Methods for Developing Naturalized Monthly Flows at Gaged and Ungaged Sites

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Abstract: The state of Texas recently implemented a water availability modeling (WAM) system to support water management activities in its 23 river basins. Hydrology is represented in the modeling system by sequences of naturalized streamflows at all pertinent locations for each month of a several decade long period of analysis. Flows at stream gaging stations are adjusted to remove the effects of historical water resources development and use. The resulting naturalized flows are distributed to numerous ungaged sites of interest in modeling water management. Methods are incorporated into the WAM system for converting gaged flows to naturalized flows and transferring the flows from gaged to ungaged locations. Flow naturalization adjustments consist primarily of removing the effects of historical reservoir storage and evaporation, water supply diversions, and return flows from surface and groundwater supplies, and in some cases other considerations. The WAM system includes several alternative methods for distributing sequences of monthly naturalized flows from gaged to ungaged locations. The option most often used is based on the Natural Resource Conservation Service curve-number-based rainfall-runoff relationship. The methodologies for developing naturalized flows at gaged and ungaged sites incorporated in the Texas WAM system are generally applicable for similar modeling applications in other places.

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Introduction

Sequences of monthly naturalized streamflows representing historical natural hydrology unaffected by people are fundamental to many modeling applications addressing various aspects of river basin management. A general approach for developing these data consists of adjusting flows recorded at stream gaging stations to remove the effects of human activities and then transferring the flows to ungaged sites of interest. Although very important in practical applications, little attention has been devoted in the published literature to methods for developing and spatially distributing sequences of monthly naturalized flows.

The Texas Natural Resource Conservation Commission, renamed the Texas Commission on Environmental Quality (TCEQ) in 2002, its partner agencies, and contractors developed a water availability modeling (WAM) system during 1997–2004 pursuant to water management legislation enacted by the Texas Legislature in 1997 (Wurbs 2005a). The WAM system consists of the generalized water rights analysis package (*WRAP*) model, input data sets for all the river basins of the state, and other databases and data management systems. The *WRAP* input data sets include sequences of monthly naturalized flows covering simulation periods ranging from 50 to 62 years at about 500 gages that are used to estimate flows at about 12,500 ungaged sites. The Texas experience in developing and applying methods for naturalizing gaged monthly flows and distributing the flows to ungaged locations is described in this paper.

In general, the essentially synonymous terms "naturalized, virgin, unregulated, or unimpaired" refer to sequences of past streamflows adjusted to represent a specified condition of river basin development that includes either no human impact or some defined level of development. The objective is to develop a homogeneous set of flows at pertinent locations that represent the hydrologic characteristics of the river basin. Water managers are concerned with the future, not the past. However, since the future is unknown, these sets of adjusted streamflows are assumed to capture the relevant characteristics of climate and natural river basin hydrology. From the perspective of the Texas WAM system, naturalized flows would ideally be flows that would have occurred historically, in the absence of reservoirs, water supply diversions and return flows, and other types of water management activities that are reflected in the water rights input data set, but with all other aspects of the river basin reflecting constant present conditions. The naturalized flow adjustment procedures provide estimates that approximate this condition.

Texas Water Availability Modeling System

Development of the Texas WAM system was motivated by modeling needs encountered by the TCEQ in administering a water rights permit program, but the modeling system supports a broad range of water resources planning and management activities (Wurbs et al. 2005). River authorities, water districts, cities, private companies, and individual citizens hold about 8,000 permits to use the surface water resources of the state. Changes in water use or management practices or development of new water projects require TCEQ approval of either new permits or revi-

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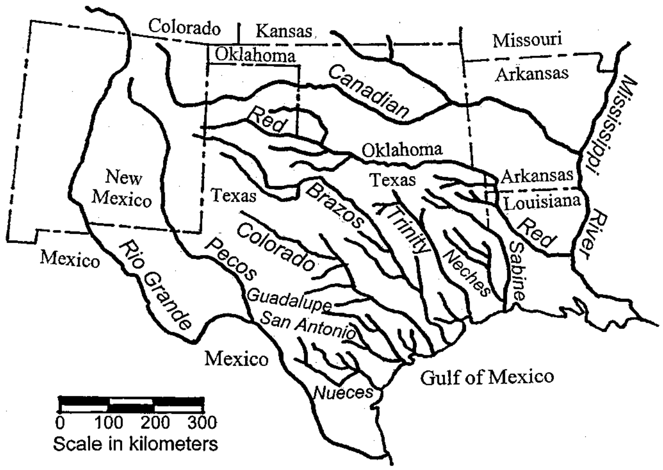

Fig. 1. Major rivers in Texas

sions to existing permits. The TCEQ uses the WAM system to determine whether sufficient water is available to supply the proposed use and to evaluate the impacts on other water users. Water management entities and their consultants apply the modeling system in local and regional planning studies and preparation of permit applications. The Texas Water Development Board (TWDB) applies the WAM system in its statewide planning activities.

The Texas WAM system consists of the generalized *WRAP* model, hydrology and water rights input data sets, and other supporting data systems. Six consulting engineering firms working under contract with the TCEQ during 1997–2004 developed *WRAP* input data sets for all of the river basins of the state. The data sets and simulation software are publicly available to the water management community and may be downloaded from the WAM website maintained by the TCEQ ⟨http://www.tceq.state.tx.us/permitting/water_supply/water_rights/wam.html⟩.

Texas has 15 major river basins and eight coastal basins along the Gulf of Mexico between the lower reaches of the major river basins. The larger rivers are shown in Fig. 1. The WAM system data sets were developed for assessing water availability in Texas. For the interstate and international river basins, hydrology and water management in neighboring states and Mexico are considered to the extent required to assess water availability in Texas. The Texas river basins exhibit a broad diversity of climate, geography, economic development, population density, and water management practices. Mean annual precipitation ranges from 200 mm/year at El Paso on the Rio Grande in arid west Texas to 1400 mm/year in the lower Sabine River Basin.

The WAM system data sets listed in Table 1 cover the entire state subdivided by the river basins shown in Fig. 2. Three of the 20 data sets combine two adjoining basins. The 20 *WRAP* input data sets covering 23 basins contain the 3,365 reservoirs for which water right permits have been issued. Permits are required to store more than 246,800 m^3 (200 acre-ft). Over 90% of the total capacity of the 3,365 reservoirs is contained in the 211 reservoirs that have conservation capacities exceeding 6,170,000 m^3 (5,000 acre-ft). Numerous reservoirs are modeled,

Table 1. River Basin Models in Texas Commission on Environmental Quality Texas WAM System

WAM dataset for major river basin or coastal basin	Area in Texas (km^2)	Area outside Texas (km^2)	Period of analysis	Mean natural flow (10^6 m^3/year)	Number of lakes	Total storage capacity (10^6 m^3)	Primary control points	Total control points
Rio Grande	125,000	347,000	1940–2000	—	90	16,150	77	974
Brazos River and San Jacinto-Brazos	115,000	6,660	1940–1997	7,850	650	5,760	77	3,818
Colorado River and Brazos-Colorado	108,000	5,100	1940–1998	3,700	503	5,880	45	2,263
Red River	63,400	61,000	1948–1998	19,200	240	4,970	50	443
Trinity River	46,500	0	1940–1996	8,490	702	9,250	40	1,329
Nueces River	43,900	0	1934–1996	1,070	122	1,280	41	544
Canadian River	32,900	90,700	1948–1998	235	47	1,190	12	85
Nueces-Rio Grande	27,000	0	1948–1998	307	64	140	20	197
Guadalupe and San Antonio	26,500	0	1934–1989	2,590	233	997	46	1,334
Neches River	25,900	0	1940–1996	7,690	175	4,820	20	304
Sabine River	19,200	6,040	1940–1998	8,500	206	7,870	27	373
San Jacinto River and San Jacinto-Trinity	14,500	0	1940–1996	2,720	111	787	16	386
Sulphur River	9,220	492	1940–1996	3,080	51	930	6	77
Cypress Bayou	7,280	259	1948–1998	2,150	85	1,080	22	158
San Antonio-Nueces	6,860	0	1948–1998	697	9	2	13	49
Lavaca River	5,980	0	1940–1996	1,200	22	290	7	176
Lavaca-Guadalupe	2,590	0	1940–1996	194	0	0	1	68
Colorado-Lavaca	2,440	0	1940–1996	167	10	67	2	105
Neches-Trinity	1,990	0	1940–1996	749	31	40	2	216
Trinity-San Antonio	648	0	1940–1996	223	14	6	9	83
Total	685,000	517,000		70,800	3,365	61,510	533	12,982

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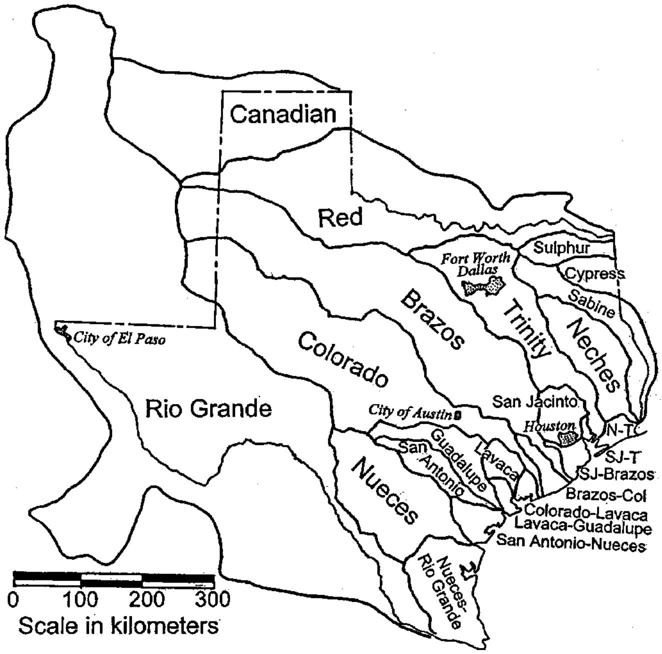

Fig. 2. Texas water availability modeling system river basins

but most of the storage is contained in a few large reservoirs.

The spatial configuration of a river basin system is defined in the model by a set of control points. All reservoirs, diversions, return flows, hydropower plants, environmental instream flow requirements, and other system components are assigned control point locations. The number of primary control points and the total number are listed as the last two columns of Table 1. Primary control points are sites for which naturalized flows are provided as an input file. For all other control points, naturalized flows are computed within the *WRAP* simulation using watershed parameters from an input file. Most primary control points are U.S. Geological Survey (USGS) gaging stations.

Capabilities for meeting specified water use requirements are assessed with basin hydrology represented by sequences of naturalized flows and reservoir net evaporation less precipitation rates at all pertinent locations for each month of the period of analysis. The hydrologic period of analysis adopted for the Texas WAM system basin models is tabulated as column 4 of Table 1. For most of Texas, the most hydrologically severe drought on record began in 1951 and ended with a major flood in April 1957. The simulation periods adopted include the drought of record and other shorter duration severe droughts as well as a full range of fluctuating wet and dry periods. As the consulting firms compiled the input data sets, development of naturalized flows at the primary control points was a major initial task documented separately from the remainder of the model development effort. At some time in the future, the flows will be extended to cover the years of record accumulated since completion of these initial data sets.

Water Rights Analysis Package Model

The *WRAP* model is a river–reservoir system water allocation model designed for assessing reliabilities for water supply diversions, environmental instream flow needs, hydroelectric power generation, and reservoir storage (Wurbs 2005b,c). The generalized model developed at Texas A&M University beginning in the 1980s has been greatly expanded since 1997 for the TCEQ WAM system. The *WRAP* is generalized for application at any place, with input data files being developed for the particular river basin or multiple-basin region of concern. In Texas, application of *WRAP* involves revising available input files to reflect water management plans of interest.

Capabilities are assessed for meeting specified water management and use requirements during an assumed repetition of historical hydrology. Simulations are repeated for various water management scenarios reflecting alternative premises regarding water use, return flows, and reservoir sedimentation. The TCEQ WAM system includes a full authorization scenario based on the premise that all permit holders use the full amounts of water authorized by their water right permits and an actual current use scenario.

The overall modeling process includes the following tasks:

1. Sequences of monthly naturalized flows covering the specified period of analysis at selected gaging stations are developed;
2. Naturalized flows are distributed from gaged to all pertinent ungaged locations;
3. The water management system is simulated, with water being allocated to each water right; and
4. Water supply reliability indices, flow and storage frequency relationships, and other summary statistics are computed, and the simulation results are organized.

Task 1 has been completed for all of the river basins in Texas. Tasks 2–4 occur each time the simulation model is executed. This paper focuses specifically on Tasks 1 and 2.

The *WRAP* includes the programs *HYD*, *SIM*, and *TABLES*. Program *HYD* provides a set of computational options for developing the hydrology input files required by *SIM*. The simulation model *SIM* reads the hydrology and water rights input files and simulates the water management–allocation system. The *TABLES* model organizes the simulation results and develops reliability indices and frequency relationships.

The *SIM* reads naturalized flows at primary control points as input and distributes the flows to ungaged secondary control points. The *HYD* provides options for converting gaged flows to naturalized flows and also has the same algorithms as *SIM* for distributing flows to ungaged sites. The *SIM* and *TABLES* models were used throughout the development of the Texas WAM system and continue to be routinely applied. However, *HYD* was created later after development of the naturalized flow data sets for many of the river basins was well underway. Microsoft *Excel* was used by the consulting firms working for the TCEQ in developing sequences of naturalized flows at primary control points for most of the river basin data sets.

The modeling process results in three forms of streamflows at each control point. A *WRAP–SIM* simulation begins with naturalized flows, the subject of this paper. Regulated and unappropriated flows computed by *SIM* result from adjustments to naturalized flows that reflect water right requirements representing a specified scenario of water resources development and use. Regulated flows are physical flows considering all water rights in the input data set. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. Regulated flows may be greater than unappropriated flows at a site due to instream flow requirements at that site or commitments to other rights at downstream sites.

Naturalized flows are provided as a *WRAP–SIM* input data file for primary control points. Naturalized flows at all other sites are

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computed by the simulation model each time it is executed, using watershed parameters provided as an input file. Naturalized flows at gaging stations are included in the Texas WAM system data sets that have already been developed and are available for use by the water management community. Synthesized naturalized flows at ungaged sites may also be included in the permanent data sets but usually are not.

This paper focuses specifically on the tasks of: (1) developing sequences of monthly naturalized flows covering a specified period of analysis at selected gaging stations and (2) transferring the flows to ungaged locations. These tasks typically represent the majority of the effort in creating a complete *WRAP* data set for a river basin. The same tasks are important in many other types of river basin modeling applications involving models other than *WRAP*.

Converting Gaged Flows to Naturalized Flows

Developing sequences of monthly naturalized flows covering a specified period of analysis at selected gaging stations consists of: (1) adjusting observed flows to reflect natural conditions; and (2) filling in gaps and extending records. Gage records often do not cover the entire period of analysis. Naturalized flows for months with missing records are reconstituted by regression analyses with naturalized flows at other gages.

Basic Flow Naturalization Adjustments

The objective of streamflow naturalization procedures is to convert gaged flows to natural flows that would have occurred in the absence of water users and water management facilities and practices. Flow adjustments remove the impacts of upstream reservoirs, water supply diversions, return flows from surface and groundwater sources, and possibly other factors. The extent of the adjustments depends upon the circumstances of the particular river basin.

At a given gaging station, for a particular month during the historical record, the naturalized flow (NF) volume is computed as

$$\mathrm{NF} = \mathrm{GF} + \Sigma D_i - \sum \mathrm{RF}_i + \sum \mathrm{EP}_i + \sum \Delta S_i \tag{1}$$

GF=gaged flow; D_i=water supply diversions at locations i upstream of the gage; RF_i=return flows into the river system at locations i upstream of the gage; EP_i=net reservoir surface evaporation less precipitation upstream of the gage; and ΔS_i=change in storage in upstream reservoirs. Net evaporation EP=volume of evaporation less the proportion of the precipitation volume falling on the reservoir water surface that would not have reached the stream in the absence of the reservoir. Many reservoirs, diversions, and return flows may be located upstream of the gaging station. The monthly adjustments vary historically over the period of analysis as new reservoir and other water control facilities were constructed and water use practices changed.

The adjustments reflected in Eq. (1) are governed largely by data availability. For most major reservoirs, readily available data include water surface elevation versus surface area and storage volume relationships and end-of-month storage contents for each month since initial impoundment. However, these data are not available for numerous smaller reservoirs. The TWDB maintains a database of reservoir evaporation and precipitation rates for each of 75 1° quadrangles covering the state for each month from 1940 to the present. The TCEQ and TWDB collect data submitted by cities, water districts, and other entities on water supply diversions and return flows. Wastewater treatment plant effluent discharges and irrigation return flows to stream systems include water supplied from groundwater as well as surface water sources. Although the completeness and accuracy of these data have historically been somewhat erratic, considerable effort has been expended by the agencies in recent years to better organize available data.

For upper basin sites with relatively undeveloped watersheds, little or no adjustments may be necessary. In extensively developed river basins, quantifying and removing all effects of human activities is not possible. In most major river basins, most storage capacity is contained in a relatively few large reservoirs even though there are numerous other smaller reservoirs. Likewise, relatively few large cities, water districts, and river authorities account for most of the total volume of water diverted from and returned to streams, though there are numerous other water users. After accounting for the relatively large water management entities, the incremental increases in accuracy of including smaller water users in the computations diminish with increasing difficulty in obtaining historical water use and storage observations.

Notable effort was expended by the TCEQ and its consultants in developing naturalized flows for the Texas WAM system. Judgments were necessary regarding the practical extent of the adjustments. Reservoirs with conservation capacities of at least 6,170,000 m^3 (5,000 acre-ft) and diversions and return flows for which records are available were always included in the adjustments. The effects of numerous smaller reservoirs and diversions were neglected.

Channel losses (CLs) reflecting seepage, evapotranspiration, and illicit diversions along a stream reach during a particular month are defined in the *WRAP* model as

$$\mathrm{CL} = F_{\mathrm{CL}} Q_{\mathrm{US}} \tag{2}$$

F_{CL}=dimensionless channel loss factor varying between 0.0 and 1.0, which is provided as model input; and Q_{US}=flow at the upstream end of the stream reach. Defining X_{US} as one of the adjustments D, RF, EP, or ΔS in Eq. (1) occurring at the upstream end of a stream reach, the adjustment X_{DS} translated to the downstream end of the reach is

$$X_{\mathrm{DS}} = (1.0 - F_{\mathrm{CL}}) X_{\mathrm{US}} \tag{3}$$

Multiple delivery factors $(1 - F_{\mathrm{CL}})$ may be applied to translate an adjustment through multiple reaches between the diversion, return flow, or reservoir site and the downstream site of concern.

The stream reaches connecting the thousands of control points in the Texas WAM system data sets have channel loss factors covering the full range from 0 to 1.0. For many reaches, channel losses are considered negligible and not incorporated in the model. However, channel losses are significant and included in the data sets for many other stream reaches. Channel loss factors were developed in terms of loss per unit length based on studies of water balances for reaches between gaging stations. The loss–length estimates combined with reach lengths are used to assign loss factors to reaches connecting model control points. In the water balances performed to estimate channel losses, runoff entering the stream between the gaging stations is estimated using rainfall records combined with the Natural Resource Conservation Service (1985) curve-number-based rainfall-runoff relation. Several reservoir management agencies have acquired channel

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loss information based on extensive experience in releasing for water supply diversions that occur at locations long distances below their dams.

As the data sets for each river basin were compiled, statistical trend analyses were performed to assure that the naturalized flow sequences were homogeneous. Plots, linear trend analyses, and Kendall's rank correlation test (Helsel and Hirsch 1992) were used to detect long-term trends. The naturalized flows continue to exhibit long-term trends at a few locations even after reasonable efforts at adjustments. However, long-term trends are not detected in the naturalized flows sequences developed for most of the approximately 500 gaging stations. In general, although the naturalization procedures are necessarily approximate, the naturalized flows incorporated in the Texas WAM system are considered to be homogeneous without long-term trends.

Other Types of Flow Adjustments

Schemes for further adjustments to naturalized streamflows to reflect various aspects of climate, hydrology, and watershed land use may be devised. For example, in the TCEQ WAM system model of the San Antonio and Guadalupe River Basins, groundwater pumpage from the Edwards Aquifer is reflected in *WRAP* as spring flow adjustments to naturalized streamflows. Changes in spring flows associated with aquifer pumpage simulated with a TWDB groundwater model are added to *WRAP* naturalized streamflows.

In a research project not incorporated into the WAM system, naturalized flows for the Brazos and San Jacinto River Basins were adjusted to reflect a future climate scenario (Wurbs et al. 2005). Output from a global climate model, with and without a particular climate change scenario, was used to adjust the precipitation and temperature input data for the soil and water assessment tool (*SWAT*) watershed model. Streamflow sequences computed with *SWAT*, with and without climate change, were used to create sets of factors for each pertinent location that were used to adjust the *WRAP* naturalized streamflows to reflect the future climate change scenario.

The *SWAT* (Neitsch et al. 2002) or another watershed model may be applied similarly to adjust naturalized flows to reflect watershed land use changes. For given sequences of daily precipitation, the watershed model is executed with and without specified land use changes. In general, adjusting gaged flows to develop long sequences of naturalized streamflows at multiple locations throughout a river basin is typically significantly more accurate than flows from a watershed precipitation-runoff model, such as *SWAT*. However, dual alternative executions of *SWAT* with and without climate change and/or with and without watershed change provide sets of alternative flows from which to develop regression coefficients or adjustment factors. The original gage-based naturalized flows are adjusted using these factors.

Distributing Flows to Ungaged Locations

As indicated by Table 1, the number of gaged (known-flow, primary) and ungaged (unknown-flow, secondary) control points vary greatly between the basin models included in the TCEQ WAM system. Naturalized flows are required for all control points. The problem of estimating sequences of naturalized monthly flows at ungaged locations based on naturalized flows at gaged sites is illustrated by the hypothetical river system of Fig. 3. Naturalized flows at the 12 ungaged sites are developed from naturalized flows at the five gaging stations.

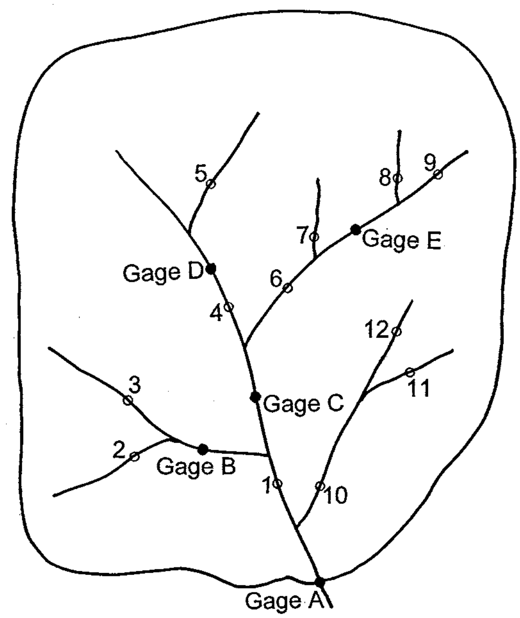

Fig. 3. Hypothetical river basin

Total and Incremental Flows and Watersheds

Judgment is required in selecting gages and incremental watersheds for synthesizing flows at ungaged sites. The watershed associated with the incremental or total flows at the source gage should have similar characteristics as the watershed of the ungaged site. The alternative flow distribution methods outlined later may be applied to either local incremental flows or total flows. If incremental watersheds are adopted, the unknown flow at an ungaged site is determined from the known flow at a gaged site in three steps.

1. The incremental flow at the source gage is computed by subtracting its total flow from the sum of flows at appropriate upstream gages, with Eq. (3) adjustments for channel losses;
2. The incremental flow at the gage is distributed to the ungaged site using one of the alternative methods described later; and
3. The incremental flow at the ungaged site is added to the flows at the appropriate upstream gages, adjusted for channel losses, to obtain the total flows at the ungaged site.

Incremental flows I_{A-B-C} at Gage A at Site 1 in Fig. 3 may be estimated from the flows Q_A, Q_B, and Q_C at Gages A, B, and C, as follows:

$$I_{A-B-C} = Q_A - (1.0 - F_{B1})(1.0 - F_{1A})Q_B - (1.0 - F_{C1})(1.0 - F_{1A})Q_C \tag{4}$$

F_{B1}, F_{C1}, and F_{1A}=channel loss factors for the reaches between Gage A and Site 1, Gage C and Site 1, and between Site 1 and Gage A. Eq. (3) may be applied to adjust flows for channel losses in any number of stream reaches. The incremental flows I_{1-B-C} for the incremental watershed above ungaged Site 1 but below Gages B and C are determined from the incremental flows I_{A-B-C} at Gage A using methods discussed later. The total flows Q_1 at ungaged Site 1 are then determined as

$$Q_1 = I_{1-B-C} + (1.0 - F_{B1})Q_B + (1.0 - F_{C1})Q_C \tag{5}$$

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Flows at ungaged Sites 2 and 3 in Fig. 3 may be determined directly from the flows at Gage *B* without considering incremental flows. Flows at ungaged Sites 10–12 may be determined following the procedure outlined for ungaged Site 1. Alternatively, total flows at Sites 11 and 12 may be determined directly from the flows at Gage *E* without determining incrementals. Flows at Site 4 will typically be estimated either from incremental flows I_{C-D-E} at Gage *C* or total flows Q_D at Gage *D*. Likewise, flows at Site 7 may be estimated from incremental flows I_{C-D-E} at Gage *C* or total flows Q_E at Gage *E* using the methods outlined next.

Methods for Transferring Flows from Gaged to Ungaged Sites

The several alternative methods for transferring naturalized flows from gaged to ungaged sites incorporated in *WRAP* were adopted based on a comparative evaluation which included investigation of the following alternative approaches (Wurbs and Sisson 1999).

- Distribution of flows in proportion to drainage area;
- Flow distribution equation with ratios for various watershed parameters;
- Adaptation of the Natural Resource Conservation Service (NRCS) curve-number (CN) method;
- Regression equations relating flows to watershed characteristics;
- Use of recorded data at gaging stations to develop precipitation-runoff relationships; and
- Use of watershed (precipitation-runoff) computer models such as *SWAT*.

Flow distribution options actually incorporated in *WRAP* are variations of three alternative approaches: (1) drainage area ratio method; (2) an adaptation of the NRCS curve-number (CN) method; and (3) a generic equation for which coefficients may be determined in various ways. An adaptation of the NRCS CN method was adopted as the standard method routinely applied in the Texas WAM system, alternatively with the drainage area ratio method also being applied in many cases. Other methods noted in the following discussion were investigated but not actually adopted for the Texas WAM system.

Drainage Area Ratio Method

The drainage area ratio (DAR) method distributes flows in proportion to drainage area (DA)

$$Q_{\text{ungaged}} = R_{\text{DA}} Q_{\text{gaged}} \tag{6}$$

$$R_{\text{DA}} = \frac{\text{DA}_{\text{ungaged}}}{\text{DA}_{\text{gage}}} \tag{7}$$

Eq. (9) may optionally be applied in situations where the ungaged site is located upstream of the gaged site with channel losses occurring between the sites at rates that are significantly greater that the loss rates in the watershed above the ungaged site

$$Q_{\text{ungaged}} = R_{\text{DA}}(Q_{\text{gaged}} + F_{\text{CL}} Q_{\text{ungaged}}) \tag{8}$$

or

$$Q_{\text{ungaged}} = Q_{\text{gaged}}\left(\frac{R_{\text{DA}}}{1 - R_{\text{DA}} F_{\text{CL}}}\right) \tag{9}$$

Modified Natural Resource Conservation Service Curve-Number Method

The NRCS relationship between precipitation depth *P* and runoff volume *V* as a depth equivalent is as follows (NRCS 1985; McCuen 2005):

$$V = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{if } P \geqslant 0.2S$$

or

$$V = 0 \quad \text{if } P < 0.2S \tag{10}$$

$$S = \frac{25{,}400}{\text{CN}} - 254 \quad (V, P, S \text{ in mm})$$

or

$$S = \frac{1{,}000}{\text{CN}} - 10 \quad (V, P, S \text{ in in.})$$

where V=runoff depth; P=precipitation depth; S=maximum potential retention after runoff begins; and CN=curve number. *V* is multiplied by the drainage area to obtain flow volume. *S* 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 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 of the rainfall becoming runoff. The CN may be estimated from empirical information developed by the NRCS relating the CN to watershed soil type, land cover and use, and antecedent moisture conditions.

An adaptation of the NRCS CN method is incorporated in the *WRAP* model for distributing flows, which is a different type of application than originally envisioned by the NRCS. The NRCS developed Eq. (10) for estimating the runoff volume to result from a storm with a given rainfall depth. In the *WRAP* adaptation, Eq. (10) is applied as follows. Given the naturalized monthly flow at the gage, precipitation *P* is computed by the NRCS equation with the CN for the gaged watershed. After adjusting the *P* by a mean annual precipitation ratio, it is substituted back into Eq. (1) with the CN for the ungaged watershed to determine the flow at the ungaged site. If the CN and mean precipitation are the same for the gaged and ungaged watersheds, this method reduces to distributing streamflow in proportion to drainage area. The algorithm consists of the following computational steps performed for each month:

1. The monthly flow volume at the gage is divided by the drainage area A_{gage} to convert to a runoff depth V_{gage};
2. V_{gage} is input to Eq. (10) to obtain P_{gage}, which is assumed to be applicable to both the ungaged and gaged watershed. Base flow is assumed to be distributed along with storm runoff; and
3. The precipitation depth is adjusted by multiplying P_{gage} by the ratio of the mean annual precipitation depths, $\text{MP}_{\text{ungaged}}$ and MP_{gaged}

$$\text{adjusted } P_{\text{ungaged}} = P_{\text{gage}}\left(\frac{\text{MP}_{\text{ungaged}}}{\text{MP}_{\text{gage}}}\right) \tag{11}$$

4. P_{ungaged} is input into Eq. (10) to obtain V_{ungaged}. The runoff depth V_{ungaged} is multiplied by A_{ungaged} to convert to a monthly flow volume.

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An option extends the procedure to deal with situations where the ungaged site is located upstream of the gaged site with channel losses occurring between the sites at rates much greater than the rates in the watershed above the ungaged site. Whereas Eq. (9) directly incorporates the F_{CL} into the DAR method, with the NRCS CN method, the following procedure is adopted with steps 2 and 3 being repeated iteratively until a stop criterion is met:

1. For the initial iteration, the channel loss $F_{CL}Q_{ungaged}$ is set equal to zero, and thus $(Q_{gaged}+F_{CL}Q_{ungaged})$ is set equal to Q_{gaged};
2. The modified CN method based on Eq. (10) is applied to compute an intermediate value for $Q_{ungaged}$ for the given $(Q_{gaged}+F_{CL}Q_{ungaged})$; and
3. Given $Q_{ungaged}$ from Step 2, $F_{CL}Q_{ungaged}$ and thus $(Q_{gaged}+F_{CL}Q_{ungaged})$ are determined.

Generic Equation

The *WRAP* also has an option for distributing flow with the following equation:

$$Q_{ungaged} = a(Q_{gage})^b + c \tag{12}$$

with coefficients a, b, and c provided as input. With default values of 1.0 and 0.0 for b and c and $a=R_{DA}$, Eq. (12) reduces to the DAR method. The coefficient a may be expressed as a function of MP, CN, and other parameters, as well as DA, with default values of 1.0 and 0.0 for b and c

$$a = \left(\frac{DA_{ungaged}}{DA_{gage}}\right)^{N_1}\left(\frac{MP_{ungaged}}{MP_{gage}}\right)^{N_2}\left(\frac{CN_{ungaged}}{CN_{gage}}\right)^{N_3}\left(\frac{Other_{ungaged}}{Other_{gage}}\right)^{N_4} \tag{13}$$

If the exponents N_i are assumed to be unity, the constant a may be related to DA, MP, and CN as

$$a = \left(\frac{DA_{ungaged}}{DA_{gage}}\right)\left(\frac{MP_{ungaged}}{MP_{gage}}\right)\left(\frac{CN_{ungaged}}{CN_{gage}}\right) \tag{14}$$

Another method for determining the coefficients for Eq. (12) involves watershed simulation with a precipitation-runoff model such as *SWAT*. The procedure is as follows:

1. Flows at both gaged and ungaged sites are generated by the rainfall-runoff model;
2. The coefficients a, b, and c in Eq. (12) are determined by regressing flows at an ungaged site with the corresponding flows at a gaged site generated with the rainfall-runoff model; and
3. Flows at the ungaged site are computed by applying Eq. (12) to the naturalized flows at the gaged site determined by adjusting gaged flows.

Raju (1998) investigated this procedure by applying *SWAT* to the San Jacinto River Basin. The *SWAT* computes daily streamflows to result from specified precipitation by simulating the hydrologic processes that occur in a watershed (Neitsch et al. 2002). Daily precipitation may be either input to *SWAT* or synthesized within the model based on statistical parameters. Runoff volumes are determined by a modification of the NRCS rainfall-runoff equation that allows the CN to vary during a simulation with changes in soil moisture. Percolation is modeled with a storage routing technique to predict flow through specified soil layers. Raju (1998) used *SWAT* to predict 20 years of daily flows at pertinent sites for input daily precipitation. Daily flows were aggregated to monthly flows. The coefficients for Eq. (12) were determined as outlined above for incorporation into *WRAP* for distributing flows for the hydrologic period of record.

A comparative evaluation (Wurbs and Sisson 1999) concluded that this approach provides little if any improvement in accuracy over the previously described methods unless extensive effort is expended to compile input reflecting in detail spatial variations in rainfall and watershed parameters. The precipitation-runoff modeling-based approach has not been used for the Texas WAM system.

Acquiring Values for Watershed Parameters

The modified NRCS and DAR methods were adopted for the Texas WAM system and both methods require a DA for all gaged and ungaged sites. The NRCS CN method also requires a CN and MP. The DA, CN, and MP for all of the approximately 13,000 control points included in the Texas WAM system are included in the *WRAP* input data sets.

The Center for Research in Water Resources at the Univ. of Texas at Austin, Austin, Tex. under contract with the TCEQ developed and applied a geographic information system (GIS) methodology based on the Environmental Systems Research Institute (ESRI) *ArcGIS* to estimate values for the watershed parameters (Mason and Maidment 2000; Maidment 2002; Goplan 2003). Spatial connectivity is defined in *WRAP* by listing the control point located immediately downstream of each control point. The GIS was also used to develop lists of the next downstream control points. Lengths of the stream reaches connecting the control points were also determined with the GIS for use in establishing channel loss factors.

The following data were used to develop watershed parameters for the Texas WAM system:

- Digital elevation models of land surface terrain available from the U.S. Geological Survey (USGS);
- Set of USGS stream gaging station locations;
- Set of water right locations developed by the TCEQ and its consultants;
- Grid of mean annual precipitation developed at Oregon State Univ. for the NRCS; and
- Grid of curve numbers.

The drainage areas for the gaging stations were found to compare closely in most cases with those published by the USGS. The CN database had been previously developed by the Texas Agricultural Experiment Station and U.S. Department of Agriculture (USDA) Agricultural Research Service for the hydrologic unit modeling of the U.S. project sponsored by the NRCS (Arnold et al. 1999). The CN grid was developed by intersecting USGS maps of land use and USDA maps of soil type and combining the results with a CN table.

Considerations in Synthesizing Flows at Ungaged Sites

Developing sequences of naturalized flows for ungaged watersheds necessarily involves uncertainties and inaccuracies that include the following:

1. Precipitation, streamflow, and other hydrologic variables are highly variable both temporally and spatially;
2. Watersheds may be highly nonhomogeneous with soils, vegetation, land use, topography, and other characteristics changing significantly over short distances;
3. Watershed characteristics are difficult to accurately measure;
4. Changes over time in land use and other watershed charac-

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teristics are typically not reflected in the process of naturalizing gaged flows;

5. The hydrologic processes that transform rainfall to streamflow, such as infiltration, surface storage–flow, subsurface storage–flow, and evapotranspiration, are complex;
6. Interactions between subsurface flows and streamflows are complex; and
7. Inaccuracies are inherent in all recorded data including gaged streamflows and the historical reservoir and water use data used to convert gaged flows to naturalized flows.

In synthesizing flows for ungaged watersheds, accuracy in estimating the actual flow for any particular month in the past is not important in Texas WAM system applications as long as relevant statistical characteristics of the long-term historical naturalized flows are adequately modeled. Achieving accuracy in the flow-frequency relationship is 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 result in the estimated flows at ungaged sites being more closely correlated to the gaged site than is actually the case. This overcorrelation between locations is acceptable as long as the flow-duration relationship at the ungaged site is reasonably accurate.

Comparative Evaluation

The flow distribution file in the Texas WAM system data sets include the DA, CN, and MP for all ungaged and gaged control points. The modified NRCS CN method [Eqs. (10) and (11)] is the standard option normally used, but simulations are also often performed using the DAR method. If the CN and MP are the same for the gaged and ungaged watersheds, the CN method adaptation reduces to the DA method.

The DA, CN, and MP estimates included in the WAM input data sets are for the total watershed above each control point. The CN and MP for incremental watersheds are computed within *WRAP* based on weighting the CN and MP in proportion to DA. Inaccuracies in the computed incremental watershed CN and MP may result from an incremental watershed DA being very small relative to the total watershed DA for which the parameters are compiled. The *WRAP* includes an option allowing specification of minimum and maximum limits on the CN and MP. If a limit is violated, the model automatically shifts to the DAR method.

The flow distribution options incorporated into *WRAP* were originally adopted based on a comparative evaluation of alternative methods (Wurbs and Sisson 1999). Subsequent experience acquired during development and application of the Texas WAM system has reaffirmed the basic conclusions of the initial investigations, which are discussed below. Alternative methods were tested by transferring naturalized flows from gaged sites to other gaged sites and comparing the results with the known naturalized flows. The following example illustrates several general findings observed throughout the river basins.

The San Gabriel River Basin located just north of Austin is a subbasin of the Brazos Basin. The gage on the South Fork of the San Gabriel River at Georgetown is located about 70 km upstream of the gage on the San Gabriel River at Laneport. The watershed above the Georgetown gage is a subbasin contained within the watershed of the Laneport gage. Watershed parameters are listed in Table 2. Granger Reservoir, with water supply and flood control capacities of 102 and 200 M m^3 and initial impoundment in 1980, is located just upstream of the Laneport gage. Naturalized monthly flows at both gages and observed flows at the Laneport gage are plotted in Fig. 4. Naturalized and gaged flows are the same at the Georgetown gage. Statistics including flow-frequency relationships are shown in columns 2–4 of Table 3.

Table 2. Watershed Parameters

U.S. Geological Survey Gaging Station	Drainage area (km^2)	Curve number	Mean precipitation (mm/year)
South Fork of San Gabriel River at Georgetown	342	74	821
San Gabriel River at Laneport	1,910	72	841

Results of applying the following alternative methods to transfer naturalized flows from the Laneport gage to the Cameron gage are also summarized in Table 3. Statistics for the flows at the Cameron gage computed with these methods are expressed as a percentage of the known naturalized flows which also happens to be the observed flows for this upper watershed site.

- Modified NRCS CN method based on Eqs. (10) and (11) (column 5 of Table 3);
- DAR method based on Eq. (6) (column 6 of Table 3);
- DA–CN–MP ratio method based on Eqs. (12) and (14) with $b=1$ and $c=0$ (column 7);
- Modified NRCS CN method with channel losses (column 8);
- DAR method with channel losses based on Eq. (9) (column 9); and
- DA–CN–MP ratio method with CL based on Eq. (9) with Eq. (14) (column 10).

A DAR of 0.179 and DA–CN–MP ratio of 0.180 are computed with Eqs. (7) and (14) with the parameters from Table 2. The corresponding ratio of mean flows from Table 3 is 0.191. The channel loss factor F_{CL} defined by Eq. (2) is 0.20 for the river reach between the gages. F_{CL} is used primarily for adjusting downstream flows for the effects of diversions, return flows, and reservoir storage but may also be used in transferring flows from gaged to ungaged sites. Results are included in Table 3 for applying the three alternative methods optionally without and with F_{CL} adjustments for channel losses between the gages. The extra adjustment to increase flows for channel losses is appropriate only if the loss rate F_{CL} for the reach between the gages represents a rate in excess of channel loss rates above the upstream gage. In Eqs. (1) and (11), the NRCS CN method without the F_{CL} adjust-

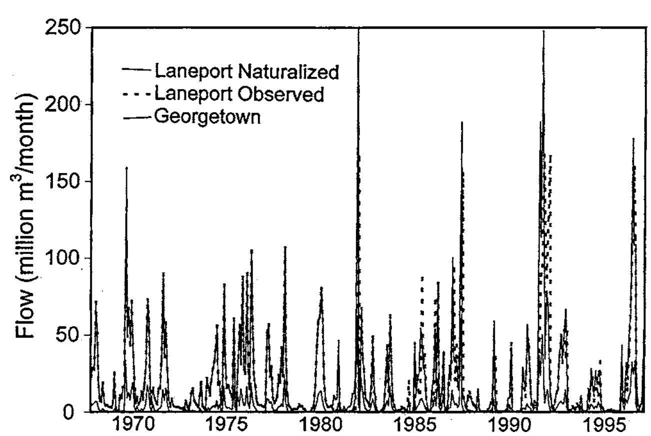

Fig. 4. Monthly flows at Laneport and Georgetown gages

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Table 3. Means, Standard Deviations, and Flow versus Exceedance Frequency Relationships

	Laneport gaged flows	Laneport natural flows	Georgetown natural flows	Flows at Georgetown transferred from Laneport: Without CL option NRCS	DAR	Ratio	With CL option NRCS	DAR	Ratio
		(1,000 m^3/month)			(Percentage of known flow in column 4)				
Mean	20,490	21,650	4,120	100.8	94.1	94.4	104.6	97.6	97.9
Standard deviation	31,120	33,800	7,600	81.4	79.7	80.0	84.4	82.6	82.9
Minimum	0	0	1	0.0	0.0	0.0	0.0	0.0	0.0
0.95%	285	60	25	152.0	44.0	44.0	163.0	45.5	45.5
0.75%	1,790	2,820	278	233.4	182.1	182.7	242.9	188.8	189.6
0.50%	7,240	8,760	1,290	141.0	121.8	122.2	146.4	126.3	126.8
0.25%	24,830	27,320	4,840	109.7	101.1	101.5	113.8	104.8	105.2
0.10%	60,460	57,230	10,840	99.7	94.6	94.9	103.3	98.1	98.5
Maximum	167,700	262,000	62,470	75.9	75.2	75.4	78.6	77.9	78.2

Note: CL=channel losses; NRCS=Natural Resource Conservation Service; and DAR=drainage area ratio.

ment, which is the first method listed above, would normally be adopted for the type of application represented by this San Gabriel River Basin example.

The following observations are based on similar analyses performed for many gaged sites which are illustrated here by this particular example. Temporal variations in flows are dramatic, ranging from zero flows to major floods. Mean flows are reproduced reasonably well with the flow distribution methods. Accuracy in predicting mean flows is much better than the accuracy of predicting the flow-frequency relationship. Performance in reproducing flow-frequency relationships is better than for reproducing flows for individual months.

Accuracy in predicting flows for individual months is extremely poor with any of the methods. The fundamental problem is illustrated by the scatter in the correlation plot of Fig. 5. For any level of flow at the Laneport gage, the corresponding flow at the Georgetown gage covers a broad range. The findings for Texas rivers are similar to those for Australian rivers reported by Gan et al. (1991), who investigated the use of regression equations for relating monthly flows from neighboring watersheds based on drainage area, mean annual precipitation, and percent of watershed covered with forest. Their findings also included the observation that transposed flows for individual months may be greatly in error. However, for the Texas WAM system and other similar applications, accuracy in predicting flows for individual months is not required as long as relevant statistical characteristics of the flows can be adequately modeled.

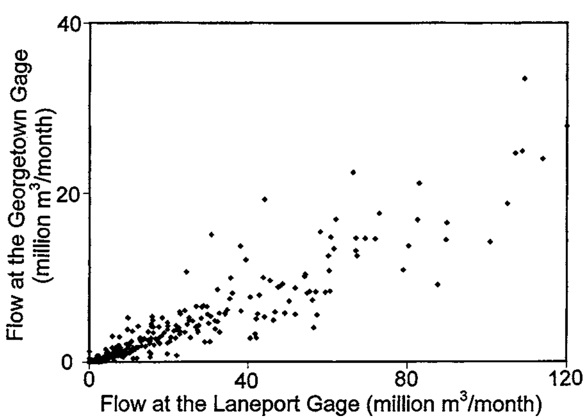

Fig. 5. Naturalized monthly flows at Laneport gage versus Georgetown gage

The NRCS CN, DAR, and DA–CN–MP ratio methods yield similar levels of accuracy. If the CN and MP are the same for the gaged and ungaged watersheds, the three alternative methods yield identical results. The DA is the most important watershed parameter. However, the NRCS method adaptation is preferable in those situations in which differences in CN (land use and soil type) and long-term MP are significantly different between the gaged and ungaged watersheds. The CN and MP are usually similar but not identical. Increasing the flow at a downstream gage by adding an adjustment for channel losses is relevant in situations in which the ungaged site is upstream of the gage and the loss rate in the reach between the sites is much higher than channel loss rates above the upstream ungaged site.

Many of the ungaged control points in the Texas WAM system are located near or between gages, which allows flow distribution to be more accurate. However, there are also many situations illustrated by the example where ungaged sites are located in upper watersheds remote from the nearest downstream gage and there are no gages located upstream.

Summary and Conclusions

Effective systematic capabilities for converting gaged flows to naturalized flows and distributing the naturalized flows to ungaged locations are fundamental requirements for the Texas WAM system. The methodologies adopted in Texas are pertinent to similar applications in other places. Successful implementation of the methodologies is dependent on sound professional judgment and efficient tools for acquiring and managing voluminous data. The adjustments applied to convert observed flows at gaging stations to naturalized flows were carried out in sufficient detail for the Texas WAM system to provide homogeneous flow sequences. Accuracy is significantly reduced as the naturalized flows at the gages are distributed to numerous ungaged sites of concern. Drainage area is the key watershed parameter. The curve number and mean annual precipitation are included in the data sets for use in the modified NRCS method to achieve improvements in accuracy for situations where the gaged and ungaged

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watersheds have significantly different soil and land use characteristics and mean rainfall.

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