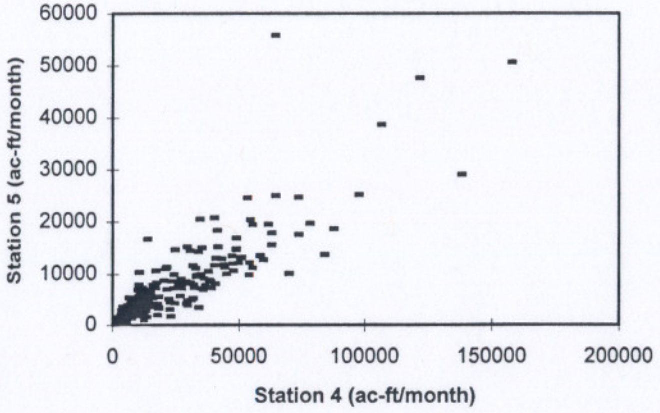


Figure 5.51. Station 6 vs Station 5

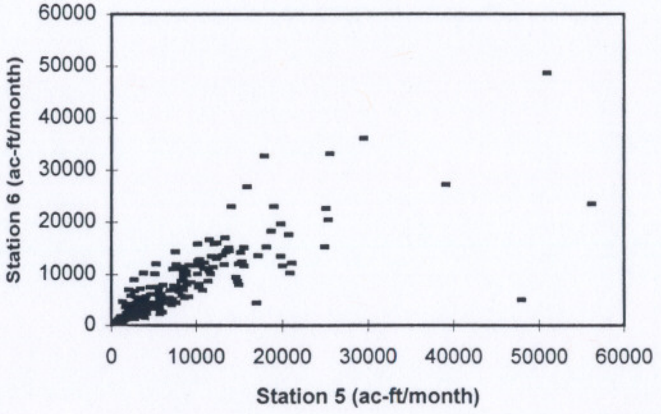


Figure 5.52. Station 1 vs Station 6

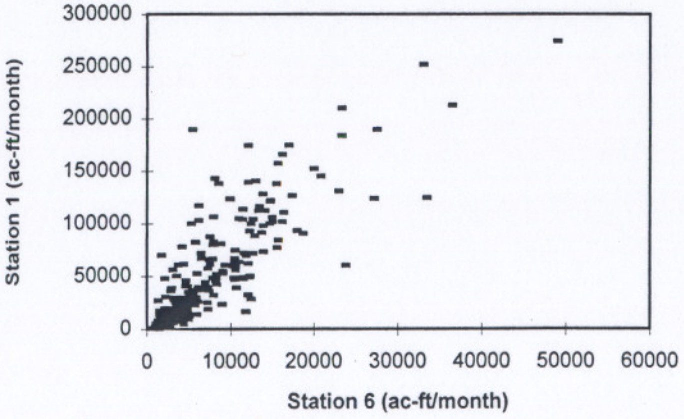
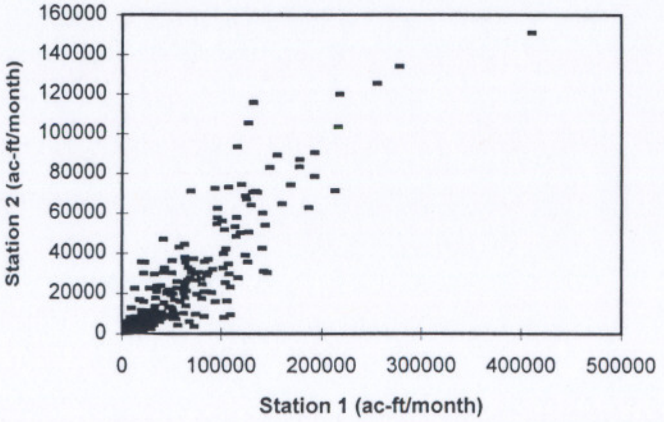


Figure 5.53. Station 2 vs Station 1



Concurrent Monthly Flows at Stations in the San Jacinto Basin

Figure 5.54. Station 3 vs Station2

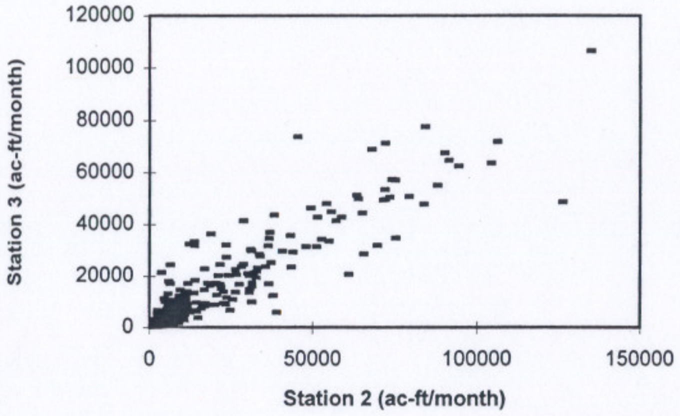


Figure 5.55. Station 8 vs Station 3

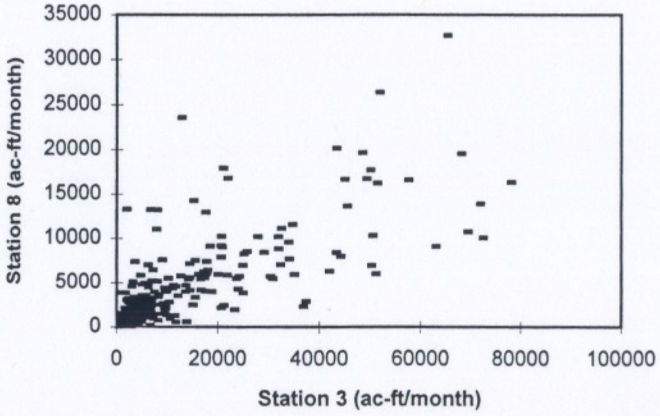


Figure 5.56. Station 11 vs Station 8

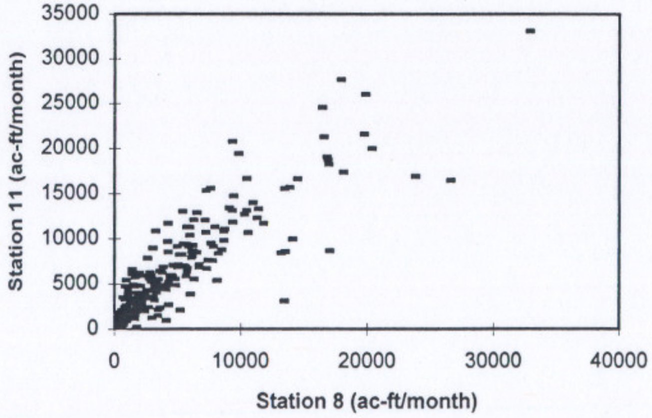


Figure 5.57. Station 10 vs Station11

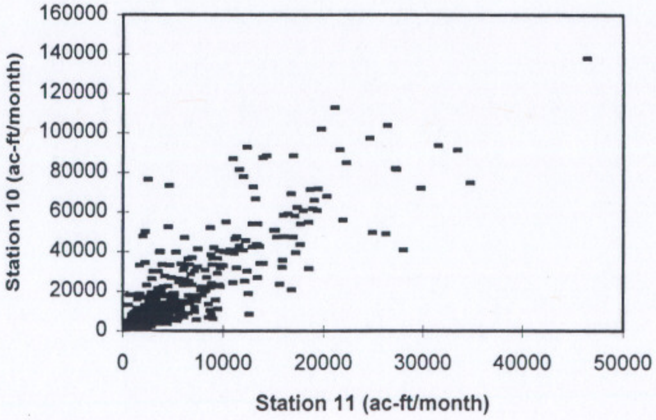


Figure 5.58. Station 10 vs Station 9

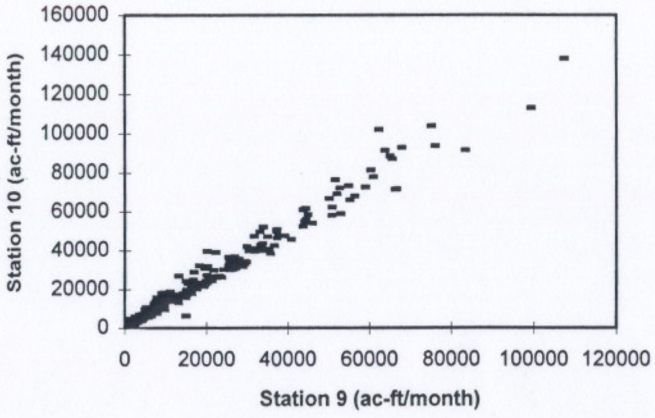


Figure 5.59 Station 12 vs Station 10

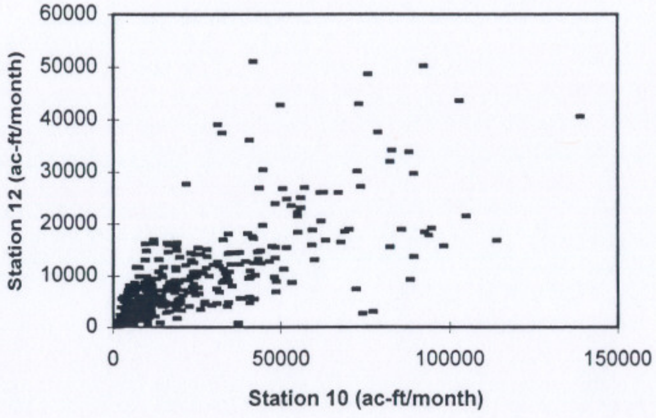
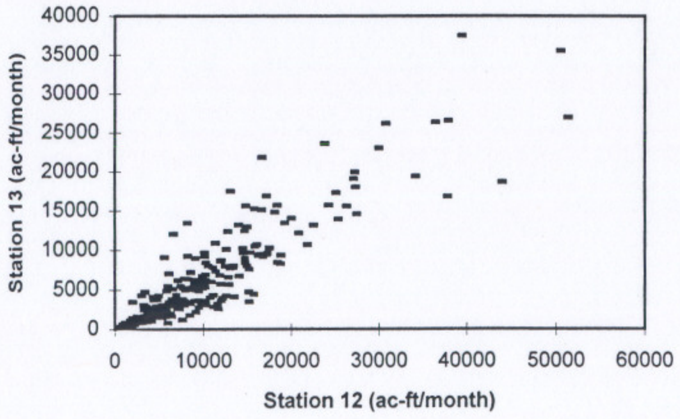


Figure 5.60. Station 13 vs Station 12



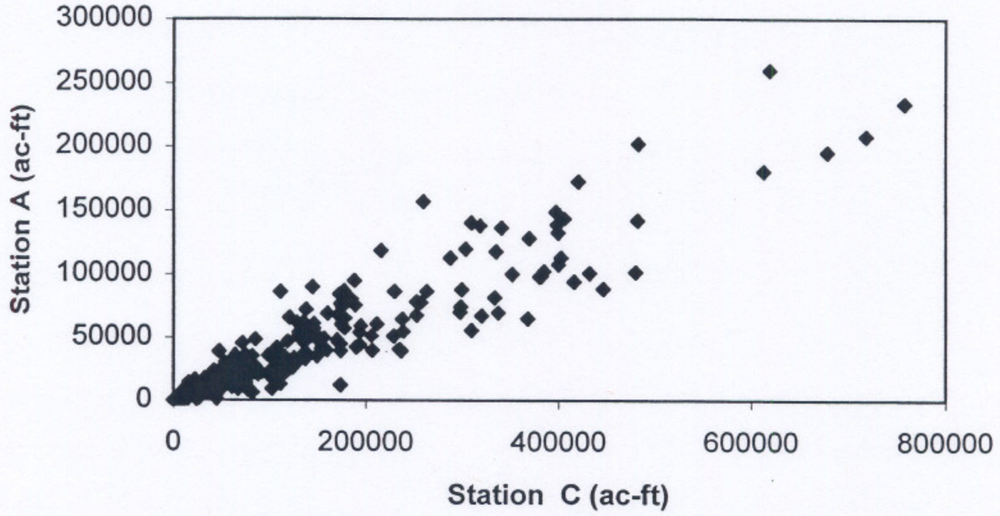


Figure 5.61 Monthly Flows at Station A versus Station C on the Sulphur River

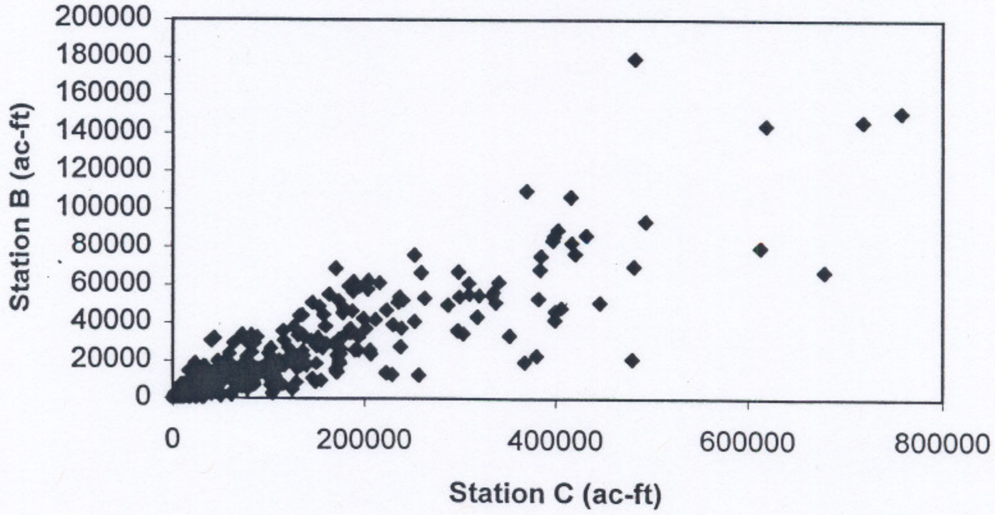


Figure 5.62 Monthly Flows at Station B versus Station C on the Sulphur River

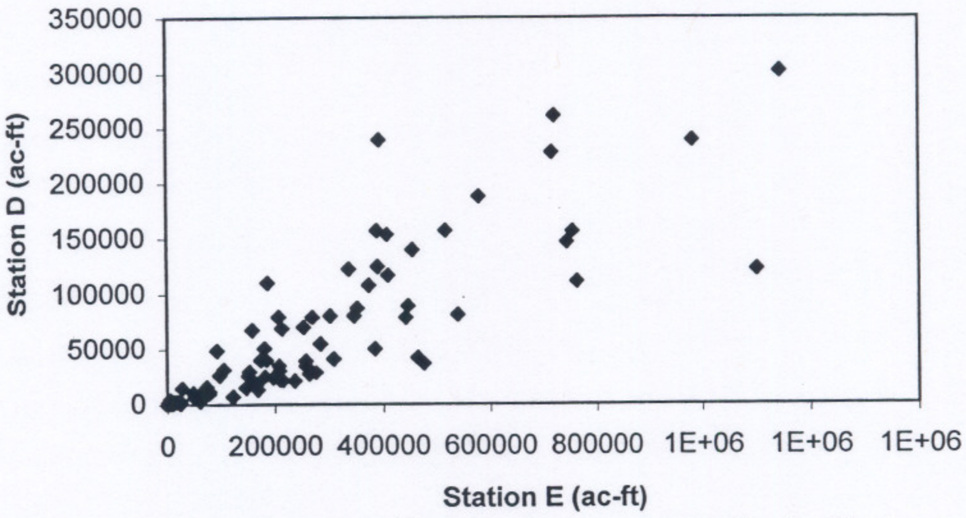


Figure 5.63 Monthly Flows at Station D versus Station E on the Sulphur River

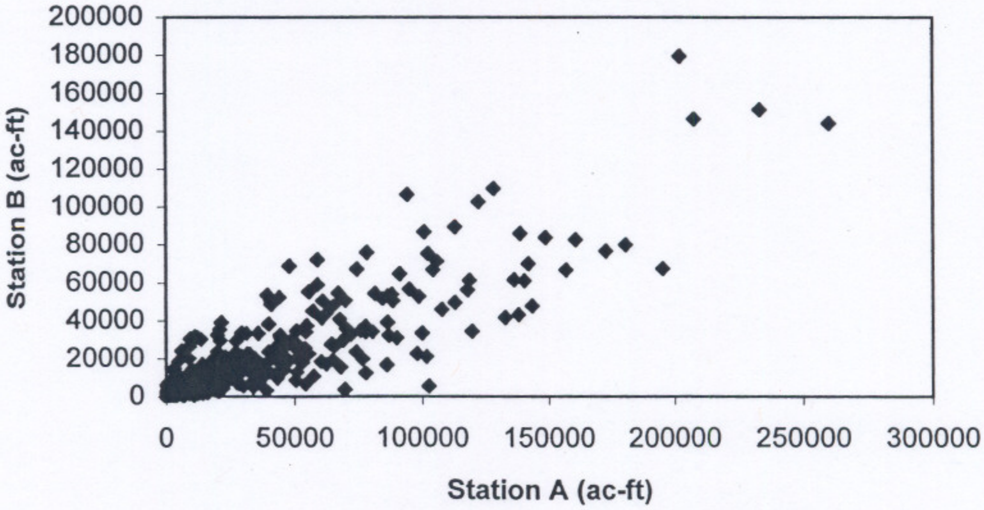


Figure 5.64 Monthly Flows at Station B versus Station A on the Sulphur River

Regression and Correlation Analyses of Flows at Different Locations

Standard least squares linear regression and correlation techniques are applied to the concurrent naturalized flows at the pairs of stations reflected in Figures 5.19 - 5.60. The first set of analyses include computation of both the y-intercept and slope coefficients. The y-intercepts are reasonably close to zero. The analyses are repeated setting the y-intercept at zero. The slope coefficients determined by the zero-intercept linear regression computations are related to watershed parameters in Chapter 6.

For all of the pairs of stations, the regression/correlation analyses were performed with the flows expressed in units of acre-feet/month. In most cases, the analyses were repeated with the flows expressed in inches/month, where an inch represents a monthly flow volume equivalent to covering the watershed to a depth of one inch. The depth equivalents of flow volumes are normalized by dividing by the watershed area.

Regression and Correlation Statistics

The computations were performed using Microsoft Excel. The regression coefficients and related statistics computed in the analyses are defined as followed. The linear regression model is

$$y = mx + b \tag{5-1}$$

where m is the slope and b is the y intercept. For our purposes, x denotes the flows at a downstream location (flows from larger watershed) and y denotes flows at a station located upstream (subwatershed outlet). The regression coefficients m and b are computed by standard methods based on minimizing S_r the sum of the squares of the deviations between observed Y_i and predicted $\hat{Y}_i$ values of y.

$$S_r = \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2 = \sum_{i=1}^{n} [(Y_i - (mX_i + b)]^2 \tag{5-2}$$

S_r represents the variation of Y_i about the regression line (y=mx+b). S_t represents the variation about the mean $\overline{Y}$.

$$S_t = \sum_{i=1}^{n} (Y_i - \overline{Y})^2 \tag{5-3}$$

The coefficient of determination r^2 is

$$r^2 = \frac{S_t - S_r}{S_t} \tag{5-4}$$

The correlation coefficient r is

$$r = \sqrt{r^2} \tag{5-5}$$

The standard error of the estimate $S_{Y|X}$ is

$$S_{Y|X} = \sqrt{\frac{S_r}{n-2}} \tag{5-6}$$

Results of the Regression Analyses

The results of the linear regression and correlation analyses for the pairs of stations in the Brazos and San Jacinto River Basins are presented in Tables 5.8-5.20. The pairs of adjacent stations for which flows are correlated/regressed are cited in the first column of the tables as y-station versus x-station. The flows at the first station cited (y) are predicted, given the flows at the second station (x). For the stations in the Brazos River Basin, flows for an upstream station are predicted as a function of flows at a downstream station. For the stations in the San Jacinto Basin, regression analyses are performed to relate flows from adjacent subwatersheds and to relate flows at each station with the combined flows from the total 2,730 mile^2 watershed.

The y-intercept *b* is fairly close to zero in all cases. The regression analyses are repeated setting the y-intercept equal to zero to obtain the regression model

$$y = mx \tag{5-7}$$

where the flow at a station is expressed simply as a constant times the flow another location. The results are presented in Tables 5.11-5.13 and 5.18-5.20. Chapter 6 includes an analysis of the relationship between constant *m* and watershed parameters.

The correlation coefficient *r* varies from about 0.6 to 1.0. The *r* is highest for pairs of stations on the same stream with relatively small difference in drainage areas. Smaller values of *r* are associated with greater difference in watershed areas.

Table 5.8 Linear Regression Coefficients
for Stations in the Little River and Navasota River Watersheds
(Flows are in acre-ft/month.)

Station	r	r^2	Sy|x	n	b	m
1 vs. 7	0.658	0.434	15723	444	294	0.084
2 vs. 7	0.936	0.876	26659	444	-4504	0.431
3 vs. 7	0.941	0.885	10614	444	-2338	0.179
4 vs.7	0.913	0.834	15341	168	-2991	0.223
5 vs. 7	0.847	0.717	3522	96	519	0.050
6 vs. 7	0.859	0.739	10075	132	989	0.133
8 vs. 9	0.994	0.989	5158	312	-1061	0.834
1 vs. 2	0.783	0.613	13003	444	226	0.216
3 vs. 4	0.949	0.900	9199	168	275	0.734
5 vs. 6	0.998	0.997	377	96	262	0.355

Table 5.9 Linear Regression Coefficients
for Stations in the Little River and Navasota River Watersheds
(Flows are in inches/month.)

Station	r	r^2	Sy|x	n	b	m
1 vs. 7	0.658	0.434	0.234	444	0.004	0.469
2 vs. 7	0.936	0.876	0.141	444	-0.024	0.858
3 vs. 7	0.941	0.885	0.161	444	-0.035	1.020
4 vs.7	0.913	0.834	0.218	168	-0.042	1.189
5 vs. 7	0.847	0.717	0.266	96	0.039	1.425
6 vs. 7	0.859	0.739	0.256	132	0.025	1.275
8 vs. 9	0.994	0.989	0.100	312	-0.021	1.252
1 vs. 2	0.783	0.613	0.193	444	0.003	0.607
3 vs. 4	0.949	0.900	0.139	168	0.004	0.782
5 vs. 6	0.998	0.997	0.029	96	0.020	1.056

Table 5.10 Linear Regression Coefficients
for Main-Stem Brazos River Stations
(Flows are in acre-ft/month.)

Stations	r	r^2	Sy|x	n	b	m
10-15	0.627	0.380	117078	444	-38.	0.149
11-15	0.814	0.663	143837	444	-12346	0.328
12-15	0.850	0.723	140424	444	-16895	0.369
13-15	0.952	0.907	143591	444	-20127	0.728
14-15	0.993	0.986	68485	444	-7732	0.937
11-12	0.906	0.822	62786	444	-7549	0.544
12-13	1.000	0.980	35453	444	-2136	0.919
13-14	0.924	0.854	101949	444	-12551	0.525
14-15	0.971	0.944	111631	444	-18624	0.787

Table 5.11 Zero-Intercept Linear Regression Coefficients
for Stations in the Little River and Navasota River Watersheds
(Flows are in acre-feet/month.)

Stations	r	r^2	Sy|x	n	b	m
1 vs. 7	0.658	0.433	15707	444	0	0.085
2 vs. 7	0.934	0.873	26890	444	0	0.418
3 vs. 7	0.939	0.881	10778	444	0	0.173
4 vs.7	0.911	0.829	15486	168	0	0.213
5 vs. 7	0.844	0.713	3524	96	0	0.052
6 vs. 7	0.859	0.737	10064	132	0	0.137
8 vs. 9	0.994	0.988	5232	312	0	0.826
1 vs. 2	0.783	0.612	12990	444	0	0.218
3 vs. 4	0.949	0.900	9174	168	0	0.738
5 vs. 6	0.998	0.996	426	96	0	0.362

Table 5.12 Zero-Intercept Linear Regression Coefficients
for Stations in the Little River and Navasota River Watersheds
(Flows are in inches/month.)

Station	r	r^2	Sy|x	n	b	m
1 vs. 7	0.658	0.433	0.234	444	0	0.473
2 vs. 7	0.934	0.873	0.142	444	0	0.833
3 vs. 7	0.939	0.881	0.163	444	0	0.982
4 vs.7	0.911	0.829	0.220	168	0	1.139
5 vs. 7	0.844	0.713	0.266	96	0	1.492
6 vs. 7	0.859	0.737	0.256	132	0	1.312
8 vs. 9	0.994	0.988	0.101	312	0	1.240
1 vs. 2	0.783	0.612	0.193	444	0	0.611
3 vs. 4	0.949	0.900	0.139	168	0	0.786
5 vs. 6	0.998	0.996	0.032	96	0	1.076

Table 5.13 Zero-Intercept Linear Regression Coefficients
for Stations on Main-Stem Brazos River
(Flows are in acre-feet/month.)

Stations	r	r^2	Sy|x	n	b	m
10-15	0.617	0.380	116946	444	0	0.149
11-15	0.813	0.662	144003	444	0	0.318
12-15	0.849	0.721	140893	444	0	0.356
13-15	0.952	0.906	144299	444	0	0.712
14-15	0.993	0.986	68677	444	0	0.930
11-12	0.905	0.820	63051	444	0	0.531
12-13	1.000	0.979	35460	444	0	0.916
13-14	0.923	0.853	102349	444	0	0.512
14-15	0.971	0.943	112480	444	0	0.772

Table 5.14 Linear Regression Coefficients for the San Jacinto Basin Stations for Flows at Each Station as a Function of Combined Flows (acre-ft/month)

Station	r	r^2	Sy|x	n	b	m
4	.9273	.8599	56515	492	27173	6.491
5	.8636	.7458	76144	492	22759	20.18
6	.9141	.8356	61223	492	10435	22.68
1	.9411	.8856	51076	492	22565	3.014
2	.9470	.8968	15949	492	-3102	0.2939
3	.9398	.8832	51601	492	28201	8.656
8	.7924	.6279	92120	492	37993	21.40
11	.8248	.6804	85379	492	16500	19.83
10	.8319	.6920	83807	492	14658	5.602
9	.8287	.6867	84527	492	22556	6.842
12	.7332	.5376	102689	492	19829	13.03
13	.7033	.4946	107358	492	36695	17.35

Table 5.15 Linear Regression Coefficients for the San Jacinto Basin Stations for Flows at Each Station as a Function of Combined Flows (inches/month)

Station	r	r^2	Sy|x	n	b	m
4	.9273	.8599	.3885	492	.1868	.7734
5	.8636	.7458	.5234	492	.1564	.8654
6	.9141	.8356	.4208	492	.0717	.8731
1	.9411	.8856	.3511	492	.1551	.8938
2	.9470	.8968	.3334	492	.2149	.9778
3	.9398	.8832	.3547	492	.1938	.9044
8	.7924	.6279	.6332	492	.2611	.5704
11	.8248	.6804	.5869	492	.1134	.6156
10	.8319	.6920	.5760	492	.1008	.7352
9	.8287	.6867	.5810	492	.1550	.7349
12	.7332	.5376	.7058	492	.1363	.4222
13	.7033	.4946	.7379	492	.2522	.4070

Table 5.16 Linear Regression Coefficients for the San Jacinto Basin Stations for Flows from Adjacent Subwatersheds (acre-ft/month)

Stations	r	r^2	Sy|x	n	b	m
4-5	.8955	.8020	2844	456	761	.2872
5-6	.8509	.7240	3024	444	1063	.7580
6-1	.8831	.7799	20621	444	-367	6.744
1-2	.9120	.8318	9214	492	-166	.4345
2-3	.9264	.8582	5889	444	1118	.6882
3-8	.7778	.6050	29096	348	1057	.2490
8-11	.9000	.8099	2278	348	1340	1.016
11-10	.8540	.7293	11667	492	2781	3.049
9-10	.9897	.9796	3103	432	1096	1.266
10-12	.7661	.5869	5462	492	2117	.2903
12-13	.9189	.8444	2257	348	-340	.6615

Table 5.17 Linear Regression Coefficients for the San Jacinto Basin Stations for Flows from Adjacent Subwatersheds (inches/month)

Stations	r	r^2	Sy|x	n	b	m
4-5	.8955	.8020	.4558	456	.1220	.7980
5-6	.8509	.7240	.5400	444	.1898	.8446
6-1	.8831	.7799	.4779	444	-.0085	.8753
1-2	.9120	.8318	.4123	492	-.0074	.8389
2-3	.9264	.8582	.3875	444	.0736	1.012
3-8	.7778	.6050	.7503	348	.2727	.9760
8-11	.9000	.8099	.5043	348	.2966	.8719
11-10	.8540	.7293	.6111	492	.1457	.7212
9-10	.9897	.9796	.1625	432	.0574	1.036
10-12	.7661	.5869	1.16	492	.4491	1.176
12-13	.9189	.8444	.6613	348	-.0997	.9137

Table 5.18 Zero-Intercept Linear Regression Coefficients for San Jacinto Basin Stations for Flows for Each Station as a Function of Combined Flows (acre-feet/month)

Stations	r	r^2	Sy|x	n	b	m
4	.9252	.8561	8176	492	0	.1271
5	.8626	.7441	3266	492	0	.0380
6	.9128	.8332	2483	492	0	.0380
1	.9396	.8829	16122	492	0	.2839
2	.9409	.8852	7603	492	0	.1311
3	.9362	.8764	5757	492	0	.0966
8	.7917	.6268	3412	492	0	.0301
11	.8145	.6633	3641	492	0	.0376
10	.8213	.6745	12782	492	0	.1355
9	.8241	.6792	10350	492	0	.1068
12	.6924	.4794	6125	492	0	.0495
13	.6843	.4682	4460	492	0	.0325

Table 5.19 Zero-Intercept Linear Regression Coefficients for San Jacinto Basin Stations for Flows for Each Station as a Function of Combined Flows (inches/month)

Station	r	r^2	Sy|x	n	b	m
4	.9252	.8561	.4718	492	0	1.066
5	.8626	.7441	.5234	492	0	.8863
6	.9128	.8332	.4434	492	0	.9885
1	.9396	.8829	.3737	492	0	.9574
2	.9409	.8852	.3402	492	0	.8538
3	.9362	.8764	.3788	492	0	.9245
8	.7917	.6268	.8801	492	0	1.129
11	.8145	.6633	.8061	492	0	1.211
10	.8213	.6745	.6694	492	0	1.032
9	.8241	.6792	.6623	492	0	.9940
12	.6924	.4794	1.299	492	0	1.528
13	.6843	.4682	1.307	492	0	1.386

Table 5.20 Zero-Intercept Linear Regression Coefficients
for San Jacinto Basin Stations for Flows from Adjacent Subwatersheds
(Flows are in acre-feet/month.)

Station	r	r^2	Sy|x	n	b	m
4-5	.8881	.7887	2968	492	0	.2884
5-6	.8538	.7290	3165	492	0	.8778
6-1	.9014	.8124	20401	492	0	6.866
1-2	.9120	.8317	9206	492	0	.4329
2-3	.9381	.8801	5673	492	0	.7055
3-8	.7297	.5324	3819	492	0	.2835
8-11	.9365	.8770	2201	492	0	1.159
11-10	.8485	.7199	11857	492	0	3.265
9-10	.9862	.9726	3709	492	0	1.252
10-12	.7410	.5491	5700	492	0	.3365
12-13	.9691	.9391	1434	492	0	.6622

Analysis of Flow Ratios

Equations 6-1 through 6-5 discussed in the next chapter are based on the premise that the naturalized monthly flows $Q_{\text{subwatershed}}$ from each individual subwatershed are approximately a constant proportion of the flows $Q_{\text{watershed}}$ from the overall watershed:

$$Q_{\text{subwatershed}} = C\, Q_{\text{watershed}} \tag{5-8}$$

or

$$C = Q_{\text{subwatershed}} \;/\; Q_{\text{watershed}}$$

where *C* is the ratio between flows at two locations. The flows at the stations in the Brazos and San Jacinto River Basins are used to:

- examine the validity of this basic premise of a constant *C*
- compare the *C* with drainage area ratios

Variations in Monthly and Annual Flow Ratios

For each of the 444 months and 37 years of the period 1940-76 included in the period-of-analysis for the Brazos Basin stations and each of the 492 months and 41 years during 1940-80 included in the period-of-analysis for the San Jacinto Basin stations, the flows at selected stations are expressed as a ratio of the corresponding flows at a downstream location. Ratios have been computed with the monthly and annual flow volumes expressed alternatively in units of acre-feet and inches.

- Flows at stations 1, 2, 3, 4, 5, and 6 in the Little River watershed are expressed as a ratio of the corresponding flows at the Cameron gage on the Little River (station 7).
- Flows at station 8 are expressed as a ratio of flows at station 9 on the Navasota River.
- Flows at stations 10-14 on the main-stem Brazos River are expressed as a ratio of the corresponding flows at the Richmond gage on the Brazos River (station 15).
- Flows at the stations in the San Jacinto River Basin are expressed as a ratio of the combined flows.
- Flows at station 9 are also expressed as a ratio of flows at station 10 on Buffalo Bayou.

The total watershed area above the 12 stations in the San Jacinto Basin is 2,730 mile^2. Stations 9 and 10 are the only stations located on the same stream with one station being upstream of another. The *combined flow* from the entire 2,730 mile^2 watershed for each month is determined as the addition of the flows at all stations except station 9, which is upstream of station 10.

The ratios of annual flows, in acre-feet/acre-feet, are tabulated in Tables 5.21 and 5.22. The ratios of annual flows, in inches/inches, are tabulated in Tables 5.23 and 5.24. The corresponding tables for monthly flows have been developed but are not reproduced in this report. The values for *C* for each month or year at each station are computed as:

$$C \;=\; flow\ ratio \;=\; \frac{subwatershed\, Q}{watershed\, Q}$$

In general, the flow ratio (value of *C*) varies greatly between months. Thus, there is not a constant *C* for the monthly flows at any of the stations. The ratios of annual flows exhibit significantly less variation from year to year than the monthly variations but still vary significantly at each station.

The inches/inches flow ratios in Tables 5.23 and 5.24 for each station are the annual flows at the station, in inches, divided by the annual flows, in inches, at the specified downstream station. An inch represents a volume equivalent to covering the watershed to a depth of one inch. Thus, these flow ratios have been normalized by dividing by the drainage area. These ratios would all be 1.00 if flows were strictly proportional to drainage area, meaning simple application of a drainage area ratio would distribute flows with perfect accuracy. However, the flow ratios vary significantly from 1.00 and between years and vary even more between months.

Observations and Conclusions

The basic concept is to evaluate capabilities for predicting flows at individual subwatersheds $Q_{subwatershed}$ from known flows from the larger watershed $Q_{watershed}$ based on a relationship of the form:

$$Q_{subwatershed} = C\, Q_{watershed} \tag{5-8}$$

As discussed in Chapter 6, the constant *C* could be estimated as a function of watershed characteristics such as drainage area *A*, mean precipitation *M*, curve number *CN*, and other parameters. The Brazos and San Jacinto Basin stations serve as a test case.

The analyses indicate that there actually is not a uniform proportionality between locations for monthly flows for the case study data. The *"coefficient C"* varies greatly between months. Thus, for these data, the flows for an individual month can not be predicted reliably regardless of the watershed parameters or form of the relation used to determine *C*. Adopting a modified nonlinear form of the basic relationship between flows at different locations such as

$$Q_{\text{subwatershed}} = C\,(Q_{\text{watershed}})^{N} \tag{5-9}$$

provides little or no improvement in predictive capabilities.

However, for most applications in water availability modeling, predicting flows reliably for each individual month is not necessary as long as reasonable accuracy is achieved in the mean, flow-frequency relationships, and other relevant statistical characteristics of the predicted sequence of flows at the ungaged site. Thus, the comparative evaluation of alternative methods should focus more on evaluating capabilities for predicting flow-frequency relationships and means. Equation 5-8 should be viewed as predicting the expected value (probability-weighted mean) at a location, given a known flow at another location. The actual predicted value in any particular month may vary significantly from the estimated expected value.

Comparison of Flow Ratios with Drainage Areas

Drainage areas for each of the stations are tabulated in Tables 5.1, 5.6, 5.7, 5.25, 5.26, and 5.27. Stations 1-6 in the Little River watershed are each paired with station 7. Stations 8 and 9 on the Navasota River are paired. Flow ratios in both ac-ft/ac-ft and inches/inches are shown in Tables 5.25. 5.26, and 5.27. A value of 1.0 for the flow ratio in inches/inches in the last column of Tables 5.25, 5.26, and 5.27 would indicate that the mean flows vary between the two stations in the same proportion as their drainage areas.

Each of the 12 stations in the San Jacinto Basin is paired with the combined total watershed. The ratios of drainage areas for pairs of stations are compared with the corresponding ratios of the period-of-analysis mean flows, in acre-feet/acre-feet, in Table 5.28. Table 5.28 includes all of the pairs of stations included in Tables 5.25, 5.26, and 5.27 plus several other station pairings. Table 5.28 also includes the drainage area ratio (DAR) expressed as a percentage of the flow ratio (FR), which is computed as (DAR/FR)100%. For example, the drainage area above station 3 is 0.176 of the drainage area of station 7 (stations 3/7 DAR=0.176). The corresponding ratio of mean flows is 0.158. Thus, the DAR/FR is 111 percent [((0.0176/0.158)100%=111%] Thus, predicting station 3 flows by applying a DAR to the station 7 flows results in predicted flows with a mean of 111 percent of the mean of the known flows at station 3. The DAR ranges from 45 percent to 393 percent of the FR for the various pairings of stations. If the drainage area ratio method of distributing flows (Equations 6.1 and 6.2) worked perfectly, the DAR would be 100 percent of the FR.

Table 5.21 Annual Flow Ratios for Stations in the Brazos River Basin in acre-feet/acre-feet

	Station/Station											
Year	1/7	2/7	3/7	4/7	5/7	6/7	8/9	10/15	11/15	12/15	13/15	14/15
1940	0.051	0.290	0.139	-	-	-	0.771	0.118	0.224	0.260	0.632	0.916
1941	0.122	0.467	0.171	-	-	-	0.806	0.260	0.405	0.413	0.746	0.882
1942	0.160	0.574	0.148	-	-	-	0.792	0.168	0.426	0.467	0.810	0.955
1943	0.091	0.378	0.117	-	-	-	0.808	0.116	0.275	0.258	0.664	0.876
1944	0.039	0.418	0.228	-	-	-	0.788	0.042	0.135	0.189	0.676	0.949
1945	0.061	0.457	0.217	-	-	-	0.791	0.062	0.246	0.308	0.698	0.965
1946	0.052	0.371	0.109	-	-	-	0.799	0.086	0.212	0.227	0.602	0.935
1947	0.037	0.313	0.126	-	-	-	0.792	0.143	0.245	0.277	0.606	0.941
1948	0.085	0.418	0.170	-	-	-	0.802	0.198	0.468	0.424	0.678	0.900
1949	0.258	0.440	0.124	-	-	-	0.757	0.183	0.379	0.395	0.625	0.977
1950	0.163	0.419	0.083	-	-	-	0.783	0.198	0.350	0.344	0.543	0.938
1951	0.165	0.381	0.104	-	-	-	0.611	0.365	0.571	0.595	0.818	0.944
1952	0.194	0.409	0.246	-	-	-	0.848	0.043	0.228	0.271	0.595	0.892
1953	0.045	0.292	0.133	-	-	-	0.797	0.172	0.219	0.270	0.633	0.948
1954	0.257	0.248	0.304	-	-	-	0.726	0.478	0.576	0.614	0.757	0.924
1955	0.180	0.428	0.235	-	-	-	0.624	0.517	0.636	0.624	0.879	0.982
1956	0.472	0.744	0.204	-	-	-	0.815	0.171	0.513	0.518	0.866	1.019
1957	0.098	0.411	0.146	-	-	-	0.824	0.246	0.432	0.449	0.786	0.931
1958	0.047	0.321	0.166	-	-	-	0.767	0.123	0.301	0.325	0.745	0.934
1959	0.088	0.415	0.175	-	-	-	0.782	0.120	0.310	0.319	0.685	0.911
1960	0.029	0.298	0.189	-	-	-	0.730	0.104	0.206	0.228	0.640	0.880
1961	0.041	0.418	0.161	-	-	-	0.795	0.093	0.250	0.283	0.630	0.856
1962	0.222	0.335	0.122	-	-	-	0.736	0.328	0.506	0.559	0.793	0.932
1963	0.317	0.478	0.091	0.114	-	-	0.429	0.345	0.449	0.536	0.694	0.941
1964	0.192	0.608	0.102	0.115	-	-	0.630	0.141	0.375	0.398	0.769	0.944
1965	0.049	0.374	0.162	0.185	-	-	0.848	0.088	0.213	0.258	0.753	0.939
1966	0.073	0.345	0.147	0.172	-	0.151	0.809	0.190	0.343	0.395	0.754	0.922
1967	0.165	0.339	0.050	0.077	-	0.176	0.883	0.271	0.402	0.469	0.883	0.951
1968	0.123	0.401	0.145	0.252	-	0.110	0.832	0.088	0.267	0.305	0.658	0.943
1969	0.139	0.333	0.146	0.201	0.057	0.147	0.771	0.178	0.350	0.394	0.672	0.929
1970	0.076	0.379	0.203	0.246	0.047	0.120	0.821	0.071	0.256	0.279	0.705	0.923
1971	0.107	0.603	0.106	0.177	0.024	0.069	0.791	0.258	0.529	0.558	0.877	0.970
1972	0.061	0.329	0.152	0.217	0.048	0.137	0.771	0.244	0.370	0.386	0.667	0.818
1973	0.065	0.271	0.106	0.145	0.068	0.184	0.812	0.049	0.179	0.228	0.542	0.870
1974	0.048	0.327	0.173	0.265	0.047	0.128	0.778	0.121	0.231	0.261	0.603	0.882
1975	0.033	0.293	0.160	0.177	0.062	0.173	0.803	0.089	0.222	0.261	0.658	0.892
1976	0.031	0.264	0.130	0.181	0.067	0.178	0.858	0.072	0.188	0.229	0.652	0.921
Mean	0.120	0.394	0.163	0.068	0.053	0.143	0.791	0.149	0.303	0.334	0.690	0.921

Table 5.22 Annual Flow Ratios for Stations in the San Jacinto River Basin in acre-feet/acre-feet

	Station/Station												
Year	1/C	2/C	3/C	4/C	5/C	6/C	8/C	9/C	9/10	10/C	11/C	12/C	13/C
1940	0.366	0.143	0.096	0.161	0.039	0.048	0.013	0.071	0.862	0.082	0.018	0.040	0.013
1941	0.246	0.132	0.090	0.121	0.035	0.037	0.037	0.144	0.861	0.167	0.047	0.053	0.035
1942	0.268	0.107	0.069	0.157	0.051	0.052	0.032	0.107	0.780	0.137	0.043	0.024	0.031
1943	0.198	0.106	0.071	0.094	0.034	0.030	0.057	0.118	0.730	0.161	0.075	0.018	0.070
1944	0.266	0.113	0.086	0.089	0.036	0.038	0.043	0.165	0.863	0.191	0.053	0.034	0.034
1945	0.299	0.135	0.096	0.124	0.035	0.038	0.026	0.130	0.828	0.157	0.034	0.047	0.021
1946	0.265	0.134	0.101	0.129	0.042	0.039	0.035	0.107	0.765	0.140	0.042	0.061	0.029
1947	0.278	0.121	0.090	0.128	0.051	0.043	0.023	0.121	0.799	0.151	0.034	0.022	0.029
1948	0.366	0.105	0.031	0.126	0.070	0.058	0.013	0.076	0.768	0.099	0.030	0.007	0.035
1949	0.198	0.101	0.098	0.144	0.075	0.047	0.037	0.115	0.770	0.149	0.046	0.032	0.041
1950	0.325	0.147	0.084	0.141	0.055	0.047	0.021	0.061	0.715	0.086	0.031	0.028	0.023
1951	0.225	0.098	0.067	0.129	0.084	0.078	0.017	0.096	0.625	0.154	0.042	0.003	0.037
1952	0.277	0.117	0.116	0.111	0.043	0.046	0.018	0.129	0.751	0.172	0.034	0.011	0.024
1953	0.282	0.110	0.100	0.126	0.042	0.030	0.021	0.134	0.809	0.166	0.034	0.022	0.034
1954	0.207	0.077	0.104	0.097	0.044	0.046	0.063	0.183	0.799	0.229	0.063	0.007	0.023
1955	0.302	0.080	0.056	0.145	0.041	0.046	0.023	0.113	0.690	0.164	0.038	0.008	0.040
1956	0.275	0.051	0.037	0.125	0.051	0.067	0.022	0.117	0.647	0.180	0.048	0.003	0.043
1957	0.337	0.080	0.066	0.143	0.031	0.033	0.020	0.123	0.775	0.159	0.038	0.025	0.046
1958	0.330	0.124	0.079	0.133	0.049	0.044	0.017	0.081	0.696	0.116	0.030	0.016	0.032
1959	0.260	0.098	0.075	0.106	0.030	0.036	0.031	0.121	0.725	0.167	0.057	0.027	0.067
1960	0.303	0.131	0.105	0.105	0.032	0.041	0.021	0.119	0.739	0.160	0.033	0.044	0.028
1961	0.240	0.130	0.085	0.106	0.047	0.040	0.041	0.131	0.729	0.180	0.048	0.042	0.033
1962	0.249	0.060	0.034	0.132	0.044	0.057	0.034	0.134	0.669	0.200	0.052	0.011	0.042
1963	0.253	0.067	0.040	0.123	0.036	0.053	0.030	0.119	0.642	0.185	0.051	0.010	0.055
1964	0.290	0.056	0.061	0.149	0.038	0.052	0.045	0.120	0.748	0.160	0.040	0.013	0.044
1965	0.400	0.074	0.072	0.072	0.020	0.031	0.022	0.132	0.733	0.181	0.033	0.013	0.035
1966	0.238	0.089	0.094	0.099	0.028	0.032	0.038	0.128	0.670	0.192	0.045	0.022	0.064
1967	0.176	0.049	0.054	0.098	0.032	0.049	0.036	0.169	0.652	0.259	0.060	0.006	0.065
1968	0.301	0.116	0.092	0.113	0.023	0.035	0.020	0.137	0.770	0.177	0.030	0.037	0.035
1969	0.304	0.097	0.073	0.125	0.032	0.040	0.025	0.103	0.699	0.147	0.038	0.023	0.050
1970	0.097	0.055	0.088	0.049	0.026	0.024	0.053	0.183	0.605	0.302	0.072	0.017	0.081
1971	0.075	0.028	0.074	0.049	0.023	0.027	0.042	0.226	0.645	0.351	0.093	0.009	0.075
1972	0.124	0.107	0.118	0.062	0.028	0.023	0.045	0.201	0.721	0.279	0.056	0.020	0.057
1973	0.269	0.127	0.092	0.124	0.049	0.034	0.032	0.097	0.727	0.134	0.040	0.065	0.041
1974	0.251	0.096	0.087	0.146	0.051	0.049	0.028	0.109	0.700	0.155	0.044	0.043	0.032
1975	0.257	0.107	0.078	0.133	0.052	0.049	0.027	0.090	0.633	0.142	0.045	0.035	0.039
1976	0.262	0.090	0.077	0.103	0.037	0.043	0.047	0.110	0.819	0.134	0.058	0.029	0.057
1977	0.284	0.132	0.072	0.112	0.042	0.044	0.033	0.074	0.820	0.091	0.049	0.021	0.049
1978	0.222	0.117	0.098	0.080	0.029	0.035	0.042	0.131	0.819	0.160	0.061	0.021	0.053
1979	0.295	0.155	0.095	0.110	0.031	0.040	0.025	0.088	0.819	0.108	0.034	0.064	0.040
1980	0.184	0.109	0.112	0.079	0.028	0.030	0.051	0.134	0.817	0.164	0.066	0.021	0.063
Mean	0.267	0.115	0.087	0.118	0.040	0.040	0.031	0.118	0.755	0.156	0.043	0.026	0.039

Table 5.23 Annual Flow Ratios for Stations in the Brazos River Basin
in inches/inches

	Station/Station											
Year	1/7	2/7	3/7	4/7	5/7	6/7	8/9	10/15	11/15	12/15	13/15	14/15
1940	0.286	0.578	0.578	-	-	-	1.159	0.223	0.370	0.395	0.720	0.939
1941	0.682	0.930	0.930	-	-	-	1.211	0.491	0.669	0.628	0.849	0.904
1942	0.894	1.143	1.143	-	-	-	1.189	0.317	0.703	0.710	0.922	0.980
1943	0.511	0.752	0.752	-	-	-	1.214	0.219	0.455	0.393	0.756	0.899
1944	0.216	0.833	0.833	-	-	-	1.183	0.080	0.224	0.287	0.770	0.973
1945	0.341	0.911	0.911	-	-	-	1.187	0.117	0.406	0.469	0.795	0.990
1946	0.290	0.740	0.740	-	-	-	1.200	0.163	0.349	0.346	0.686	0.959
1947	0.210	0.623	0.623	-	-	-	1.189	0.271	0.405	0.421	0.690	0.965
1948	0.473	0.833	0.833	-	-	-	1.204	0.375	0.773	0.646	0.772	0.923
1949	1.444	0.876	0.876	-	-	-	1.138	0.347	0.626	0.601	0.711	1.002
1950	0.910	0.834	0.834	-	-	-	1.176	0.373	0.578	0.524	0.619	0.962
1951	0.922	0.760	0.760	-	-	-	0.918	0.689	0.943	0.906	0.931	0.969
1952	1.085	0.815	0.815	-	-	-	1.273	0.081	0.377	0.413	0.678	0.915
1953	0.250	0.581	0.581	-	-	-	1.197	0.325	0.362	0.411	0.721	0.972
1954	1.436	0.495	0.495	-	-	-	1.090	0.904	0.952	0.934	0.862	0.948
1955	1.009	0.853	0.853	-	-	-	0.937	0.978	1.050	0.950	1.001	1.007
1956	2.641	1.483	1.483	-	-	-	1.225	0.323	0.847	0.789	0.986	1.045
1957	0.546	0.819	0.819	-	-	-	1.238	0.465	0.714	0.683	0.895	0.955
1958	0.262	0.640	0.640	-	-	-	1.152	0.233	0.497	0.494	0.849	0.958
1959	0.495	0.826	0.826	-	-	-	1.175	0.227	0.511	0.485	0.780	0.934
1960	0.162	0.593	0.593	-	-	-	1.096	0.196	0.340	0.347	0.729	0.902
1961	0.227	0.833	0.833	-	-	-	1.193	0.176	0.412	0.430	0.717	0.878
1962	1.240	0.667	0.667	-	-	-	1.106	0.620	0.835	0.850	0.903	0.956
1963	1.773	0.953	0.953	0.606	-	-	0.644	0.651	0.742	0.815	0.790	0.965
1964	1.074	1.212	1.212	0.612	-	-	0.947	0.267	0.620	0.605	0.876	0.968
1965	0.273	0.745	0.745	0.985	-	-	1.273	0.166	0.351	0.393	0.858	0.963
1966	0.406	0.686	0.686	0.919	-	1.441	1.215	0.360	0.567	0.600	0.859	0.945
1967	0.923	0.675	0.675	0.413	-	1.687	1.327	0.511	0.664	0.714	1.006	0.976
1968	0.686	0.800	0.800	1.344	-	1.049	1.250	0.166	0.441	0.463	0.749	0.967
1969	0.780	0.664	0.664	1.072	1.628	1.403	1.159	0.336	0.578	0.600	0.766	0.953
1970	0.425	0.756	0.756	1.315	1.331	1.151	1.233	0.134	0.423	0.424	0.803	0.946
1971	0.601	1.201	1.201	0.946	0.692	0.661	1.188	0.487	0.873	0.849	0.999	0.995
1972	0.339	0.656	0.656	1.160	1.364	1.309	1.159	0.461	0.612	0.587	0.759	0.839
1973	0.366	0.539	0.539	0.774	1.933	1.756	1.219	0.092	0.296	0.347	0.617	0.893
1974	0.268	0.652	0.652	1.413	1.348	1.228	1.168	0.229	0.382	0.398	0.687	0.904
1975	0.184	0.584	0.584	0.943	1.758	1.653	1.206	0.169	0.367	0.397	0.750	0.915
1976	0.172	0.525	0.525	0.966	1.919	1.699	1.289	0.136	0.311	0.348	0.743	0.944
Mean	0.670	0.786	0.786	0.962	1.497	1.367	1.188	0.282	0.500	0.508	0.786	0.944

Table 5.24 Annual Flow Ratios for Stations in the San Jacinto River Basin in inches/inches

	Station/Station												
Year	1/C	2/C	3/C	4/C	5/C	6/C	8/C	9/C	9/7	10/C	11/C	12/C	13/C
1940	1.233	0.929	0.919	1.354	0.900	1.242	0.502	0.659	1.054	0.626	0.594	1.240	0.549
1941	0.828	0.859	0.860	1.013	0.810	0.960	1.398	1.342	1.053	1.275	1.525	1.639	1.480
1942	0.904	0.696	0.662	1.321	1.192	1.360	1.183	0.998	0.954	1.046	1.398	0.740	1.328
1943	0.666	0.691	0.684	0.787	0.781	0.787	2.140	1.094	0.892	1.227	2.428	0.565	2.977
1944	0.898	0.737	0.819	0.743	0.831	0.984	1.609	1.533	1.054	1.454	1.712	1.052	1.430
1945	1.007	0.878	0.916	1.038	0.809	0.993	0.986	1.211	1.011	1.198	1.093	1.441	0.904
1946	0.893	0.872	0.965	1.081	0.971	1.005	1.301	1.000	0.935	1.070	1.353	1.889	1.240
1947	0.937	0.790	0.865	1.073	1.194	1.114	0.878	1.124	0.976	1.152	1.099	0.670	1.232
1948	1.235	0.686	0.298	1.059	1.640	1.515	0.493	0.706	0.938	0.752	0.962	0.211	1.493
1949	0.668	0.658	0.935	1.212	1.753	1.227	1.370	1.067	0.940	1.134	1.494	0.973	1.744
1950	1.094	0.955	0.802	1.182	1.272	1.225	0.799	0.570	0.873	0.653	0.993	0.867	0.994
1951	0.758	0.639	0.641	1.087	1.957	2.017	0.648	0.895	0.764	1.172	1.360	0.106	1.579
1952	0.933	0.760	1.111	0.930	1.011	1.204	0.665	1.205	0.917	1.314	1.110	0.340	1.025
1953	0.950	0.719	0.962	1.060	0.980	0.772	0.773	1.252	0.988	1.267	1.105	0.670	1.452
1954	0.697	0.499	0.995	0.812	1.014	1.193	2.364	1.701	0.976	1.743	2.027	0.211	0.981
1955	1.019	0.518	0.533	1.219	0.956	1.185	0.868	1.053	0.844	1.249	1.224	0.250	1.694
1956	0.926	0.335	0.358	1.050	1.189	1.746	0.826	1.086	0.790	1.374	1.530	0.105	1.812
1957	1.137	0.520	0.631	1.200	0.725	0.866	0.768	1.145	0.947	1.209	1.235	0.770	1.968
1958	1.112	0.806	0.758	1.115	1.149	1.147	0.649	0.753	0.850	0.886	0.968	0.500	1.384
1959	0.877	0.639	0.722	0.886	0.709	0.932	1.158	1.128	0.886	1.273	1.823	0.844	2.840
1960	1.023	0.852	1.003	0.883	0.743	1.061	0.795	1.104	0.903	1.222	1.052	1.371	1.206
1961	0.808	0.844	0.811	0.893	1.100	1.034	1.539	1.222	0.891	1.372	1.531	1.286	1.424
1962	0.838	0.391	0.325	1.111	1.023	1.471	1.273	1.249	0.818	1.528	1.660	0.350	1.798
1963	0.852	0.435	0.386	1.029	0.849	1.374	1.139	1.106	0.784	1.411	1.657	0.303	2.360
1964	0.979	0.362	0.583	1.249	0.887	1.349	1.677	1.117	0.914	1.221	1.272	0.408	1.873
1965	1.350	0.482	0.686	0.605	0.457	0.808	0.819	1.231	0.895	1.375	1.077	0.394	1.476
1966	0.803	0.580	0.897	0.833	0.641	0.829	1.416	1.195	0.818	1.461	1.436	0.668	2.721
1967	0.595	0.320	0.517	0.821	0.743	1.273	1.356	1.573	0.796	1.976	1.937	0.193	2.782
1968	1.013	0.757	0.884	0.949	0.540	0.914	0.735	1.271	0.941	1.351	0.958	1.156	1.511
1969	1.026	0.631	0.697	1.046	0.743	1.041	0.956	0.959	0.854	1.123	1.233	0.714	2.123
1970	0.328	0.357	0.840	0.410	0.615	0.634	1.998	1.703	0.739	2.304	2.318	0.527	3.467
1971	0.252	0.182	0.708	0.412	0.535	0.702	1.584	2.106	0.788	2.673	2.992	0.268	3.206
1972	0.419	0.695	1.129	0.519	0.659	0.603	1.692	1.875	0.881	2.129	1.805	0.626	2.409
1973	0.906	0.829	0.881	1.044	1.151	0.885	1.203	0.904	0.888	1.018	1.281	2.014	1.734
1974	0.847	0.626	0.831	1.226	1.186	1.274	1.048	1.012	0.855	1.183	1.421	1.331	1.354
1975	0.868	0.696	0.750	1.120	1.223	1.275	1.012	0.835	0.774	1.079	1.451	1.075	1.642
1976	0.884	0.583	0.735	0.865	0.868	1.110	1.749	1.020	1.001	1.019	1.865	0.884	2.410
1977	0.956	0.859	0.686	0.944	0.973	1.132	1.225	0.693	1.002	0.692	1.567	0.640	2.100
1978	0.749	0.764	0.939	0.675	0.679	0.897	1.575	1.219	1.000	1.219	1.955	0.652	2.245
1979	0.995	1.010	0.912	0.924	0.726	1.040	0.950	0.820	1.000	0.820	1.082	1.976	1.697
1980	0.620	0.713	1.073	0.664	0.663	0.783	1.928	1.246	0.999	1.247	2.136	0.643	2.686
Mean	0.900	0.746	0.836	0.989	0.928	1.042	1.177	1.095	0.922	1.188	1.392	0.814	1.677

Table 5.25 Drainage Area and Flow Ratios for Stations in the Brazos River Basin

Station	Stream	Drainage Area (mile^2)	Drainage Area Ratio	Mean Flow (ac-ft/yr)	Flow (ac-ft/yr) Ratio	Mean Flow (inches/yr)	Flow (inches/yr) Ratio
1	Leon River	1,261	0.178	114,812	0.086	1.71	0.484
2	Leon River	3,542	0.501	518,327	0.390	2.74	0.776
3	Lampasas River	1,240	0.176	210201	0.158	3.18	0.901
4	Lampasas River	1,321	0.187	261,249	0.197	3.71	1.050
5	San Gabriel River	248	0.035	69,573	0.052	5.26	1.490
6	San Gabriel River	738	0.104	189,608	0.143	4.82	1.365
7	Little River	7,065	-	1,328,563	-	3.53	-
8	Navasota River	968	0.666	319,479	0.817	6.19	1.228
9	Navasota River	1,454	-	390,989	-	5.04	-

Table 5.26 Ratios of Station Versus Combined Areas and Flows for the Stations in the San Jacinto River Basin

Station	Stream	Drainage Area (mile^2)	Drainage Area Ratio	Mean Flow (ac-ft/yr)	Flow (ac-ft/yr) Ratio	Mean Flow (inches/yr)	Flow (inches/yr) Ratio
1	WF San Jacinto	809	0.297	370,000	0.267	8.6	0.90
2	Spring Creek	419	0.154	158,000	0.115	7.1	0.75
3	Cypress Creek	285	0.105	121,000	0.0870	8.0	0.84
4	EF San Jacinto	325	0.119	163,000	0.118	9.4	0.99
5	Peach Creek	117	0.0429	55,200	0.0398	8.8	0.93
6	Caney Creek	105	0.0385	55,600	0.0401	9.9	1.04
8	Greens Bayou	72.7	0.0267	43,500	0.0314	11.2	1.18
9	Buffalo Bayou	293	0.107	163,000	0.118	10.4	1.10
10	Buffalo Bayou	358	0.131	216,000	0.156	11.3	1.19
11	White Bayou	84.7	0.0310	59,900	0.0432	13.3	1.40
12	Brays Bayou	88.4	0.0324	88,100	0.0260	18.7	0.81
13	Sims Bayou	64.0	0.0235	54,500	0.0393	16.0	1.68
Combined		2,728		1,386,400		9.53	

Table 5.27 Drainage Area and Flow Ratios for Stations in the Sulphur River Basin

Station	Stream	Drainage Area (mile^2)	Drainage Area Ratio	Mean Flow (ac-ft/yr)	Flow (ac-ft/yr) Ratio	Mean Flow (inches/yr)	Flow (inches/yr) Ratio
A	South Sulphur	541	0.392	320,670	0.337	11.1	0.860
B	North Sulphur	311	0.225	175,270	0.184	10.6	0.822
C	Sulphur	1,380	-	952,520	-	12.9	-
D	White Oak Creek	546	0.192	387,050	0.195	13.3	1.015
E	Sulphur	2,850	-	1,983,620	-	13.1	-

Table 5.28 Comparison of Flow Ratios and Drainage Area Ratios

Brazos River Basin Stations

Station	D. Area Ratio	Flow Ratio	DAR/FR Percent
1 / 7	0.178	0.086	206.54
2 / 7	0.501	0.390	128.50
3 / 7	0.176	0.158	110.93
4 / 7	0.187	0.197	95.09
5 / 7	0.035	0.052	67.03
6 / 7	0.104	0.143	73.19
1 / 2	0.356	0.222	160.72
3 / 4	0.939	0.805	116.66
5 / 6	0.336	0.367	91.58
8 / 9	0.666	0.817	81.48
10 / 15	0.529	0.135	393.05
11 / 15	0.605	0.274	220.65
12 / 15	0.657	0.302	217.49
13 / 15	0.878	0.626	140.26
14 / 15	0.975	0.835	116.78
10 / 11	0.874	0.491	178.13
11 / 12	0.921	0.908	101.45
12 / 13	0.748	0.483	155.07
13 / 14	0.901	0.750	120.10
7 / 13	0.179	0.332	53.92
9 / 14	0.033	0.073	45.29

San Jacinto Basin Stations

Station	D. Area Ratio	Flow Ratio	DAR/FR Percent
1 / C	0.297	0.267	111.2
2 / C	0.154	0.105	133.9
3 / C	0.104	0.087	120.7
4 / C	0.119	0.118	100.8
5 / C	0.043	0.040	107.8
6 / C	0.038	0.040	96.0
8 / C	0.027	0.031	85.0
9 / C	0.107	0.118	90.7
10 / C	0.131	0.156	84.0
11 / C	0.031	0.043	71.8
12 / C	0.032	0.026	124.6
13 / C	0.023	0.039	59.8
9 / 10	0.818	0.755	108.3

Sulphur River Basin

Station	D. Area Ratio	Flow Ratio	DAR/FR Percent
A/C	0.392	0.337	116.32
B/C	0.225	0.184	122.28
D/E	0.192	0.195	98.46
B/A	0.575	0.545	105.50

CHAPTER 6
COMPARATIVE EVALUATION OF ALTERNATIVE APPROACHES FOR DISTRIBUTING FLOWS

Chapter 6 is a comparative evaluation of alternative methods outlined in Chapter 4 based on using the naturalized flows at the stations in the Brazos, San Jacinto, and Sulphur River Basins described in Chapter 5. Chapter 6 begins with a description of the flow distribution methods tested and the estimation of values for the parameters incorporated in these methods. Next, relationships are examined between the flow regression coefficients computed in Chapter 5 and combinations of the ratios of drainage areas, mean precipitation, and curve numbers representing land use and soil type. The last section of the chapter summarizes the results of a comparative evaluation of flows predicted using alternative flow distribution approaches. Alternative methods are applied to predict flows at selected stations from known flows at other stations. The flows computed with the alternative methods are compared with each other and with the known flows at the station.

Alternative Flow Distribution Methods

All of the methods described in Chapter 4 for distributing flows from gaged watersheds to ungaged subwatersheds have been considered in this investigation to varying extents. However, based on considerations outlined in Chapters 3, 4, and 5, the analyses reported in Chapter 6 focus on the following alternative approaches, which are listed in hierarchical order from simple to complex.

1. distribution of flows in proportion to drainage area (Equations 6-1, 6-2, and 6-3)
2. distribution of flows in proportion to drainage area, CN, and mean precipitation (Equations 6-1, 6-4, and 6-5)
3. adaptation of the Natural Resource Conservation Service curve number (CN) method (Equations 6-6 and 6-7)
4. application of the Soil and Water Assessment Tool (SWAT) hydrologic simulation model
    a. develop relationships between flows at gaged and ungaged locations using SWAT
    b. directly use flow sequences developed by SWAT

The first three approaches and estimation of their parameters (drainage area, CN, and mean precipitation) are described next, followed by a separate section addressing application of SWAT.

Distribution of Flows in Proportion to Ratios of Watershed Parameters

The first and second approaches listed above involve multiplying flows by ratios of watershed parameters. Naturalized monthly streamflows are transposed from a gaged site to an ungaged site by the following simple linear relation discussed in previous chapters:

$$Q_{ungaged} = C\ Q_{gage} \qquad (6\text{-}1)$$

where C is a constant. The general strategy of using Equation 6-1 for computing flows requires that the coefficient C be estimated from characteristics of both the gaged and ungaged watersheds. A logical approach for relating C to watershed characteristics is to express C in terms of the ratio of parameters such as drainage area, mean precipitation, curve number, and other parameters. The most common approach is to simply use the drainage area ratio:

$$C = \left(\frac{A_{ungaged}}{A_{gage}} \right)^{N} \tag{6-2}$$

If the exponent N is determined to be one, the expression for C is as follows:

$$C = \frac{A_{ungaged}}{A_{gage}} \tag{6-3}$$

Alternatively, ratios for other watershed parameter could also be used. C may be expressed as a function of mean precipitation M, curve number CN, and other parameters, as well as drainage area A.

$$C = \left(\frac{A_{ungaged}}{A_{gage}} \right)^{N1} \left(\frac{M_{ungaged}}{M_{gage}} \right)^{N2} \left(\frac{CN_{ungaged}}{CN_{gage}} \right)^{N3} \left(\frac{Other_{ungaged}}{Other_{gage}} \right)^{N4} \tag{6-4}$$

If all the exponents N_i are assumed to be unity, the constant C would be related to the watershed characteristics as

$$C = \left(\frac{A_{ungaged}}{A_{gage}} \right) \left(\frac{M_{ungaged}}{M_{gage}} \right) \left(\frac{CN_{ungaged}}{CN_{gage}} \right) \left(\frac{Other_{ungaged}}{Other_{gage}} \right) \tag{6-5}$$

NRCS Curve Number (CN) Method Adaptation

The Natural Resource Conservation Service (NRCS) curve number (CN) method adaptation is advantageous over the parameter ratio approach (Equations 6.1 and 6.4) from the perspective of providing a more conceptual relationship for incorporating the CN and mean precipitation. The concept of distributing flows in direct proportion to drainage area is also explicitly inherent in the NRCS CN method. If the CN and mean precipitation are assumed to be identical for both watersheds, the NRCS CN method adaptation predicts identically the same flows as the drainage area ratio method.

The NRCS CN method is a widely applied approach for predicting the runoff volume to result from a specified precipitation volume. The general methodology is modified here for transferring flows from one location to another. Thus, the method is being adapted to a different type of application than that for which it was originally developed. The procedure has been modified in this investigation for applicability to the task of distributing flows. As normally applied, storm runoff volumes are computed for given precipitation volumes. In the adaptation, monthly streamflow volumes at a specified location are computed for given monthly flow volumes at another location.

Chapter 4 outlines both the conventional NRCS curve number method (Equation 4-4) and the step-by-step procedure for adapting the method to transposing flows from gaged to ungaged sites. The NRCS CN method is based on the following relationship between rainfall depth *P*, in inches, and runoff depth *Q*, in inches.

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \tag{6-6}$$

$$Q = 0 \quad if \quad P < 0.2S$$

$$S = \frac{1{,}000}{CN} - 10$$

P and *Q* in inches must be multiplied by the watershed area to obtain volumes in acre-feet or other units. The potential maximum retention *S*, in inches, is expressed in terms of a curve number *CN* which is a dimensionless watershed parameter ranging from 0 to 100. The watershed parameter *CN* is determined from empirical information, such as that reproduced as Table 4.1, developed by the NRCS as a function of watershed soil type, land cover/use/condition, and antecedent moisture condition.

The computational algorithm for the modified NRCS CN method consists of the following steps performed for each month.

Step 1: The flow at the gage, in acre-feet/month, is divided by the drainage area A_{gage} and multiplied by a unit conversion factor to convert to an equivalent depth Q_{gage} in inches.

Step 2: Q_{gage} is input to Equation 6-6 to obtain P_{gage} in inches. An iterative algorithm is required to solve for *P* given *Q*. This approximation for precipitation depth is assumed to be applicable to the ungaged subwatershed as well as the gaged watershed. Base flow is being distributed along with storm runoff, all in the same proportion.

Step 3: The precipitation depth is adjusted by multiplying P_{gage} by the ratio of the long-term mean precipitation depth $M_{ungaged}$ of the subwatershed to that of the watershed M_{gaged} to obtain a $P_{ungaged}$.

$$adjusted\ P_{ungaged} = P_{gage}\left(\frac{M_{ungaged}}{M_{gage}}\right) \tag{6-7}$$

Step 4: $P_{ungaged}$ is input into the Equation 6-6 to obtain $Q_{ungaged}$ in inches. $Q_{ungaged}$ in inches is multiplied by $A_{ungaged}$ and a unit conversion factor to convert to flow in acre-feet/month.

Watershed Parameters for the Selected Stations

TNRCC/CRWR GIS

During 1998-1999, the Center for Research in Water Resources (CRWR) at the University of Texas, under contract with the TNRCC, is developing an ArcView based geographic information system (GIS) to:

- delineate the spatial connectivity of gaging stations, water rights, and other pertinent sites
- determine the drainage area, curve number, and mean precipitation for each water right and pertinent stream gaging station in the 22 river basins

The investigation reported herein provided a basis to determine the types of watershed parameters to be adopted for the statewide water availability modeling effort. The Brazos and San Jacinto River Basin analyses presented here were performed prior to the CRWR developing the GIS. The Sulphur River Basin analyses were performed later and used watershed parameters developed by the GIS. The curve number and mean annual precipitation data for the Sulphur River Basin were developed by the CRWR for use in the TNRCC/Brandes water availability modeling study.

The CRWR GIS uses digital elevation models produced by the U.S. Geological Survey to delineate watersheds. The GIS uses a grid database of curve numbers (CN) developed by the Blackland Research Center of the Texas Agricultural Experiment Station (TAES) in conjunction with the nationwide Hydrologic Unit Modeling of the United States (HUMUS) project sponsored by the USDA Natural Resource Conservation Service (NRCS). The grid of mean annual precipitation adopted for the GIS was developed at Oregon State University for the NRCS (Hudgens and Maidment 1998).

Watershed Parameters

The only parameters required for the drainage area ratio approach (Equation 6-2) are the watershed areas of all pertinent sites. The curve number CN and mean precipitation as well as drainage areas are used in both the parameter ratio (Equation 6-4) approach and NRCS CN method adaptation (Equation 6-6). This section describes estimates of these three parameters for these three flow distribution approaches.

Estimates of parameter values for the watersheds of the gaging stations in the Brazos, San Jacinto, and Sulphur River Basins are presented in Tables 6.1, 6.2, and 6.3, respectively. The drainage areas published by the USGS in the gaging station information were adopted for the stations in the Brazos and San Jacinto Basins. The mean annual precipitation values for the Brazos and San Jacinto watersheds were estimated from a mean annual precipitation map for Texas published by the Texas Water Development Board (1984). Estimation of CN's for subwatersheds in the Brazos and San Jacinto Basins are discussed in the following paragraphs. The drainage area, mean precipitation, and CN data for the stations in the Sulphur Basin were taken from the TNRCC/Brandes report (R. J. Brandes Company 1999). These data for the Sulpur Basin were developed in conjunction with the TNRCC/CRWR GIS project noted above.

Stations 10-15 on the Brazos River have extremely large complicated watersheds. Consequently, curve numbers were not estimated. The drainage area ratio method is the only flow distribution approach applied to the stations on the main-stem Brazos River.

For the San Jacinto River Basin, Table 6.2 includes parameter values for the combined watershed above all of the stations. The combined drainage area is the summation of the areas for all stations except station 9, since the station 9 drainage area is included in the station 10 area. The CN and mean precipitation for the combined watershed was estimated as a drainage area-weighted average of the values for the individual subwatersheds.

The curve numbers *CN* for the Brazos and San Jacinto watersheds above the stations were estimated based on reviewing NRCS soil maps and USGS quadrangle maps to determine soil type and land use. The percentage of each watershed represented by each predominate soil type and land use was related to the standard NRCS *CN* table (Table 4.1) to estimate a composite *CN* for the watershed (Equation 4-5). The land use and soil type estimates for each watershed are shown in Tables 6.4 and 6.5. The curve number estimates are necessarily approximate and of course are determined with less precision than implied by the significant figures shown in Tables 6.3 and 6.4.

Table 6.1 Watershed Parameters for the Stations in the Brazos River Basin

Station	Drainage Area ($mile^2$)	Curve Number	Mean Precipitation (inches/year)
1	1,261	81.6	27.1
2	3,542	79.2	30.0
3	1,240	80.1	28.5
4	1,321	78.5	32.3
5	248	82.8	31.7
6	738	82.8	31.5
7	7,065	79.7	30.1
8	968	83.3	37.7
9	1,454	83.3	39.0
10	23,811	-	-
11	27,244	-	-
12	29,573	-	25
13	39,515	-	27
14	43,880	-	-
15	45,007	-	28

Table 6.2 Watershed Parameters for the Stations in the San Jacinto River Basin

Station	Drainage Area (mile^2)	Curve Number	Mean Precipitation (inches/year)
1	809	66.5	42.9
2	419	70.8	42.7
3	285	82.8	43.0
4	325	64.8	45.0
5	117	64.7	45.0
6	105	62.7	44.5
8	72.7	84.5	44.8
9	293	83.6	43.1
10	358	83.4	43.2
11	84.7	88.1	45.0
12	88.4	88.9	45.5
13	64.0	86.3	45.5
Combined	2,728	73.0	43.6

Table 6.3 Watershed Parameters for the Stations in the Sulphur River Basin (R. J. Brandes Company 1999)

Station	Drainage Area (mile^2)	Curve Number	Mean Precipitation (inches/year)
A	541	64.4	42.7
B	311	70.0	43.2
C	1,382	69.5	43.4
D	546	70.8	44.1
E	2,849	69.0	44.4

Table 6.4 Watershed Characteristics Used to Estimate Curve Numbers for the Stations in the Brazos River Basin

Station	CN	Land Use	Soil Type
1	81.6	20% Crops, 80% Pasture	60% C, 40%D
2	79.2	10% Crops, 40% Pasture, 50% Military Reserve(Brush, Meadow)	50%C, 50%D
3	80.1	15% Crops, 65%Pasture, 25% Brush	60%C, 40%D
4	78.5	15% Crops, 65%Pasture, 25% Brush	15%B, 40%C, 45%D
5	82.8	20% Crops, 80% Pasture	35%C, 65%D
6	82.8	20% Crops, 80% Pasture	65%D, 35%C
7	79.7	15% Crops, 65% Pasture, 10%	50%C, 50%C
8	83.3	20% Crops, 80% Pasture	20% Crops, 80% Pasture
9	83.3	20% Crops, 80% Pasture	20% Crops, 80% Pasture

Table 6.5. Watershed Characteristics Used to Estimate Curve Numbers for the Stations in the San Jacinto River Basin

Station	CN	Land Use	Soil Type
1	66.5	60% woods; 8% crops; 32% pasture	15% A; 50% B 35% D
2	70.8	40% woods; 12% crops 48% pasture	10% A; 35% B 35% C; 20% D
3	82.8	20% residential; 8% crops 32% pasture	50% C 50% D
4	64.8	100% woods	75% B; 25% D
5	64.7	90% woods; 2% crops 8% pasture	75% B; 15% C 10% D
6	62.7	90% forest; 2% crops 8% pasture	10% A; 65% B 10% C; 15% D
8	84.5	40% residential; 12% crops 48% pasture	20% C 80% D
9	83.6	10% residential; 18% crops 72% pasture	15% C 85% D
10	83.4	20% residential; 5% commercial 15% crops; 60% pasture	50% C 50% D
11	88.1	70% residential; 10% commercial 4% crops; 16% pasture	15% C 85% D
12	88.9	75% residential; 10% commercial 3% crops; 12% pasture	100% D
13	86.3	45% residential; 11% crops 44% pasture	100% D

Adjusted Curve Numbers

The flow predictions with the NRCS CN method adaptation were repeated for two sets of curve numbers. The first set of CN's, which are tabulated in Tables 6.1 and 6.2, was developed using conventional procedures as outlined in the preceding paragraphs. Another adjusted set of curve numbers was developed through a *quasi-calibration* procedure based on reproducing long-term means. Calibration is obviously not possible in estimating flows for ungaged subwatersheds. However, the adjusted curve numbers used in this study simply provided another way to test flow distribution methods. The purpose of the adjusted CN's was to examine the extent of monthly deviations between known and predicted flows given that the long-term means are about the same. Even with adjusted CN's set to reproduce long-term means, significant deviations between predicted and known flows were found to occur in individual months.

After performing an initial series of analyses, more precise precipitation values were determined and used to update most of the analyses. However, updating the adjusted CN's was considered to not be warranted. Thus, the adjusted CN's were determined using a slightly different set of precipitation values than shown in the report.

In the Brazos Basin, given the CN for the watershed above the Cameron gage on the Little River (station 7) from Table 6.1, the CN's for each subwatershed above station 7 were determined such that the mean of the computed flows equal the mean of the known flows. Likewise, the CN for the watershed above station 8 on the Navasota River was determined, given the CN for station 9. For each of the 12 stations in the San Jacinto Basin, adjusted curve numbers were determined that result in the 1940-1980 mean flows at the station being predicted when the combined flows are used for the prediction.

The adjusted CN's were computed as follows. Given the flows at the specified downstream location, the flows at the station were computed using the modified NRCS CN method computer program developed in conjunction with the project. The CN, drainage area, and mean precipitation for both the overall watershed and the station subwatershed were provided as input to the Fortran program as well as the overall watershed monthly flows. The monthly flows at the station and their mean were computed by the program. The computed mean was compared with the corresponding mean for the actual known naturalized flows for the station. With all other input held constant, the CN for the station was adjusted and the computer model executed again. This process was repeated iteratively until the predicted mean of the flows at the station matched the mean of the known naturalized flows for the station. The original estimates for the CN and the adjusted CN values are tabulated in Tables 6.6 and 6.7. The results of flow predictions performed using the NRCS CN method adaptation with the two alternative sets of CN's are presented later in this chapter.

Table 6.6 Original and Adjusted Curve Numbers (CN) for Stations in the Brazos Basin

Station	Original Curve Number	Adjusted Curve Number
1	81.6	76.1
2	79.2	78.5
3	80.1	82.1
4	78.5	79.4
5	82.8	87.5
6	82.8	84.2
8	83.3	74.7

Table 6.7 Original and Adjusted Curve Numbers (CN) for Stations in the San Jacinto Basin

Station	Original Curve Number	Adjusted Curve Number
1	66.5	72.9
2	70.8	67.5
3	82.8	69.7
4	64.8	72.1
5	64.7	69.9
6	62.7	73.1
8	84.5	76.5
9	83.6	75.0
10	83.4	76.7
11	88.1	80.1
12	88.9	87.9
13	86.3	84.3
Combined	73.0	81.2

Relationships between Watershed Parameters and Flow Regression Coefficients

In applying Equation 6-1 to transfer flows from gaged to ungaged sites, the coefficient *C* must be estimated from watershed parameters. The known naturalized flows at the gaging stations a data base to examine the relationships for *C* reflected in Equations 6-2, 6-3, 6-4, and 6.5. This section summarizes the results of investigating the relationship between *C* determined from estimates of watershed parameter ratios and the *C* determined from regression of known flows.

In applying Equations 6-1 through 6-5, the flow at an ungaged location is assumed to be equal to the flow at the gage site multiplied by a constant *C* reflecting the characteristics of the gaged and ungaged watersheds. This relation has the same form as the zero-intercept linear regression equation

$$y = m\,x$$

adopted in Chapter 5 to relate known flows at different stations. In the following presentation, the slope coefficient ***m***, determined in Chapter 5 from two sets of concurrent known flows, is compared with the equivalent *C* determined from watershed characteristics. Drainage area, curve number, and mean precipitation are the watershed parameters incorporated into Equations 6-2 through 6-5 to estimate values for *C*.

Thus, the following analyses investigate the relationship:

$$Q_{\text{station i}} = C\,Q_{\text{station j}}$$

between flows Q_i and Q_j at the locations *i* and *j*, respectively, where *C* is estimated from the ratios of parameter values for the watersheds of locations *i* and *j*. For the stations in the San Jacinto Basin, this relationship is also expressed as:

$$Q_{\text{station}} = C\,Q_{\text{combined}}$$

where Q_{combined} is the total flow from the 2,730 mile^2 combined watershed above all the stations, computed by summing the flows at the individual stations.

Determination of the Exponents N in Equations 6-2 and 6-4

The slope coefficients ***m*** from Tables 5.11, 5.16, and 5.18 are reproduced in Tables 6.8-6.13 along with the corresponding ratios of drainage area R_A curve number R_{CN} and mean precipitation R_M. The *C* determined from regression analysis of known flows is represented by the slope coefficient ***m***. The following relationships are considered for estimating *C* from watershed parameters.

$$m = C = R_A{}^N$$

$$m = C = (R_A)^{N1}(R_{CN})^{N2}$$

$$m = C = (R_A)^{N1}(R_{CN})^{N2}(R_M)^{N3}$$

where the ratios of drainage area R_A, curve number R_{CN}, and mean precipitation R_M for two locations i and j are defined as follows.

R_A = drainage area for watershed j divided by drainage area for watershed i
R_{CN} = curve number for watershed j divided by curve number for watershed i
R_M = mean precipitation for watershed j divided by mean precipitation for watershed i

In some cases, values for the *N* computed for the following relationships are also presented.

$$m = [(R_A)(R_{CN})]^N$$
$$m = [(R_A)(R_{CN})(R_M)]^N$$

Based on the analyses presented in Tables 6.8 - 6.10, one (N=1.0) is concluded to be the most appropriate value for the drainage area $(R_A)^N$ exponent N. The values for the exponents $N2$ and $N3$ for the curve number and precipitation ratios (R_{CN} and R_M) exhibit great variation between stations. The data are inadequate to reach a conclusion regarding the most appropriate R_{CN} and R_M exponents $N2$ and $N3$. The $N2$ and $N3$ are probably not constants at all but rather vary significantly from station to station and from month to month. In the flow predictions presented in the later section entitled *Comparison of Flow Distribution Approaches*, these exponents are set at one ($N2$=$N3$=1). The products of the ratios with all exponents set equal to unity are tabulated in Tables 6.11 - 6.13 and adopted in the predictions reported later in the chapter.

Comparison of Flow Ratios and Parameter Ratios

The validity of Equations 6-1 through 6-5 is examined by the comparison of the regression slope coefficient m with the ratios of parameters tabulated in Tables 6.11 - 6.13. The parameter ratios provide estimates for C in Equations 6-1 through 6-5 which are equivalent to the slope m determined from the linear regression analysis of known flows in Chapter 5. Tables 6.11 - 6.13 provide some measure of the extent to which the estimates for C provided by the alternative combinations of parameter ratios approximate the m representing the known flows. The curve numbers and mean precipitation are similar for the different watersheds as indicated by the ratios R_{CN} and R_M being close to 1.0. Thus, drainage area represents the greatest difference in watershed characteristics between pairs of stations. Thus, Tables 6.11 - 6.13 may be viewed from the following perspectives.

- Comparison of the m and R_A provides a measure of the validity of the drainage area ratio approach (Equations 6-1 and 6-2) as a method for predicting the expected value (mean) of the flow at one location given the flow at another location. If the drainage area method worked perfectly, R_A would equal m. Of course, the tables show variations between R_A and m.

- This comparison also provides a measure of the validity of Equations 6-1 and 6-5. The products R_AR_{CN} and $R_AR_{CN}R_M$ should provide a closer approximation of m than is provided by R_A alone. A review of Tables 6.10-6.20 indicates that this is sometimes but not always the case.

Based on a review of Tables 6.11-6.13, the drainage area ratio method appears to provide a rough approximation of the mean flow. The CN and precipitation ratios appear to provide only minimal improvement over using the drainage area ratio alone to proportion flows.

Table 6.8 Exponents for Watershed Parameter Ratios
for Stations in the Brazos River Basin

	Regression		Ratios			Exponent *N* for	
Station	Slope m	R_A	R_{CN}	R_M	$(R_A)^N$	$R_A(R_{CN})^N$	$R_A R_{CN}(M)^N$
1 vs. 7	0.085	0.178	1.024	0.900	1.430	-31.488	7.290
2 vs.7	0.418	0.501	0.994	0.997	1.263	28.890	52.748
3 vs. 7	0.173	0.176	1.005	0.947	1.008	-2.881	0.356
4 vs. 7	0.213	0.187	0.985	1.073	0.922	-8.589	2.062
5 vs. 7	0.052	0.035	1.039	1.053	0.883	10.298	6.851
6 vs. 7	0.137	0.104	1.039	1.047	0.890	7.107	6.126
8 vs. 9	0.826	0.666	1.000	0.967	0.470	-	-6.362
1 vs. 2	0.218	0.356	1.030	0.903	1.475	-16.430	5.118
2 vs. 3	0.734	0.939	1.020	0.882	4.887	-12.190	2.126
3 vs. 4	0.362	0.336	1.000	1.006	0.932	-	11.756

Table 6.9 Exponents for Watershed Parameter Ratios
for Station Versus Combined Flows for the Stations in the San Jacinto River Basin

	Regression		Ratios				Exponent *N* for		
Station	Slope m	R_A	R_{CN}	R_M	$(R_A)^N$	$(R_A R_{CN})^N$	$(R_A \underset{N}{R_M} R_{CN})$	$R_A(R_{CN})^N$	$R_A R_{CN}(M)^N$
1	0.2839	0.2966	0.911	0.984	1.036	0.962	0.950	0.467	-3.055
2	0.1311	0.1536	0.969	0.979	1.085	1.067	1.055	5.10	6.084
3	0.0966	0.1045	1.134	0.986	1.035	1.096	1.181	-0.625	26.793
4	0.1271	0.1191	0.887	1.032	0.970	0.918	0.931	-0.538	5.851
5	0.0380	0.0429	0.886	1.032	1.038	1.000	1.010	1.003	-0.008
6	0.0380	0.0385	0.858	1.021	1.004	0.959	0.965	0.0842	6.856
8	0.0301	0.0267	1.157	1.028	0.966	1.007	1.015	0.835	-0.956
9	0.1068	0.1074	1.145	0.989	1.003	1.067	1.061	-0.0423	12.225
10	0.1355	0.1312	1.143	0.991	0.984	1.053	1.048	0.240	11.003
11	0.0376	0.0311	1.207	1.032	0.945	0.999	1.009	1.017	0.053
12	0.0495	0.0324	1.217	1.032	0.876	0.930	0.939	2.178	7.196
13	0.0325	0.0235	1.181	1.044	0.913	0.956	0.967	1.96	3.701

Table 6.10 Exponents for Watershed Parameter Ratios for Adjacent-Subwatershed Flows for the Stations in the San Jacinto River Basin

	Regression	Ratios			Exponent *N* for		
Station	Slope m	R_A	R_{CN}	R_M	$(R_A)^N$	$R_A(R_{CN})^N$	$R_AR_{CN}(M)^N$
4-5	0.287	0.360	0.999	1.000	1.221	365	-
5-6	0.758	0.897	0.968	0.989	2.560	5.25	12.158
6-1	6.744	7.705	1.061	0.964	0.935	-2.25	5.255
1-2	0.4345	0.518	1.065	0.995	1.267	-2.81	50.892
2-3	0.688	0.680	1.170	1.007	0.970	0.0747	-14.133
3-8	0.249	0.255	1.020	1.042	1.018	-1.20	-1.064
8-11	1.016	1.165	0.982	1.004	0.104	7.61	-26.644
11-10	3.049	4.227	1.004	0.960	0.773	-90.7	8.100
9-10	1.266	1.222	0.998	0.998	1.176	-17.669	-706.034
10-12	0.290	0.247	1.065	1.042	0.885	2.549	-23.955
12-13	0.662	0.724	0.971	1.011	1.277	3.042	-52.811

Table 6.11 Comparison of Watershed Parameter Ratios and Flow Regression Coefficients for Stations in the Brazos River Basin

	Regression	Ratios				
Station	Slope m	R_A	R_{CN}	R_M	R_AR_{CN}	$R_AR_MR_{CN}$
1 vs. 7	0.085	0.178	1.024	0.900	0.182	0.164
2 vs.7	0.418	0.501	0.994	0.997	0.498	0.496
3 vs. 7	0.173	0.176	1.005	0.947	0.176	0.167
4 vs. 7	0.213	0.187	0.985	1.073	0.184	0.198
5 vs. 7	0.052	0.035	1.039	1.053	0.036	0.038
6 vs. 7	0.137	0.104	1.039	1.047	0.109	0.113
8 vs. 9	0.826	0.666	1.000	0.967	0.666	0.643
1 vs. 2	0.218	0.356	1.030	0.903	0.367	0.331
2 vs. 3	0.734	0.939	1.020	0.882	0.958	0.845
3 vs. 4	0.362	0.336	1.000	1.006	0.334	0.338

Table 6.12 Comparison of Watershed Parameter Ratios and Flow Regression Coefficients for Station Versus Combined Flow in the San Jacinto River Basin

	Regression		Ratios			
Station	Slope m	R_A	R_{CN}	R_M	R_AR_{CN}	$R_AR_MR_{CN}$
1	0.2839	0.2966	0.911	0.984	0.270	0.266
2	0.1311	0.1536	0.969	0.979	0.149	0.146
3	0.0966	0.1045	1.134	0.986	0.119	0.138
4	0.1271	0.1191	0.887	1.032	0.106	0.109
5	0.0380	0.0429	0.886	1.032	0.038	0.039
6	0.0380	0.0385	0.858	1.021	0.033	0.034
8	0.0301	0.0267	1.157	1.028	0.031	0.032
9	0.1068	0.1074	1.145	0.989	0.123	0.122
10	0.1355	0.1312	1.143	0.991	0.150	0.149
11	0.0376	0.0311	1.207	1.032	0.038	0.039
12	0.0495	0.0324	1.217	1.032	0.0278	0.041
13	0.0325	0.0235	1.181	1.044	0.0278	0.029

Table 6.13 Comparison of Watershed Parameter Ratios and Flow Regression Coefficients for Flows from Adjacent-Subwatersheds in the San Jacinto River Basin

	Regression		Ratios			
Station	Slope m	R_A	R_{CN}	R_M	R_AR_{CN}	$R_AR_MR_{CN}$
4-5	0.287	0.360	0.999	1.000	0.368	0.360
5-6	0.758	0.897	0.968	0.989	0.868	0.859
6-1	6.744	7.705	1.061	0.964	8.175	7.881
1-2	0.4345	0.518	1.064	0.995	0.551	0.549
2-3	0.688	0.680	1.170	1.007	0.780	0.765
3-8	0.249	0.255	1.020	1.042	0.260	0.271
8-11	1.016	1.165	0.982	1.004	1.144	1.149
11-10	3.049	4.227	1.004	0.960	4.244	4.074
9-10	1.266	0.247	0.998	0.998	0.247	0.246
10-12	0.290	0.724	1.065	1.042	0.771	0.803
12-13	0.662	1.222	0.971	1.011	1.187	1.200

Soil and Water Assessment Tool (SWAT) Analyses

SWAT Description

Background information regarding the Soil and Water Assessment Tool (SWAT) is provided in Chapter 2. SWAT computes sequences of daily streamflows to result from specified precipitation input by simulating the hydrologic processes that occur in the watershed and subsurface (Arnold et al. 1996; http://brcsun0.tamu.edu/swat/index.html). A detailed daily water balance accounts for subsurface/surface water interactions as well as surface runoff. SWAT is more sophisticated with greater input data requirements than the previous methods. However, the level of sophistication and effort required can be controlled to significant degree by the optional features selected by the model user. SWAT also includes extensive optional water quality modeling capabilities that are not pertinent to water availability modeling. These options are simply not used if not needed. SWAT interacts with GIS databases that facilitate estimation of values for the model parameters.

A modification of the NRCS curve number method is incorporated in SWAT for determining the runoff volume to result from a given precipitation amount. The curve number is allowed to vary during a simulation with changes in soil moisture. The percolation component of the model uses a storage routing technique to predict flow through specified soil layers in the root zone. The downward flow rate is governed by the hydraulic conductivity of the soil. Upward flow may occur when a lower layer exceeds field capacity. Lateral flow in each soil layer is modeled with a kinematic storage routine that accounts for variations in conductivity, slope, and soil water content. Several optional methods are provided for computing evapotranspiration. Evaporation from soils and plants are treated separately. Stream channel losses are determined as a function of channel length and width and flow duration. The groundwater flow contribution to streamflow may be simulated by creating shallow aquifer storage. The aquifer is recharged by percolation from the soil layers in the root zone. A recession constant may be used to lag flow from the aquifer to the stream. Other flow components reflected in the aquifer storage computations include evaporation, pumping withdrawals, and seepage to a deep aquifer.

The weather variables driving SWAT are precipitation, air temperature, solar radiation, wind speed, and relative humidity. If available, daily precipitation and maximum/minimum temperature data can be input directly to SWAT. If not, the simulator within the model can synthesize daily rainfall and temperature. Solar radiation, wind speed, and relative humidity are always simulated within the model. One set of weather variables may be simulated for the entire basin, or different weather may be simulated for each subbasin.

Essentially all of the input data required for a SWAT simulation is available from existing databases accessed through the SWAT/GRASS Interface (Srinivasan and Arnold 1994; Srinivasan et al. 1996). These databases include the State Soil Geographic (STATSGO) data developed by the USDA, Land Use and Land Cover (LULC) data developed by the USGS, National Weather Service precipitation and climatic data, as well as curve numbers, soil parameters, and other data compiled by the ARS and TAES in conjunction with developing SWAT and the SWAT/GRASS Interface. The geographical information system (GIS) interface was developed using the

Graphical Resources Analysis Support System (GRASS). The SWAT/GRASS Interface will automatically subdivide a basin (grids or subwatersheds) and then extract model input data from map layers and the associated relational data bases for each subbasin. Soils, land use, weather, management, and topographic data are collected and written to appropriate input files.

SWAT or other computer models for simulating watershed hydrology may be applied at various levels of sophistication. More conventional approaches involve using the observed flows at the gages to calibrate the model, and then applying the model to directly produce flows at ungaged sites. The objective of the SWAT component of the present investigation was to adapt the model to the problem of distributing naturalized monthly flows in a reasonably simple manner that still incorporates the capabilities provided by a watershed simulation model. The strategy outlined below was developed in conjunction with the present comparative evaluation of alternative approaches for distributing flows.

Application of SWAT to Predict Flows at the Stations in the San Jacinto Basin

Raju (1998) applied SWAT and the SWAT/GRASS Interface to predict flows at each of the 12 stations in the San Jacinto River Basin described in Chapter 5, given the combined flows. Due to the effort involved, the stations in the Brazos River Basin were not included in the SWAT study. Essentially all weather and watershed data required to perform the SWAT hydrologic simulation were obtained from existing databases through the SWAT/GRASS Interface. The results of the analyses documented in detail by Raju (1998) are briefly summarized here.

As discussed in Chapter 5, the combined known 1940-1980 monthly naturalized flow from the 2,730 mile^2 watershed above the stations is the sum of the concurrent flows at the individual stations. The following procedure was adopted for applying SWAT to distribute known naturalized monthly flows from the combined 2,730 mile^2 watershed to each of the 12 subwatersheds. The flows predicted with the SWAT-based strategy are included in the overall comparison of flows determined using the alternative flow distribution methods.

SWAT performs its computations with a daily time step and then aggregates the results to monthly streamflows. Daily streamflow sequences at each of the 12 stations for the period 1960-1980 were simulated with SWAT for input sequences of 1960-1980 daily precipitation for the Conroe and Houston precipitation gages. These are the only precipitation gages in the database located in the San Jacinto Basin that cover the entire period 1960-1980. The database has no precipitation data prior to 1960.

The required weather data and watershed parameters required for input to SWAT were acquired through the SWAT/GRASS Interface. Developing GIS delineations of the watersheds above the 12 stations represented a major portion of the effort in applying SWAT. With the watershed and stream network delineation files provided as input, the SWAT input data for each subbasin was obtained from existing databases through the automated SWAT/GRASS Interface. Although the subbasin delineations may be performed within GRASS, Raju (1998) actually used Arc/View-based software. ArcView and its Spatial Analyst extension were used to delineate the watersheds and stream networks from digital elevation models. This information was input to the

SWAT/GRASS Interface for use as templates in developing the SWAT simulation input files from the databases. The SWAT simulation was then performed with these input files.

The overall SWAT-based strategy for distributing flows consists of the following steps:

1. SWAT was applied to predict 1960-1980 daily flows at each of the 12 stations for input sequences of 1960-1980 daily precipitation at the Houston and Conroe precipitation gages. Daily flows are aggregated within the model to obtain monthly flows.

2. The 1960-1980 SWAT-predicted monthly flows at the individual stations were summed to obtain combined flows from the 2,730 mile^2 watershed above the stations. Standard least-squares linear regression techniques were applied to the SWAT-predicted flows to obtain a set of equations relating flows at each station to the combined flows.

3. The regression equations noted above were combined with the known combined flows to develop 1940-1980 sequences of naturalized monthly flows at each of the 12 stations.

Results of the SWAT Application

The results of the SWAT simulation are summarized in Figures A.1-A.36 of Appendix A, Tables 6.14 and 6.15, and other tables presented in the next section comparing the alternative methods. Appendix A consists of three sets of regression/correlation plots for the 12 stations corresponding to the steps 1, 2, and 3 listed above. Each of the 36 scatter plots (three sets of 12 stations) compares two sets of monthly naturalized flows. The linear regression equation and coefficient of determination r^2 are shown along with the graphs. The 36 values for the coefficient of determination r^2 are also tabulated as Table 6.14.

As discussed above, the SWAT simulation resulted in 1960-1980 monthly flows at each of the 12 stations. The SWAT predicted flows are compared with the known flows in Figures A.1 through A.12 of Appendix A. Considerable scatter is apparent in the plots. The values of r^2 shown in the second column of Table 6.14 range from 0.38 at station 5 to 0.75 at station 12. In general, the correlation is weak between the monthly flows computed by the uncalibrated SWAT model are the corresponding known flows.

The 1960-1980 SWAT-predicted monthly flows at the individual stations were summed to obtain combined flows from the 2,730 mile^2 watershed above the stations. Linear regression equations were developed relating the SWAT-predicted flows at each station to the combined flows computed by summing the SWAT-predicted flows at the individual stations. Graphs of SWAT-predicted flows at the individual stations versus the combined SWAT-predicted flows are presented as Figures A.13-A.24. The r^2 values are tabulated in the third column of Table 6.14.

The regression equations were applied to the known combined flows to develop 1940-1980 sequences of naturalized monthly flows at each of the 12 stations. The flows predicted from the SWAT-based regression equations are compared to the known flows in Figures A.25 through A.36. The r^2 values for predicted versus known flows are tabulated in the fourth column of Table

6.14. Although there is significant variation between stations, in general, the 1940-1980 flows predicted with the regression equations correlate more closely to the 1940-1980 known flows than the directly-computed SWAT 1960-1980 flows versus 1960-1980 known flows.

Table 6.14 Coefficient of Determination r^2 Values for the SWAT Predictions

Station	SWAT Predicted versus Known Flows r^2	SWAT Predicted Station versus Combined Flows r^2	Regression versus Known Flows r^2
1	0.702	0.941	0.886
2	0.577	0.938	0.897
3	0.613	0.912	0.883
4	0.579	0.854	0.861
5	0.380	0.779	0.746
6	0.619	0.909	0.836
7	0.642	0.503	0.628
9	0.385	0.827	0.687
10	0.458	0.815	0.692
11	0.746	0.499	0.680
12	0.752	0.551	0.538
13	0.706	0.562	0.495

Table 6.15 Comparison of SWAT Predicted Mean Flows

Station	1940-80 Means of Known Flows (ac-ft/month)	1960-80 Means of Known Flows (ac-ft/month)	1940-80 Means Drainage Area Ratio Flows (ac-ft/month)	1960-80 Means SWAT Predicted Flow (ac-ft/month)	1940-80 Means SWAT Regression (ac-ft/month)
1	30,850	31,050	34,200	48,000	33,700
2	13,240	13,380	17,700	20,900	14,800
3	10,090	10,560	12,100	16,200	11,800
4	13,610	13,220	13,700	15,200	10,500
5	4,600	4,490	4,940	4,800	3,390
6	4,630	4,740	4,430	6,590	4,640
7	3,620	3,980	3,060	4,820	3,780
9	13,590	14,370	12,300	22,200	16,240
10	18,010	19,800	15,100	28,800	21,200
11	5,000	5,490	3,570	8,200	6,400
12	7,350	9,050	3,730	3,140	2,320
13	4,550	5,370	2,710	4,350	3,200

The means of the 1960-1980 flows computed directly with the uncalibrated SWAT model, in step 1, and the means of the 1940-1980 flows computed with the regression equations applied to known combined flows, in steps 2 and 3, are tabulated in Table 6.15. The corresponding means of the known flows and the flows determined using drainage area ratios are included in the table for comparison. For the majority of the stations, of the three sets of computed flows:

- the means of the flows computed by the regression equations correlate most closely with the known flows
- the drainage area ratio approach ranks second in most closely reproducing known means
- the direct uncalibrated SWAT results are least accurate

Comparison of Flow Distribution Approaches

This section presents a comparative evaluation of the results of applying the alternative methods outlined earlier in this chapter to compute flows at specified stations from flows at other stations. The following flow distribution methods are applied.

1. drainage area ratio (Equations 6-1 and 6-3)
   [referred to as *Area Ratio* in table headings]
2. combined drainage area, CN, and mean precipitation ratios (Equations 6-1 and 6-5)
   [referred to as *A-CN-M* in table headings]
3. modified NRCS curve number (CN) method (Equations 6-6 and 6-7)
   [referred to as *NRCS CN* in table headings]
4. regression equations from Soil and Water Assessment Tool (SWAT) simulation results
   [referred to as *SWAT Regression* in table headings]

All of the methods, including SWAT, are applied to all of the stations in the San Jacinto River Basin. All of the methods, except SWAT, are applied to the stations in the Little River and Navasota River watersheds of the Brazos River Basin. Only the drainage area ratio method is applied to the stations on the Brazos River, because the large size and complexity of these watersheds made estimation of other watershed parameters difficult. The drainage area ratio and the NRCS curve number methods are applied for the stations in the Sulphur River Basin.

Watershed parameters used in the first three methods listed above are tabulated in Tables 6.1, 6.2, and 6.3. Flows are predicted using the NRCS CN method adaptation with the two alternative sets of curve numbers presented in Tables 6.6 and 6.7. The original set of CN's was developed following conventional procedures with the information summarized in Tables 6.4 and 6.5. As previously discussed, The set of adjusted CN's was developed by iteratively changing the CN for each station until the mean of the predicted flows matched the mean of the known flows.

Stations are paired as follows for purposes of these analyses.

- *Little River Watershed*. Stations 1-6 are paired with station 7 such that flows at each station are computed given the corresponding flows at the station 7. Stations on the same tributaries are also paired such that flows at upstream station are computed given the corresponding flows at the station located downstream. All of the alternative methods except SWAT are used to transpose flows.

- Navasota River Watershed. Flows at station 8 are computed from the flows at station 9. All of the alternative methods except SWAT are applied.

- Main-stem Brazos River Stations. Stations 10 through 15 are paired such that flows at each station are computed given the corresponding flows at the station located immediately downstream. Only the drainage area ratio method is used.

- San Jacinto River Basin. The combined flow from the total watershed above all the stations is distributed to each of the 12 individual stations. All of the alternative methods including SWAT are used. Stations 9 and 10 on Buffalo Bayou are the only stations on the same tributary; station 9 flows are predicted from station 10 flows. For the other stations, given the subwatershed flow at one station, the flow at the station of an adjacent subwatershed is predicted. All of the alternative methods except SWAT are used to transfer flows.

- Sulphur River Basin. The curve number and drainage area ratio methods are used. For stations A, B, and D, flows are transferred from a downstream gage. Flows at station B are computed from flows at the adjacent station A.

The flows computed at each station using the alternative methods are compared with each other and with the known flows at the station. The known and computed sets of monthly flows are summarized by their means, standard deviations, and flow-frequency tables. The relationships between known flows at a station and those computed by the alternative methods are also compared by the standard error of estimate, sum of the deviations, and sum of the percent deviations.

The computations associated with the parameter ratio approaches and NRCS CN method adaptation were performed with the *CurNum*, *Ratio*, and *RECORDS* Fortran programs developed in conjunction with the investigation and described below. The other two Fortran programs noted below were developed to summarize the flows resulting from any of the alternative methods. Microsoft Excel was used in various exercises to analyze and present results.

- Program *CurNum* uses the NRCS CN method adaptation to compute the flows for one location from known flows at another location provided as input. The watershed areas, curve numbers, and mean precipitation for both watersheds are provided as input.

- Program *Ratio* simply multiplies the input set of flows by a ratio also provided as input.

- Program *RECORDS* developed later in conjunction with the *WRAP* model incorporates both the curve number method and the DAR method into one program and essentially replaced programs *CurNum* and *Ratio* used earlier in the study. RECORDS has since been superceded by the *WRAP-HYD* program developed for the *WRAP* model.

- Program *Compare* reads sets of flows for two stations as input and develops statistics comparing them, including monthly and annual means and standard deviations for both stations, mean deviations between the flow sets, sum of squared deviations, mean percent deviations, and standard error of the estimate.

- Program *Frequency* develops a flow-frequency table for an input set of flows.

Comparative Summary of Results

Summary statistics of the period-of-analysis monthly naturalized flows predicted by each of the alternative flow distribution approaches along with values for the known flows are presented in Tables 6.17 through 6.31 and Appendix B Tables B.1 through B.33. The means, standard deviations, standard errors, mean deviations, and mean percent deviations, presented in Tables 6.17-6.31 were computed as follows:

$$mean = \frac{\sum Q_i}{N}$$

$$standard\ deviation = \sqrt{\frac{\sum (Q_i - \overline{Q})^2}{N-1}}$$

$$standard\ error = \sqrt{\frac{\sum (Q_{computed} - Q_{known})^2}{N-2}}$$

$$mean\ deviation = \frac{\sum \left|(Q_{computed} - Q_{known})\right|}{N}$$

$$mean\ percent\ deviation = \frac{\sum \left|\frac{(Q_{computed} - Q_{known})}{Q_{known}}\right| * 100\%}{N}$$

The columns in Tables 6.17-6.31 are explained as follows.

Given Flows - The known flows that are being distributed to other locations consist of either: (1) the known flows at the station cited in the first column that are used to predict flows at the station cited in the second column or (2) the combined flows from the entire 2,730 mile^2 watershed that are being distributed to each of the 12 subwatersheds in the San Jacinto Basin.

Computed Flows at Station - The station at which flows are predicted using the alternative flow distribution approaches.

Known Flows - Statistic (mean, standard deviation, standard error, mean deviation, or mean percent deviation) of the known naturalized monthly flows at the station cited in the second column.

Area Ratio - Statistic of the predicted flows at the station cited in the second column computed by applying a drainage area ratio to the flows cited in the first column.

A-CN-M Ratio - Statistic of the predicted flows at the station cited in the second column computed by applying the product of drainage area, curve number, and mean precipitation ratios to the flows cited in the first column.

NRCS CN Original - Statistic of the predicted flows at the station cited in the second column computed by applying the modified NRCS CN method to the flows cited in the first column, using the original estimates of CN's noted in Tables 6.5 and 6.6.

NRCS CN Adjusted - Statistic of the predicted flows at the station cited in the second column computed by applying the modified NRCS CN method to the flows cited in the first column, using the adjusted estimates of CN's noted in Tables 6.5 and 6.6.

SWAT Regression - Statistic of the predicted flows at the station cited in the second column computed by applying the regression equations developed from SWAT simulation results to the flows cited in the first column.

Flow versus exceedance frequency (also called flow-duration) relationships are provided as Tables B.1 - B.37 of Appendix B. Flows associated with specified exceedance frequencies are also cited in Tables 6.16, 6.32, and 6.33. These are known or computed monthly flow volumes that are equaled or exceeded a specified percentage of the total number of months during the period-of-analysis. For example, Table B.1 indicates that a flow of 547 acre-feet/month is equaled or exceeded during 80 percent of the 444 months of the 1940-1976 sequence of known naturalized flows at Station 1 on the Leon River in the Brazos Basin.

Observations and Conclusions

Stations 10 through 15 on the main-stream Brazos River are significantly different from the others due to their extremely large complicated watersheds. The following discussion is organized such that the analyses of the flows at stations 10-15, representing very large watersheds, are addressed first. Then the results of flow predictions at all the other stations, which represent more moderately sized watersheds, are discussed.

Flows at the Main Stream Brazos River Stations

As discussed in Chapter 5, the 45,000 mile^2 Brazos River Basin above the Richmond gage (station 15) varies dramatically from the upper through the middle and lower portions of basin. Mean annual precipitation varies from about 16 inches to 50 inches. According to the USGS, about 9,750 mile^2 of the extreme upper basin contribute essentially no runoff to the river. Much more of the basin area in the arid high plains above Possum Kingdom Reservoir (station 10) has runoff characteristics represented by a curve number of near zero. Interactions between ground water and surface water are also complex in the upper basin above Possum Kingdom Reservoir.

Due to the size and complexity of the basin, the drainage area method was the only approach applied in the analysis of flows at stations 10 through 15 on the Brazos River. Results are summarized in Table 6.16. Flows at stations 10, 11, 12, 13, and 14 are predicted by applying the drainage area ratios shown in the fourth column of Table 6.16 to the 1940-1976 monthly naturalized flows at station 15. Alternatively, flows at each station are predicted by applying the appropriate drainage area ratio to flows at the adjacent station located immediately downstream. The means of the computed flows, expressed as a percentage of the mean of the known flows, are tabulated in the fifth column. The values of the predicted flow that are equaled or exceeded during 90% and 50% of the 444 months of the 1940-1976 period-of-analysis are tabulated in the last two columns, expressed as a percentage of the corresponding known flows.

Table 6.16 Flows at Brazos River Stations Computed with Drainage Area Ratio Method Expressed as a Percentage of Known Flows

Stations	Drainage Area		Drainage Area Ratio	Predicted Flows as a Percentage of Known Flows		
	(mile^2)	(mile^2)		Mean	90%	50%
10 - 15	23,810	45,010	0.529	393%	2,120%	600%
11 - 15	27,240	45,010	0.605	221%	353%	252%
12 - 15	29,570	45,010	0.657	217%	279%	212%
13 - 15	39,520	45,010	0.878	140%	173%	143%
14 - 15	43,880	45,010	0.975	116%	120%	109%
10 - 11	23,810	27,240	0.874	178%	602%	238%
11 - 12	27,240	29,570	0.921	101%	126%	119%
12 - 13	29,570	39,520	0.748	155%	161%	148%
13 - 14	39,520	43,880	0.901	120%	144%	131%
11 - 10&12	3,430	5,760	0.596	85%	88%	92%
12 - 11&13	2,330	12,280	0.190	113%		
13 - 12&14	9,950	14,310	0.695	107%	126%	116%
14 - 13&15	4,360	5,490	0.794	111%	110%	103%

Applying drainage area ratios to the downstream station 15 total flows results in high predictions of flows at the upstream stations. This is to be expected since the extreme upper basin contributes little runoff per unit of area relative to the middle and lower basin. The accuracy of the flow prediction increases with increases in the drainage area ratio. Application of drainage area ratios to station 15 flows results in the means of the predicted flows ranging from 393 percent of the mean of the known flows at station 10 to 116 percent of the known flows at station 14. Of course, applying drainage area ratios to the flows at the next station located immediately downstream provides better predictions, with the means of the predicted flows ranging form 101 percent to 178 percent of the corresponding means of known flows. For example, predicting flows at station 13 by multiplying the flows at station 14 by a area ratio of 0.901 results in predicted flows with a mean of 120 percent of the mean of the known flows at station 14.

The predictions of low flows are less accurate than the means. The estimates of flows equaled or exceeded 50% of the time are less accurate than the means. Likewise, as indicated by the last two columns of Table 6.16, the predicted 90% flows deviate from the corresponding known flows more the 50% flows.

Better flow predictions are obtained by applying incremental area ratios to incremental flows as indicated by the last four rows of Table 6.16.

$$Q_i = (Q_{i+1} - Q_{1-1})(\frac{A_i - A_{i-1}}{A_{i+1} - A_{i-1}}) + Q_i$$

The flows Q_{11} at station 11 are estimated from the flows Q_{10} and Q_{12} at stations 10 and 12 and drainage areas A_{10}, A_{11}, and A_{12} at stations 10, 11, and 12 as follows:

$$Q_{11} = (Q_{12} - Q_{10})(\frac{A_{11} - A_{10}}{A_{12} - A_{10}}) + Q_{10}$$

Incremental flows from the watershed between stations 10 and 11 obtained by applying a drainage area ratio are added to the flows at station 10 to obtain the flows at station 11. The mean of the resulting predicted flows at station 11 is 85% of the mean of the known flows at station 11. As indicated by Table 6.16, the means of flows predicted in this manner for stations 11 - 14 range from 85% to 113% of the corresponding means of the known flows.

Flows at the Stations on Tributary Streams

The previously described alternative flow distribution methods were applied to flows at stations 1-7 on tributaries in the Little River watershed, stations 8 and 9 on the Navasota River, the 12 stations in the San Jacinto River Basin, and the five stations in the Sulphur River Basin. The watersheds of these 26 stations range in size from 64.0 mile^2 for station 13 on Sims Bayou in Houston to 7,065 mile^2 for station 7 on the Little River. In general, the subwatershed stations for which flows are predicted are fairly small relative to the watershed stations from which the flows are distributed. As indicated in Tables 6.32 and 6.33, drainage area ratios for the pairs of stations on tributaries of the Brazos River vary from 0.178 to 0.939, with three drainage area ratios exceeding 0.5. Subwatershed to total combined watershed area ratios for the 12 stations in the San Jacinto Basin range from 0.023 to 0.297. Comparisons are also made between adjacent subwatersheds where neither is a subwatershed of the other.

The results of applying alternative methods to predict flows at these stations are presented as summary statistics in Tables 6.17 - 6.31 and as flow-frequency tables in Appendix B. Tables 6.32 and 6.33 provide a more concise comparative summary of the information presented in the other tables. Tables 6.32 and 6.33 include mean flows and the flows equaled or exceeded 95%, 80%, and 50% of the months of the period-of-analysis. These statistics of the flows predicted with the alternative methods are expressed as percentages of the corresponding values for the known flows.

In general, predictions for individual months tend to be inaccurate with any of the flow distribution methods. The analyses of Chapter 5 demonstrate a considerable scatter in the relationship between concurrent flows at different stations, thus implying that no method would be very accurate in regard to predicting flows in individual months. Predicted flows are found in the Chapter 6 analyses to deviate greatly from the known flows as expected. Deviations are summarized in by the statistics tabulated in Tables 6.20 through 6.31. Of course, at a given station, the predictions are closer to known flows in some months than in others. The average deviation between predicted and known flows, expressed as a percentage of the known flows, are tabulated in Tables 6.26, 6.27, and 6.28.

The means and flow-frequency relationships also depart significantly from those of the known flows. However, means are reproduced much more accurately than the flows in individual months. Means are compared in Tables 6.17, 6.18, 6.19, and 6.33. Predicted and known means are fairly close for those pairs of stations for which the subwatershed comprised a major portion of the watershed. Means compare less favorably for those stations where the subwatershed area for the station for which flows are computed is small relative to the watershed area of the given-flows station.

The predicted means are also more accurate than the low flows. Complete flow-frequency tables are provided in Appendix B. Means and 95%, 80%, and 50% exceedance frequency flows are expressed as a percentage of the corresponding values of the known flows in Tables 6.32 and 6.33. Values of 100% would indicate a perfect agreement between the known versus computed flows at a station. The values in Tables 6.32 and 6.33 vary greatly from the perfect 100 percent. The means are reproduced more closely than the 50% exceedance frequency flows which, in turn, are reproduced better than the 80% frequency flows. The 95% exceedance frequency flows vary from the known flows more than the 80% exceedance frequency flows.

The relative performance of the alternative flow distribution methods vary significantly between stations. Each method reproduces the mean and flow-frequency relationship of the known flows at some stations more closely than the other alternative methods but performs worst at other stations. The scatter of the results prevents a clear conclusion in regard to which method performed best overall for the selected stations investigated.

Table 6.17 Means for Alternative Flow Distribution Approaches for the Brazos Basin

Given Flows	Computed Flows at Station	Mean (ac-ft/mon)				
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
7	1	9568	19708	18158	18174	9564
7	2	43194	55471	54918	52965	43329
7	3	17657	19487	18490	17712	17480
7	4	20309	20379	21920	22264	21810
7	5	7548	5695	4004	5384	5829
7	6	15729	13375	12552	16129	15672
9	8	26623	21704	26623	20845	12978
2	1	9568	15377	14297	14871	9576
4	3	17993	20443	18396	17401	17547
6	5	7548	5244	5275	5314	4599

Table 6.18 Means for Alternative Flow Distribution Approaches for the San Jacinto Basin

Given Flows	Computed Flows at Station	Mean (ac-ft/mon)					
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
Combined	1	30848	34199	30681	23425	30795	33710
Combined	2	13237	17733	16840	15171	13209	14841
Combined	3	10089	12090	15917	18643	13648	11843
Combined	4	13613	13702	12572	9532	10108	10505
Combined	5	4598	4940	4522	3412	4601	3386
Combined	6	4633	4433	3887	2660	4632	4636
Combined	8	3623	3063	3656	5471	3620	3778
Combined	9	13590	12321	14072	19939	13576	16238
Combined	10	18008	15084	17186	24236	17996	21166
Combined	11	4995	3570	4464	7475	4986	6398
Combined	12	7345	3731	4695	8194	7342	2322
Combined	13	4545	2706	3345	5306	4545	3201
4	5	4598	4901	4901	4877	4612	
5	6	4633	4125	3950	3602	4649	
6	1	30848	35699	36510	4633	30755	
1	2	13237	15979	16936	19393	13128	
2	3	10089	9107	10126	12824	10092	
3	8	3623	2270	2734	3002	3551	
8	11	4995	4221	4167	3623	4732	
11	10	18008	21113	20329	4988	18219	
10	9	13590	14730	4430	14822	13622	
10	12	7345	13038	14460	6223	7254	
12	13	4545	8976	8814	4778	4615	

Table 6.19 Means for Alternative Flow Distribution Approaches for the Sulphur Basin

Given Flows	Computed Flows at Station	Mean (ac-ft/mon)				
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
C	A	27099	33758	-	26761	-
C	B	16292	19680	-	19918	-
E	D	43084	35916	-	37917	-
A	B	14762	14551	-	18522	-

Table 6.20 Standard Deviations for Alternative Flow Distribution Approaches for the Brazos Basin

Given Flows	Computed Flows at Station	Standard Deviation (acre-feet/month)				
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
7	1	11053	14783	13620	13485	9379
7	2	41482	41609	41193	40615	35616
7	3	16897	14617	13870	13545	12928
7	4	29292	25320	22040	22424	21698
7	5	7141	6054	3201	3709	3592
7	6	17311	15747	9608	10415	10359
9	8	20074	16383	10763	10589	11923
2	1	11053	14768	13731	13761	11159
4	3	27497	23544	21187	20511	20053
6	5	7141	3941	3964	3983	4239

Table 6.21 Standard Deviations for Alternative Flow Distribution Approaches for the San Jacinto Basin

Given Flows	Computed Flows at Station	Standard Deviation (ac-ft/mon) Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
Combined	1	25745	24698	21541	20277	22964	26199
Combined	2	12334	12806	11823	11526	11272	11032
Combined	3	9138	8732	11176	9897	8067	7956
Combined	4	12449	9896	8827	8415	10005	8953
Combined	5	3842	3568	3175	3022	3550	2568
Combined	6	3581	3202	2729	2531	3298	3590
Combined	8	3285	2212	2567	2719	2365	1903
Combined	9	10057	8898	9880	10328	9264	10957
Combined	10	11472	10894	12066	12617	11689	13959
Combined	11	3688	2578	3134	3335	2936	3300
Combined	12	4531	2694	3296	3556	3436	1488
Combined	13	3367	1954	2350	2490	2369	2095
4	5	3842	4482	4482	4473	4446	
5	6	3581	3446	3300	3261	3536	
6	1	25745	27593	28219	3581	25045	
1	2	12334	13336	14134	14419	13457	
2	3	9139	8486	9435	10904	8798	
3	8	3285	2056	2477	2535	2666	
8	11	3688	3827	3778	3285	4290	
11	10	11472	15589	15010	3692	14681	
10	9	10057	9389	2822	9400	9041	
10	12	4531	8306	9212	3347	3481	
12	13	3367	5537	5437	3153	3113	

Table 6.22 Standard Deviations for Alternative Flow Distribution Approaches for the Sulphur Basin

Given Flows	Computed Flows at Station	Standard Deviation (acre-feet/month) Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
C	A	19931	23337	-	20551	-
C	B	11487	12353	-	12403	-
E	D	43501	32726	-	33788	-
A	B	8933	8339	-	9868	-

Table 6.23 Standard Error for Alternative Flow Distribution Approaches for the Brazos Basin

Given Flows	Computed Flows at Station	Standard Error (acre-feet/month) Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
7	1	-0-	24290	22248	22102	16407
7	2	-0-	31544	31039	29849	26237
7	3	-0-	10811	10930	10992	11335
7	4	-0-	43492	41327	41640	15963
7	5	-0-	8726	9227	9041	3619
7	6	-0-	27421	25704	10112	10229
9	8	-0-	55077	17140	17729	24439
2	1	-0-	17736	16333	16568	13565
4	3	-0-	42643	40304	39630	9635
6	5	-0-	760	9760	9764	8599

Table 6.24 Standard Error for Alternative Flow Distribution Approaches for the San Jacinto Basin

Given Flows	Computed Flows at Station	Standard Error (acre-feet/month) Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
combined	1	-0-	16351	16481	19209	16204	16513
combined	2	-0-	8744	8324	7603	7149	7495
combined	3	-0-	6004	10347	11561	5683	5949
combined	4	-0-	8338	9313	10470	8279	9407
combined	5	-0-	3399	3772	3902	3349	3596
combined	6	-0-	2486	2798	3460	2507	2646
combined	8	-0	3486	3612	4122	3405	3549
combined	9	-0-	10424	11002	13000	10401	11592
combined	10	-0-	12896	13435	15121	12702	14484
combined	11	-0-	3870	3852	4647	3526	2905
combined	12	-0-	6957	6556	5966	5656	8435
combined	13	-0-	4802	4673	4533	4304	4582
4	5	-0-	3487	3489	3477	3418	
5	6	-0-	3172	3172	3297	3132	
6	1	-0-	21048	21848	49327	20484	
1	2	-0-	10391	11305	12954	9427	
2	3	-0-	5697	5586	8220	5626	
3	8	-0-	3986	3831	3771	3740	
8	11	-0-	2203	2204	2444	2245	
11	10	-0-	14164	13518	21721	13036	
10	9	-0-	3086	15809	3127	2873	
10	12	-0-	12528	14589	5515	5381	
12	13	-0-	6683	6448	1973	6683	

Table 6.25 Standard Error for Alternative Flow Distribution Approaches for the Sulphur Basin

Given Flows	Computed Flows at Station	Standard Error (ac-ft/mon)				
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
C	A	0	18347	-	14273	-
C	B	0	13239	-	13366	-
D	E	0	32711	-	31936	-
A	B	0	11047	-	12892	-

Table 6.26 Mean Deviation for Alternative Flow Distribution Approaches for the Brazos Basin

Given Flows	Computed Flows at Station	Mean Deviation (ac-ft/mon)				
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
7	1	-0-	13589	12444	12447	7762
7	2	-0-	17467	17165	16114	13401
7	3	-0-	6037	5978	5893	5976
7	4	-0-	24742	24677	24909	8262
7	5	-0-	6010	5930	6068	2234
7	6	-0-	18405	17006	5386	6057
9	8	-0-	30794	8286	8617	13125
2	1	-0-	8945	8305	8639	6353
4	3	-0-	23683	22227	21626	4784
6	5	-0-	558	6666	6670	5447

Table 6.27 Mean Deviation for Alternative Flow Distribution Approaches for the San Jacinto Basin

	Computed	Mean Deviation (ac-ft/mon)					
Given Flows	Flows at Station	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
combined	1	-0-	9861	9572	11051	9326	9580
combined	2	-0-	5778	5357	4404	3797	4384
combined	3	-0-	3977	6585	9088	3259	4098
combined	4	-0-	4819	5044	5727	4791	5324
combined	5	-0-	1852	1823	2012	1831	1865
combined	6	-0-	1430	1572	2253	1433	1594
combined	8	-0	1753	1860	2861	1847	2143
combined	9	-0-	6066	6392	8963	6158	6933
combined	10	-0-	7672	7814	9951	7633	8581
combined	11	-0-	2273	2146	3343	2116	2709
combined	12	-0-	4215	3878	3742	3468	5159
combined	13	-0-	2490	2370	2680	2353	2317
4	5	-0-	1680	1680	1677	1697	
5	6	-0-	1294	1347	1558	1253	
6	1	-0-	12956	13275	26231	11310	
1	2	-0-	5568	6090	7688	4859	
2	3	-0-	2877	3083	4491	3010	
3	8	-0-	1941	1865	1821	1848	
8	11	-0-	1346	1363	1652	1147	
11	10	-0-	8170	7759	13068	7319	
10	9	-0-	1847	9166	1893	1539	
10	12	-0-	6917	8095	3087	3130	
12	13	-0-	4506	4350	1088	1040	

Table 6.28 Mean Deviation for Alternative Flow Distribution Approaches for the Sulphur Basin

	Computed	Mean Deviation (ac-ft/mon)				
Given Flows	Flows at Station	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
C	A	0	9603	-	7746	-
C	B	0	7023	-	7119	-
D	E	0	17206	-	17136	-
A	B	0	6019	-	7245	-
				-		

Table 6.29 Mean Percent Deviations for Alternative Flow Distribution Approaches for the Brazos Basin

Given Flows	Computed Flows at Station	Mean Percent Deviation (%)				
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
7	1	-0-	1337	1227	1266	238
7	2	-0-	735	727	543	148
7	3	-0-	90	81	74	80
7	4	-0-	352	965	980	67
7	5	-0-	355	125	167	133
7	6	-0-	360	602	116	105
9	8	-0-	2394	209	195	75
2	1	-0-	643	594	706	179
4	3	-0-	1465	1315	1243	43
6	5	-0-	12	183	184	372

Table 6.30 Mean Percent Deviations for Alternative Flow Distribution Approaches for the San Jacinto Basin

Given Flows	Computed Flows at Station	Mean Percent Deviation (%)					
		Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
Combined	1	-0-	152	134	82	123	120
Combined	2	-0-	142	135	95	64	95
Combined	3	-0-	311	462	1165	157	522
Combined	4	-0-	90	84	66	88	76
Combined	5	-0-	58	55	59	55	53
Combined	6	-0-	46	46	67	46	56
Combined	8	-0	248	320	1024	391	977
Combined	9	-0-	131	170	448	167	242
Combined	10	-0-	61	76	178	83	112
Combined	11	-0-	67	83	309	123	281
Combined	12	-0-	68	74	178	144	69
Combined	13	-0-	65	74	178	130	75
4	5	-0-	41	41	41	46	
5	6	-0-	25	26	36	27	
6	1	-0-	165	171	69	117	
1	2	-0-	73	79	125	69	
2	3	-0-	170	190	256	258	
3	8	-0-	95	107	146	263	
8	11	-0-	46	47	51	35	
11	10	-0-	64	61	69	56	
10	9	-0-	53	59	56	31	
10	12	-0-	125	144	64	93	
12	13	-0-	136	132	33	32	

Table 6.31 Mean Percent Deviations for Alternative Flow Distribution Approaches for the Sulphur Basin

Given Flows	Computed Flows at Station	Mean Percent Deviation (%) Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
C	A	0	128	-	55	-
C	B	0	144	-	156	-
E	D	0	58	-	70	-
A	B	0	92	-	139	-

Table 6.32 95% and 80% Exceedance Frequency Flows as a Percentage of Known Flows

		Flow Exceeded 95% of Time with Alternative Flow Prediction Methods					Flow Exceeded 80% of Time with Alternative Flow Prediction Methods			
Drainage Area Ratio	Stations	Area Ratio	A-CN-M Ratio	NRCS CN	SWAT Regressed	Stations	Area Ratio	A-CN-M Ratio	NRCS CN	SWAT Regressed
	Little River Subbasin Stations									
0.178	1-7	860	793	896	-	1-7	469	432	450	-
0.501	2-7	522	517	378	-	2-7	205	203	179	-
0.176	3-7	82	78	58	-	3-7	177	168	149	-
0.187	4-7	23	177	178	-	4-7	38	111	112	-
0.035	5-7	51	137	293	-	5-7	63	89	162	-
0.104	6-7	39	157	328	-	6-7	42	103	184	-
0.356	1-2	165	154	333	-	1-2	229	212	265	-
0.939	3-4	277	250	211	-	3-4	265	238	213	-
0.336	5-6	87	87	90	-	5-6	89	89	91	-
	Navasota River Stations									
0.666	8-9	86	190	110	-	8-9	126	190	162	-
	San Jacinto Basin Station Versus Combined									
0.297	1-C	294	256	37	0	1-C	279	251	82	151
0.154	2-C	254	235	136	121	2-C	236	224	156	161
0.104	3-C	655	838	2491	1192	3-C	281	369	794	375
0.119	4-C	141	126	13	0	4-C	164	150	44	49
0.043	5-C	70	62	6.1	14	5-C	87	79	23	42
0.038	6-C	50	42	.47	0	6-C	74	65	9.6	44
0.027	8-C	782	907	3996	4720	8-C	205	233	747	669
0.107	9-C	313	348	1325	746	9-C	157	179	484	277
0.131	10-C	134	148	555	390	10-C	91	103	276	185
0.031	11-C	146	177	1078	1220	11-C	98	123	486	449
0.032	12-C	67	81	541	100	12-C	49	62	264	49
0.023	13-C	76	91	480	196	13-C	69	85	299	122
	San Jacinto Basin Adjacent Subwatersheds									
0.360	4-5	49	49	48	-	4-5	53	53	52	-
0.897	5-6	71	68	46	-	5-6	85	81	61	-
7.705	6-1	592	604	77	-	6-1	378	387	49	-
0.518	1-2	86	92	167	-	1-2	84	89	163	-
0.680	2-3	260	289	377	-	2-3	120	134	175	-
0.255	3-8	107	129	300	-	3-8	65	78	123	-
1.165	8-11	19	18	16	-	8-11	48	47	41	-
4.227	11-10	92	88	11	-	11-10	92	89	22	-
0.247	10-12	146	162	167	-	10-12	159	176	123	-
0.662	12-13	193	189	65	-	12-13	237	233	100	-
0.816	9-10	71	71	244	-	10-9	52	52	177	
	Sulphur River Basin									
0.392	C-A	3800	-	100	-	C-A	237	-	14	-
0.225	C-B	138	-	195	-	C-B	152	-	166	-
0.192	E-D	52	-	105	-	E-D	75	-	103	-
0.575	A-B	100	-	100	-	A-B	45	-	77	-

Table 6.33 50% Exceedance Frequency and Mean Flows as a Percentage of Known Flows

		Flow Exceeded 50% of Time with Alternative Flow Prediction Methods					Mean of Flows Computed with Alternative Flow Prediction Methods			
	Stations	Area Ratio	A-CN-M Ratio	NRCS CN	SWAT Regressed	Stations	Area Ratio	A-CN-M Ratio	NRCS CN	SWAT Regressed
		Little River Subbasin Stations								
0.178	1-7	333	307	312	-	1-7	206	190	190	-
0.501	2-7	164	162	151		2-7	128	127	123	-
0.176	3-7	156	148	138		3-7	111	105	100	-
0.187	4-7	77	130	131	-	4-7	100	108	110	-
0.035	5-7	90	81	120	-	5-7	75	53	71	-
0.104	6-7	71	90	132	-	6-7	85	80	103	-
0.356	1-2	204	190	211	-	1-2	161	149	155	-
0.939	3-4	156	140	129	-	3-4	114	102	97	-
0.336	5-6	88	88	89	-	5-6	70	70	70	-
		Navasota River Stations								
0.666	8-9	87	140	131	-	8-9	82	100	78	-
		San Jacinto Basin Station Versus Combined								
0.297	1-C	146	133	75	132	1-C	111	100	76	109
0.154	2-C	227	219	178	185	2-C	134	127	115	112
0.104	3-C	197	263	400	210	3-C	120	160	185	117
0.119	4-C	138	128	69	78	4-C	101	92	70	77
0.043	5-C	105	97	52	68	5-C	107	98	74	74
0.038	6-C	91	81	33	87	6-C	96	84	57	100
0.027	8-C	108	131	266	181	8-C	85	101	151	104
0.107	9-C	100	117	218	143	9-C	91	104	147	119
0.131	10-C	82	95	175	127	10-C	84	94	135	118
0.031	11-C	65	82	199	156	11-C	71	89	150	128
0.032	12-C	39	50	128	28	12-C	51	64	112	32
0.023	13-C	57	72	160	76	13-C	60	74	117	71
		San Jacinto Basin Adjacent Subwatersheds								
0.360	5-4	76	76	75	-	4-5	107	107	106	-
0.897	6-5	87	87	83	-	5-6	89	85	78	-
7.705	1-6	161	164	21	-	6-1	116	118	15	-
0.518	2-1	155	164	227	-	1-2	121	128	147	-
0.680	3-2	88	98	128	-	2-3	90	100	127	-
0.255	8-3	49	59	75	-	3-8	63	75	83	-
1.165	11-8	60	58	51	-	8-11	85	83	73	-
4.227	10-11	127	122	30	-	11-10	117	113	28	-
0.247	12-11	140	155	81	-	10-12	178	197	85	-
0.662	13-12	247	242	122	-	12-13	197	194	105	-
0.816	9-10	37	37	124	-	10-9	108	33	109	-
	Sulphur River Basin									
	C-A	158	-	96	-	C-A	125	-	99	-
	C-B	118	-	121	-	C-B	121	-	122	-
	E-D	113	-	127	-	E-D	83	-	88	-
	A-B	94	-	158	-	A-B	99	-	126	-

CHAPTER 7
SUMMARY AND CONCLUSIONS

This report documents an investigation of methodologies for transposing sequences of monthly naturalized streamflows from gaged watersheds to ungaged subwatersheds. The objective is to develop improved capabilities for synthesizing flows at numerous ungaged water rights sites in conjunction with the TNRCC Water Availability Modeling (WAM) System. Key watershed characteristics to be incorporated into flow distribution methodologies are investigated. Alternative approaches for distributing flows are identified, developed, and evaluated. Several methods are tested by predicting flows at locations for which known flows are available for comparison. Analyses of naturalized monthly flows at 32 stream gaging stations in the Brazos, San Jacinto, and Sulphur River Basins include (1) an investigation of the relationships between flows at different locations and (2) a comparative evaluation of methods for distributing flows.

Alternative Flow Distribution Methods

A review of the published literature and the practices of agencies and consulting firms resulted in identification of the following alternative approaches for distributing flows.

- distribution of flows in proportion to drainage area
- flow distribution equation with ratios for various watershed parameters including drainage area, curve number, and mean precipitation
- adaptation of the NRCS curve number method
- use of stream gage records to develop regression equations relating flows to watershed characteristics
- use of recorded data at gaging stations to develop precipitation-runoff relationships
- watershed (precipitation-runoff) simulation computer models

Selected methods were examined in greater depth through application to the Brazos and San Jacinto River Basin data sets. Gaging stations in the Sulphur River Basin were added later in the investigation to further expand the data base. Flows computed with alternative methods were compared with each other and with known flows.

The first general strategy investigated in the analyses of flows at the selected gaging stations is based on the following relationship.

$$Q_{\text{ungaged}} = C\, Q_{\text{gage}}$$

$$C = \left(\frac{A_{ungaged}}{A_{gage}}\right)^{N1}\left(\frac{CN_{ungaged}}{CN_{gage}}\right)^{N2}\left(\frac{M_{ungaged}}{M_{gage}}\right)^{N3}$$

The exponent $N1$ for the drainage area A ratio was found to be reasonably constant with a value of approximately one (1.0). The exponents $N2$ and $N3$ for the curve number CN and mean precipitation M ratios appear to vary greatly between months and between locations. Values of one for $N1$ and $N2$ were assumed, resulting in the following expression for C.

$$C = \left(\frac{A_{ungaged}}{A_{gage}} \right) \left(\frac{CN_{ungaged}}{CN_{gage}} \right) \left(\frac{M_{ungaged}}{M_{gage}} \right)$$

This expression reduces to application of a simple drainage area ratio if the CN and mean precipitation are the same for both the gaged and ungaged watersheds.

$$\mathrm{Q}_{\mathrm{ungaged}} = \left(\frac{A_{ungaged}}{A_{gage}} \right) \mathrm{Q}_{\mathrm{gage}}$$

The second approach consists of adapting the Natural Resource Conservation Service (NRCS) rainfall-runoff relationship to the problem of distributing monthly flows, realizing that the method was not originally designed for this particular type of application. The modified NRCS curve number (CN) method is advantageous over the parameter ratio approach from the perspective of providing a more conceptual relationship for incorporating the CN and mean precipitation. The concept of distributing flows in direct proportion to drainage area is also explicitly inherent in the NRCS CN method. If the CN and mean precipitation are assumed to be identical for both watersheds, the NRCS CN method adaptation predicts identically the same flows as the drainage area ratio method.

Another approach for developing flows at ungaged watersheds is to apply a computer simulation model that simulates the processes by which precipitation is transformed to streamflow. Leading generalized watershed (precipitation-runoff) models include the U.S. Environmental Protection Agency's *Hydrologic Simulation Program-Fortran (HSPF)*, Danish Hydraulic Institute's *MIKE SHE (Systeme Hydroloqique Europeen)*, and USDA Agricultural Research Service's *Soil and Water Assessment Tool (SWAT)*. These are comprehensive models for simulating watershed hydrology and water quality. SWAT is particularly advantageous from the perspective obtaining simulation input from existing databases through a GIS interface.

The last alternative strategy adopted in the study involved application of the *SWAT* hydrologic simulation model in combination with the SWAT/GRASS GIS Interface which facilitates access to existing databases for developing precipitation, weather, and watershed parameter input data. The *SWAT* portion of the study was limited in scope and involved only the San Jacinto River Basin. The general strategy for applying *SWAT* adopted in this study consists of the following steps.

- Daily flows at all pertinent locations are computed by SWAT for input sequences of daily precipitation. Daily flows are aggregated to monthly flows.

- Least-squares linear regression techniques are applied to the SWAT-simulated monthly flows to obtain a set of equations relating SWAT-predicted flows at the site of given known flows versus SWAT-predicted flows at the sites to which the given flows are to be distributed.

- The regression equations are combined with the given known flows to develop sequences of monthly flows at each of the sites.

Conclusions

- *Concurrent subwatershed versus watershed flows in individual months are not closely correlated. Long-term means are much more closely correlated than the flows in specific months.*

Scatter plots, regression/correlation analyses, and examination of flow ratios indicate that the correlation between concurrent flows in specific months at the sets of stations adopted for the study tends to be fairly weak. Subwatershed flows are not a constant proportion of watershed flows.

Long-term means and other statistical characteristics of flows at different locations are significantly more closely related than the actual flows in individual months. However, there is also significant scatter in relating means and flow-frequency relationships at different locations.

The correlation is dependent on the proportion of the watershed area that is contained within the subwatershed. For the majority of the pairs of stations in the case study, the subwatershed stations to which flows were distributed represent a relatively small portion of the larger watershed of the given flows. In some cases, flows were transposed between adjacent separate watersheds. Flows are more closely correlated in situations where an ungaged subwatershed covers most of the gaged watershed.

Temporal and spatial variations in rainfall probably account for much of the scatter in the monthly flow comparisons. A particular rainfall event will be centered over a portion of one watershed with little rain falling in adjacent watersheds. The next rain storm will then be concentrated in another subwatershed. Over the course of a year or many years, the temporal and spatial variations of rainfall tend to average out. However, the temporal variations for storm event runoff and monthly runoff are great. Precipitation gages are too sparsely located to capture the significant variation in rainfall over short distances. The flow distribution methods should reflect pertinent characteristics of precipitation even though the spatial rainfall variations within each month are not captured.

- *Flow predictions for a specific month with any flow distribution method are not highly accurate. However, means and others flow characteristics can be estimated with a reasonable degree of accuracy.*

Since concurrent flows are not closely correlated, none of the methods investigated for distributing flows will be highly reliable for predicting flows in any specified month. However, in water availability modeling, the primary concern is that the predicted flow sequences reproduce relevant characteristics of historical flows, not necessarily an accurate flow estimate for each individual month. The temporal correlation in the sequencing of multiple months of low flows or higher flows reflected in the gaged flows is explicitly transposed to the ungaged site by any of the methods. Reproducing flow-frequency relationships is also important and is not achieved by any of the methods as well as hoped.

With all of the flow distribution methods, predicted flows vary greatly from the known flows in individual months. All of the methods predict long-term means and flow-frequency relationships much more accurately than flows in individual months. However, none of the flow characteristics are reproduced with a really high degree of accuracy with any of the flow distribution methods. Means are estimated more accurately than flow-frequency relationships and low flows.

- *The most important watershed parameters are drainage area, land cover and soil type (represented by the curve number), and mean precipitation.*

The drainage area is the most important watershed parameter. In general, application of a simple drainage area ratio predicts long-term means and frequency-flow relationships at the selected stations tolerably well. The DA-CN-M parameter ratio equation and NRCS CN method adaptation incorporate the CN (reflecting soil type and land use) and mean precipitation as well as drainage area. The incremental gains or losses in accuracy in reproducing known flows associated with these two methods vary significantly between the sets of stations investigated. Although the incremental improvements in accuracy resulting from incorporation of the curve number and mean precipitation are relatively small in general, the improvements may be significant if there are significant differences in land use, soil type, and/or mean precipitation.

SWAT incorporates the drainage area and curve number as well as sequences of daily precipitation, other weather data affecting evapotranspiration and other hydrologic processes, and parameters affecting subsurface flow and storage. However, while incorporating much more information, in general, the SWAT-based approach provided about the same level of accuracy as the other methods in reproducing known flows at the 12 stations for which it was applied. The regression equations developed from the SWAT simulation results reproduced the known flows significantly better than using the uncalibrated SWAT output directly.

- *The alternative flow distribution methods provide about the same level of accuracy.*

Alternative methods may be evaluated in terms of improvements over the simple drainage area ratio method in reproducing means, flow-frequency relationships, and other relevant flow characteristics. For the case study watersheds, the other methods provide only minimal, if any, improvements in reproducing characteristics of the known flows. The DA-CN-M parameter ratio equation, modified NRCS CN method, and SWAT regression procedure performed at about the same level of accuracy. However, for most of the pairs of stations analyzed, the differences in CN and mean precipitation are relatively small. Improvements over the drainage area ratio method are dependent on the relative magnitude of the differences in land cover, soil type, and/or mean precipitation. Conceptually, flow distribution methods incorporating land use, soil type, and precipitation along with drainage area should logically be more accurate than the simple drainage area ratio approach.

- *Modeling validity depends upon capabilities for accurately estimating values for the watershed parameters as well as the flow distribution methodology selected. Estimating values for watershed parameters involves uncertainties and is not necessarily highly precise.*

Recommended Methods

The following methods are recommended for adoption by the Texas Natural Resource Conservation Commission (TNRCC) for distributing flows from gaged watersheds to ungaged subwatersheds in conjunction with the statewide Water Availability Modeling (WAM) Project.

- drainage area ratio method (Equations 6-1 and 6-3 on pages 89-90)
- NRCS curve number adaptation (Equations 6-6 and 6-7 on page 91)

The drainage area ratio method and modified NRCS curve number method are recommended for most routine applications in water availability modeling. The modified NRCS CN method allows differences in land cover, soil types, and mean precipitation to be reflected in the flow distribution. If these parameters are the same for both the gaged watershed and ungaged subwatershed, the NRCS CN method adaptation reduces to the drainage area ratio method. The decision to use the NRCS CN method rather than the drainage area ratio method for a particular subwatershed is based on judgment considering the relative importance of the differences between the CN and mean precipitation of the ungaged subwatershed and gaged watershed and capabilities for estimating values for the parameters. If the CN's and mean precipitation are about the same within some reasonable range of estimation accuracy, there is no need to use the NRCS CN method adaptation; the drainage area ratio method is adequate.

The drainage area ratio method and NRCS CN method adaptation can be readily incorporated into the *Water Rights Analysis Package (WRAP)*. An *ArcView* based GIS is being developed at the Center for Research in Water Resources of the University of Texas, under contract with the TNRCC, that will read a list of coordinates associated with the sites of available naturalized streamflows and water rights and perform the following tasks for each site:

- delineate watersheds and determine drainage areas
- access soils, land use, and mean precipitation databases
- generate curve numbers for grid cells
- determine the curve number and mean precipitation for each watershed and subwatershed

The Soil and Water Assessment Too (*SWAT*) provides greater sophistication in simulating hydrologic processes. Further research is required to formulate roles for hydrologic simulation models in water availability modeling. Areas of complexity that could be further investigated regarding the potential for applying *SWAT* include the following.

- Flows from subwatersheds that are extremely small relative to the watershed of the nearest stream gage can not be predicted accurately with any of the flow distribution methods. Flows computed with SWAT from daily precipitation might be a better approach for very small watersheds located far from any stream gaging station.

- Improved capabilities for modeling the interactions between streamflow and subsurface flows are important for certain river reaches. SWAT provides capabilities for modeling the processes involved in surface/subsurface interactions.

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APPENDIX A

REGRESSION PLOTS
FROM THE
SWAT ANALYSES

Figure A.1 Predicted flows Vs Naturalized flows at station 1

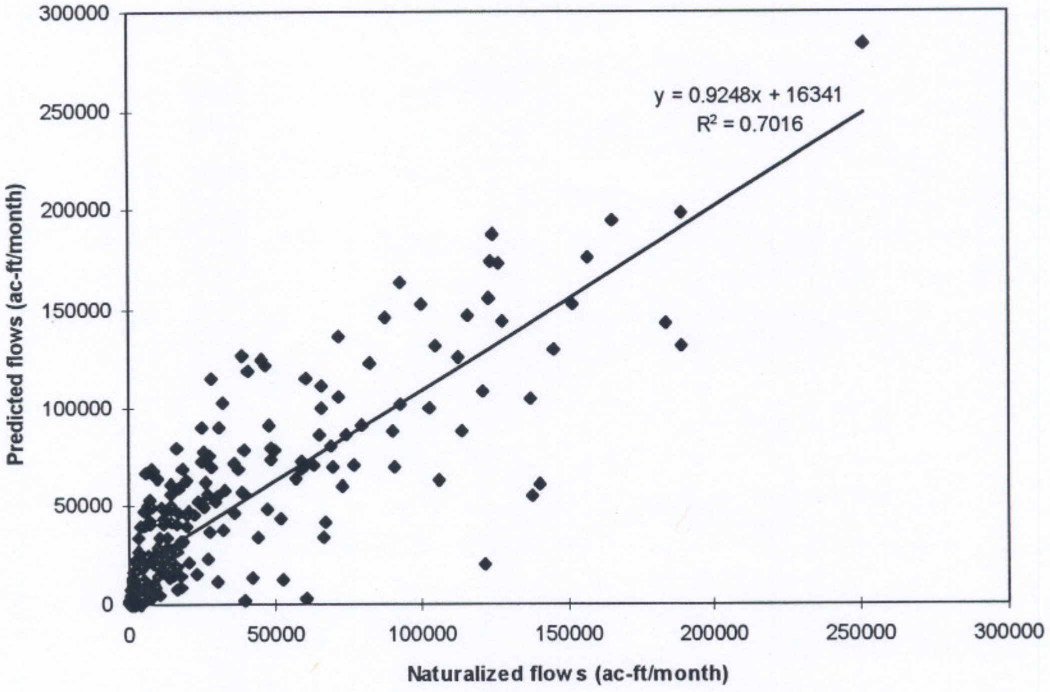


Figure A.2 Predicted flows Vs Naturalized flows at station 2

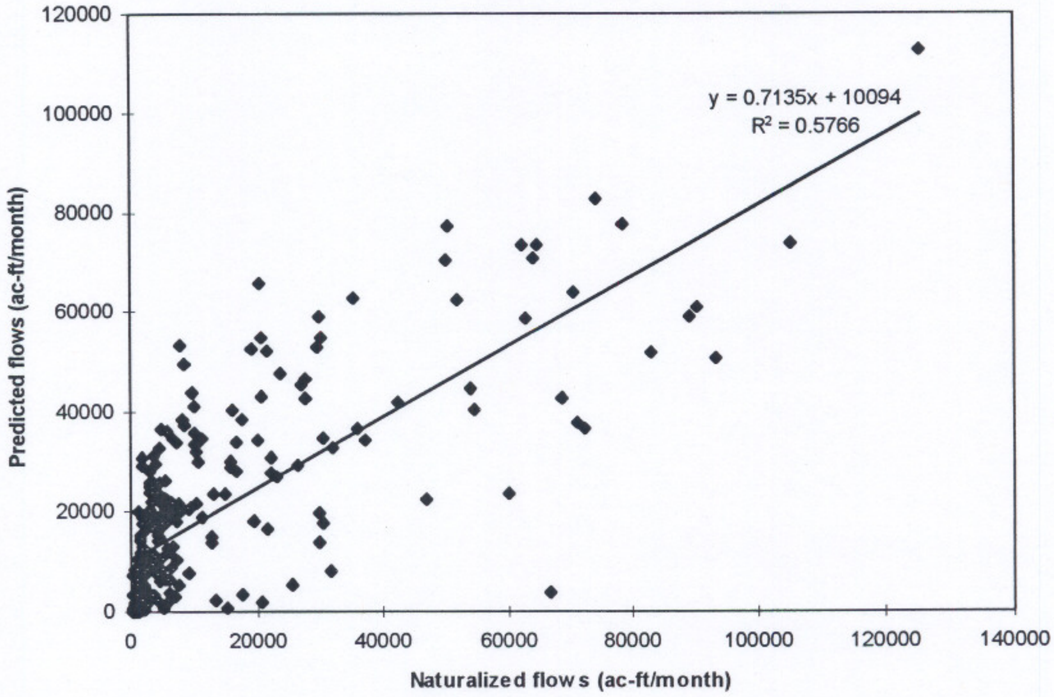


Figure A.3 Predicted flows Vs Naturalized flows at station 3

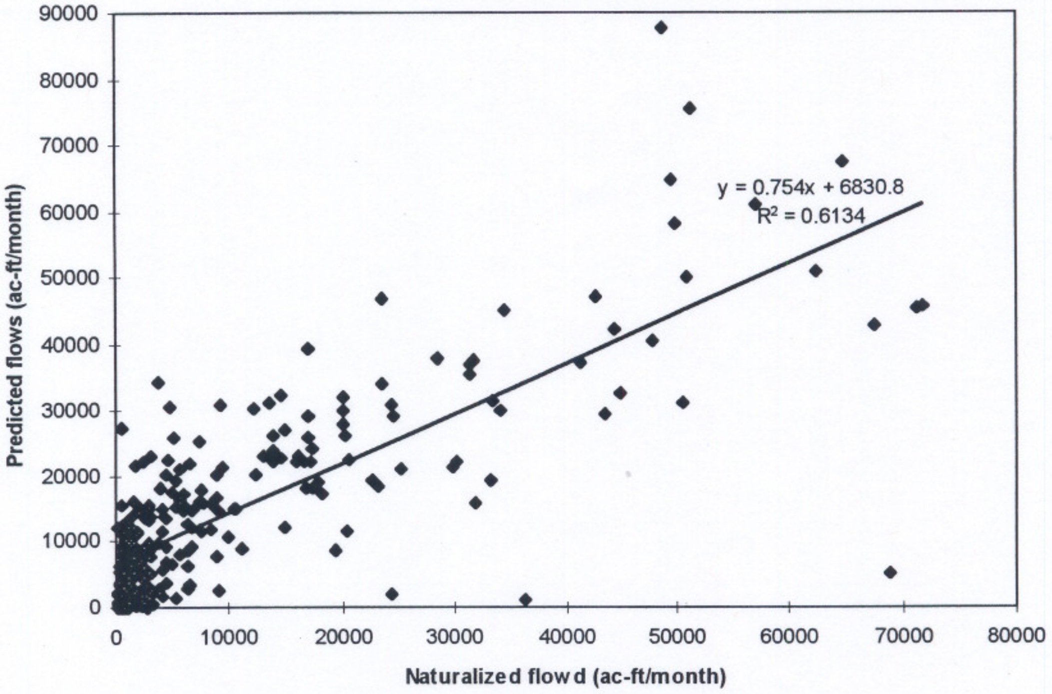


Figure A.4 Predicted flows Vs Naturalized flows at station 4

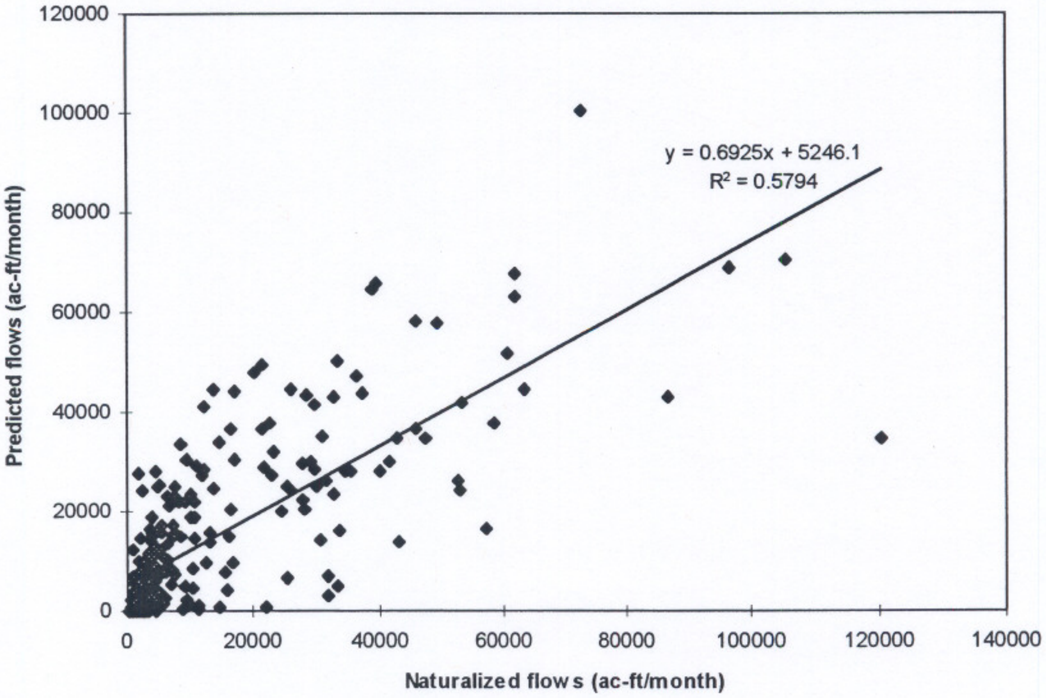


Figure A.5 Predicted flows Vs Naturalized flows at station 5

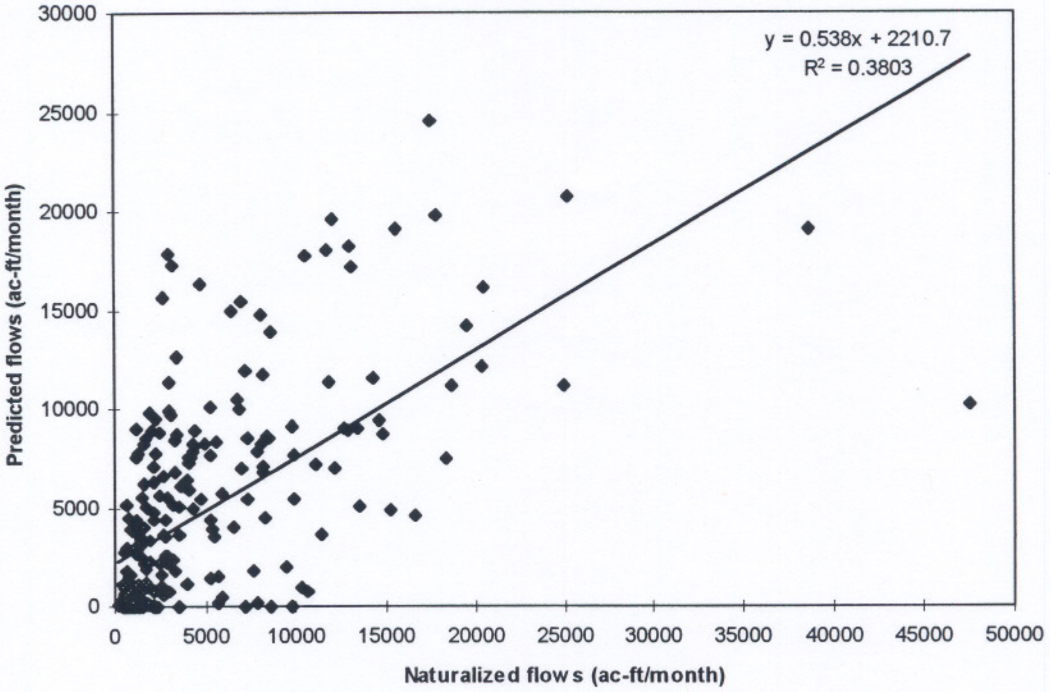


Figure A.6 Predicted flows Vs Naturalized flows at station 6

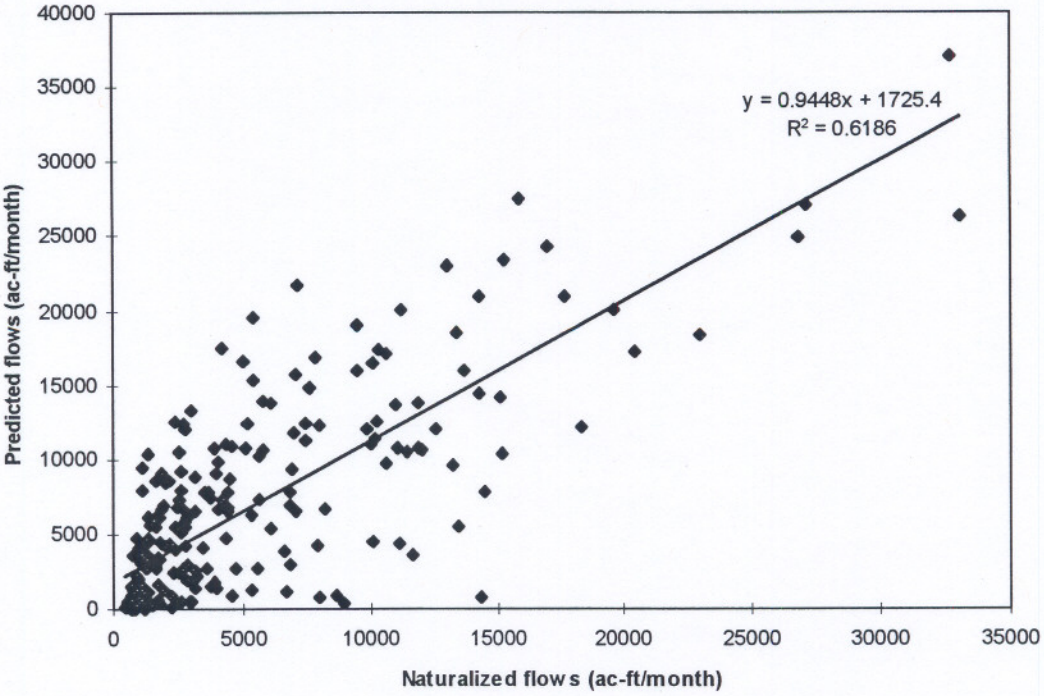


Figure A.7 Predicted flows Vs Naturalized flows at station 8

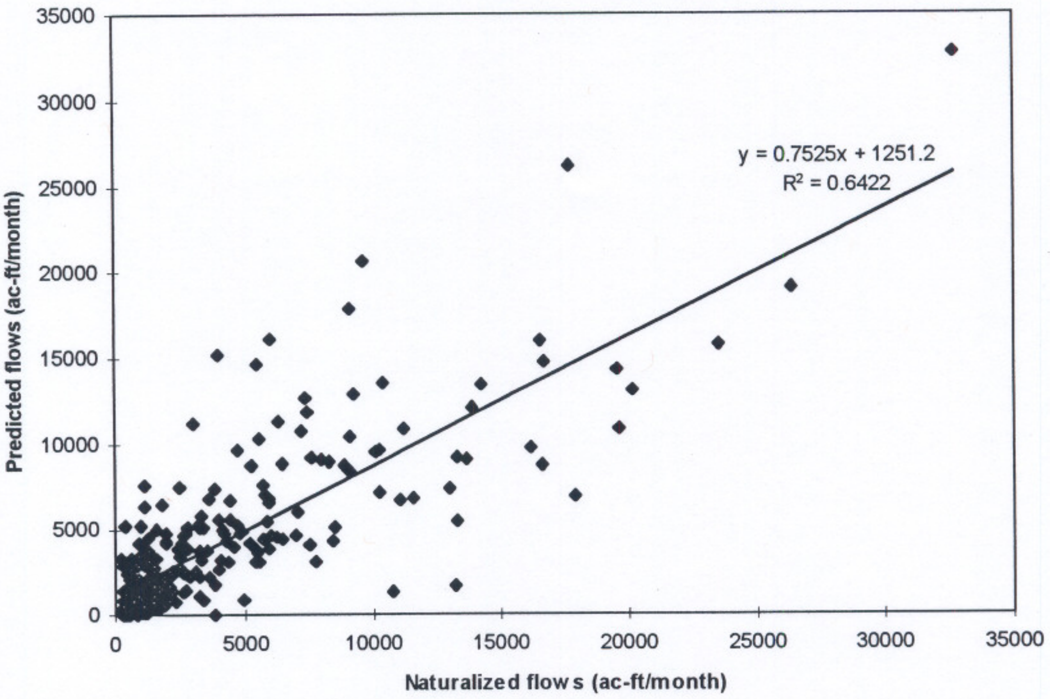


Figure A.8 Predicted flows Vs Naturalized flows at station 9

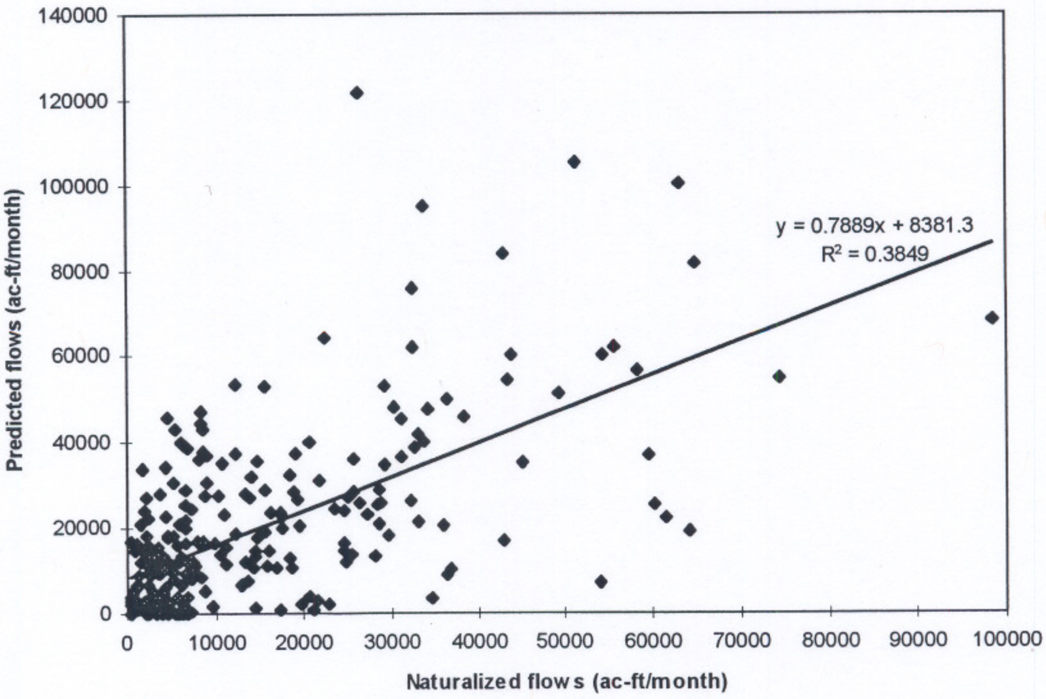


Figure A.9 Predicted flows Vs Naturalized flows at station 10

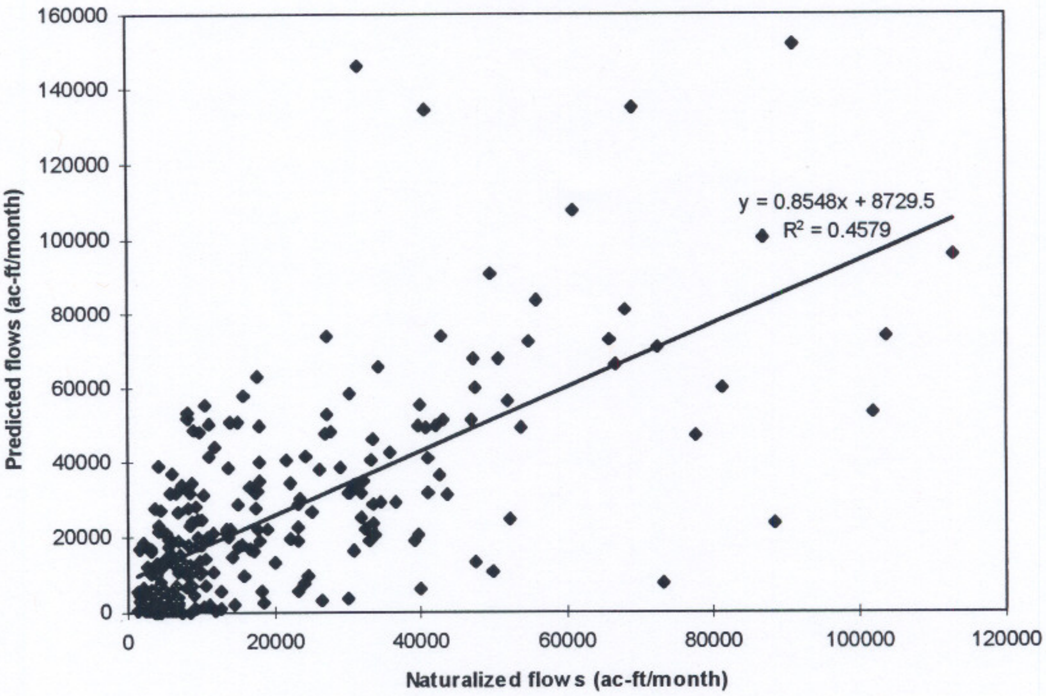


Figure A.10 Predicted flows Vs Naturalized flows at station 11

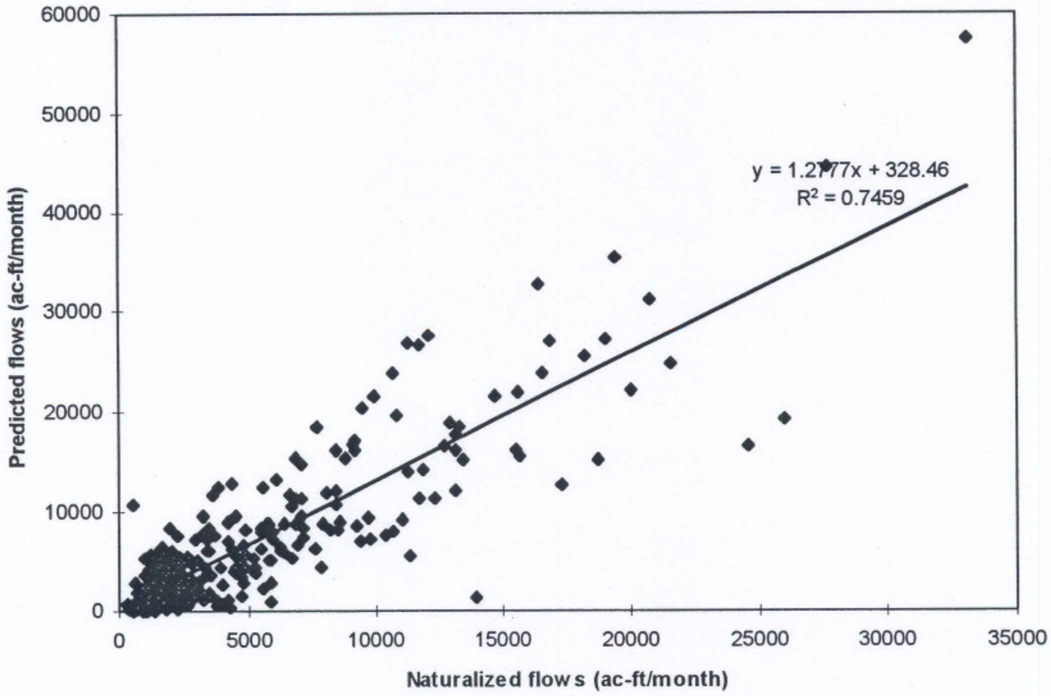


Figure A.11 Predicted flows Vs Naturalized flows at station 12

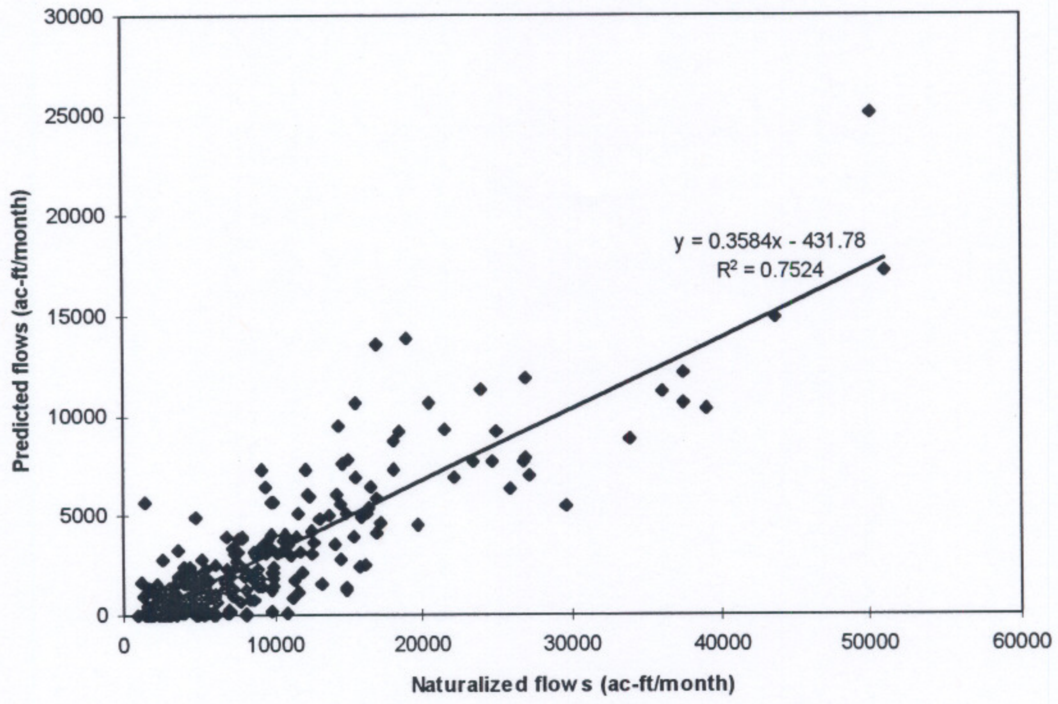


Figure A.12 Predicted flows Vs Naturalized flows at station 13

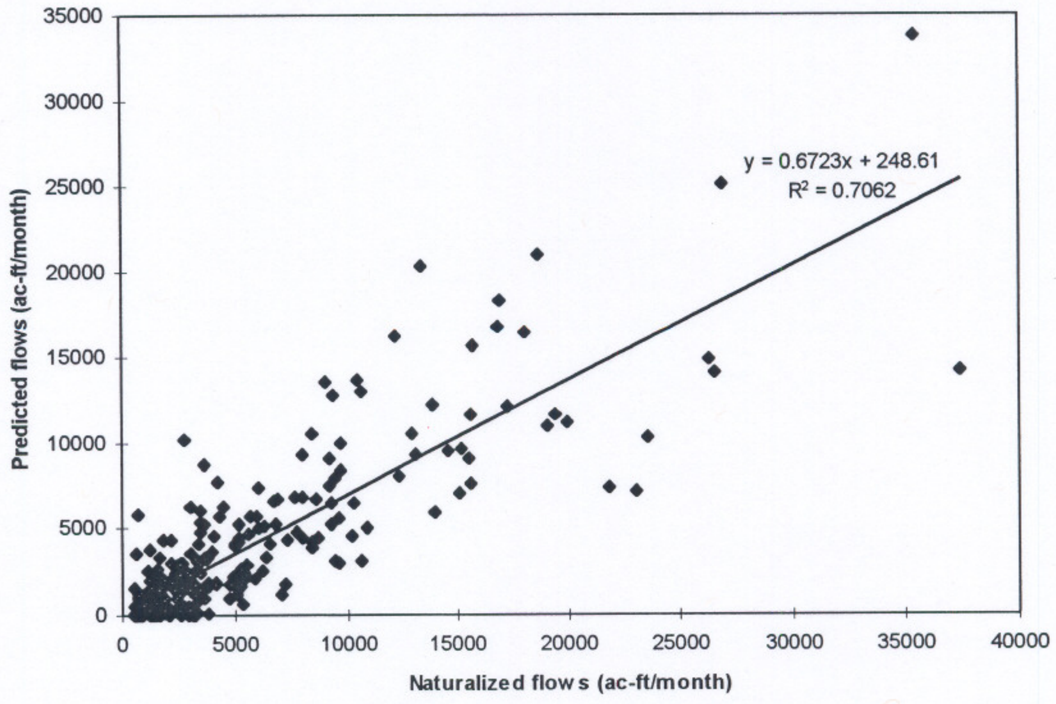


Figure A.13 Predicted flows at station 1 Vs Predicted combined flows

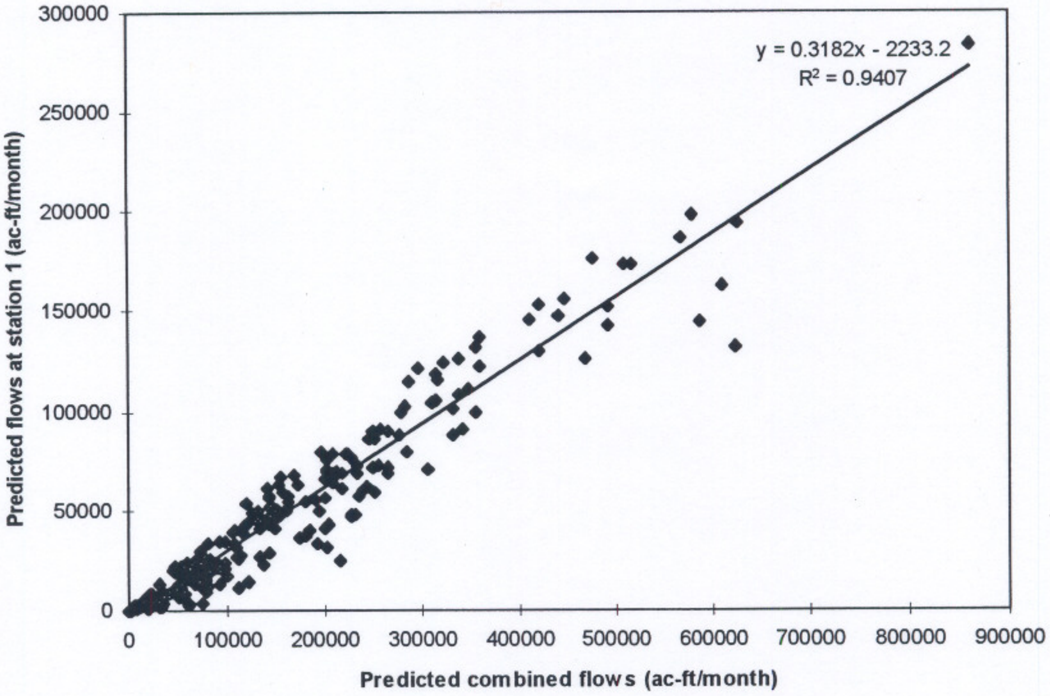


Figure A.14 Predicted flows at station 2 Vs Predicted combined flows

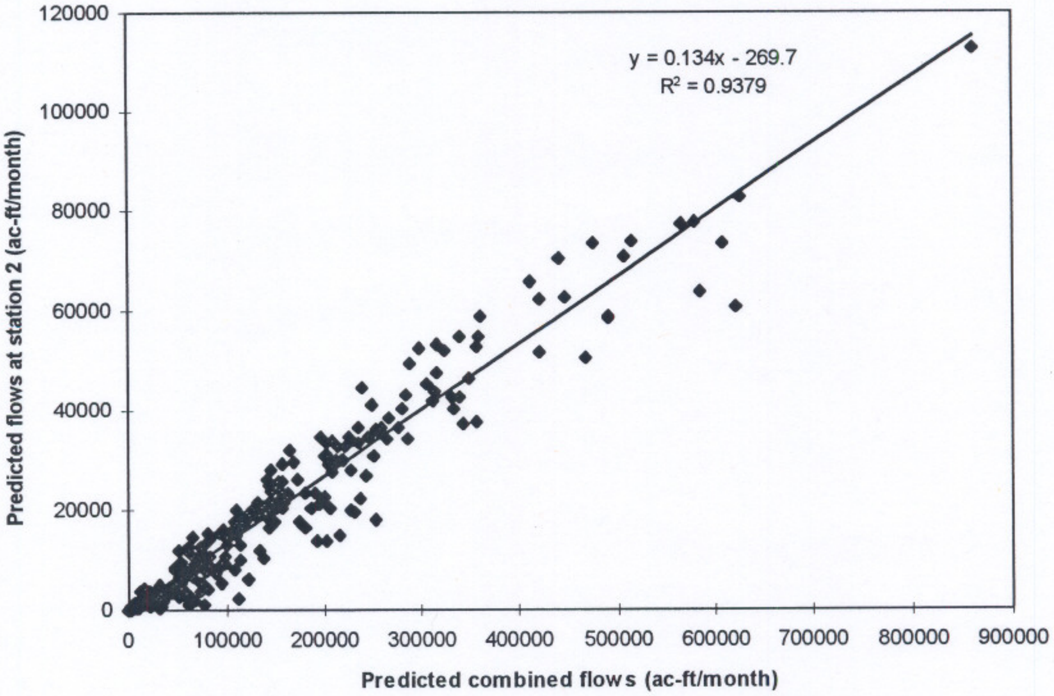


Figure A.15 Predicted flows at station 3 Vs Predicted combined flows

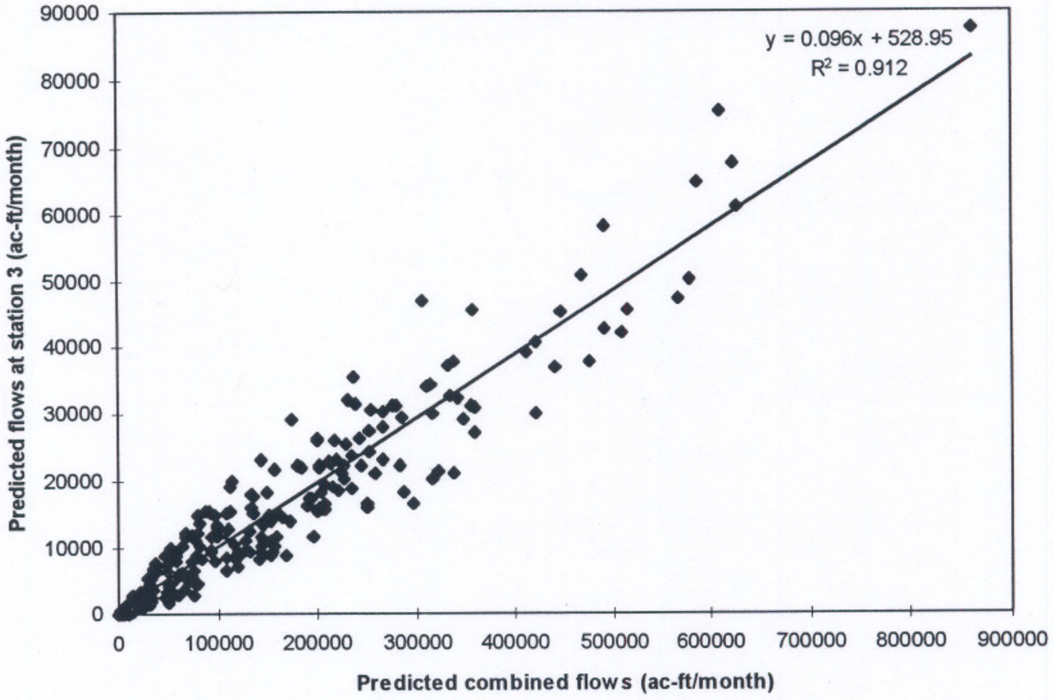


Figure A.16 Predicted flows at station 4 Vs Predicted combined flows

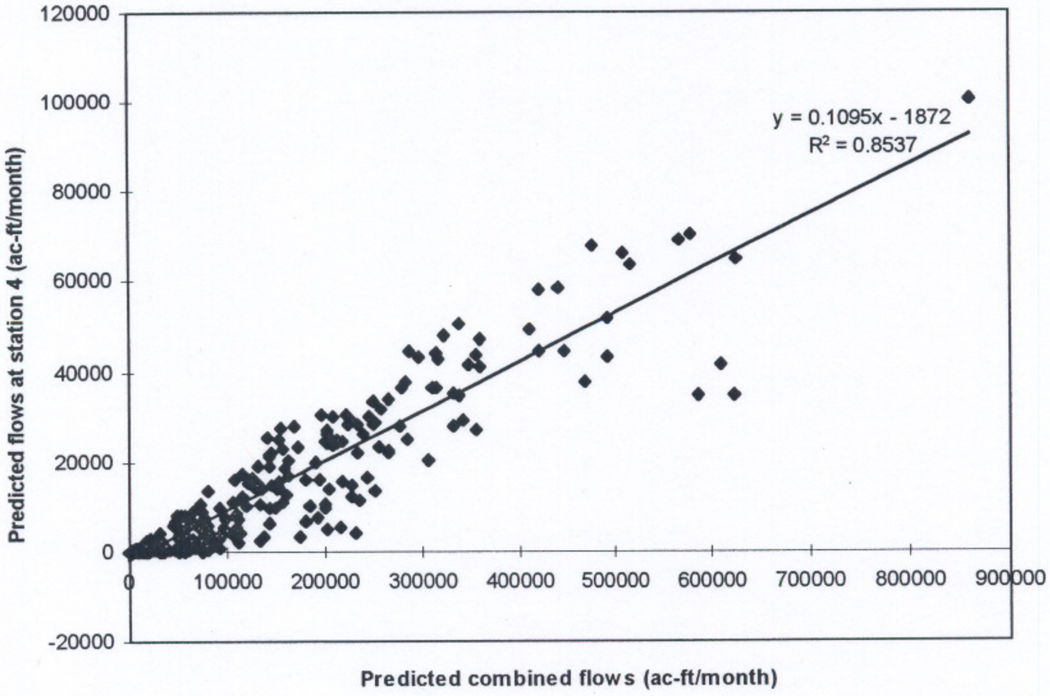


Figure A.17 Predicted flows at station 5 Vs Predicted combined flows

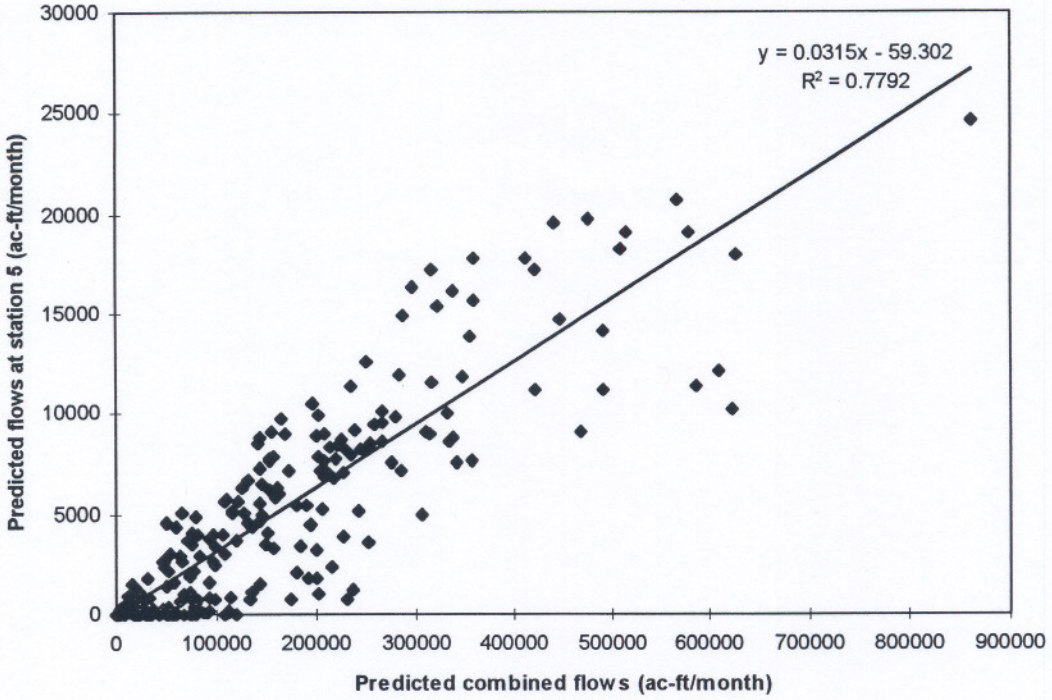


Figure A.18 Predicted flows at station 6 Vs Predicted combined flows

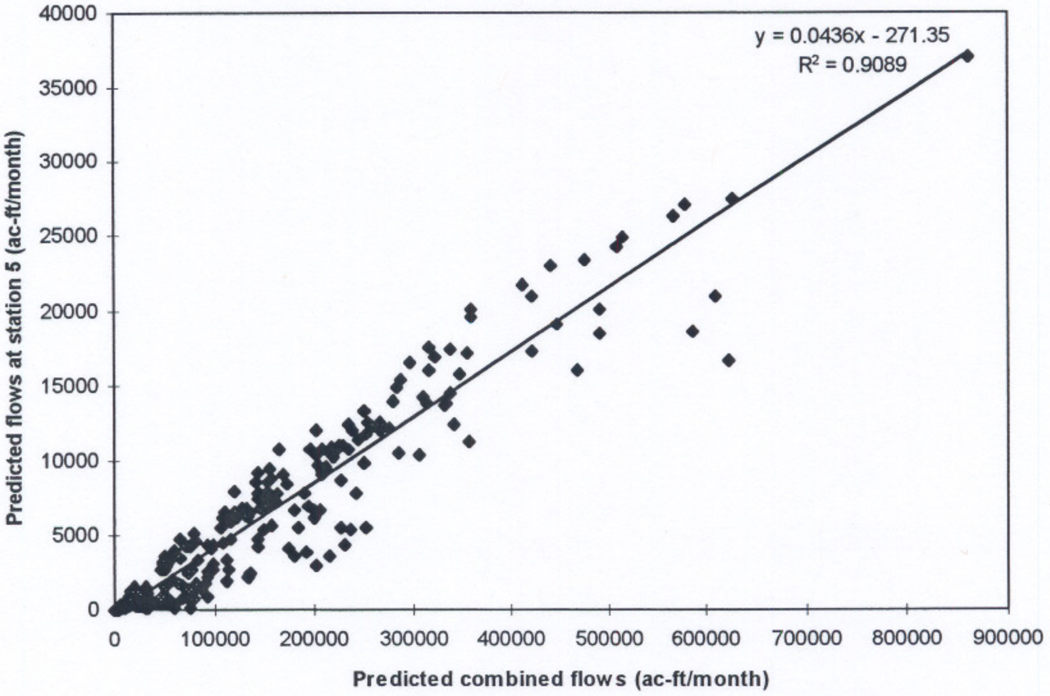


Figure A.19 Predicted flows at station 8 Vs Predicted combined flows

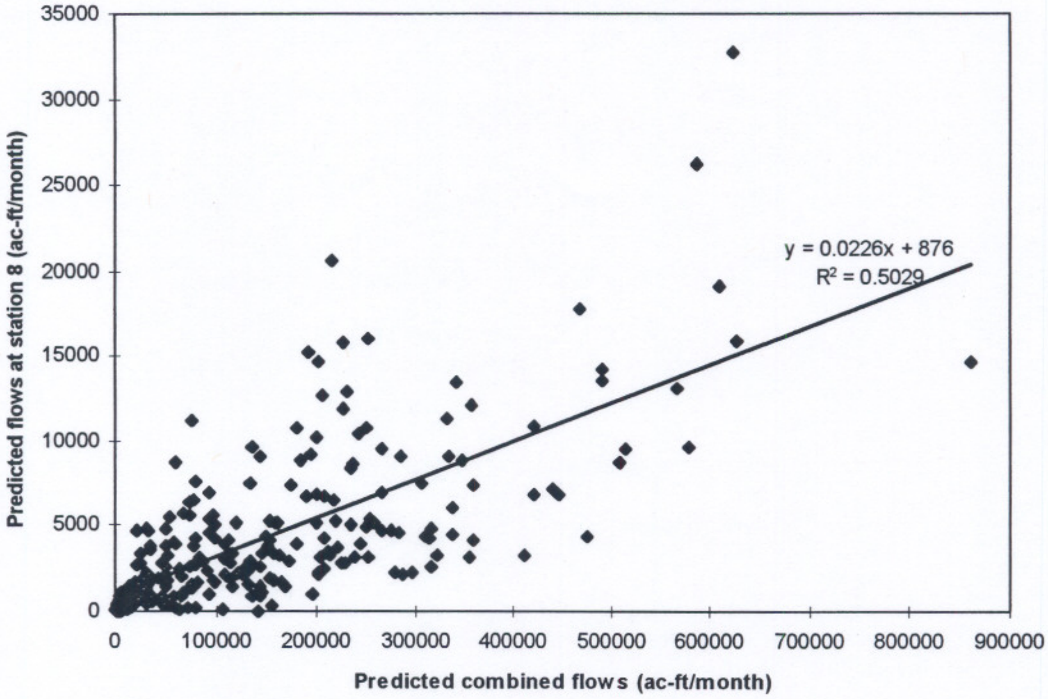


Figure A.20 Predicted flows at station 9 Vs Predicted combined flows

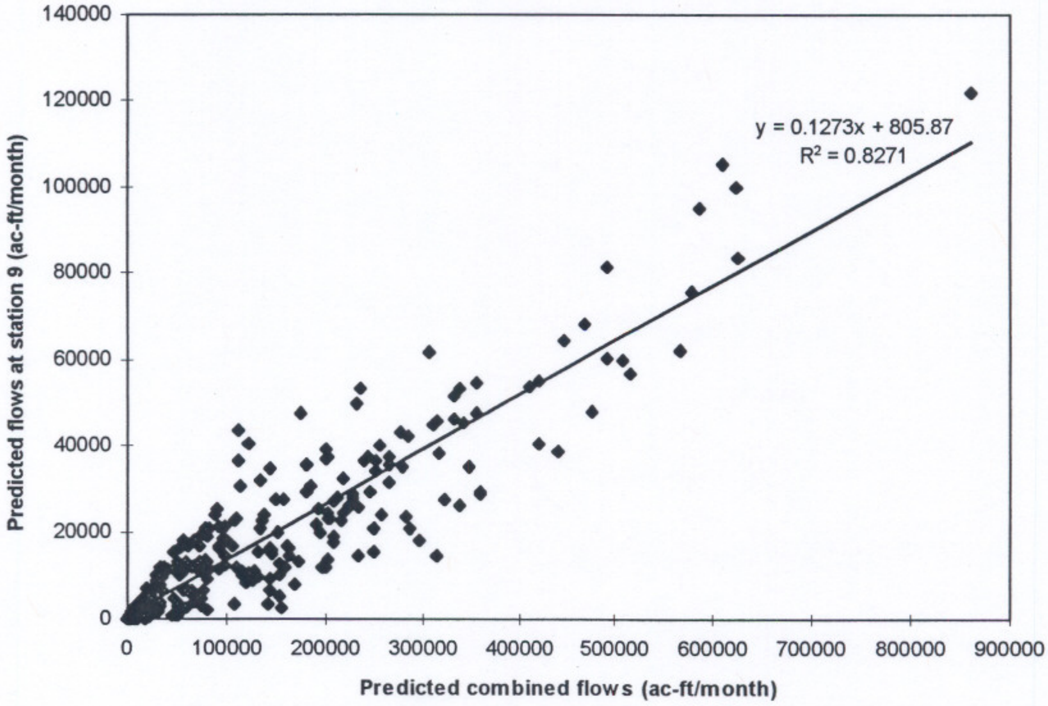


Figure A.21 Predicted flows at station 10 Vs Predicted combined flows

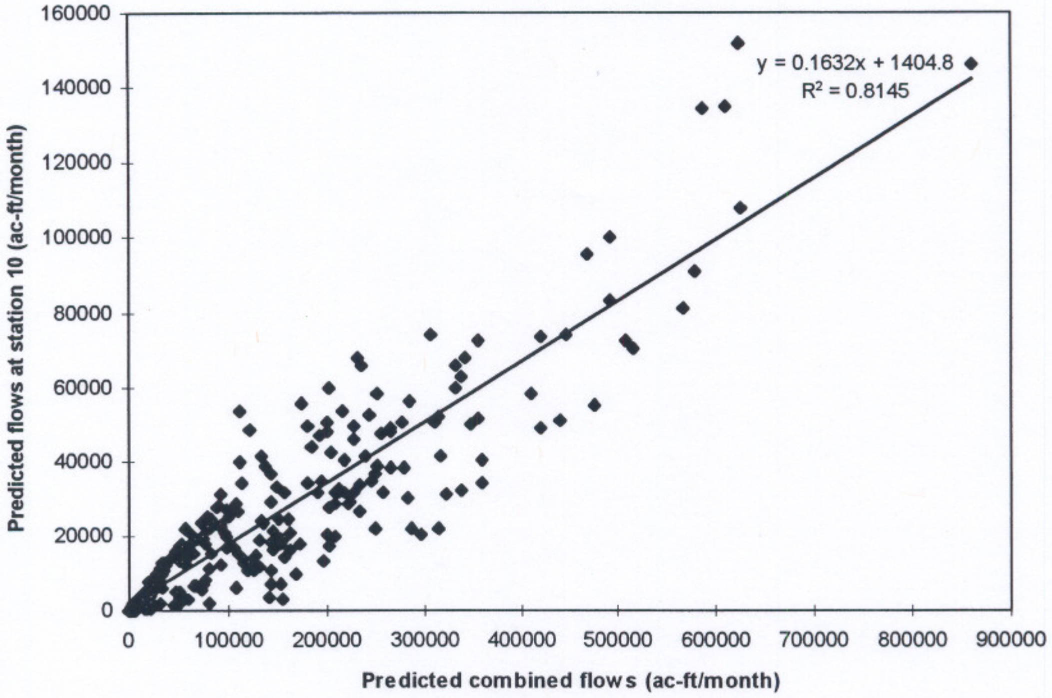


Figure A.22 Predicted flows at station 11 Vs Predicted combined flows

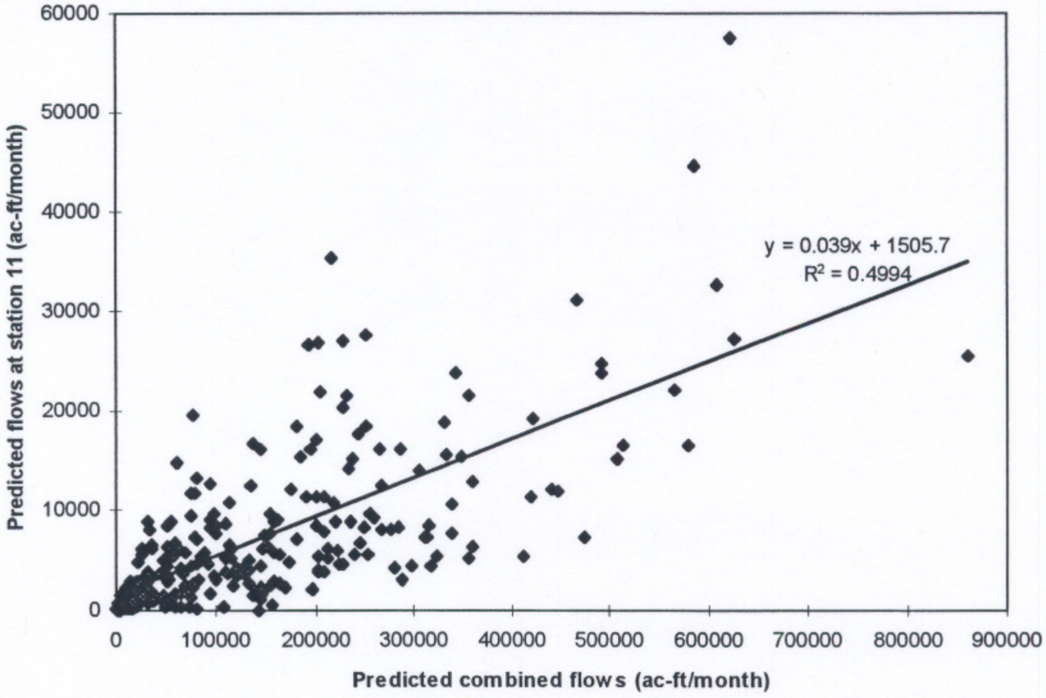


Figure A.23 Predicted flows at station 12 Vs Predicted combined flows

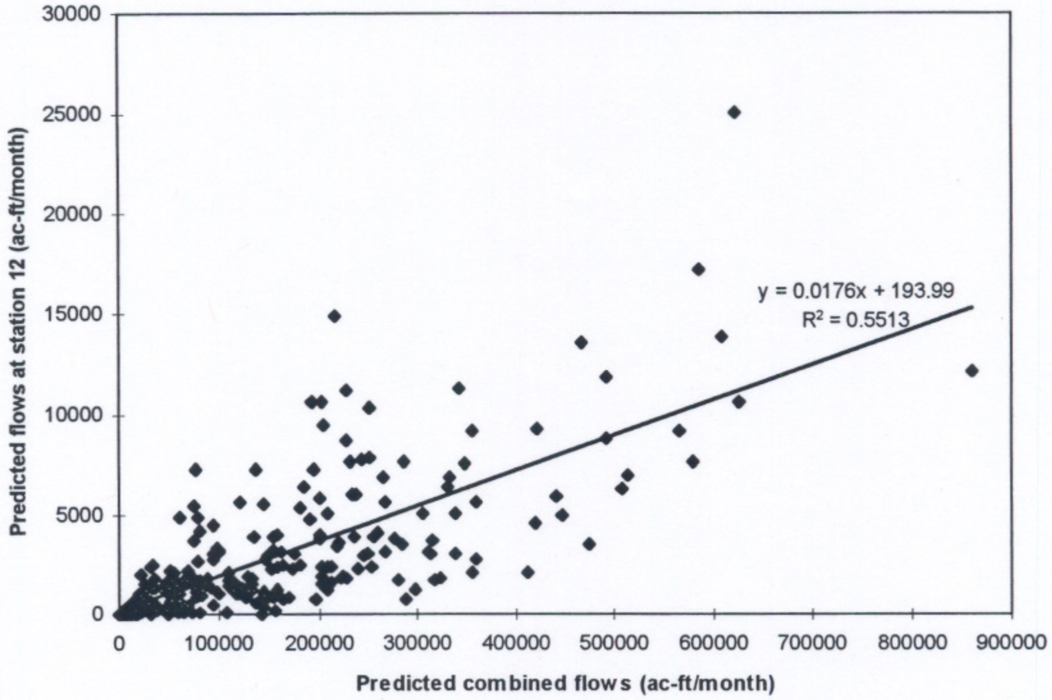


Figure A.24 Predicted flows at station 13 Vs Predicted combined flows

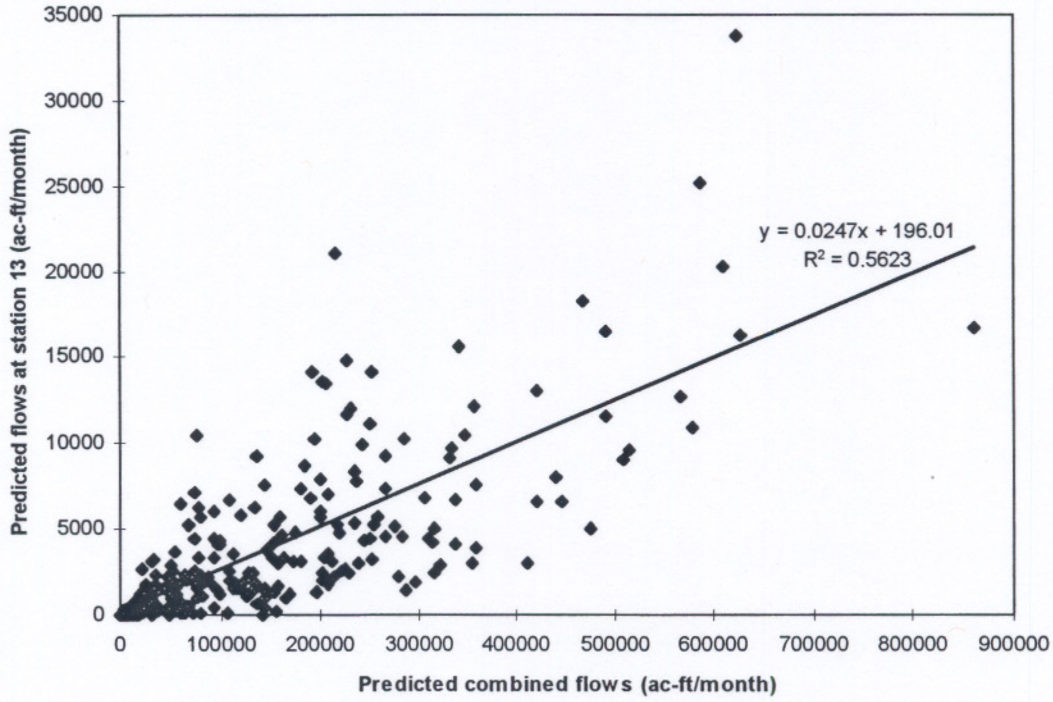


Figure A.25 Predicted flows by regression equation at station 1 Vs Naturalized flows at station 1

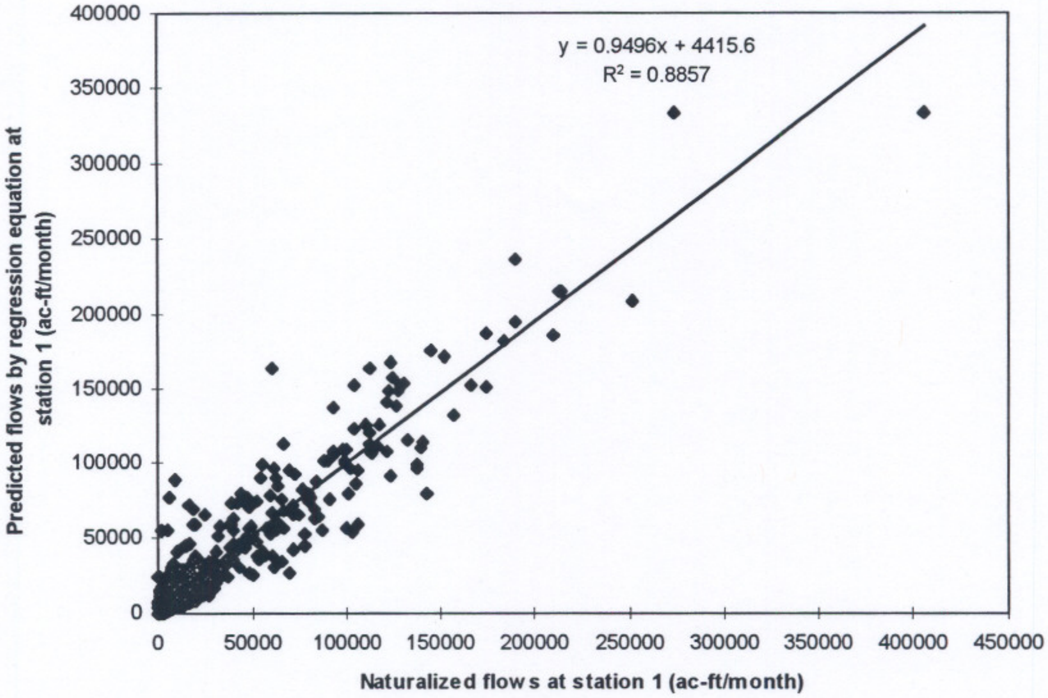


Figure A.26 Predicted flows by regression equation at station 2 Vs Naturalized flows at station 2

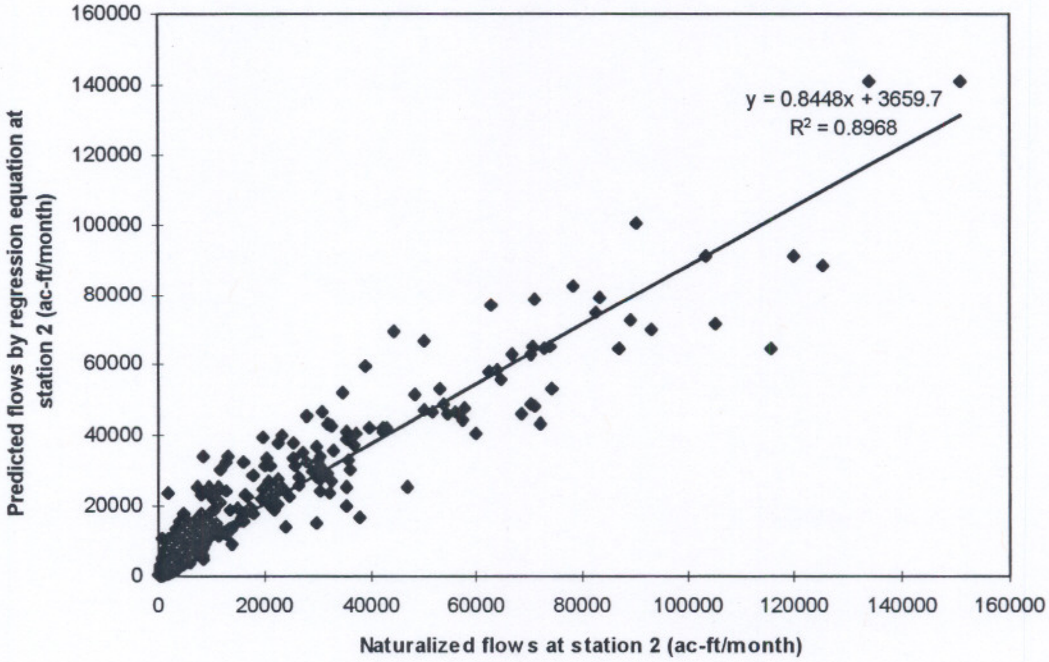


Figure A.27 Predicted flows by regression equation at station 3 Vs Naturalized flows at station 3

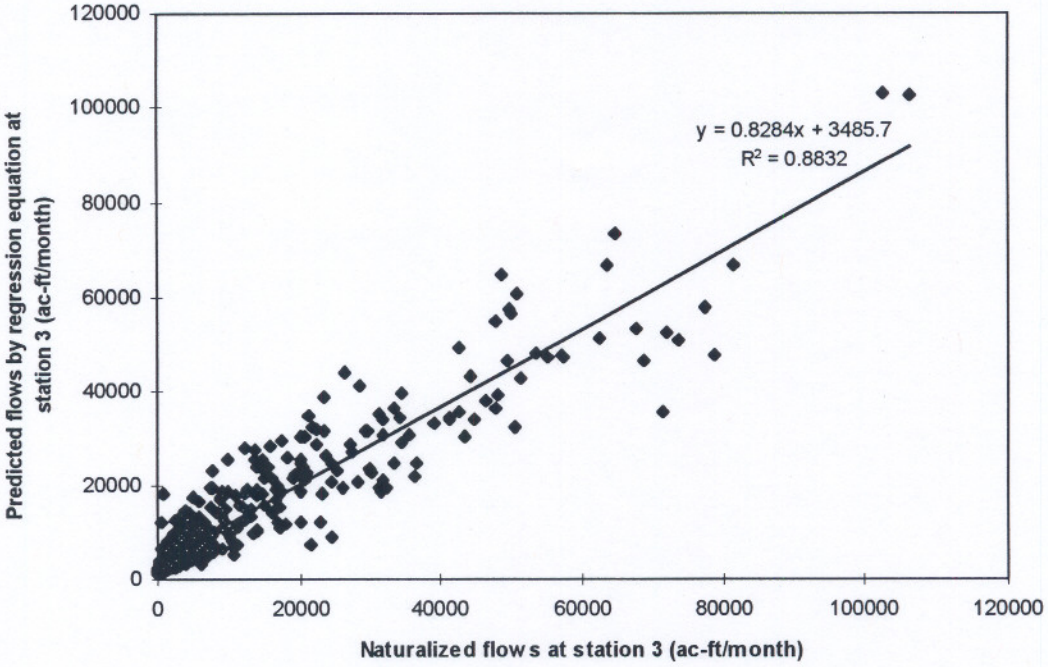


Figure A.28 Predicted flows by regression equation at station 4 Vs Naturalized flows at station 4

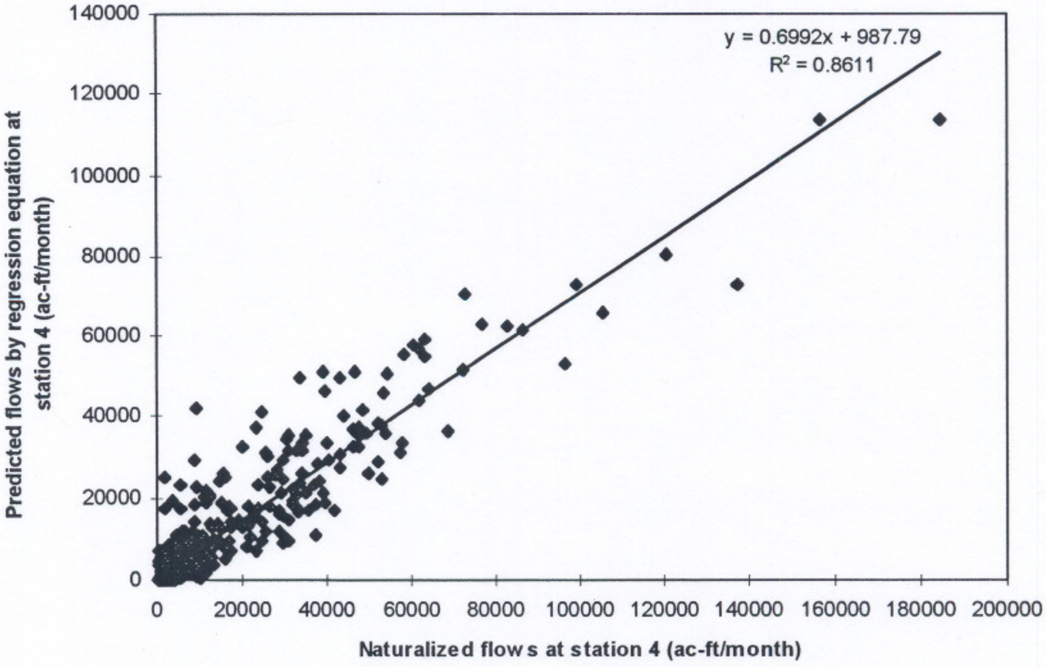


Figure A.29 Predicted flows by regression equation at station 5 Vs Naturalized flows at station 5

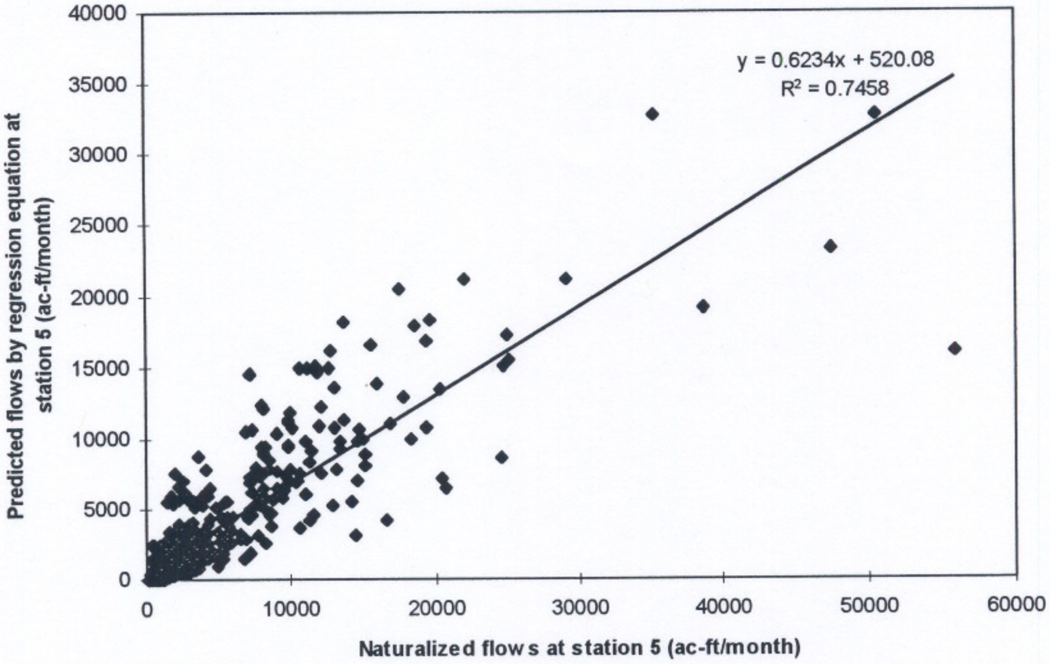


Figure A.30 Predicted flows by regression equation at station 6 Vs Naturalized flows at station 6

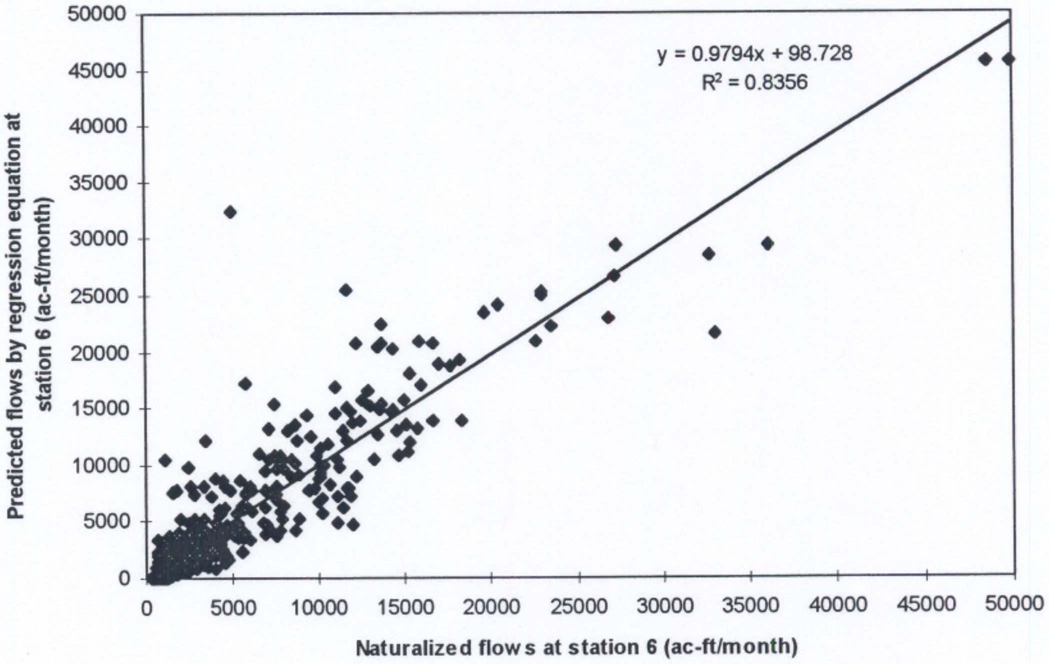


Figure A.31 Predicted flows by regression equation at station 8 Vs Naturalized flows at station 8

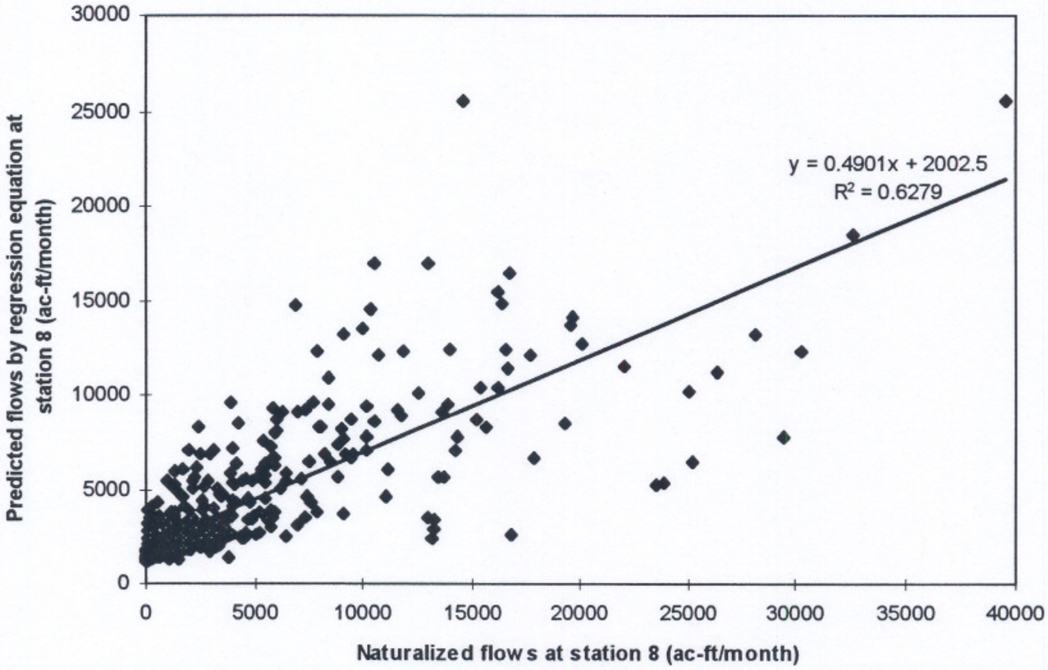


Figure A.32 Predicted flows by regression equation at station 9 Vs Naturalized flows at station 9

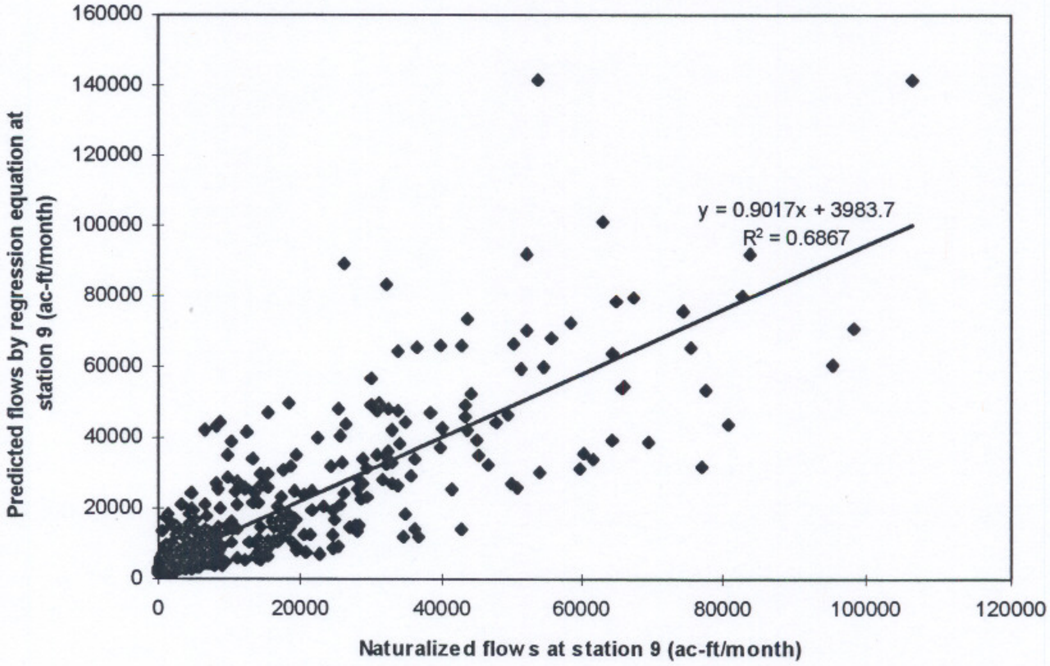


Figure A.33 Predicted flows by regression equation at station 10 Vs Naturalized flows at station 10

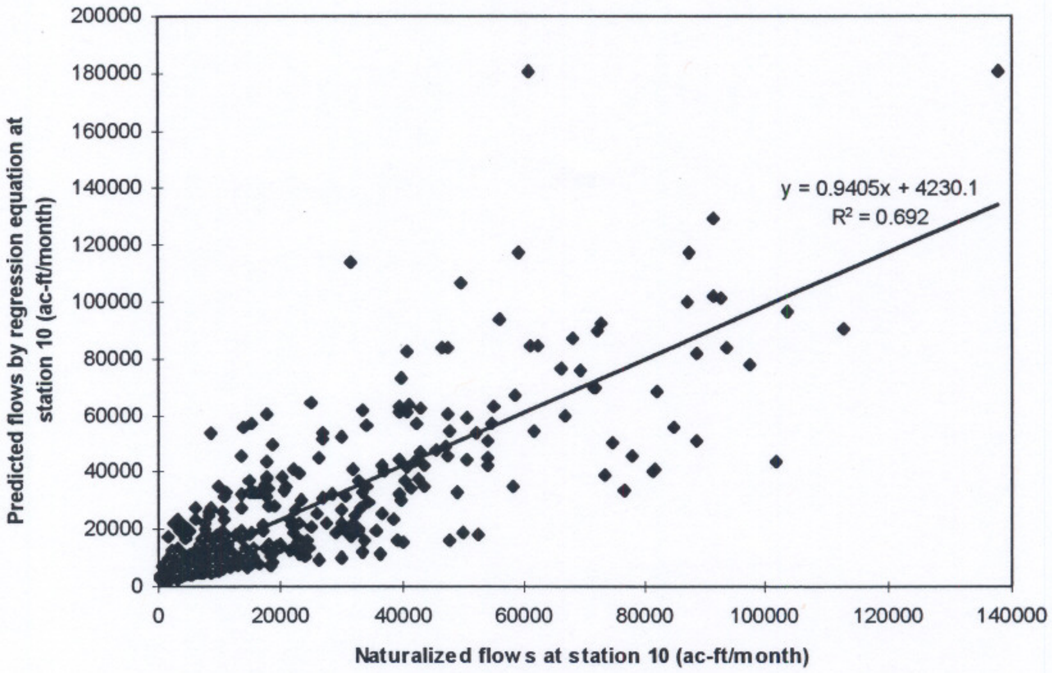


Figure A.34 Predicted flows by regression equation at station 11 Vs Naturalized flows at station 11

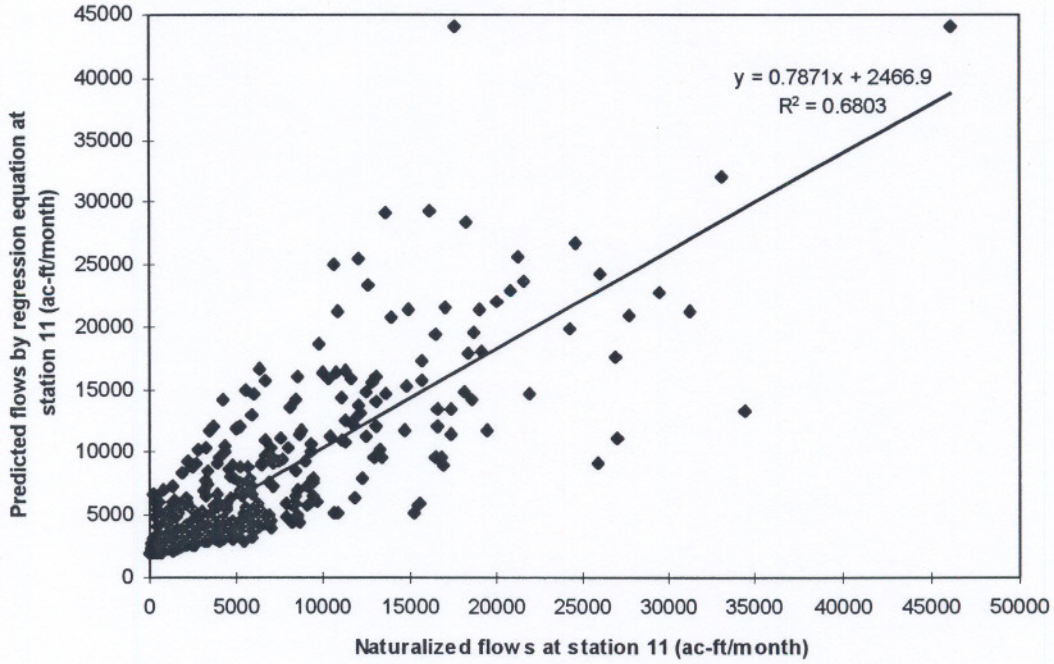


Figure A.35 Predicted flows by regression equation at station 12 Vs Naturalized flows at station 12

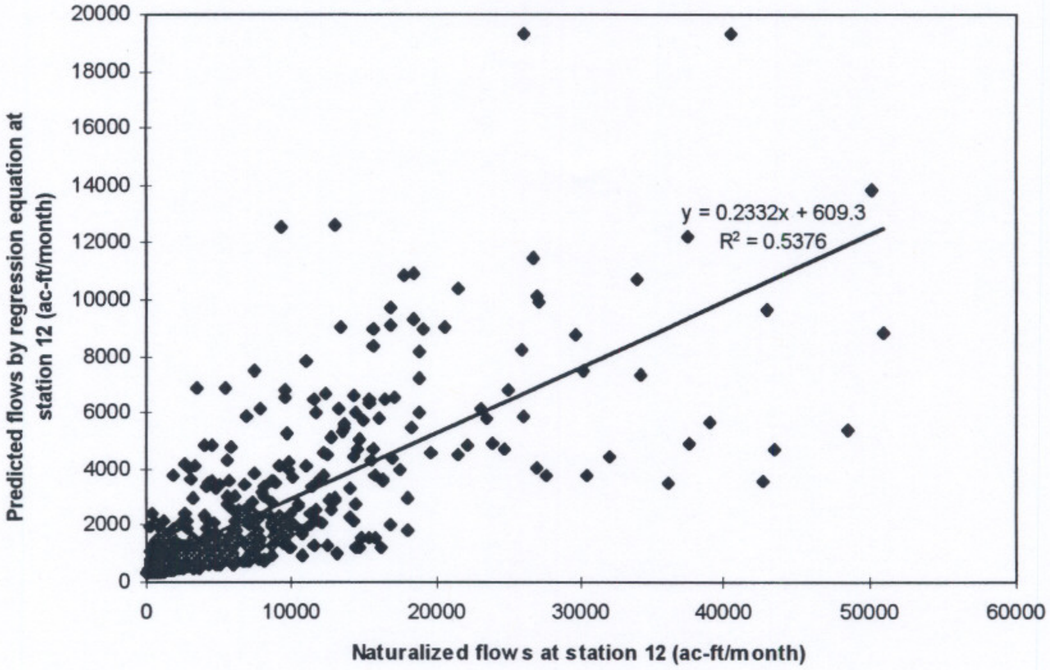
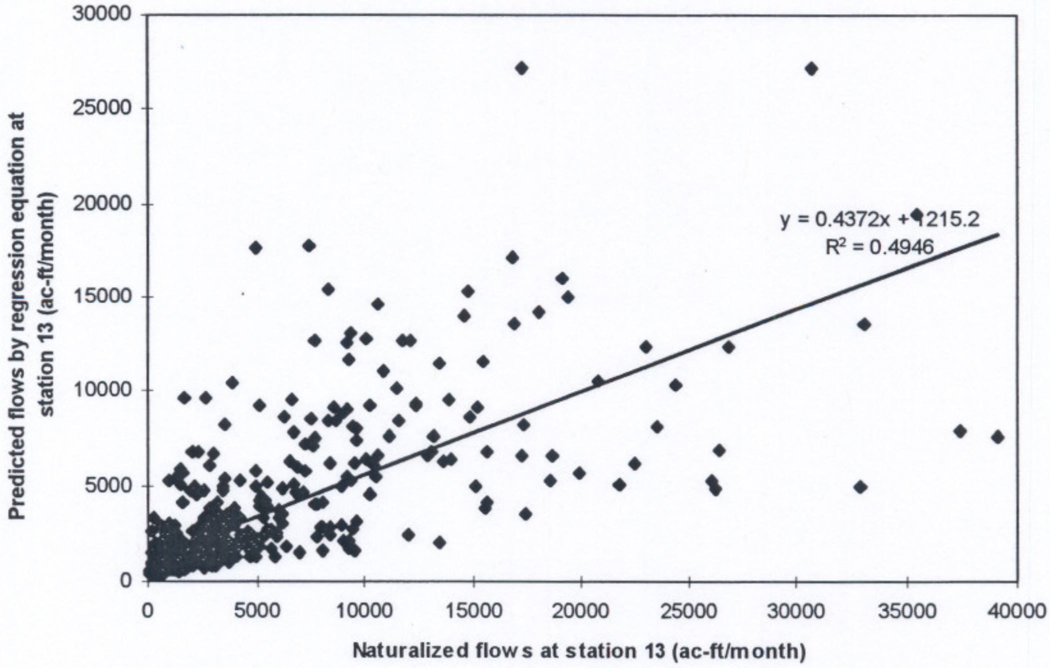


Figure A.36 Predicted flows by regression equation at station 13 Vs Naturalized flows at station 13



APPENDIX B

FLOW-FREQUENCY TABLES FROM THE COMPARATIVE EVALUATION OF ALTERNATIVE METHODS

Table B.1. Frequency-Flow Relationship For Station 1 Flows Predicted from Station 7 Flows in the Brazos River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	25	23	38	0
99	0	89	82	107	0
98	1	211	194	230	0
95	48	413	381	430	0
90	142	977	900	971	0
80	547	2564	2362	2464	139
70	938	3873	3569	3684	463
60	1525	5792	5337	5465	1105
50	2553	8509	7840	7974	2207
40	3781	11931	10993	11126	3787
30	6343	19015	17519	17628	7458
20	11206	29548	27224	27266	13494
10	20118	52891	48731	48560	28179
Max	217095	244928	225664	222773	169422

Table B.2. Frequency-Flow Relationship For Station 2 Flows Predicted from Station 7 Flows in the Brazos River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	72	71	13	0
99	0	252	249	120	0
98	1	593	587	375	16
95	223	1164	1152	842	171
90	1574	2750	2723	2225	911
80	3513	7216	7144	6300	3676
70	6132	10902	10793	9736	6229
60	9268	16304	16141	14826	10170
50	14620	23950	23711	22094	15981
40	24562	33582	33247	31311	23534
30	39425	53520	52986	50521	39650
20	63398	83167	82336	79271	64304
10	112228	148868	147382	143400	120494
Max	624904	689376	682496	677055	605966

Table B.3. Frequency-Flow Relationship For Station 3 Flows
Predicted from Station 7 Flows in the Brazos River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	97	25	24	6	41
99	141	88	84	45	111
98	220	208	198	133	233
95	500	409	388	292	428
90	760	966	917	761	954
80	1432	2535	2405	2131	2399
70	2297	3830	3634	3284	3576
60	3593	5227	5435	4989	5291
50	5380	8414	7983	7422	7707
40	8064	11797	11194	10503	10736
30	14606	18801	17840	16920	16981
20	24963	29216	27722	26516	26230
10	48417	52297	49623	47903	46644
Max	292679	242176	229792	225614	213379

Table B.4. Frequency-Flow Relationship For Station 4 Flows
Predicted from Station 7 Flows in the Brazos River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	68	1139	1146	1194
99	0	94	1213	1222	1270
98	575	115	1678	1692	1741
95	1477	335	2608	2635	2678
90	2319	641	3230	3265	3302
80	4034	1530	4474	4528	4548
70	4782	2726	6286	6367	6356
60	5942	4459	8522	8638	8583
50	8929	6871	11573	11738	11616
40	12298	11634	15834	16067	15843
30	18117	19684	23368	23725	23302
20	26309	33837	31452	31945	31292
10	46677	58932	48824	49615	48435
Max	312711	200090	271072	275831	266778

Table B.5. Frequency-Flow Relationship For Station 5 Flows Predicted from Station 7 Flows in the Brazos River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	154	324	800	1177
99	0	154	324	800	1177
98	114	161	345	834	1218
95	376	192	515	1100	1522
90	496	366	682	1348	1798
80	1077	679	961	1744	2231
70	1703	1124	1252	2140	2654
60	2250	1966	1766	2815	3361
50	3161	2834	2547	3802	4371
40	4237	4739	3287	4709	5280
30	7361	6862	4611	6287	6834
20	10432	10283	6067	7977	8470
10	12870	13998	9418	11754	12053
Max	39758	37450	22422	25719	24870

Table B.6. Frequency-Flow Relationship For Station 6 Flows Predicted from Station 7 Flows for the Brazos River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	200	963	2323	2303
99	0	200	963	2323	2303
98	517	255	1070	2495	2468
95	977	384	1532	3203	3148
90	1384	571	1879	3713	3635
80	2733	1157	2806	5017	4879
70	4072	2260	3677	6193	5997
60	5539	3386	5234	8215	7916
50	8244	5955	7380	10902	10456
40	11570	8267	9689	13707	13103
30	18985	13627	13711	18453	17570
20	25305	25676	18939	24453	23203
10	36826	37897	30053	36815	34781
Max	114758	111280	83983	93693	87810

Table B.7. Frequency-Flow Relationship For Station 8 Flows
Predicted from Station 9 Flows for the Brazos River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	0	0	0	0
99	0	0	0	0	0
98	0	3	24	7	0
95	49	42	93	54	0
90	164	140	347	266	0
80	521	655	991	843	0
70	1127	1269	1964	1745	0
60	2138	2151	4278	3933	18
50	5436	4723	7600	7118	575
40	11259	8949	12406	11764	2243
30	21174	17782	19805	18965	6921
20	38147	27653	32125	31025	13075
10	82911	70261	59339	57819	44395
Max	321161	242319	234315	231551	194895

Table B.8. Frequency-Flow Relationship For Station 1 Flows
Predicted from Station 2 Flows in the Brazos River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	0	0	0	0
99	0	0	0	0	0
98	1	0	0	1	0
95	48	79	74	160	0
90	142	560	521	721	0
80	547	1251	1163	1452	122
70	938	2183	2030	2404	449
60	1525	3299	3068	3519	948
50	2553	5205	4839	5393	1937
40	3781	8744	8130	8821	4011
30	6343	14035	13050	13880	7405
20	11206	22570	20985	21955	13266
10	20118	39953	37147	38235	25965
Max	217095	222466	206843	205845	1751147

Table B.9. Frequency-Flow Relationship For Station 3 Flows
Predicted from Station 4 Flows in the Brazos River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	97	0	0	0	0
99	141	0	0	0	0
98	220	540	486	378	492
95	500	1387	1248	1056	1233
90	760	2178	1960	1705	1920
80	1432	3788	3409	3045	3312
70	2297	4490	4041	3634	3918
60	3593	5580	5021	4552	4856
50	5380	8384	7545	6928	7267
40	8064	11548	10392	9623	9981
30	14606	17012	15309	14301	14662
20	24963	24704	22231	20918	21241
10	48417	43830	39442	37456	37571
Max	292679	293636	264241	256020	250017

Table B.10. Frequency-Flow Relationship For Station 5 Flows
Predicted from Station 6 Flows in the Brazos River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	0	0	0	0
99	0	0	0	0	0
98	114	129	129	135	129
95	376	328	330	339	237
90	496	465	468	479	417
80	1077	954	960	976	696
70	1703	1561	1570	1592	1130
60	2250	1890	1901	1926	1677
50	3161	2770	2786	2817	2487
40	4237	3758	3780	3817	3524
30	7361	6379	6417	6467	4923
20	10432	9058	9112	9173	8008
10	12870	12374	12447	12520	9977
Max	39758	38180	38407	38538	38564

Table B.11. Frequency-Flow Relationship For Station 1 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach					
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	0	1049	575	0	720	0
99	494	1473	1318	63	1064	0
98	560	1631	1437	90	1193	0
95	831	2443	2131	305	1870	0
90	1209	3308	2962	649	2605	790
80	1887	5272	4727	1555	4304	2842
70	3284	7852	7165	3028	6571	5610
60	6179	10737	9843	4818	9134	8810
50	10734	15675	14298	8041	13564	14124
40	16397	21310	19717	12224	18661	19961
30	27499	32153	30366	20968	28548	31529
20	53334	56840	50908	38976	51277	57581
10	98744	93385	83253	69017	85219	96377
max	406604	316554	283513	271161	295006	333297

Table B.12. Frequency-Flow Relationship For Station 2 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach					
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	175	544	316	98	34	0
99	278	764	724	356	96	169
98	354	846	789	401	125	239
95	498	1267	1170	678	297	602
90	761	1715	1626	1029	515	1005
80	1160	2734	2595	1813	1084	1869
70	1682	4072	3933	2942	1922	3034
60	2251	5567	5402	4221	2930	4381
50	3586	8128	7848	6401	4762	6617
40	5750	11050	10822	9110	6959	9074
30	9110	16672	16667	14545	11386	13943
20	20861	29473	27942	25271	22031	24907
10	36790	48422	45695	42514	38565	41235
max	150903	164139	155612	152507	146426	140947

Table B.13. Frequency-Flow Relationship For Station 3 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	3	371	298	1766	108	1125
99	14	521	684	2558	190	1262
98	37	577	745	2670	223	1312
95	132	864	1106	3288	404	1574
90	294	1169	1537	3965	610	1865
80	664	1864	2453	5273	1112	2488
70	1159	2776	3717	6921	1810	3328
60	1829	3796	5106	8609	2621	4299
50	2811	5542	7418	11244	4055	5912
40	4954	7534	10229	14265	5738	7684
30	7767	11367	15754	19854	9061	11195
20	16117	20095	26411	29915	16868	19102
10	31355	33015	43191	44779	28753	30878
max	106401	111913	147086	128862	104182	102787

Table B.14. Frequency-Flow Relationship For Station 4 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	265	420	236	0	371	0
99	400	590	540	12	532	0
98	520	654	589	20	593	0
95	692	979	873	92	906	0
90	874	1325	1214	217	1242	0
80	1291	2112	1937	563	2012	0
70	2022	3146	2936	1142	3030	628
60	2980	4302	4033	1855	4175	1731
50	4561	6281	5859	3153	6142	3561
40	7140	8538	8079	4852	8396	5571
30	11272	12883	12443	8427	12749	9556
20	23640	22774	20861	15841	22704	18529
10	38910	37417	34115	28284	37501	31892
max	184500	126835	116176	112725	128365	113495

Table B.15. Frequency-Flow Relationship For Station 5 Flows Predicted from the Combined Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	147	151	85	0	76	0
99	267	213	194	4	121	0
98	376	236	212	6	138	0
95	505	353	314	31	230	70
90	603	478	437	75	332	164
80	878	762	697	198	574	365
70	1180	1134	1056	404	902	636
60	1561	1551	1451	658	1279	950
50	2163	2264	2107	1122	1937	1471
40	2991	3078	2906	1730	2701	2043
30	4180	4644	4475	3010	4196	3176
20	7529	8210	7502	5670	7671	5729
10	11600	13489	12269	10137	12910	9532
max	55830	45724	41781	40493	45715	32750

Table B.16. Frequency-Flow Relationship For Station 6 Flows Predicted from the Combined Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	351	136	73	0	158	0
99	488	191	167	0	218	0
98	537	211	182	0	240	0
95	638	317	270	3	354	0
90	718	429	375	20	473	127
80	926	683	599	89	744	408
70	1221	1018	908	225	1097	787
60	1549	1392	1247	405	1490	1226
50	2240	2032	1811	749	2159	1954
40	3001	2762	2498	1216	2921	2754
30	4431	4168	3847	2227	4381	4339
20	7550	7368	6450	4387	7692	7908
10	11851	12105	10547	8099	12574	13224
max	49926	41035	35919	34149	42236	45684

Table B.17. Frequency-Flow Relationship For Station 8 Flows Predicted from the Combined Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	0	94	69	645	209	1213
99	6	132	157	894	266	1246
98	12	146	171	929	287	1258
95	28	219	254	1119	390	1321
90	71	296	353	1325	495	1390
80	230	472	536	1717	725	1539
70	492	703	854	2203	1014	1741
60	859	962	1173	2695	1328	1973
50	1300	1404	1704	3454	1852	2359
40	1970	1909	2350	4314	2436	2783
30	3330	2880	3619	5887	3535	3623
20	5710	5091	6067	8679	5965	5515
10	10310	8364	9921	12752	9471	8333
max	39551	28351	33787	35404	30128	25540

Table B.18. Frequency-Flow Relationship For Station 9 Flows Predicted from the Combined Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	30	378	264	2056	614	1476
99	84	531	605	2927	810	1665
98	127	588	659	3050	882	1735
95	281	880	977	3723	1242	2095
90	486	1192	1359	4457	1616	2496
80	1212	1899	2168	5869	2445	3353
70	2411	2829	3286	7637	3506	4510
60	4159	3868	4514	9438	4673	5848
50	5623	5647	6558	12238	6639	8069
40	8180	7677	9043	15434	8853	10509
30	14420	11584	13927	21321	13055	15345
20	24560	20478	23349	31863	22467	26235
10	36782	33644	38184	47362	36191	42452
max	106502	114045	130032	134466	118300	141488

Table B.19. Frequency-Flow Relationship For Station 10 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	278	463	322	2162	1068	2362
99	511	650	738	3511	1357	2602
98	604	719	805	3659	1461	2691
95	807	1078	1194	4475	1978	3150
90	1231	1459	1659	5364	2505	3660
80	2568	2325	2648	7078	1650	4753
70	4175	3464	4013	9225	5093	6227
60	6151	4736	5513	11416	6657	7931
50	8450	6914	8009	14824	9262	10761
40	11542	9400	11044	18718	12161	13869
30	18642	14182	17010	25896	17606	20029
20	31789	25071	28516	38763	29637	33902
10	47623	41190	46634	57701	46963	54561
Max	137903	139625	158810	164264	148869	180723

Table B.20. Frequency-Flow Relationship For Station 11 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	37	109	84	1191	453	1952
99	67	154	192	1562	547	2009
98	120	170	209	1612	580	2030
95	175	255	310	1887	741	2138
90	279	345	431	2178	902	2259
80	561	550	688	2724	1240	2517
70	1191	820	1042	3385	1654	2866
60	1810	1121	1432	4041	2092	3269
50	2530	1636	2080	5037	2806	3938
40	3590	2224	2869	6147	3586	4673
30	5481	3356	4418	8140	5020	6130
20	8371	5933	7406	11607	8111	9410
10	13100	9747	12112	16574	12460	14295
max	46080	33041	41248	43555	37247	44126

Table B.21. Frequency-Flow Relationship For Station 12 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	45	114	88	1399	1312	318
99	147	161	202	1811	1483	343
98	290	178	220	1868	1542	353
95	401	267	326	2171	1821	402
90	560	361	453	2493	2086	456
80	1171	575	723	3092	2621	572
70	2161	857	1096	3814	3242	730
60	3170	1171	1506	4527	3872	911
50	4381	1710	2188	5605	4857	1213
40	6031	2325	3017	6802	5892	1544
30	8591	3508	4646	8942	7722	2201
20	11659	3201	7789	12649	11472	3680
10	16821	10187	12738	17937	16512	5883
max	51001	34533	43380	46513dv	43610	19333

Table B.22. Frequency-Flow Relationship For Station 13 Flows
Predicted from the Combined Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach					
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted	SWAT Regression
100	68	83	63	740	615	380
99	130	117	144	993	713	416
98	204	129	157	1028	747	429
95	254	193	232	1219	910	498
90	328	262	323	1423	1067	574
80	604	417	515	1808	1392	738
70	961	621	781	2279	1776	960
60	1530	850	1073	2751	2174	1215
50	2170	1240	1559	3472	2808	1640
40	3119	1686	2150	4283	3484	2107
30	4350	2544	3311	5749	4702	3031
20	7540	4497	5550	8325	7251	5113
10	11773	7389	9076	12044	10746	8214
max	39128	25047	30909	32457	30005	27150

Table B.23. Frequency-Flow Relationship For Station 5 Flows Predicted from Station 4 Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	147	95	95	92	48
99	267	144	144	140	84
98	376	187	187	182	117
95	505	249	249	243	167
90	603	315	315	308	220
80	878	465	465	457	347
70	1180	728	728	718	577
60	1561	1073	1073	1060	886
50	2163	1642	1642	1626	1407
40	2991	2570	2570	2549	2274
30	4180	4058	4058	4031	3687
20	7529	8510	8510	8469	8000
10	11600	14008	14008	13954	13412
max	55830	66420	66420	66313	66180

Table B.24. Frequency-Flow Relationship For Station 6 Flows Predicted from Station 5 Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	351	132	126	59	252
99	488	239	229	133	398
98	537	337	323	206	524
95	638	453	434	296	668
90	718	541	518	366	776
80	926	788	754	567	1071
70	1221	1058	1014	793	1387
60	1549	1400	1341	1058	1779
50	2240	1940	1858	1555	2386
40	3001	2683	2569	2212	3207
30	4431	3749	3591	3170	4365
20	7550	6754	6467	5923	7558
10	11851	10405	9964	9328	11362
max	49926	50080	47958	47514	51258

Table B.25. Frequency-Flow Relationship For Station 1 Flows Predicted from Station 6 Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
9100	0	2704	2766	351	1855
99	494	3760	3845	488	2696
98	560	4138	4232	537	3001
95	831	4916	5027	6389	3634
90	1209	5532	5658	718	4140
80	1887	7135	7297	926	5469
70	3284	9408	9621	1221	7378
60	6179	11935	12206	1549	9525
50	10734	17259	17651	2240	14102
40	16397	23123	23648	3001	19201
30	27499	34141	34916	4431	28888
20	53334	58173	59494	7550	50297
10	98744	91312	93386	11851	80169
max	406604	384680	393417	49926	349809

Table B.26. Frequency-Flow Relationship For Station 2 Flows Predicted from Station 1 Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	175	0	0	0	0
99	278	256	271	494	7
98	354	290	307	560	13
95	498	430	456	831	52
90	761	626	664	1209	128
80	1160	977	1036	1887	302
70	1682	1707	1803	3130	734
60	2251	3201	3392	5156	1773
50	3586	5560	5893	8156	3581
40	5750	8494	9002	11732	5973
30	9110	14244	15097	18488	10909
20	20861	27627	29280	33583	23015
10	36790	51149	54210	59159	45285
max	150903	210621	223226	224248	205326

Table B.27. Frequency-Flow Relationship For Station 3 Flows Predicted from Station 2 Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	3	120	134	175	279
99	14	191	213	278	385
98	37	244	271	354	459
95	132	343	381	498	595
90	294	524	582	761	832
80	664	798	887	1160	1177
70	1159	1157	1287	1682	1613
60	1829	1549	1722	2251	2077
50	2811	2467	2743	3586	3139
40	4954	3956	4399	5750	4816
30	7767	6268	6969	9110	3761
20	16117	14352	15959	20861	16018
10	31355	25312	28144	36790	27485
max	106401	103821	115441	127690	107280

Table B.28. Frequency-Flow Relationship For Station 8 Flows Predicted from Station 3 Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	1	1	3	93
99	6	3	4	14	116
98	12	8	10	37	146
95	28	30	36	84	226
90	71	66	80	149	329
80	230	149	180	282	521
70	492	261	314	449	745
60	859	412	496	665	1022
50	1300	632	762	973	1400
40	1970	1115	1343	1622	2168
30	3330	1748	2105	2450	3114
20	5710	3626	4368	4838	5738
10	10310	7055	8497	9076	10220
max	39551	23940	28835	29384	30718

Table B.29. Frequency-Flow Relationship For Station Flows 11
Predicted from Station 8 Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	37	0	0	0	0
99	67	7	7	6	59
98	120	14	14	12	78
95	175	33	32	28	120
90	279	83	82	71	210
80	561	268	265	230	488
70	1191	573	566	492	897
60	1810	1001	988	859	1433
50	2530	1515	1459	1300	2053
40	3590	2295	2266	1970	2964
30	5481	3879	3830	3330	4755
20	8371	6652	6567	5710	7790
10	13100	12011	11857	10310	13489
max	46080	46077	45484	39551	48382

Table B.30. Frequency-Flow Relationship For Station 10 Flows
Predicted from Station 11 Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	278	156	151	0	8
99	511	283	273	0	48
98	604	507	488	30	153
95	807	740	712	92	282
90	1231	1179	1136	255	559
80	2568	2371	2283	561	1401
70	4175	5034	4847	1191	3483
60	6151	7651	7367	1810	5648
50	8450	10694	10297	2530	8248
40	11542	15175	14611	3590	12178
30	18642	23168	22308	5481	19377
20	31789	35384	34070	8371	30661
10	47623	55374	53317	13100	49540
Max	137903	194780	187546	46080	185693

Table B.31. Frequency-Flow Relationship For Station 9 Flows
Predicted from Station 10 Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	30	69	68	242	740
99	84	126	126	438	935
98	127	149	149	516	1004
95	281	199	199	685	1145
90	486	304	303	1038	1410
80	1212	634	632	2147	2117
70	2411	1031	1027	3476	2852
60	4159	1519	1513	5105	3672
50	5623	2086	2079	6999	4557
40	8180	2850	2839	9541	5675
30	14420	4603	4586	15372	8058
20	24560	7849	7820	26150	12116
10	36782	11758	11715	39115	16698
max	106502	34048	33924	112927	40783

Table B.32. Frequency-Flow Relationship For Station 12 Flows
Predicted from Station 10 Flows for the San Jacinto River Basin
(Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	45	201	223	278	740
99	147	370	410	511	935
98	290	437	485	564	1004
95	401	584	648	670	1145
90	560	891	988	873	1410
80	1171	1859	2062	1443	2117
70	2161	3023	3353	2061	2852
60	3170	4453	4939	2771	3672
50	4381	6118	6785	3556	4557
40	6031	8356	9268	4568	5675
30	8591	13497	14970	6779	8058
20	11659	23015	25527	10656	12116
10	16821	34479	38241	15141	16698
max	51001	99842	110736	39531	40785

Table B.33. Frequency-Flow Relationship For Station 13Flows Predicted from Station 12 Flows for the San Jacinto River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	68	55	54	4	1
99	130	180	176	41	27
98	204	354	348	108	84
95	254	490	481	165	134
90	328	684	672	250	210
80	604	1431	1405	602	536
70	961	2641	2593	1212	1112
60	1530	3874	3804	1858	1731
50	2170	5354	5257	2654	2500
40	3119	7370	7237	3760	3576
30	4350	10498	10309	5507	5287
20	7540	14247	13991	7634	7380
10	11773	20555	20185	11256	10963
max	39128	62323	61201	35681	35309

Table B.34. Frequency-Flow Relationship For Station A Flows Predicted from Station C Flows in the Sulphur River Basin (Flows are in acre-feet/month)

Exceedance Frequency (percent)	Flow Prediction Approach				
	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	0	-	0	-
99	0	3	-	0	-
98	0	9	-	0	-
95	0	38	-	0	-
90	6	132	-	0	-
80	294	697	-	42	-
70	1153	2621	-	875	-
60	3267	5644	-	2717	-
50	8025	12677	-	7708	-
40	14889	22940	-	15682	-
30	23620	38527	-	28511	-
20	39004	57074	-	44393	-
10	69636	98854	-	81504	-
max	259718	297135	-	266906	-

Table B.35. Frequency-Flow Relationship For Station B Flows
Predicted from Station C Flows in the Sulphur River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	0	-	1	-
99	0	2	-	6	-
98	5	8	-	15	-
95	21	29	-	41	-
90	71	116	-	140	-
80	367	556	-	609	-
70	1352	1948	-	2051	-
60	3054	3989	-	4140	-
50	6910	8161	-	8381	-
40	11454	13729	-	14013	-
30	17312	23051	-	23412	-
20	27938	34482	-	34905	-
10	48025	53202	-	53688	-
max	179508	170550	-	171025	-

Table B.36. Frequency-Flow Relationship For Station D Flows
Predicted from Station E Flows in the Sulphur River Basin
(Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	63	77	-	212	-
99	63	77	-	212	-
98	202	85	-	226	-
95	373	192	-	390	-
90	714	407	-	685	-
80	1749	1319	-	1809	-
70	2696	2786	-	3505	-
60	3520	4724	-	5672	-
50	13335	15116	-	16864	-
40	26347	32279	-	34837	-
30	40232	41172	-	44040	-
20	79033	66471	-	69997	-
10	124601	89172	-	93112	-
max	301552	219910	-	224808	-

Table B.37. Frequency-Flow Relationship For Station B Flows Predicted from Station A Flows in the Sulphur River Basin (Flows are in acre-feet/month)

Exceedance	Flow Prediction Approach				
Frequency (percent)	Known Flows	Area Ratio	A-CN-M Ratio	NRCS CN Original	NRCS CN Adjusted
100	0	0	-	0	-
99	0	0	-	0	-
98	0	0	-	0	-
95	8	0	-	0	-
90	41	0	-	0	-
80	321	143	-	248	-
70	722	573	-	996	-
60	2540	1956	-	3401	-
50	4833	4552	-	7646	-
40	9068	8624	-	12949	-
30	15475	13986	-	19572	-
20	22860	25336	-	32955	-
10	44021	44676	-	54806	-
max	179508	149338	-	166700	-