Conditional Reliability, Sub-Monthly Time Step, Flood Control, and Salinity Features of WRAP

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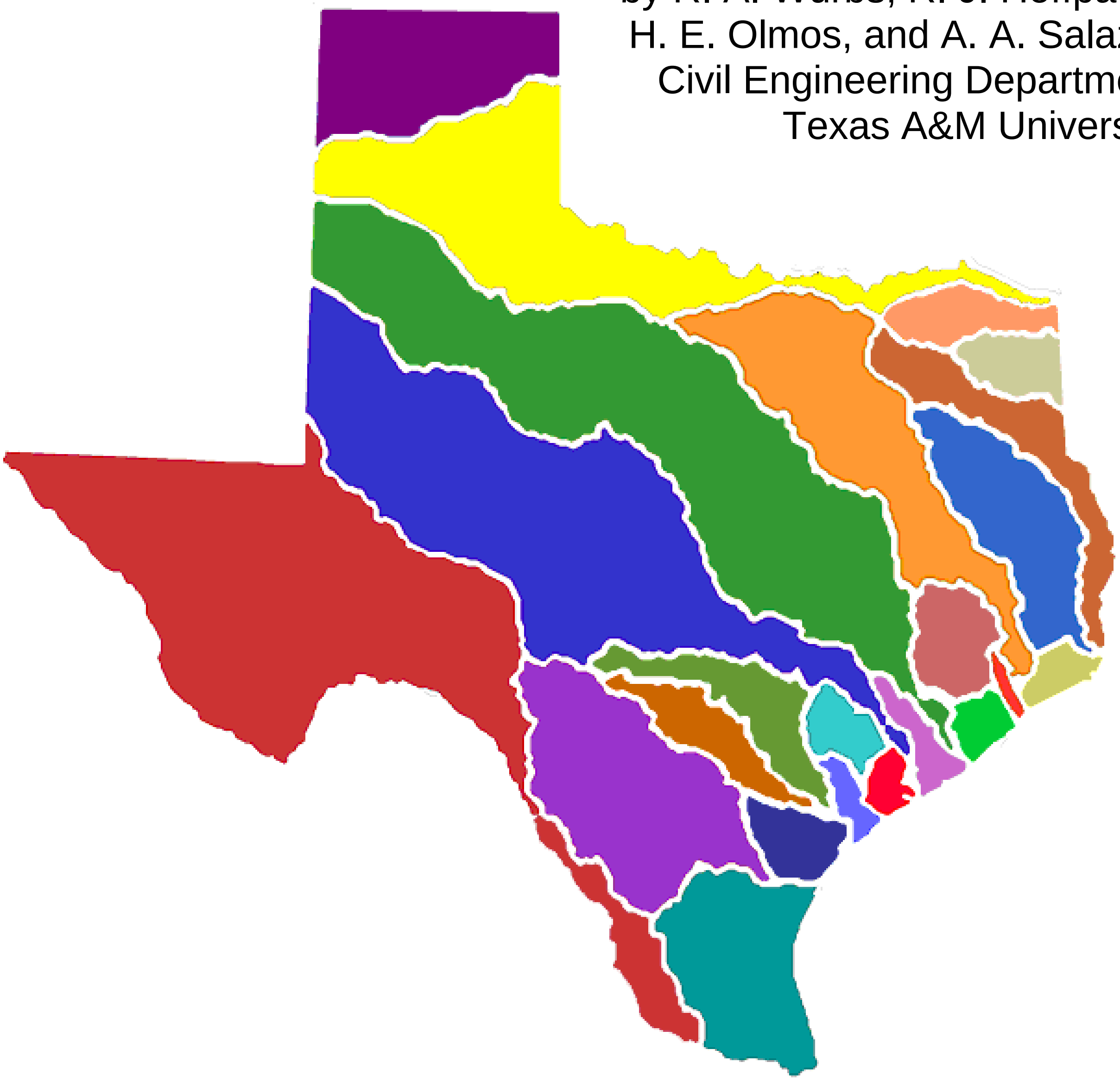

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D R A F T

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All interested persons are welcome to use the WRAP model. The software and documentation may be freely copied. However, the model must be applied at the user's own risk. Conceptual mistakes, coding errors, data inaccuracies, and misinterpretation of results are always possible with any computer model. The authors of this report, their employers, and the research sponsors assume no responsibility for model accuracy, results, or usage.

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CHAPTER 1
INTRODUCTION

WRAP is a generalized river/reservoir system simulation model providing flexible capabilities for analyzing water resources development, management, control, allocation, and use. This supplemental reference and users manual documents expanded WRAP modeling capabilities that are not covered in the following basic reference and users manuals.

> *Water Rights Analysis Package (WRAP) Modeling System Reference Manual,*
> TWRI TR-255, 1st Edition August 2003, 2nd Edition April 2005.
>
> *Water Rights Analysis Package (WRAP) Modeling System Users Manual,*
> TWRI TR-256, 1st Edition August 2003, 2nd Edition April 2005.

A Water Availability Modeling (WAM) System was developed by the Texas Commission on Environmental Quality (TCEQ) and its partner agencies and contractors during 1997-2003 pursuant to Senate Bill 1 enacted by the Texas Legislature in 1997 and subsequent legislation. The WAM System includes the generalized WRAP simulation model and input datasets for the river basins of the state. The *Reference* and *Users Manuals* cited above cover the WRAP capabilities that are reflected in the original Texas WAM System datasets plus several recently added enhancements. This *Supplemental Manual* covers the following other major modeling capabilities added to WRAP since completion of the original TCEQ WAM System datasets.

Expanded Modeling Capabilities

This report serves as both reference and users manuals for WRAP features providing capabilities for conditional reliability modeling, salinity tracking, simulation of flood control reservoir system operations, and use of options related to sub-monthly time steps that include flow forecasting, flow routing, and disaggregation of monthly naturalized flows to daily flows.

Conditional Reliability Modeling

Conditional reliability modeling (CRM) provides estimates of the likelihood of meeting water supply diversion, environmental instream flow, hydroelectric power, and reservoir storage requirements during time periods of one month to several months to a year or perhaps longer into the future, given current reservoir storage contents. Short-term reliabilities are conditioned upon preceding reservoir storage levels. Applications include developing reservoir operating policies and drought management plans, operational planning studies, administration of water right permit systems and water supply contracts, and decision-support during droughts.

CRM uses the same input datasets as conventional WRAP applications. However, the naturalized stream flows and net evaporation depths are divided into many short sequences. For example, a 1940-2004 hydrologic period-of-analysis may be divided into 65 annual sequences. Simulations are repeated with each sequence, starting with the same initial storage conditions. Water supply reliability and storage frequency relationships are developed from the simulation results. Options are provided for dividing the hydrologic period-of-analysis into multiple shorter sequences, assigning probabilities to the sequences, and evaluating simulation results.

Sub-Monthly Time Step Modeling Capabilities

The original WRAP uses a monthly time step. The expanded version allows each of the 12 months to be subdivided into any number of time intervals with the default being daily. Model input may either include daily or other sub-monthly time interval naturalized flows or options may be activated for disaggregating monthly flows to smaller time intervals. Alternative methods for subdividing monthly naturalized flow volumes into daily flows range from a simple linear interpolation routine, that allows use of Texas WAM System datasets without additional data, to options based on reproducing daily variations reflected in daily flow sequences provided as input.

Future time steps extending over a user-defined forecast period are considered in the simulation model in determining both water availability from a supply perspective and remaining flood control channel capacity. An adaptation of the Muskingum routing method has been added for use with daily or other sub-monthly computational time steps. Calibration methods for determining routing parameters are included in the modeling package.

Routines in the *TABLES* post-simulation program organize sub-monthly simulation results and develop frequency relationships and reliability indices reflecting the sub-monthly time interval. Simulation results are also aggregated to monthly values for use in the monthly tables and indices produced by *TABLES* and for salinity modeling. Results from simulations using either monthly or sub-monthly time steps may be used in conditional reliability modeling analyses.

Flood Control Reservoir Operations

Any number of flood control reservoirs may be operated in the simulation model either individually or as multiple-reservoir systems to reduce flooding at any number of downstream control points. Operating rules are based on emptying flood control pools expeditiously while assuring that releases do not contribute to flows exceeding specified flood flow limits at downstream control points during a specified future forecast period. Forecasting and routing capabilities associated with sub-monthly time steps facilitate modeling of flood control operations. Frequency analyses of annual peak naturalized flow, regulated flow, and reservoir storage volumes are performed based on the log-Pearson type III probability distribution.

Salinity Modeling Capabilities

Natural salt pollution in several major river basins in Texas and neighboring states motivated addition of capabilities for tracking salt concentrations through river/reservoir systems for alternative water management/use scenarios. The *WRAP-SALT* program reads water quantity data from the main simulation results file along with additional input data regarding salt concentrations and loads of flows entering the river system. The model computes concentrations of conservative water quality constituents in the regulated streamflows, diversions, and reservoir storage throughout the river basin. Concentration frequency and supply reliability analysis options are provided. Salinity modeling capabilities are limited to a monthly time step, though monthly output from a daily quantity simulation may be incorporated in a *SALT* simulation. Water quality throughout a river basin system of stream reaches and reservoirs may be simulated in planning studies for alternative scenarios of water use, reservoir system operating policies, and salt control measures.

Scope and Organization of Manual

This manual supplements and extends the basic *Reference Manual* and *Users Manual* cited at the beginning of page 1. The expanded modeling capabilities outlined here build upon the previously documented WRAP organizational structure and methodologies. This *Supplemental Manual* is written based on the premise that the reader is familiar with the information provided by the basic *Reference* and *Users Manuals* or is at least familiar with the fundamentals covered in the *Fundamentals Manual*. The *Fundamentals Manual* cited below provides an introductory tutorial allowing new users to learn the basics of the modeling system quickly.

Fundamentals of Water Availability Modeling with WRAP,
Texas Water Resources Institute TR-283, April 2005.

The example presented in the *Fundamentals Manual* is expanded in Chapters 2, 3, 4, and 5 of this *Supplemental Manual* to illustrate the expanded modeling capabilities presented. The hypothetical example was adapted from the TCEQ WAM System dataset for the Brazos River Basin, which has about 650 reservoirs and 1,600 water rights. The simplified example designed for illustrative purposes is reduced to a system of six reservoirs, 11 control points, and hypothetical water management and use requirements. However, the expanded modeling capabilities documented herein have been similarly applied using the complete Brazos Basin TCEQ WAM System dataset. The modeling capabilities are applicable to systems covering the full range of complexity from studying operation of a single reservoir to investigations of river basins with hundreds of water users and hundreds of reservoirs operated for an array of purposes.

Conditional reliability modeling, flow disaggregation/forecasting/routing methods related to sub-monthly time steps, simulation of flood control reservoir operations, and salinity tracking capabilities are explained in Chapters 2, 3, 4, and 5, respectively. Appendices B, C, D, and E provide instructions for preparing input records for programs *SIMD*, *DAY*, *SALT*, and *TABLES*, respectively. Appendices B and E include those *SIMD* and *TABLES* input records that are not already covered in the basic *Users Manual*. Appendices C and D cover all of the input records for *DAY* and *SALT*, which are completely new programs. Definition of variables and information regarding organization of the Fortran code for all of the WRAP programs are covered in the *Programming Manual*.

Auxiliary software products used with WRAP including Microsoft programs, *HEC-DSSVue*, and ESRI's *ArcGIS* are discussed in Chapter 1 of the *Reference and Users Manuals*. Appendix A of this *Supplemental Manual* outlines a method for applying the ArcMap feature of ArcGIS to spatially display WRAP simulation results. The GIS display of results is for WRAP applications in general, not just those applications adopting the features covered by this manual.

Modeling applications combine the generalized WRAP programs with input datasets describing specific systems of rivers, reservoirs, other constructed facilities, and water resources management/control/allocation/use requirements. Certain WRAP programs read files that have been created by other WRAP programs. The interface program *WinWRAP* facilitates connecting programs and data files within a Microsoft Windows operating system environment. The remainder of this chapter provides an overview inventory of computer programs and data files.

WRAP Programs

The software package documented by the previously cited basic *Reference and Users Manuals* includes the following programs.

WinWRAP facilitates execution of the *WRAP* programs within the *Microsoft Windows* environment along with Microsoft programs and *HEC-DSSVue*.

WRAP-SIM simulates the river/reservoir water allocation/management system for input sequences of monthly naturalized flows and net evaporation rates.

TABLES develops tables, data listings, and reliability/frequency indices for organizing, summarizing, and displaying simulation results.

WRAP-HYD assists in developing monthly naturalized streamflow and reservoir net evaporation rate data for the *WRAP-SIM* hydrology input files.

The *WinWRAP* user interface program has been expanded to execute the new programs cited below as well as the original *WRAP-SIM*, *TABLES*, and *WRAP-HYD*. The post-simulation program *TABLES* has been expanded to organize simulation results from the new *WRAP-SIMD* and *WRAP-SALT* as well as continuing to organize the simulation results from *WRAP-SIM*. Conditional reliability modeling capabilities have been added to both *WRAP-SIM* and *TABLES*. *WRAP-HYD* is the only program not affected by the expanded capabilities covered in this *Supplemental Manual*.

The following new programs were added to the package to provide the expanded modeling capabilities documented by this report.

WRAP-SIMD (*D* for daily) is an expanded version of *WRAP-SIM* that includes sub-monthly time step and flood control operation features along with all of the simulation capabilities of *WRAP-SIM*.

WRAP-DAY assists in developing sub-monthly (daily) time step hydrology input for *WRAP-SIMD* including disaggregating monthly flows to sub-monthly time intervals and calibrating routing parameters.

WRAP-SALT reads the main *WRAP-SIM* or *WRAP-SIMD* output file and a salinity input file and tracks salt constituents through the river/reservoir/use system.

The Fortran programs are compiled as separate individual programs, which may be executed independently of each other and independently of *WinWRAP*. However, *WinWRAP* facilitates running the programs within *Microsoft Windows* in an integrated manner along with use of Microsoft programs and *HEC-DSSVue* (Hydrologic Engineering Center 2005). The programs are listed in Table 1.1 with the filenames for the executable files. The third column of Table 1.1 indicates whether the program is documented solely by the basic *Reference* and *Users Manuals* or if this *Supplemental Reference/Users Manual* is required along with the basic manuals. The citations of pertinent chapters and appendices refer to this *Supplemental Manual*. The *Programming Manual* facilitates revisions to the Fortran code but is not needed to apply the computer programs.

Table 1.1 WRAP Programs

Program	Filename	Documentation	Function
WinWRAP	WinWRAP.exe	basic manuals	Microsoft Windows interface.
TABLES	TAB.exe	Chapters 2,3,4,5, Appendix E and basic manuals	Post-simulation summary tables, reliability indices, frequency tables.
SIM	SIM.exe	Chapter 2 and basic manuals	Monthly simulation model.
SIMD	SIMD.exe	Chapters 3 and 4 and Appendix B	Simulation model with monthly or sub-monthly time intervals.
SALT	SALT.exe	Chapter 5 and Appendix D	Salinity simulation model.
HYD	HYD.exe	basic manuals	Monthly hydrology data.
DAY	DAY.exe	Chapter 3 and Appendix C	Sub-monthly hydrology data.

Any and all of the programs may be executed from *WinWRAP*. Program *TABLES* has sub-monthly time interval, conditional reliability, flood frequency analysis, and salinity features described by this *Supplemental Manual* as well as the capabilities covered by the basic *Reference* and *Users Manuals*. Conditional reliability capabilities are provided by both *SIM* and *SIMD*.

SIM is limited to a monthly time step. The expanded *SIMD* contains all of the capabilities of the monthly time step *SIM*, plus options related to reservoir operations for flood control, forecasting and routing, sub-monthly targets, and synthesizing sub-monthly time step naturalized stream flows. Although any sub-monthly time interval may be used in *SIMD*, the model is called the daily version of *SIM* since the day is the default sub-monthly time step expected to be adopted most often.

SIMD duplicates simulation results for datasets prepared for *SIM*. At some time in the future, *SIMD* may be declared to have replaced *SIM*. However, *SIM* is currently being maintained as a separate program. *SIM* is complex, and addition of sub-monthly time steps, flow forecasting and routing, flood control operations, and other features to *SIMD* add significantly more complexity. *SIM* has been applied extensively as a component of the Texas WAM System. As a safeguard, maintenance of *SIM* allows ongoing applications of the Texas WAM System datasets that do not need the expanded modeling capabilities to continue with the basic *SIM* software without necessarily switching to the new more dramatically revised *SIMD*.

Significant recent improvements developed during 2004–2006 are included in both *SIM* and *SIMD* and documented in the basic *Reference and Users Manuals*. Additional future enhancements are anticipated that will be incorporated in both versions of the simulation model.

SIMD provides capabilities for performing a simulation using a daily or other sub-monthly time step for the computations with the sub-monthly interval results optionally being aggregated to monthly quantities. *SALT* can use the aggregated monthly quantities provided by *SIMD* in a salinity tracking simulation. Monthly or sub-monthly *SIMD* simulation results may be used by *TABLES* to perform conditional reliability analyses. The time parameters adopted to organize conditional reliability (CRM) simulation sequences and present results are based on whole months, but the internal model computations may be performed using a daily or other sub-monthly time step.

The program *DAY* provides a set of computational routines that facilitate developing *SIMD* hydrology input related to sub-monthly time steps. The *DAY* routines include (1) disaggregation of monthly flows to sub-monthly time intervals and (2) calibrating routing parameters. Multiple options are provided for performing these tasks.

Program *SALT* is applied in combination with either *SIM* or *SIMD* to simulate salinity. *SALT* uses a monthly time step. *SALT* obtains monthly water quantities by reading the main *SIM* or *SIMD* output file, obtains water quality data by reading a salinity input file, and tracks the water quality constituents through the river/reservoir system. All of the simulation capabilities of *SIM/SIMD* are preserved while adding salt accounting capabilities. *TABLES* includes routines for organizing *SALT* simulation results as tables or DSS records, performing frequency analyses, and determining water supply diversion reliabilities with and without considerations of specified maximum allowable salinity concentrations.

WRAP Input and Output Files

The WRAP programs are generalized for application to any river/reservoir system, with input files being developed for the particular river basin of concern. The TCEQ WAM System includes datasets for all of the river basins of Texas. Application of WRAP in Texas involves modifying existing data files for a river basin of concern. Proposed water development projects and management strategies and changes in water use are added to the existing WAM System datasets to support particular studies and analyses. For applications outside of Texas where datasets have not been compiled, collecting data and creating input datasets for the river basin or region of concern represents the majority of the effort of a WRAP simulation study. The expanded modeling capabilities outlined in this manual continue to use the datasets required for all WRAP applications, but additional data are required for some of the new features.

The *WinWRAP* interface facilitates executing programs and assigning data files. The user must create or obtain previously created files describing the hydrology and the water management facilities and practices for the river basin or region of concern along with other related information. The programs are connected through input/output files. Certain programs create files with intermediate results to be read by other programs. File access occurs automatically, controlled by the software. Tables 1.2 and 1.3 are reproduced from and discussed in the *Users Manual*. Table 1.2 is a matrix of computer programs and input/output files. Table 1.3 lists the different types of WRAP data files.

Input and output datasets are in the format of text files, which can be read by Microsoft Word, WordPad, NotePad, Excel, and other editors. Program *TABLES* also provides options to convert essentially any of the simulation results produced by the *SIM*, *SIMD*, and *SALT* to HEC-DSS files, to be read with *HEC-DSSVue* (Hydrologic Engineering Center 2005) for plotting graphs or other data processing manipulations.

Table 1.2 Matrix of Input/Output Files and Programs

File	File	WRAP Programs					
Name	Function	SIM	SIMD	SALT	TABLES	HYD	DAY
	Main Required Input File for Each Program						
DAT	*SIM* and *SIMD* input data file	Input	input				
SIN	*SALT* input file			input			
TIN	*TABLES* input file				input		
HIN	*HYD* input file					input	
DIN	*DAY* input file						input
	Hydrology Input Data						
FLO	*IN* record naturalized flows	Input	input			in & out	input
EVA	*EV* record net evaporation	Input	input			in & out	
DIS	flow distribution parameters	Input	input			input	
HYD	hydrology, *IN* and *EV* records	Input	input				
FAD	flow adjustments	Input	input				
DCP	daily or sub-monthly flow data		input				input
	Main Simulation Results Output File for Each Program						
OUT	*SIM* and *SIMD* output file	output	output	input	input		
CRM	conditional reliability model	output	output		input		
SUB	*SIMD* output file		output		input		
SAL	*SALT* output file			output	input		
TAB	*TABLES* output file				output		
DSS	*TABLES* HEC-DSS output file				output		
DAY	*DAY* output file						output
	Message File for Each Program						
MSS	*SIM* and *SIMD* message file	output	output				
SMS	*SALT* message file			output			
TMS	*TABLES* message file				output		
MSS	*HYD* message file					output	
DMS	*DAY* message file						output
	Special Purpose Files						
HRR	hydropower and reservoir release	output	output		input		
YRO	yield reliability output	output	output				
BES	beginning/ending storage	in & out					
BRS	beginning reservoir storage	output	output	input	input		
BRC	beginning reservoir concentration			in & out			
SFF	storage-flow-frequency array				In & out		
FFA	flood frequency analysis		output		input		
DSC	HEC-DSS catalog				output		

Table 1.3 Input and Output Files

SIM and *SIMD* Input Files

root1.DAT	required main input file containing all input ***dat***a, except the voluminous hydrology related data contained in the following files
root2.FLO	inflow *IN* records with naturalized stream ***flo***ws (optional filename root.INF)
root2.EVA	***eva***poration *EV* records with net evaporation-precipitation rates
root2.DIS	flow ***dis***tribution *FD & FC* and watershed parameter *WP* records for transferring flows from the *IN* records to other control points
root2.HYD	*IN* and *EV* records provided in a single ***hyd***rology file in modified format in lieu of the root.INF and root.EVA files
root2.FAD	***f***low ***ad***justment *FA* records for adjusting naturalized stream flows
root1.BES	***b***eginning and/or ***e***nding ***s***torage listing activated by *JO* record field 5
root2.DCF	***d***aily or other sub-monthly ***c***ontrol point and ***f***low data read by *SIMD*

SIM and *SIMD* Output Files

root1.OUT	main simulation results ***out***put file read by *TABLES* and *SALT*
root1.MSS	***mess***ages reporting simulation progress and input data errors
root1.HRR	***h***ydropower and ***r***eservoir ***r***elease file read by *TABLES*
root1.YRO	***y***ield-***r***eliability ***o***utput table presenting the results of a *FY*-record analysis
root1.CRM	***c***onditional ***r***eliability ***m***odeling simulation results read by *TABLES*
root1.BES	***b***eginning and/or ***e***nding ***s***torage listing activated by *JO* record field 5 for use with beginning-ending-storage options
root1.BRS	***b***eginning ***r***eservoir ***s***torage listing activated by *FO* record field 9 to provide beginning reservoir storage for program *SALT* and *TABLES 5CR2* record routines
root1.SUB	*SIMD* ***sub***-monthly time step simulation results
root1.FFA	*SIMD* ***f***lood ***f***requency ***a***nalysis file with annual series of peak flow and storage

SALT Input Files

root2.SIN	required ***s***alinity ***in***put file with concentrations or loads of entering flows
root2.DAT	required main *SIM/SIMD* input file from which *CP* records are read
root2.OUT	required main *SIM/SIMD* ***out***put file with simulation results
root2.BRS	***b***eginning ***r***eservoir ***s***torage file created by *SIM/SIMD* and read by *SALT* to provide beginning reservoir storage if specified by *JC* record field 8
root2.BRC	***b***eginning ***r***eservoir ***c***oncentration file created by *SALT* and also read by *SALT* as specified by *JC* record field 9

SALT Output Files

root1.SAL	***sal***inity simulation results read by *TABLES*
root1.SMS	***s***alinity ***m***essage ***f***ile with simulation trace, error and warning messages, and intermediate and summary simulation results tables
root1.BRC	***b***eginning ***r***eservoir ***c***oncentration file created and read by *SALT* as specified by *JC* record field 9

Table 1.3 Input and Output Files (continued)

TABLES Input Files

root3.TIN	required ***T***_ABLES_ ***in***put file with specifications regarding tables to be developed
root1.DAT	*SIM/SIMD* input DAT file
root1.OUT	*SIM/SIMD* output OUT file
root1.HRR	*SIM/SIMD* output HRR file
root1.DIS	*SIM/SIMD* input DIS file
root1.FFA	*SIMD* ***f***lood ***f***requency ***a***nalysis output file with annual series of peak flow and storage
root1.CRM	*SIM/SIMD* ***c***onditional ***r***eliability ***m***odeling output file
root1.SFF	***s***torage-***f***low-***f***requency file created by *TABLES 5CR1* record and read by *5CR2* record in conjunction with the SFF conditional reliability option

TABLES Output Files

root4.TAB	***TAB***_LES_ output file with the tables developed by the various routines
root4.TMS	***T***_ABLES_ ***m***e***s***sage file
root4.DSS	Hydrologic Engineering Center ***D***ata ***S***torage ***S***ystem file read by *HEC-DSSVue*
root4.DSC	***c***atalog listing the pathnames of the records stored in a HEC-DSS file
root4.SFF	***s***torage-***f***low-***f***requency file created by *TABLES 5CR1* record and read by *5CR2* record in associated with the SFF conditional reliability option

HYD Input Files

root5.HIN	***H***YD file with all ***in***put data not included in the following hydrology files
root5.FLO	inflow *IN* records with stream ***flo***ws
root5.EVA	***eva***poration *EV* records with net evaporation-precipitation rates
root5.DIS	flow ***dis***tribution *FD & FC* and watershed parameter *WP* records
root5.HYD	*IN* and *EV* records in single ***hyd***rology file in modified format

HYD Output Files

root6.OUT	file with all ***out***put not included in the following files
root6.MSS	***m***e***s***sages tracing the computations and reporting input data errors
root6.FLO	inflow *IN* records with naturalized stream ***flo***ws
root6.EVA	***eva***poration *EV* records with net evaporation-precipitation rates

DAY Input Files

root1.DIN	main ***DAY in***put file
root1.FLO	inflow *IN* records with naturalized monthly stream ***flo***ws read by *SIM, SIMD*, or *DAY*
root1.DCF	input file of ***d***aily ***f***lows at ***c***ontrol points in either *DF* record or columnar format

DAY Output Files

root2.DAY	***DAY*** output file
root2.DMS	***D***AY ***m***e***s***sage file

The names of the data files read and written by the WRAP programs are in the format *root.extension*. The root is an arbitrary name assigned by the model user. The 3-character extensions are set by naming conventions incorporated in the programs. The extensions listed in Table 1.3 define the types of data contained in the files. File types are referred to by their extensions. For example, a DAT file has a filename with the extension DAT and consists of certain basic input data read by the programs *SIM* and *SIMD*. A FLO file has the filename extension FLO and contains naturalized flows. Several years ago, the extension FLO replaced a previously used extension INF. Now FLO and INF are the only two WRAP filename extensions that can be used interchangeably.

With the exception of the programs *HYD*, all files for all programs may be named with the same root. Certain files used in a single execution of a program must have the same filename root. However, as discussed in the *Fundamentals Manual*, various options allow filename roots to differ based on user preference, as indicated by the terms *root1*, *root2*, and *root3* in Table 1.3. The root for *SIM* and *SIMD* hydrology files (root2.FLO, root2.EVA, and root2.DIS) may differ from the main input data file (root1.DAT) if the user so prefers. Thus, multiple DAT files reflecting different water management scenarios may be combined with the same FLO, EVA, and DIV files representing river basin hydrology. The root for *TABLES* files may differ from *SIM/SIMD* files. Of course, all of these files may also have the same filename root.

In executing the WRAP programs from *WinWRAP*, the user enters one or optionally perhaps two filename roots. The software assigns the extensions automatically. However, input files created with an editor must be saved with a filename with the appropriate extension.

CHAPTER 2
CONDITIONAL RELIABILITY MODELING

Conditional reliability modeling (CRM) consists of developing short-term reliability and frequency estimates conditioned on preceding reservoir storage. The terms *conditional reliability* and *short-term reliability* modeling are used interchangeably. CRM is based on dividing a long hydrologic period-of-analysis into many shorter simulation sequences. The simulation is repeated for each hydrologic sequence with the same initial storage condition. Water supply and hydropower reliability indices and flow and storage frequency relationships are developed from the simulation results. The programs *WRAP-SIM* or *WRAP-SIMD* perform the multiple short-term simulations with the specified starting storage contents. Routines in the program *TABLES* read the simulation results and perform reliability and frequency analyses.

An initial CRM version of *WRAP* described by Salazar (2002) and Salazar and Wurbs (2004) involved separate programs designed specifically for CRM. The modeling strategy was subsequently redesigned and integrated directly in the generic *WRAP-SIM* and *TABLES*. Olmos (2004) investigated alternative CRM methodologies and issues involved in their application.

Conventional Versus Conditional Reliability Modeling

WRAP was originally designed for long-term planning studies and preparation and evaluation of water right permit applications. Conditional reliability modeling (CRM) features expand WRAP capabilities to support short-term drought management and operational planning activities in which consideration of preceding reservoir storage levels is important. Using CRM, the likelihood of meeting reservoir storage, water supply diversion, instream flow, and hydroelectric power generation targets during the next month, next several months, next year, or next several years is assessed as a function of the amount of water currently in storage along with all the other information otherwise reflected in WRAP. Water supply reliabilities and flow and storage frequencies are conditioned on preceding storage contents.

A WRAP simulation study, either conventional or CRM, involves assessing capabilities for meeting specified water management and use requirements, with river basin hydrology being represented by historical naturalized streamflow sequences and net reservoir evaporation less precipitation rates. For example, based on the availability of historical flow records, a 1940-2004 period-of-analysis may be adopted to represent the hydrologic characteristics of a river basin. In a conventional WRAP simulation, the model allocates water to meet specified water management/use requirements during each sequential month of a single 780-month hydrologic sequence starting in January 1940. Initial reservoir storage contents are specified corresponding to the beginning of January 1940 in the hydrologic period-of-analysis. In CRM, the long sequences of naturalized flows and net evaporation rates are divided into many short sequences. For example, the 1940-2004 hydrologic period-of-analysis may be divided into 65 annual simulation sequences starting and ending in specified months. The system is simulated 65 times with 65 different naturalized streamflow and net evaporation sequences, with each simulation sequence having the same starting reservoir storage contents. The reliability indices and frequency relationships developed from the CRM simulation results have the same format as with the conventional WRAP modeling approach but are interpreted differently.

With the conventional WRAP modeling approach, reliability parameters provide a measure of the likelihood of meeting water supply, environmental instream flow, and hydroelectric power production requirements during any randomly selected future month or year without regard to the amount of water actually contained in reservoir storage today. This type of modeling is designed for long-term planning studies and preparation and evaluation of water right permit applications. The purpose of the CRM features is to expand WRAP capabilities to include evaluation of reliabilities in meeting water needs during the next relatively short periods of time typically ranging from a month to a year, perhaps longer, which is highly dependent on the amount of water currently in storage. Reliabilities and frequencies are conditioned upon preceding storage. The likelihood of a reservoir being full or almost full three months from now is significantly higher if the reservoir is almost full now than if it is almost empty now.

CRM is a decision-support tool for water management during drought, developing river/reservoir system operating policies, administration of water right systems and water supply contracts, and related applications. CRM may be applied by a regulatory agency in deciding upon water use curtailment actions during drought. Reservoir management agencies may use the model to develop permanent operating rules or to develop operating plans for the next year or season in ongoing operational planning activities. Commitments to water users may be set annually or seasonally depending on the amount of water in storage at the beginning of the season or year. For proposed reservoir construction projects, CRM may be used to evaluate impacts on the other water users in the river basin during the initial impoundment period.

Computer Programs, Data Files, and Input Records

Conditional reliability modeling capabilities are included in *SIM*, *SIMD*, and *TABLES*. The multiple short-term simulations are performed within either *SIM* or *SIMD*. The *SIMD* version provides the option of performing the simulation computations using a daily time interval and then aggregating the daily results to monthly totals. Otherwise, a CRM analysis is performed in the same manner with either *SIM* or *SIMD*. *TABLES* reads the monthly simulation results from a *SIM* or *SIMD* output file and creates reliability and frequency tables.

SIM or *SIMD* is switched to the CRM mode by entering a conditional reliability *CR* record in the input file. The *CR* record is the only *SIM/SIMD* input record that is used solely for CRM. The *CR* record sets the time parameters that control the subdivision of the hydrologic period-of-analysis into multiple short-term sequences. Without a *CR* record, the model performs a conventional single hydrologic period-of-analysis simulation. Simulation results are stored in the main *SIM/SIMD* OUT or CRM output file which is read by *TABLES*.

Instructions for preparing CRM-related input records for *TABLES* are provided in Appendix D. *TABLES* provides alternative approaches for assigning probabilities to each of the CRM hydrologic sequences. With the default relative frequency option, the *TABLES* input records are the same as with a conventional non-CRM analysis, with the exception of adding a *5CRM* record. The *5CRM* record, which has no actual input data, is used to switch *TABLES* from the conventional to CRM mode of analysis. A set of optional *5CR1* and *5CR2* records activates options that assign probabilities to each hydrologic sequence, which may vary between sequences, based on either a storage-flow-frequency (SFF) or flow-frequency (FF) relationship.

The correlation coefficient *5COR* record provides auxiliary capabilities for investigating the correlation between naturalized flow volume and preceding reservoir storage content.

The results of *SIM/SIMD* conventional long-term and CRM short-term simulations are recorded in OUT and CRM files, respectively. The OUT and CRM output files contain the same type of simulation results data in the same format. However, the CRM file created by *SIM* or *SIMD* reflects repetition of the same user-specified initial storage conditions at the beginning of each of the multiple user-defined hydrologic sequences.

The *TABLES 5CR1* record optional creation of a storage-flow-frequency (SFF) array uses an OUT output file from a conventional long-term *SIM/SIMD* simulation. The *5CR2* record uses a CRM output file from a CRM application of *SIM* or *SIMD*. Thus, output files from two separate executions of *SIM/SIMD* may be read by *TABLES* in performing CRM computations activated by *5CR1* and *5CR2* record options. The *5CR1* and *5CR2* records contain options that allow creation of an extra file, with filename extension SFF, for a storage-flow-frequency (SFF) array. However, the SFF array may also be developed and applied without reading and writing to a SFF file. Options also allow a beginning-of-simulation storage file, with filename extension BRS, to be written by *SIM/SIMD* and read by *TABLES*.

All of the various tables and data listings created by *TABLES* are applicable to either CRM or conventional simulations. The format of the tables and data listings are essentially the same for either CRM or conventional simulations. The primary difference in appearance is that whereas a conventional simulation is organized based on 12-month years, CRM simulation results are organized by sequences with lengths in months specified by the *SIM CR* record. Some tables provide additional information in the headings for CRM applications regarding the sequence timing parameters from the *CR* record.

Reiterating, the difference between a conventional *WRAP* simulation and a CRM application is:

- A conventional simulation is based on sequential computations for the entire hydrologic period-of-analysis as a single simulation.

- In a CRM execution of *SIM* or *SIMD*, the hydrologic period-of-analysis is divided into many shorter simulation periods with the storage contents of each reservoir being reset to pre-specified initial levels at the beginning of each simulation period.

SIM/SIMD input files are the same for either a conventional or CRM simulation, except a conditional reliability *CR* record is added for a CRM simulation. The output filenames have the extensions OUT and CRM, respectively. The content and format of *SIM* output records are defined in Tables 2.2, 2.3, 2.4, and 2.5 of the basic *Users Manual*. The first two parameters from the *CR* record are added to the 5th record of the *SIM* output file. The content and format of the individual water right, control point, and reservoir/hydropower output records are identical for CRM versus conventional simulations. The only difference in the output file format is the monthly sequencing of the records. All output is written within a monthly computational loop. As discussed below, the CRM annual option may exclude certain months of the year, and the monthly option may exclude a few months and may repeat years and months multiple times.

Multiple Short-Term Simulations with the Same Initial Storage

The variables entered on the *CR* record are shown in Table 2.1, which is reproduced from the basic *Users Manual*. Entering a *CR* record in the input file switches *SIM* or *SIMD* from the default conventional simulation mode to the conditional reliability modeling (CRM) mode.

Table 2.1 Conditional Reliability *CR* Record
(Reproduced from *Users Manual*)

field	columns	variable	format	value	description
1	1-2	CD	A2	CR	Record identifier.
2	3-8	CR1	I6	blank,0	Default = 12 months
				+	Length of simulation period in months.
3	9-16	CR2	I8	blank,0,-	Monthly cycle option is activated.
				+	Starting month for annual cycle option.
4	17-24	CR3	I8	blank,0	Months excluded from CRM file are still simulated.
				-1, 1	Only the months written to CRM file are simulated.
5	25-32	CR4	F8.0	blank,0,-	Default = 1.0
				+	Factor by which all starting storages are multiplied.

Specifying Simulation Sequences

The following parameters are specified on the *CR* record. CR1 is the only required parameter, and it has a default of 12 if field 2 is left blank. The other *CR* record parameters are optional. CR3 is applicable only if CR2 is non-zero.

CR1	is the length of simulation period in months.
CR2	activates the annual cycle option and is the starting month of the cycle.
CR3	is a switch used with the annual cycle option to skip simulations during the months of each year that are not used in the conditional reliability analyses.
CR4	is a factor by which all beginning storages are multiplied (default=1.0)

The following two alternative approaches are provided for organizing the simulation sequences.

1. The *annual cycle option* is defined by CR1 and CR2 in *CR* record fields 2 and 3.
2. The *monthly cycle option* is automatically activated if CR2 is zero (blank field 3).

The *annual cycle option* is defined by a starting month (CR2) ranging from 1 to 12 and a simulation period (CR1) ranging from 1 to 12 months. Consider a *SIM* input dataset with a

1940-2000 hydrologic period-of-analysis which contains 61 years and 732 months. The CRM sequences could be organized with a starting month of May (CR2 = 5) and simulation period of three months (CR1 = 3). Sixty-one simulation sequences would be defined as follows.

Sequence 1: May 1940 through July 1940
Sequence 2: May 1941 through July 1941
Sequence 3: May 1942 through July 1942
•••
Sequence 60: May 1999 through July 1999
Sequence 61: May 2000 through July 2000

The annual cycle option results in one sequence per year, and the sequence length cannot exceed 12 months. Results are written to the output file for all of the months included in the simulation sequences. For the example, the output file will contain results for May, June, and July for each of the 61 years.

As another example, assume that the starting month is set at May (CR2 = 5) and the simulation period (CR1) is the default of 12 months. The 1940-2000 hydrologic period-of-analysis is divided into the following 60 annual sequences.

Sequence 1: May 1940 through April 1941
Sequence 2: May 1941 through April 1942
Sequence 3: May 1942 through April 1943
•••
Sequence 60: May 1999 through April 2000

If the sum of CR1 and CR2 is 13 or less, the number of sequences equals the number of years. If the sum of CR1 and CR2 exceeds 13, the number of sequences used in the CRM analysis is one less than the number of years.

The optional parameter CR3 is related to the months that are not included in the simulation period. In the CR1=3 and CR2=5 example, January-April and August-December are not included in the simulation period. The default is recommended. The default is to not activate the CR3 switch in which case all 12 months are simulated each year regardless of whether they are included in the simulation period defined by CR1 and CR2. Only the results for the months actually included in the specified simulation period are written to the CRM output file. However, the CR3 allows the computations to be skipped for the months not included in the CR1/CR2 defined simulation period. The only reason for selecting this option would be to save computer run time. Results associated with the next-month return flow option and next-month hydropower return flow option may be affected by the choice of whether or not all months are simulated. With these next-month options in effect, return flows or hydropower releases during the last month of a year or simulation sequence enter the stream system in the first month of the next year or sequence. Certain target setting options activated by *TO* records are also based on amounts from the preceding month and thus may be affected by the CR3 switch. CR3 applies only to the annual cycle option. All months are simulated with the monthly cycle option even though a few of the months are not included in the CRM file simulation results.

The *monthly cycle option* is the other alternative for organizing simulation sequences. This approach allows the sequences to be defined without being restricted to a single sequence each year. The first sequence begins in the first month of the first year and has the length specified by CR1. The second sequence begins in the next month following completion of the first sequence. The sequencing recycles after reaching the end of the last year. Each cycle begins one month after the preceding cycle. The number of complete sequences is:

$$\text{number of sequences} = (12)(\text{number of years}) - \text{CR1} + 1 \qquad (2.1)$$

Applying the monthly cycle option to the 1940-2000 example, for a CR1 of 4 months, 729 sequences will be created as follows with the computations performed and the simulation results output in the order shown.

Cycle 1

Sequence 1: January 1940 through April 1940
Sequence 2: May 1940 through August 1940
Sequence 3: September 1940 through December 1940
Sequence 4: January 1941 through April 1941
•••
Sequence 179: May 1999 through August 1999
Sequence 183: September 1999 through December 1999

Cycle 2

Sequence 184: February 1940 through May 1940
Sequence 185: June 1940 through September 1940
•••
Sequence 364: February 2000 through May 2000
Sequence 365: June 2000 through September 2000
Three months not used: October–December 2000

Cycle 3

Sequence 366: March 1940 through June 1940
Sequence 367: July 1940 through October 1940
•••
Sequence 546: March 2000 through June 2000
Sequence 547: July 2000 through October 2000
Two months not used : November–December 2000

Cycle 4

Sequence 548: April 1940 through July 1940
Sequence 549: August 1940 through November 1940
•••
Sequence 728: April 2000 through July 2000
Sequence 729: August 2000 through November 2000
One month not used: December 2000

The message file displays trace messages during a *SIM/SIMD* execution which are partially controlled by the variable ICHECK on the *JD* record. An ICHECK of 10 activates a trace written to the MSS file that shows the sequencing of years and months in the conditional reliability simulations. The trace is written within the computational loops and lists all months, shows the subdivision of months into simulation sequences, and indicates which months are excluded from the simulation results.

The annual cycle option captures seasonality. All of the simulations reflect the same season of the year. However, the number of simulations is limited to the number of years in the total period-of-analysis. With the monthly cycle option, the number of simulations is limited to the number of months indicated by Equation 2.1. Thus, the monthly option allows up to 12 times more simulations than the annual option. The accuracy of reliability estimates depends both on properly modeling seasonal characteristics of hydrology and maximizing the number of hydrologic sequences used in the analyses. The choice of which option to adopt for a particular application depends upon the relative importance of these two considerations. Also, unlike the annual option, the monthly option allows the simulation length to exceed 12 months.

Specifying Initial Storage Contents of Each Reservoir

In conditional reliability modeling, the same initial reservoir storage contents are reset at the beginning of each of the simulations. *SIM/SIMD* options for specifying initial storages do not differentiate between a conventional and CRM simulation other than the factor CR4 entered on the *CR* record. Initial storage content may be entered in *WS* record field 8 for individual reservoirs. Initial storages may be entered as a beginning storage file (*JO* record field 5) for any or all reservoirs. Initial storage content is automatically set equal to the storage capacity by default for any reservoir for which an initial storage is not otherwise specified. CR4 entered on the *CR* record is a factor by which the initial storage of all reservoirs is multiplied. For example, to set the initial storage in all reservoirs at 75 percent of capacity, a value of 0.75 may be entered on the *CR* record for CR4 with initial storages not otherwise specified and thus defaulting to capacity. With 0.75 entered for CR4, each simulation sequence begins with the storage level of each reservoir at 75 percent of the beginning-of-simulation storage contents otherwise specified.

Program *TABLES* Reliability and Frequency Tables

The program *TABLES* performs reliability and frequency analyses using the simulation results read from a *SIM* or *SIMD* output file. *TABLES* also contains routines that simply reorganize and tabulate the simulation results as user-specified tables. The *TABLES* routines applied in conventional applications are also applicable to CRM. The tables created for conventional non-CRM applications have the same format and content when used with CRM.

The *2REL* record creates reliability tables for diversion or hydropower targets for water rights, water right groups, control points, or reservoirs. The *2FRE* and *2FRQ* records create frequency tables for naturalized flow, regulated flow, unappropriated flow, reservoir storage, and instream flow shortages. The *2RES* record creates reservoir storage draw-down frequency and storage reliability tables. These tables may be developed from the results of either a conventional simulation or a CRM simulation with any of the CRM options.

TABLES reliability and frequency tables are based on the concepts expressed by Equations 2.2–2.7 and described by the remainder of this chapter. With a dataset for a conventional WRAP simulation available, the switch from conventional modeling to CRM can be simple with little additional input required or a little more complex depending upon the CRM options adopted. Two alternative strategies, called the *relative frequency option* and *probability array option*, are provided for *TABLES* to associate probabilities with each of the multiple simulation sequences generated by *SIM* or *SIMD*. With the *relative frequency option*, the reliability and frequency computations activated by *2REL*, *2FRE*, *2FRQ*, and *2RES* records are the same for either a CRM analysis or conventional long-term simulation. Each simulation sequence is weighted equally or counted once in applying Eqs. 2.2−2.4. The alternative *probability array option* activated by the *5CR1* and *5CR2* records is based on developing an array assigning probabilities to the multiple simulation sequences which allows probabilities to vary between the simulation sequences. The default relative frequency approach is simple, generally valid, covered first in the following presentation, and illustrated with an example. Most of the complexity of this chapter is associated with the optional probability array option methods for enhancing probability estimates, which are presented later after the example.

Reliability and frequency indices may consider all months or alternatively may be for a specified month. For example, a frequency table may be created for regulated flows at specified control points during August or end-of-month storage contents for August. Likewise, a reliability table may be constructed for meeting water supply diversion targets in any randomly selected future month or alternatively may be defined for a particular month such as August.

Reliability Analyses of Water Supply Diversions and Hydropower Generation

Period reliability is based on counting the number of periods of the simulation during which the specified demand target is either fully supplied or a specified percentage of the target is equaled or exceeded. A *TABLES* reliability summary includes tabulations of period reliabilities expressed both as the percentage of months and the percentage of years during the simulation during which either water supply diversions or hydroelectric energy produced equaled or exceeded specified magnitudes expressed as a percentage of the target demand. The various variations of period reliability R_P are computed by *TABLES* from the results of a *SIM/SIMD* simulation as:

$$R_P = \frac{n}{N} \ (100\%) \tag{2.2}$$

where n denotes the number of periods during the simulation for which the specified percentage of the demand is met, and N is the total number of periods considered.

Volume reliability is the percentage of the total demand that is actually supplied. For water supply diversions, the demand is a volume. For hydropower, the demand is energy generated. Volume reliability R_V is the ratio of the total diversion volume supplied or energy produced (v) to the total volume or energy target demanded (V).

$$R_V = \frac{v}{V} \ (100\%) \tag{2.3}$$

Equivalently, R_V may be viewed as the ratio of the mean actual water supply diversion rate to mean target diversion rate or the ratio of the mean energy production rate to mean target rate.

In either a conventional or CRM application, *TABLES* applies Eqs. 2.2 and 2.3 using data from the simulation results output file created by *SIM* or *SIMD*. For a conventional simulation, the reliability indices are expressions for capabilities for meeting water supply or hydropower requirements in the long-term without consideration of the amount of water in storage today. In a CRM application, the reliabilities reflect capabilities for meeting water supply or hydropower requirements during the next several months on in a particular month in the near future given known preceding reservoir storage levels. Short-term CRM reliabilities are conditioned on known initial reservoir storage contents.

Frequency Analyses of Stream Flow and Reservoir Storage Volumes

In general, the exceedance frequency, expressed as a percentage ranging from 0 to 100%, or the exceedance probability, expressed as a fraction between 0 and 1.0, represents the estimated likelihood of equaling or exceeding particular values of a random variable. Exceedance frequency is an expression of the percentage of time that particular flow or storage amounts can be expected to occur or equivalently the probability of a certain amount of water being available. *TABLES* provides options to model the probabilistic nature of naturalized flows, regulated flows, unappropriated flows, instream flow shortages, and reservoir storage in terms of relative frequency (Equation 2.4) or alternatively using the normal or log-normal probability distribution functions (Eqs. 2.6 and 2.7).

From a relative frequency perspective, exceedance frequency (F) and exceedance probability (P) are expressed as:

$$F = \frac{n}{N}\ (100\%) \tag{2.4}$$

$$P = \frac{n}{N} \tag{2.5}$$

where *n* is the number of time periods that a specified amount is equaled or exceeded and *N* is the total number of time periods considered. Exceedance frequency is computed in the *TABLES 2FRE*, *2FRQ*, and *2RES* record routines based on Equation 2.4 with *n* being the number of months during the *SIM* simulation that a particular flow or storage amount is equaled or exceeded. *N* is the total number of months considered.

Alternatively, the *TABLES 2FRE* record provides options to apply the normal or log-normal probability distribution to the series of monthly flow and storage volumes generated by *SIM*. The random variable X in Eq. 2.6 may be naturalized flows, regulated flows, unappropriated flows, instream flow shortages, or reservoir storage volumes.

$$X = \overline{X} + z\,S \tag{2.6}$$

The frequency factor (z) is derived from a normal probability table, and $\overline{X}$ and S denote the sample mean and standard deviation of the data read from the *SIM* output file. The log-normal distribution consists of the normal distribution applied to the logarithms of X, with Eq. 2.6 expressed as Eq. 2.7 with z still derived from the normal distribution.

$$\log X = \overline{\log X} + z\, S_{\log X} \tag{2.7}$$

In the probability distribution options activated by the *2FRE* record, exceedance probabilities are assigned to the random variable X by fitting the normal or log-normal distribution in a standard manner outlined in statistics textbooks. The mean $\overline{\log X}$ and standard deviation $S_{\log X}$ of the logarithms of the data from the *SIM* output file are computed. The frequency factor z for specified exceedance probabilities from a normal probability table are built into *TABLES*.

The *2FRE* record choice between applying the concept of relative frequency directly (Eq. 2.4) versus adopting the normal (Eq. 2.6) or log-normal (2.7) probability distribution function depends upon the particular variable and application. The normal or log-normal probability distributions offer improvements in accuracy of the frequency estimates if probability plots or statistical tests made outside of WRAP show the data to fit the distributions. If the data do not closely fit the probability distribution functions, Eq. 2.4 is the optimal choice of computation method. The log-normal distribution will typically be a reasonably valid model for monthly naturalized stream flow volumes. Regulated and unappropriated flows are affected by water management practices that may invalidate application of the log-normal distribution. Storage capacity sets an upper limit on storage volumes that likely prevent proper fitting of the normal or log-normal distributions. The log-normal distribution allows the random variable to range from zero upward with no defined upper limit, which is consistent with stream flows. The normal distribution is symmetric about the mean with no lower and upper limits.

Program TABLES Input Records and Resulting Tables

The default relative frequency CRM option consists of performing the reliability and frequency computations activated by *2REL*, *2FRE*, *2FRQ*, and *2RES* records identically the same for a CRM analysis as with a conventional long-term simulation. The format and content of the *SIM/SIMD* output file records are the same with either a conventional or CRM simulation. Program *TABLES* reads the *SIM/SIMD* simulation results and processes the data through reliability and frequency algorithms that are not affected by whether the data was generated by a single conventional long-term simulation or multiple equally-weighted CRM simulations. Of course, resetting initial storage contents does significantly affect the numerical values reflected in the *SIM/SIMD* simulation results and corresponding *TABLES* reliability and frequency analysis results. Information from the *CR* record is included in the table headings.

Although the content and format of the *SIM*/*SIMD* output file records are the same for either CRM or conventional non-CRM applications, the total number of output records varies with variations in the number of years and months. For a conventional simulation, there are 12 months in each year. With the CRM annual cycle option, there are CR1 months for each year, but the number of sequences is either the number of years or one less. With the CRM monthly cycle option, there are also CR1 months for each sequence, but the number of sequences given by Equation 2.1 approaches the total number of months in the overall period-of-analysis. In all cases, the *TABLES* routines cycle through *SIM* simulation results organized by groups of months contained within years. For each month, the output records are organized by user-specified groups of control points, water rights, and reservoirs.

Reliability indices are developed by *TABLES* as specified by a *2REL* record. Frequency tables are created with a *2FRE* or *2FRQ* record. Storage reliabilities and draw-down frequencies are determined with a *2RES* record. Reliabilities are computed for either water supply diversion or hydroelectric energy targets for individual water rights, the aggregation of all rights associated with individual control points or reservoirs, groups of selected rights, or the aggregation of all rights in the model. Frequency tables may be developed for naturalized flow, regulated flow, unappropriated flow, and reservoir storage for specified control points and instream flow shortages and reservoir storage for specified water rights.

Reliability and frequency analyses may be performed for a specified individual month of the year or for the aggregation of all the months included in the simulation. All 12 months of the year are included in a conventional *SIM* simulation. For a CRM analysis, the months for which reliabilities and frequencies may be computed are those included in the *SIM* simulation sequences as defined by the *CR* record. The annual portion of a reliability table refers to the aggregation of 12 months for a conventional simulation and the number of months entered for CR1 on the *CR* record for a CRM analysis.

A *5CRM* record activates the CRM mode of analysis. The *2REL* record diversion or hydropower reliability table, *2RES* reservoir storage tables, and *2FRE* and *2FRQ* record flow and storage frequency tables are used to display the results of either CRM or conventional non-CRM analyses. Additional routines activated by the *5CR1* and *5CR2* records described later in this chapter develop the storage-flow-frequency (SFF) or flow-frequency (FF) relationship and incremental probability (IP) array used in the CRM probability distribution option for assigning probabilities to the multiple simulation sequences. Without the *5CR1* and *5CR2* records, all of the simulation sequences are weighted equally in applying Equations 2.2, 2.3, and 2.4. The format of the tables created with the *2REL*, *2FRE*, *2FRQ*, and *2RES* records are the same with or without the probability distribution option routines activated by the *5CR1* and *5CR2* records, though the numerical values are of course dependent upon the options adopted for the computations. Table headings include information from the *SIM CR* record regarding organization of the CRM simulation sequences.

5CRM, *5CR1*, *5CR2*, and *5COR* records are the only *TABLES* input records used solely for conditional reliability modeling. The *5CRM* record simply tells *TABLES* to open a *SIM* CRM output file in preparation for performing CRM analyses. The *5CR1* and *5CR2* records control the optional routines for assigning probabilities to the simulation sequences. The *5COR* record is used to compute correlation coefficients that measure the degree of linear correlation between naturalized flow volumes and preceding reservoir storage volumes at selected control points. The correlation coefficients provide information that is useful in selecting reservoirs, control points, time periods, and computational options for use in the procedures that assign probabilities to the multiple simulation sequences. The *5CRM* record is the only extra record required for conditional reliability modeling if the simulation sequences are weighted equally, with each sequence counted once in the frequency and reliability analysis counts.

Conditional Reliability Modeling Example

The *Fundamentals Manual* (Wurbs 2005) presents an example of a conventional WRAP simulation of the system shown in Figure 2.1, which consists of eleven control points, six reservoirs, and 30 water rights. The hydrologic period-of-analysis is 1940-1997. Input files and simulation results are presented in Chapters 3 and 5 and the Appendices of the *Fundamentals Manual*. The following CRM example consists of converting the conventional simulation presented in the *Fundamentals Manual* to a conditional reliability modeling application. Storage frequencies and water supply reliabilities are conditioned upon specified preceding storage conditions. The default CRM relative frequency option is implicitly adopted for the conditional reliability analyses, meaning that each of the N multiple short-term hydrologic sequences is equally-weighted or counted once in applying Equations 2.2, 2.3, and 2.4. A *SIM CR* record and *TABLES 5CRM* record are the only additional input records required to convert from the conventional long-term simulation mode to the short-term CRM mode.

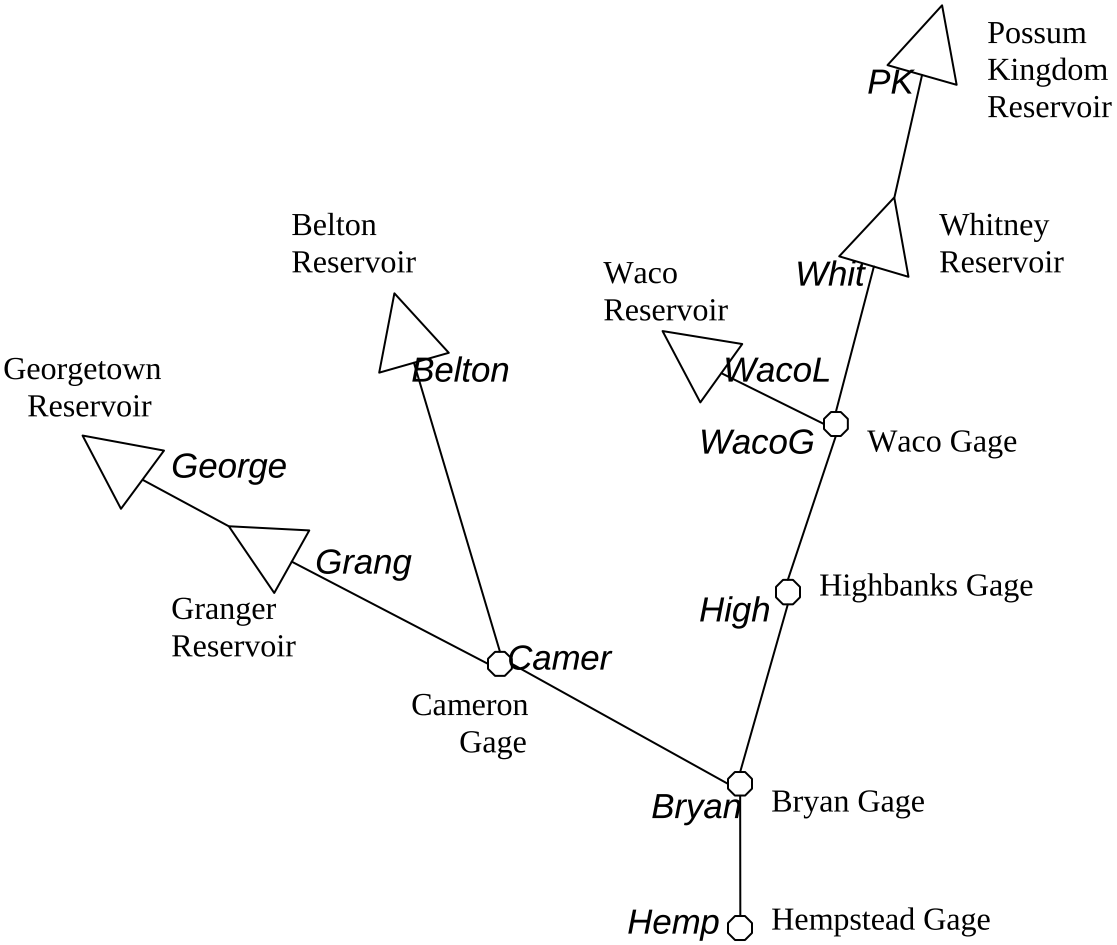

Figure 2.1 System Schematic for the Example

The following *CR* record is inserted following the *JO* record in the *SIM* DAT file listed in the *Fundamentals Manual*.

```
CR    6     4     0    0.10
```

The parameters entered on the *CR* record are defined by Table 2.1 presented earlier in this chapter. The *CR* record in this example divides the 1940-1997 period-of-analysis into 58 six-month hydrologic sequences covering April (month 4) through September. Although not included here in this example, *JD* record ICHECK option 10 provides a listing in the message file showing the subdivision of months into hydrologic simulation sequences. The CR2 value of 4 means that each simulation begins in April with the same user-specified beginning-of-April reservoir storage contents. Although several options are available for specifying beginning-of-simulation storage, the example adopts the combined options of the *SIM* default of starting at full to capacity which is modified by the CR4 multiplier factor of 0.10. The reservoirs all have beginning-of-month storage contents for each April of 10.0 percent of their storage capacities.

The initial few output records of the *SIM* simulation results output file, with filename extension CRM, is reproduced as Table 2.2. The CRM file contains simulation results for months 4, 5, 6, 7, 8, and 9 (April through September) for 58 years (1940-1997). The variables are defined in Tables 2.2-2.5 of the *Users Manual*. Program *TABLES* reads the CRM file and develops a TAB file in accordance with specifications provided by a TIN file.

The *TABLES* TIN input file is reproduced as Table 2.3. The *5CRM* record activates the CRM mode, with *TABLES* reading a *SIM* output file with extension CRM rather than OUT. CRM information is also included in the table headings generated by *TABLES*. Without the *5CR1* and *5CR2* records discussed later in this chapter, the *TABLES* computational routines are the same for the CRM application as with a conventional simulation. Of course, the reliabilities and frequencies in the example are conditioned upon all reservoirs having storage contents of 10 percent of capacity at the beginning of April.

The reliability tables in Table 2.4 are reproduced from the TAB file created by *TABLES* in accordance with the *2REL* records shown in Table 2.3. With the exception of the CRM information added to the headings, these tables have the same format for either CRM or conventional analyses. The first reliability table shows reliabilities associated with meeting water supply diversion requirements in during the period April through September given that reservoir storage contents are at 10 percent of capacity at the beginning of April. The second reliability table shows reliabilities of meeting diversion requirements during June (month 6), given that reservoir storage contents are at 10 percent of capacity at the beginning of April. The third reliability table is for September (month 9). With reliability tables generated for a specified month, such as the month 6 and month 9 tables in the example, only diversion data for that month is used is computing the values shown in the second through 12th columns of the table. However, the 13th through 18th columns are annual period reliabilities for the year or entire sequence length. This is the percentage of time that the specified percentages of the total April through September diversion requirement is supplied.

The frequency table in Table 2.5 is reproduced from the TAB file created by *TABLES* in accordance with the *2FRQ* record shown in Table 2.3. The frequency relationship is for end-of-month storage for June (month 6) in Belton Reservoir given that storage at the beginning of April was at 10% of the reservoir capacity for all six reservoirs including Belton. Given that storage in Belton Reservoir is at 10% of capacity at the beginning of April, there is an estimated probability of 0.7069 that the storage volume will be at least 50,000 acre-feet at the end of June and probability of 0.1379 that the storage will equal or exceed 450,000 ac-ft at the end of June.

The frequency tables in Table 2.6 are created with the *2FRE* records shown in Table 2.3. The first regulated flow frequency table in Table 2.6 shows the percentage-of-time or likelihood of monthly flow volumes equaling or exceeding various amounts during the period April through September conditioned upon storage in all reservoirs being at 10% of capacity at the beginning of April. Regulated flow frequency tables are also included in Table 2.6 for monthly flow volumes during June and September given the preceding storage conditions at the beginning of April. Likewise, Table 2.6 includes end-of-month storage frequency tables for all months during the period April-September as well as tables for June and September.

Referring to Table 2.6, all exceedance frequency estimates reflect known storage levels at the beginning of April in all reservoirs equal to 10% of their storage capacity. Selecting any month during the period April through September at random, there is a 10% probability that the end-of-month storage of Belton Reservoir will equal or exceed 429,356 acre-feet. For Belton Reservoir, there is a 10% probability that the storage at the end of June will equal or exceed 457,600 acre-feet or at the end of September will equal or exceed 399,196 acre-feet.

The *2RES* records create the storage drawdown and storage reliability tables shown in Table 2.7. The storage reliability table for month 6 shows that with PK Reservoir having a storage content of 10% of its capacity at the beginning of April, there is an estimated 12.1% frequency, probability, or likelihood that PK Reservoir will be 100% full to capacity at the end of June and a 36.2% probability that the end-of-June storage content will be at least 50% of capacity. The table shows a 77.6% percentage-of-time or probability of PK Reservoir having an end-of-June storage volume of at least 10% of storage capacity given that the preceding beginning-of-April storage is 10% of capacity.

The storage tables for PK and Belton Reservoirs shown in Table 2.8 were created with the *2STO* record in the TIN file listed as Table 2.3. Of course, for a conventional simulation, the *2STO* record tabulates the end-of-month storage for all 12 months of the year. For the example, only April through September are included in the CRM file and *2STO* record tables. The UNIT record is included in the TIN file of Table 2.3 so that the table headings in the tables of Table 2.8 will begin with April rather than January.

Hundreds of tables may be generated to provide an array of information of interest in a particular decision-support situation. Tables 2.3-2.8 provide a small illustrative sampling of reliability and frequency tables. *2STO* and similar time series records also write any of the *SIM* simulation results time series data as HEC-DSS records for plotting with HEC-DSSVue.

Table 2.2
Beginning of *SIM* Output CRM File for the CRM Example

```
Program WRAP-SIM (December 2005 Version) Output File
  File CRMexample.DAT - WRAP-SIM Input Data File for the Example Dataset
  WRAP Fundamentals Manual
  Expanded Capabilities Manual, Chapter 2 CRM, Added CR Record
  1940    58    11    29     6     6     4   0.100
IF   4      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1  322.39    0.00
IF   4      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2 10746.3     0.0
1940 4    0.000 4255.200   -224.2  51934.0  36755.0   36755.0      0.0            WR-5WacoLake          1489.3
1940 4    0.000  705.600    542.1  72548.3  16772.0   16772.0      0.0            WR-1      PK           247.0
1940 4    0.00020375.752    475.5  52239.1      0.0       0.0      0.0            WR-2      PK             0.0
1940 4    0.000  361.600      0.0      0.0    361.6  110452.8      0.0           WR-14 Cameron            36.2
1940 4    0.000 1104.000      0.0      0.0   1104.0  173643.0      0.0           WR-20   Bryan            55.2
1940 4    0.000 1587.200      0.0      0.0   1587.2  168225.5      0.0           WR-22    Hemp             0.0
1940 4    0.000 1033.600      0.0      0.0   1033.6   73940.3      0.0           WR-16WacoGage             0.0
1940 4    0.000 1433.600      0.0      0.0   1433.6   97269.2      0.0           WR-17Highbank             0.0
1940 4    0.000 1765.400      0.0      0.0   1765.4  110091.2      0.0           WR-13 Cameron           882.7
1940 4    0.000 3783.000      0.0      0.0   3783.0  166786.8      0.0           WR-19   Bryan          2458.9
1940 4    0.000 9273.200      0.0      0.0   9273.2  158928.7      0.0           WR-21    Hemp             0.0
1940 4    0.000 5958.720    -38.2  69774.5  29935.0   29935.0      0.0            WR-8  Belton          2681.4
1940 4    0.000 8108.717    -36.7  61664.3      0.0       0.0      0.0            WR-9  Belton          1621.7
1940 4    0.000 1768.859      2.1   5958.1   4019.0    4019.0      0.0           WR-10  George           849.1
1940 4    0.000 2900.901    -45.7  13488.0   9793.2    9793.2      0.0           WR-11 Granger          1160.4
1940 4    0.000   29.670   -224.2  51904.3      0.0       0.0      0.0            WR-6WacoLake             0.0
1940 4 1296.000 1296.000   -294.0  88716.4  25712.3   25712.3      0.0            WR-3 Whitney             0.0
1940 4    0.000 2947.200      0.0      0.0   2947.2   67652.3      0.0           WR-12 Cameron          1031.5
1940 4    0.000 1754.354      0.0      0.0   1754.4   86569.5      0.0           WR-18   Bryan           701.7
1940 4    0.000 1497.600   -222.6  50405.2      0.0       0.0      0.0            WR-7WacoLake           599.0
1940 4    0.000 6078.078      0.0      0.0   6078.1   64705.1      0.0           WR-15 Cameron          2127.3
1940 4    0.000 2384.000      0.0      0.0   2384.0   76982.0      0.0           WR-23    Hemp             0.0
1940 4    0.00062162.160      0.0      0.0  62162.2   74598.0      0.0           WR-24    Hemp             0.0
1940 4    0.000    0.000    475.5  52239.1      0.0       0.0      0.0           WR-25      PK             0.0
1940 4    0.000    0.000    -36.7  61664.3      0.0       0.0      0.0           WR-26  Belton             0.0
1940 4    0.000    0.000      2.1   5958.1      0.0       0.0      0.0           WR-27  George             0.0
1940 4    0.000    0.000    -45.7  13488.0      0.0       0.0      0.0           WR-28   Grang             0.0
    PK    0.00021081.352    475.5  52239.1  16772.0       0.0      0.0   16772.0       0.0  1023.    0.     0.
  Whit 1296.000 1296.000   -294.0  88716.4  25712.3       0.0    233.2   41228.0       0.0   373.    2.     0.
 WacoL    0.000 5782.470   -222.6  50405.2  36755.0       0.0      0.0   36755.0       0.0     0.    0.     0.
 WacoG    0.000 1033.600      0.0      0.0   1033.6   13066.4  25013.3  101058.0   47425.8   789.  252.     0.
  High    0.000 1433.600      0.0      0.0   1433.6   12935.8      0.0  125139.0   70609.5  1113.  350.     0.
Belton    0.00014067.438    -36.7  61664.3  29935.0       0.0      0.0   29935.0       0.0   838.    0.     0.
George    0.000 1768.859      2.1   5958.1   4019.0       0.0      0.0    4019.0       0.0    32.    0.     0.
 Grang    0.000 2900.901    -45.7  13488.0   9793.2       0.0    849.1   12931.0       0.0   207.   13.     0.
 Camer    0.00011152.277      0.0      0.0  11152.3   13231.0   5060.6  106875.0   58949.4  1938.  212.     0.
 Bryan    0.000 6641.354      0.0      0.0   6641.4   12754.7   3427.1  232186.0  129005.4  3423.  844.     0.
  Hemp    0.00075406.562      0.0      0.0  75406.6   12435.8   2907.7  196282.0   23182.1     0.    0.     0.
    PK      0.0      0.0    475.5  52239.1  16772.0       0.0  21081.4       0.0   0.19100
  Whit   2250.0      0.0   -294.0  88716.4  25712.3       0.0      0.0       0.0  -0.07000
 WacoL      0.0      0.0   -222.6  50405.2  36755.0       0.0   5782.5       0.0  -0.06300
Belton      0.0      0.0    -36.7  61664.3  29935.0       0.0  14067.4       0.0  -0.01200
George      0.0      0.0      2.1   5958.1   4019.0       0.0   1768.9       0.0   0.00600
 Grang      0.0      0.0    -45.7  13488.0   9793.2       0.0   2900.9       0.0  -0.04000
IF   5      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1  333.13    0.00
IF   5      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2 11104.5     0.0
1940 5    0.000 5023.500   1500.7  43880.9      0.0       0.0      0.0            WR-5WacoLake          1758.2
1940 5    0.000  833.000   1138.9 164670.2 114403.0  114403.0      0.0            WR-1      PK           291.5
1940 5    0.00023076.152   1048.8 141684.2      0.0       0.0      0.0            WR-2      PK             0.0
1940 5    0.000  847.500      0.0      0.0    847.5  122797.0      0.0           WR-14 Cameron            84.8
1940 5    0.000 2587.500      0.0      0.0   2587.5  174958.9      0.0           WR-20   Bryan           129.4
1940 5    0.000 3720.000      0.0      0.0   3720.0  262913.2      0.0           WR-22    Hemp             0.0
1940 5    0.000 2422.500      0.0      0.0   2422.5   18394.5      0.0           WR-16WacoGage             0.0
1940 5    0.000 3360.000      0.0      0.0   3360.0   43888.5      0.0           WR-17Highbank             0.0
1940 5    0.000 1947.400      0.0      0.0   1947.4  121949.5      0.0           WR-13 Cameron           973.7
1940 5    0.000 4173.000      0.0      0.0   4173.0  164816.5      0.0           WR-19   Bryan          2712.4
1940 5    0.00010229.200      0.0      0.0  10229.2  247758.5      0.0           WR-21    Hemp             0.0
1940 5    0.000 7034.600    770.3  60810.4   6951.0    6951.0      0.0            WR-8  Belton          3165.6
1940 5    0.000 9183.367    730.4  51666.9      0.0       0.0      0.0            WR-9  Belton          1836.7
```

Table 2.3
TABLES Input TIN File for the CRM Example

```
**   File CRMexample.TIN - TABLES Input File for the CRM Example
**
5CRM
****     1         2         3         4         5         6
****567890123456789012345678901234567890123456789012345678901234
****---!---!---!---!---!---!---!---!---!---!---!---!---!---!---!
**    Reliability Tables
2REL   0   0   1
2REL   0   0   1   6
2REL   0   0   1   9
****---!---!---!---!---!---!---!---!---!---!---!---!---!---!---!
**    Frequency Tables
2FRQ   4   6   5  Belton  50000. 100000. 200000. 400000. 450000.
2FRE   2
2FRE   2   6
2FRE   2   9
2FRE   4
2FRE   4   6
2FRE   4   9
****---!---!---!---!---!---!---!---!---!---!---!---!---!---!---!
**    Reservoir Storage Tables
2RES   4   6   6      PK    Whit   WacoL  Belton  George   Grang
2RES             570240. 627100. 192100. 457600.  37100.  65500.
2RES                  0. 379000.    580.      0.    240.    220.
2RES   4   9   6      PK    Whit   WacoL  Belton  George   Grang
2RES             570240. 627100. 192100. 457600.  37100.  65500.
2RES                  0. 379000.    580.      0.    240.    220.
****---!---!---!---!---!---!---!---!---!---!---!---!---!---!---!
**    Reservoir Storage Tables
UNIT            APR
2STO   1   0   0   2
ENDF
```

Table 2.4
Reliability Tables for CRM Example Created with 2REL Records

RELIABILITY SUMMARY FOR SELECTED WATER RIGHTS

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
----------------------------------------------------------------------------------------------------------------------------
                 TARGET       MEAN    *RELIABILITY*| +++++++++ PERCENTAGE OF MONTHS +++++++++|----- PERCENTAGE OF SEQUENCES -----
    NAME       DIVERSION    SHORTAGE  PERIOD VOLUME|  WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT
              (AC-FT/SQ)  (AC-FT/SQ)   (%)     (%) | 100%   95%   90%   75%   50%   25%  >0% | 100%   98%   95%   90%   75%   50%
----------------------------------------------------------------------------------------------------------------------------

WR-5             34100.7      426.66   98.56  98.75| 98.6  98.6  98.6  98.9  98.9  98.9 100.0| 94.8  96.6  96.6  96.6  96.6 100.0
WR-1              5654.6       80.43   98.28  98.58| 98.3  98.3  98.6  98.9  98.9  98.9 100.0| 93.1  94.8  96.6  96.6  96.6 100.0
WR-2            146558.0     9534.81   91.38  93.49| 91.4  91.7  92.0  92.0  93.7  95.4 100.0| 72.4  74.1  74.1  74.1  91.4  96.6
WR-14            10531.6      134.88   97.99  98.72| 98.0  98.0  98.3  98.6  98.6  98.9 100.0| 89.7  91.4  91.4  94.8  98.3 100.0
WR-20            32154.0      572.34   97.70  98.22| 97.7  97.7  97.7  98.3  98.9  98.9 100.0| 87.9  87.9  87.9  94.8  96.6 100.0
```

```
WR-22            46227.2    2169.58   95.40  95.31| 95.4  95.4  95.4  95.7  96.3  97.7 100.0| 81.0  81.0  81.0  86.2  89.7  98.3
WR-16            30103.6    4047.60   86.49  86.55| 86.5  87.1  88.2  89.1  91.1  92.2 100.0| 50.0  53.4  55.2  62.1  74.1  91.4
WR-17            41753.6    7177.99   83.05  82.81| 83.0  83.6  84.5  85.9  88.8  91.7 100.0| 44.8  46.6  50.0  51.7  70.7  87.9
WR-13            11975.6     908.72   91.95  92.41| 92.0  92.2  92.2  92.5  92.8  93.1 100.0| 72.4  72.4  72.4  72.4  87.9  96.6
WR-19            25662.0    2184.22   91.38  91.49| 91.4  91.7  91.7  91.7  92.2  92.5 100.0| 67.2  69.0  69.0  70.7  86.2  96.6
WR-21            62904.8    6786.11   88.51  89.21| 88.5  88.5  88.5  89.1  90.2  90.5 100.0| 62.1  62.1  63.8  65.5  82.8  96.6
WR-8             47752.5    4901.92   88.79  89.73| 88.8  89.1  89.4  90.5  90.5  91.4 100.0| 69.0  70.7  72.4  72.4  82.8  91.4
WR-9             58324.2    7450.98   86.78  87.22| 86.8  87.1  87.1  87.4  87.9  88.2 100.0| 63.8  63.8  65.5  67.2  75.9  87.9
WR-10            14689.2    3220.78   75.00  78.07| 75.0  76.1  76.1  77.9  78.7  81.9 100.0| 41.4  43.1  46.6  50.0  58.6  77.6
WR-11            24090.1    4041.71   81.32  83.22| 81.3  81.6  81.6  82.8  84.8  86.5 100.0| 56.9  58.6  58.6  58.6  70.7  82.8
WR-6               815.5      12.73   98.56  98.44| 98.6  98.6  98.6  98.6  98.6  98.6 100.0| 94.8  94.8  94.8  94.8  96.6 100.0
WR-3             10386.0    7220.40   28.45  30.48| 28.4  28.7  28.7  29.0  29.3  29.6 100.0|  5.2   5.2   5.2   5.2  24.1  32.8
WR-12            85837.2   33143.88   64.66  61.39| 64.7  65.5  66.7  68.4  72.7  78.4 100.0| 17.2  17.2  17.2  19.0  37.9  63.8
WR-18            14568.8    3799.68   75.29  73.92| 75.3  75.3  75.3  75.6  76.1  76.4 100.0| 39.7  39.7  41.4  41.4  58.6  72.4
WR-7             12001.6     202.54   97.99  98.31| 98.0  98.3  98.3  98.3  98.6  98.6 100.0| 93.1  93.1  93.1  94.8  96.6 100.0
WR-15            50474.5    7170.73   85.63  85.79| 85.6  85.6  85.9  86.8  86.8  87.4 100.0| 65.5  67.2  67.2  67.2  75.9  87.9
WR-23            69434.0   26456.25   68.39  61.90| 68.4  68.7  68.7  70.1  72.1  74.4 100.0| 25.9  25.9  25.9  32.8  39.7  56.9
WR-24           516216.0   60207.66   85.06  88.34| 85.1  85.3  85.6  87.4  88.8  92.0 100.0| 63.8  63.8  67.2  70.7  79.3  93.1
WR-25            This water right has zero diversion target.
WR-26            This water right has zero diversion target.
WR-27            This water right has zero diversion target.
WR-28            This water right has zero diversion target.
-------------------------------------------------------------------------------------------------------------------------------
Total          1352215.4  191852.59          85.81
--------------------------------------------------
```

RELIABILITY SUMMARY FOR SELECTED WATER RIGHTS FOR MONTH 6

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
-------------------------------------------------------------------------------------------------------------------------------
                  TARGET       MEAN    *RELIABILITY*| +++++++++ PERCENTAGE OF MONTHS +++++++++|----- PERCENTAGE OF SEQUENCES -----
    NAME        DIVERSION   SHORTAGE   PERIOD VOLUME|  WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT
               (AC-FT/SQ)  (AC-FT/SQ)   (%)     (%) | 100%   95%   90%   75%   50%   25%  >0% | 100%   98%   95%   90%   75%   50%
-------------------------------------------------------------------------------------------------------------------------------
WR-5              5496.3       0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 94.8  96.6  96.6  96.6  96.6 100.0
WR-1               911.4      15.71   98.28  98.28| 98.3  98.3  98.3  98.3  98.3  98.3 100.0| 93.1  94.8  96.6  96.6  96.6 100.0
WR-2             25776.5     963.51   93.10  96.26| 93.1  93.1  93.1  93.1  98.3  98.3 100.0| 72.4  74.1  74.1  74.1  91.4  96.6
WR-14             2135.7       0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 89.7  91.4  91.4  94.8  98.3 100.0
WR-20             6520.5       0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 87.9  87.9  87.9  94.8  96.6 100.0
WR-22             9374.4       0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 81.0  81.0  81.0  86.2  89.7  98.3
WR-16             6104.7     158.59   96.55  97.40| 96.6  96.6  96.6  96.6  96.6  98.3 100.0| 50.0  53.4  55.2  62.1  74.1  91.4
WR-17             8467.2     185.49   91.38  97.81| 91.4  91.4  94.8  96.6  98.3 100.0 100.0| 44.8  46.6  50.0  51.7  70.7  87.9
WR-13             2256.8       0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 72.4  72.4  72.4  72.4  87.9  96.6
WR-19             4836.0      35.29   98.28  99.27| 98.3  98.3  98.3  98.3 100.0 100.0 100.0| 67.2  69.0  69.0  70.7  86.2  96.6
WR-21            11854.4     393.07   94.83  96.68| 94.8  94.8  94.8  94.8  96.6  98.3 100.0| 62.1  62.1  63.8  65.5  82.8  96.6
WR-8              7696.7     231.02   94.83  97.00| 94.8  94.8  94.8  96.6  96.6  98.3 100.0| 69.0  70.7  72.4  72.4  82.8  91.4
WR-9             10258.0     601.42   93.10  94.14| 93.1  93.1  93.1  93.1  94.8  94.8 100.0| 63.8  63.8  65.5  67.2  75.9  87.9
WR-10             2691.7     337.06   81.03  87.48| 81.0  84.5  84.5  84.5  87.9  89.7 100.0| 41.4  43.1  46.6  50.0  58.6  77.6
WR-11             4414.4     431.91   86.21  90.22| 86.2  86.2  86.2  87.9  89.7  93.1 100.0| 56.9  58.6  58.6  58.6  70.7  82.8
WR-6               146.6       0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 94.8  94.8  94.8  94.8  96.6 100.0
WR-3              1674.0    1040.42   36.21  37.85| 36.2  37.9  37.9  37.9  37.9  37.9 100.0|  5.2   5.2   5.2   5.2  24.1  32.8
WR-12            17406.9    2664.16   77.59  84.69| 77.6  77.6  77.6  82.8  86.2  87.9 100.0| 17.2  17.2  17.2  19.0  37.9  63.8
WR-18             2669.7     392.93   82.76  85.28| 82.8  82.8  82.8  82.8  86.2  86.2 100.0| 39.7  39.7  41.4  41.4  58.6  72.4
WR-7              1934.4       0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 93.1  93.1  93.1  94.8  96.6 100.0
WR-15             9249.2     713.78   91.38  92.28| 91.4  91.4  91.4  91.4  91.4  93.1 100.0| 65.5  67.2  67.2  67.2  75.9  87.9
WR-23            14080.5    2106.24   82.76  85.04| 82.8  82.8  82.8  84.5  84.5  86.2 100.0| 25.9  25.9  25.9  32.8  39.7  56.9
WR-24            94594.5    7106.76   87.93  92.49| 87.9  87.9  87.9  87.9  93.1  94.8 100.0| 63.8  63.8  67.2  70.7  79.3  93.1
WR-25            This water right has zero diversion target.
WR-26            This water right has zero diversion target.
WR-27            This water right has zero diversion target.
WR-28            This water right has zero diversion target.
-------------------------------------------------------------------------------------------------------------------------------
Total           250550.6   17377.37          93.06
--------------------------------------------------
```

RELIABILITY SUMMARY FOR SELECTED WATER RIGHTS FOR MONTH 9

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
-----------------------------------------------------------------------------------------------------------------------------------
                   TARGET      MEAN    *RELIABILITY*| +++++++++ PERCENTAGE OF MONTHS +++++++++|----- PERCENTAGE OF SEQUENCES -----
    NAME         DIVERSION   SHORTAGE  PERIOD VOLUME|  WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT
                (AC-FT/SQ)  (AC-FT/SQ)   (%)    (%) | 100%   95%   90%   75%   50%   25%  >0% | 100%   98%   95%   90%   75%   50%
-----------------------------------------------------------------------------------------------------------------------------------

WR-5              5614.5    205.12   94.83  96.35| 94.8  94.8  94.8  96.6  96.6  96.6 100.0| 94.8  96.6  96.6  96.6  96.6 100.0
WR-1               931.0      0.00  100.00 100.00|100.0 100.0 100.0 100.0 100.0 100.0 100.0| 93.1  94.8  96.6  96.6  96.6 100.0
WR-2             23567.1   2717.43   86.21  88.47| 86.2  86.2  86.2  86.2  86.2  91.4 100.0| 72.4  74.1  74.1  74.1  91.4  96.6
WR-14              892.7     46.17   94.83  94.83| 94.8  94.8  94.8  94.8  94.8  94.8 100.0| 89.7  91.4  91.4  94.8  98.3 100.0
WR-20             2725.5     93.66   96.55  96.56| 96.6  96.6  96.6  96.6  96.6  96.6 100.0| 87.9  87.9  87.9  94.8  96.6 100.0
WR-22             3918.4    222.66   93.10  94.32| 93.1  93.1  93.1  93.1  93.1  96.6 100.0| 81.0  81.0  81.0  86.2  89.7  98.3
WR-16             2551.7    361.59   82.76  85.83| 82.8  82.8  84.5  86.2  86.2  86.2 100.0| 50.0  53.4  55.2  62.1  74.1  91.4
WR-17             3539.2    366.12   89.66  89.66| 89.7  89.7  89.7  89.7  89.7  89.7 100.0| 44.8  46.6  50.0  51.7  70.7  87.9
WR-13             1419.6    128.12   89.66  90.98| 89.7  89.7  89.7  91.4  91.4  91.4 100.0| 72.4  72.4  72.4  72.4  87.9  96.6
WR-19             3042.0    209.79   93.10  93.10| 93.1  93.1  93.1  93.1  93.1  93.1 100.0| 67.2  69.0  69.0  70.7  86.2  96.6
WR-21             7456.8    707.80   87.93  90.51| 87.9  87.9  87.9  89.7  91.4  91.4 100.0| 62.1  62.1  63.8  65.5  82.8  96.6
WR-8              7862.2   1567.64   75.86  80.06| 75.9  77.6  77.6  79.3  79.3  81.0 100.0| 69.0  70.7  72.4  72.4  82.8  91.4
WR-9              9378.8   2610.23   70.69  72.17| 70.7  70.7  70.7  72.4  72.4  72.4 100.0| 63.8  63.8  65.5  67.2  75.9  87.9
WR-10             2563.6   1010.69   48.28  60.57| 48.3  48.3  48.3  55.2  56.9  65.5 100.0| 41.4  43.1  46.6  50.0  58.6  77.6
WR-11             4204.2   1077.80   67.24  74.36| 67.2  69.0  69.0  69.0  74.1  77.6 100.0| 56.9  58.6  58.6  58.6  70.7  82.8
WR-6               105.2      5.44   94.83  94.83| 94.8  94.8  94.8  94.8  94.8  94.8 100.0| 94.8  94.8  94.8  94.8  96.6 100.0
WR-3              1710.0   1061.38   37.93  37.93| 37.9  37.9  37.9  37.9  37.9  37.9 100.0|  5.2   5.2   5.2   5.2  24.1  32.8
WR-12             7275.9   1965.64   67.24  72.98| 67.2  69.0  72.4  72.4  72.4  74.1 100.0| 17.2  17.2  17.2  19.0  37.9  63.8
WR-18             2542.5    745.23   70.69  70.69| 70.7  70.7  70.7  70.7  70.7  70.7 100.0| 39.7  39.7  41.4  41.4  58.6  72.4
WR-7              1976.0    119.18   93.10  93.97| 93.1  93.1  93.1  93.1  94.8  94.8 100.0| 93.1  93.1  93.1  94.8  96.6 100.0
WR-15             8808.8   2275.03   74.14  74.17| 74.1  74.1  74.1  74.1  74.1  74.1 100.0| 65.5  67.2  67.2  67.2  75.9  87.9
WR-23             5885.5   2188.05   58.62  62.82| 58.6  60.3  60.3  62.1  62.1  65.5 100.0| 25.9  25.9  25.9  32.8  39.7  56.9
WR-24            90090.1  17223.20   74.14  80.88| 74.1  75.9  75.9  77.6  79.3  84.5 100.0| 63.8  63.8  67.2  70.7  79.3  93.1
WR-25             This water right has zero diversion target.
WR-26             This water right has zero diversion target.
WR-27             This water right has zero diversion target.
WR-28             This water right has zero diversion target.
-----------------------------------------------------------------------------------------------------------------------------------
Total           198061.3  36907.97          81.37
--------------------------------------------------
```

Table 2.5
Frequency Table for CRM Example Created with 2FRQ Record

STORAGE-FREQUENCY FOR CONTROL POINT Belton FOR MONTH 6

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Length of simulation period (CR1) is 6 months.
Initial Storage Multiplier (CR4) = 0.100
Annual cycles with each sequence starting in CR2 month 4

```
--------------------------------------------------------------------------------------
  STORAGE  FREQ(%)  STORAGE  FREQ(%)  STORAGE  FREQ(%)  STORAGE  FREQ(%)  STORAGE  FREQ(%)
--------------------------------------------------------------------------------------
   50000.0   70.69  100000.0   58.62  200000.0   41.38  400000.0   20.69  450000.0   13.79
--------------------------------------------------------------------------------------
```

Table 2.6
Frequency Tables for CRM Example Created with 2FRE Records

FLOW-FREQUENCY FOR REGULATED STREAMFLOWS

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
------------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD      PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION  100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10%  MAXIMUM
------------------------------------------------------------------------------------------------------------------------
PK       41368.0 128466.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.  49586. 107827.1782155.
Whit     44739.1 170211.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.   5927.  44193. 104343.2623459.
WacoL     9473.0  32191.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.      0.  22224. 259093.
WacoG    83004.1 201740.     0.0     0.0     0.0     0.0  1863.2 11614.8  28859.  43221.  62133.  97448. 136203.3016976.
High    111107.7 229821.     0.0     0.0     0.0     0.0   814.1 22527.5  43290.  62133.  82071. 105820. 235149.3239995.
Belton   16614.3  42951.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.    683.  10059.  62208. 514528.
George    2529.9   7409.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.    146.   8192.  48006.
Grang     9291.8  21184.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.    523.   8595.  31909. 138793.
Camer    66850.6 110155.     0.0   322.4   322.4   322.4   333.1  5203.6  15544.  28628.  46315.  85400. 156768. 835780.
Bryan   207244.9 343614.     0.0     0.0   750.6  9406.2 33895.2 68367.6  95642. 104313. 116504. 164118. 513540.4223090.
Hemp    216280.7 453268.     0.0     0.0     0.0  5970.4  8902.4 10746.3  11104.  11104.  51971. 216067. 739766.5164094.
------------------------------------------------------------------------------------------------------------------------
```

FLOW-FREQUENCY FOR REGULATED STREAMFLOWS FOR MONTH 6

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
------------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD      PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION  100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10%  MAXIMUM
------------------------------------------------------------------------------------------------------------------------
PK       51580.1  53180.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.  59161. 109133. 691191.
Whit     65711.1  63977.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.   4225.  61745. 288929. 716828.
WacoL    13354.0  11485.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.   7856.  68737. 118260.
WacoG   108048.9  75358.     0.0     0.0     0.0     0.0  2369.5 11232.0  31806.  47711.  65333. 103558. 385435. 848094.
High    143671.1  86349.     0.0     0.0     0.0     0.0  4051.9 16083.4  50428.  66632.  95615. 139981. 411494. 951363.
Belton   22080.6  18241.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.  27938.  86558. 207696.
George    4702.6   3964.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.   5715.  21710.  48006.
Grang    17991.6  11720.     0.0     0.0     0.0     0.0     0.0     0.0    807.   2803.   9231.  22455.  62379. 138793.
Camer    94954.7  54615.   322.4   322.4   322.4   322.4   322.4 11920.5  32043.  47247.  68879. 110025. 314296. 564876.
Bryan   280051.4 136532.     0.0  9143.5 16754.6 30927.6 46057.1 75558.5  96694. 107812. 144981. 360483. 873651.1413380.
Hemp    323754.5 182636.     0.0  1633.5  3334.0  7494.9 10732.9 10746.3  10746.  54385. 260364. 549639.1140469.1650457.
------------------------------------------------------------------------------------------------------------------------
```

FLOW-FREQUENCY FOR REGULATED STREAMFLOWS FOR MONTH 9

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
------------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD      PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION  100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10%  MAXIMUM
------------------------------------------------------------------------------------------------------------------------
PK       40285.9  23957.     0.0     0.0     0.0     0.0     0.0     0.0      0.    694.  34680.  86492. 101723. 327589.
Whit     30808.5  15525.     0.0     0.0     0.0     0.0     0.0     0.0      0.   1117.  32998.  66602.  95518. 106342.
WacoL     2576.5   4992.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.      0.      0.  81978.
```

```
WacoG    51463.0  16791.     0.0     0.0     0.0   727.3  2115.3  7090.7  29168.  59441.  70203.  88762. 101423. 143678.
High     59181.2  19242.     0.0     0.0    40.2   403.8  1977.2 19755.1  43406.  59026.  73633.  96263. 107834. 227079.
Belton   10551.5   9838.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.   8750.  36597. 111253.
George     639.6   1377.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.      0.    100.  25001.
Grang     2693.2   3290.     0.0     0.0     0.0     0.0     0.0     0.0      0.      0.      0.    182.   8864.  43446.
Camer    26169.5  17540.     0.0   112.5   214.5   322.4   322.4  1249.5   4664.   8709.  18360.  35065.  83128. 266678.
Bryan    95028.8  35880.     0.0     0.0   212.3  3808.9 10399.6 49373.2  82278.  94856.  98822. 107951. 150527. 514507.
Hemp     54073.7  57342.     0.0     0.0   236.7  4952.6  6403.2 10746.3  10746.  10746.  10746.  16320. 118677. 905383.
------------------------------------------------------------------------------------------------------------------------
```

STORAGE-FREQUENCY FOR SPECIFIED CONTROL POINTS

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
------------------------------------------------------------------------------------------------------------------------
CONTROL          STANDARD     PERCENTAGE OF MONTHS WITH STORAGE EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT      MEAN DEVIATION  100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10%  MAXIMUM
------------------------------------------------------------------------------------------------------------------------
PK       190116. 181551.      0.      0.      0.      0.      0.  42920.  85233. 130138. 184376. 308449. 493418. 570240.
Whit     270191. 172757.  56512.  60224.  64846.  76166.  88548. 131326. 173146. 200109. 263567. 386351. 562592. 627100.
WacoL     96050.  70213.      0.      0.    274.  10805.  15619.  29300.  50561.  80129. 121318. 177174. 192100. 192100.
WacoG         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
High          0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Belton   145188. 149688.      0.      0.      0.      0.      0.  26207.  56705.  89727. 136079. 232184. 429356. 457600.
George    10662.  13134.      0.      0.      0.      0.      0.      0.   2039.   4012.   8512.  16447.  35434.  37100.
Grang     23287.  24509.      0.      0.      0.      0.      0.      0.   7896.  13939.  23281.  41294.  65500.  65500.
Camer         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Bryan         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Hemp          0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Total    735494. 538752.  57625.  76168.  92591. 125994. 162637. 245631. 415358. 595142. 800486.1184996.1575485.1949640.
------------------------------------------------------------------------------------------------------------------------
```

STORAGE-FREQUENCY FOR SPECIFIED CONTROL POINTS FOR MONTH 6

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
------------------------------------------------------------------------------------------------------------------------
CONTROL          STANDARD     PERCENTAGE OF MONTHS WITH STORAGE EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT      MEAN DEVIATION  100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10%  MAXIMUM
------------------------------------------------------------------------------------------------------------------------
PK       235951.  78987.      0.      0.      0.      0.      0.  70017. 149336. 202808. 273606. 407886. 570240. 570240.
Whit     302086.  74400.  60661.  75933.  87909. 103730. 125812. 143970. 184136. 238936. 285164. 459642. 627100. 627100.
WacoL    111097.  28160.   8651.   9237.   9804.  11123.  19484.  41753.  93067. 106722. 141796. 192100. 192100. 192100.
WacoG         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
High          0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Belton   182237.  66772.      0.      0.      0.      0.      0.  44338.  84093. 133703. 202246. 303387. 457600. 457600.
George    15165.   6057.      0.      0.      0.      0.      0.    146.   5383.  10984.  16280.  31930.  37100.  37100.
Grang     31862.  11306.      0.      0.      0.      0.      0.    443.  11817.  36333.  45946.  65500.  65500.  65500.
Camer         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Bryan         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Hemp          0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Total    878399. 229986.  74763.  91668. 106319. 123919. 172247. 390423. 615709. 810247.1080497.1325594.1665068.1949640.
------------------------------------------------------------------------------------------------------------------------
```

STORAGE-FREQUENCY FOR SPECIFIED CONTROL POINTS FOR MONTH 9

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
------------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD    PERCENTAGE OF MONTHS WITH STORAGE EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT      MEAN DEVIATION  100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10%  MAXIMUM
------------------------------------------------------------------------------------------------------------------------
PK       208170.  77014.      0.      0.      0.      0.      0.   9466.  97767. 207712. 254844. 364286. 487162. 570240.
Whit     316693.  65007.  58389.  96070. 124127. 128393. 140875. 177423. 238970. 304370. 373942. 406970. 587258. 627100.
WacoL    101028.  28441.      0.      0.      0.      0.  14150.  28964.  59249. 104042. 145218. 170798. 191444. 192100.
WacoG         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
High          0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Belton   133431.  61816.      0.      0.      0.      0.      0.      0.  35196.  77849. 118966. 230198. 399196. 457600.
George     6771.   4748.      0.      0.      0.      0.      0.      0.      0.      0.   1335.   9882.  32227.  33169.
Grang     14926.   8477.      0.      0.      0.      0.      0.      0.     56.   2649.  10412.  24955.  58914.  64866.
Camer         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Bryan         0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Hemp          0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
Total    781020. 215858.  58389.  98864. 131172. 151178. 163061. 239897. 563387. 721181. 939014.1221854.1594225.1934003.
------------------------------------------------------------------------------------------------------------------------
```

Table 2.7
Reservoir Storage Tables for CRM Example Created with 2RES Records

RESERVOIR STORAGE DRAWDOWN DURATION FOR MONTH 6

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
----------------------------------------------------------------------------------------------------------------------
               MEAN        BOTTOM       TOP          NUMBER OF PERIODS WITH DRAWDOWNS EQUALING OR EXCEEDING PERCENT
NAME         STORAGE      OF ZONE     OF ZONE                           OF ZONE STORAGE CAPACITY
             (AC-FT)      (AC-FT)     (AC-FT)       0%      2%      5%     10%     25%     50%     75%     90%    100%
----------------------------------------------------------------------------------------------------------------------
PK         235951.45           0.     570240.      58.     50.     50.     49.     45.     37.     23.     13.      8.
Whit       302086.47      379000.     627100.      58.     52.     52.     52.     49.     45.     43.     40.     40.
WacoL      111096.91         580.     192100.      58.     40.     40.     39.     36.     25.     17.      6.      0.
Belton     182236.80           0.     457600.      58.     50.     47.     46.     45.     37.     26.     16.      8.
George      15165.00         240.      37100.      58.     46.     45.     44.     42.     37.     27.     22.     15.
Grang       31861.91         220.      65500.      58.     40.     40.     39.     37.     29.     25.     19.     15.
----------------------------------------------------------------------------------------------------------------------
```

RESERVOIR STORAGE RELIABILITY FOR MONTH 6

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
----------------------------------------------------------------------------------------------------------
               MEAN      BOTTOM        TOP          PERCENTAGE OF MONTHS WITH STORAGE EQUALING OR EXCEEDING
NAME         STORAGE     OF ZONE    OF ZONE                       PERCENTAGE OF STORAGE CAPACITY
             (AC-FT)     (AC-FT)    (AC-FT)   100%    98%    95%    90%    75%    50%    25%    10%    >0%
----------------------------------------------------------------------------------------------------------
PK         235951.45          0.    570240.   12.1   13.8   13.8   15.5   22.4   36.2   60.3   77.6  100.0
Whit       302086.47     379000.    627100.   10.3   10.3   10.3   10.3   15.5   22.4   25.9   31.0   37.9
WacoL      111096.91        580.    192100.   27.6   31.0   31.0   32.8   37.9   56.9   70.7   89.7  100.0
Belton     182236.80          0.    457600.   13.8   13.8   19.0   20.7   22.4   36.2   55.2   72.4  100.0
George      15165.00        240.     37100.   19.0   20.7   22.4   24.1   27.6   36.2   53.4   62.1   74.1
Grang       31861.91        220.     65500.   31.0   31.0   31.0   32.8   36.2   50.0   56.9   67.2   74.1
----------------------------------------------------------------------------------------------------------
```

RESERVOIR STORAGE DRAWDOWN DURATION FOR MONTH 9

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
----------------------------------------------------------------------------------------------------------
               MEAN      BOTTOM        TOP        NUMBER OF PERIODS WITH DRAWDOWNS EQUALING OR EXCEEDING PERCENT
NAME         STORAGE     OF ZONE    OF ZONE                         OF ZONE STORAGE CAPACITY
             (AC-FT)     (AC-FT)    (AC-FT)     0%     2%     5%    10%    25%    50%    75%    90%   100%
----------------------------------------------------------------------------------------------------------
PK         208170.28          0.    570240.    58.    54.    54.    54.    48.    39.    26.    19.    15.
Whit       316693.25     379000.    627100.    58.    55.    55.    53.    52.    49.    45.    44.    40.
WacoL      101028.48        580.    192100.    58.    52.    48.    46.    34.    26.    20.    10.     4.
Belton     133430.77          0.    457600.    58.    55.    55.    53.    49.    44.    34.    25.    19.
George       6771.36        240.     37100.    58.    58.    58.    58.    50.    48.    44.    42.    33.
Grang       14925.81        220.     65500.    58.    56.    56.    53.    51.    48.    40.    32.    24.
----------------------------------------------------------------------------------------------------------
```

RESERVOIR STORAGE RELIABILITY FOR MONTH 9

CONDITIONAL RELIABILITY MODELING: Relative Frequency Option
Annual cycles starting in month 4
Length of simulation period (CR1) = 6 months
Initial storage multiplier (CR4) = 0.100

```
----------------------------------------------------------------------------------------------------------
               MEAN      BOTTOM        TOP          PERCENTAGE OF MONTHS WITH STORAGE EQUALING OR EXCEEDING
NAME         STORAGE     OF ZONE    OF ZONE                       PERCENTAGE OF STORAGE CAPACITY
             (AC-FT)     (AC-FT)    (AC-FT)   100%    98%    95%    90%    75%    50%    25%    10%    >0%
----------------------------------------------------------------------------------------------------------
PK         208170.28          0.    570240.    5.2    6.9    6.9    6.9   17.2   32.8   55.2   67.2  100.0
Whit       316693.25     379000.    627100.    5.2    5.2    5.2    8.6   10.3   15.5   22.4   24.1   37.9
WacoL      101028.48        580.    192100.    6.9   10.3   17.2   20.7   41.4   55.2   65.5   82.8   93.1
Belton     133430.77          0.    457600.    5.2    5.2    5.2    8.6   15.5   24.1   41.4   56.9  100.0
George       6771.36        240.     37100.    0.0    0.0    0.0    0.0   13.8   17.2   24.1   27.6   43.1
Grang       14925.81        220.     65500.    0.0    3.4    3.4    8.6   12.1   17.2   31.0   44.8   58.6
----------------------------------------------------------------------------------------------------------
```

Table 2.8
Reservoir Storage Tables for CRM Example Created with 2STO Record

END-OF-PERIOD STORAGE (AC-FT) FOR RESERVOIR PK

```
--------------------------------------------------------------------------------------------------------------------------------------
YEAR        APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC      JAN      FEB      MAR       MEAN
--------------------------------------------------------------------------------------------------------------------------------------
1940    52239.1 141684.2 403855.3 410398.6 463142.9 382817.1      0.0      0.0      0.0      0.0      0.0      0.0   309022.9
1941   237043.5 570240.0 570240.0 570240.0 570240.0 570240.0      0.0      0.0      0.0      0.0      0.0      0.0   514707.2
1942   507521.3 570240.0 570240.0 544145.0 451661.8 570240.0      0.0      0.0      0.0      0.0      0.0      0.0   535674.7
1943    92339.5  85131.8  97576.8      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    45841.3
1944    58598.9  88088.8 109035.3 109898.1  96740.3  95594.9      0.0      0.0      0.0      0.0      0.0      0.0    92992.7
1945   134504.4 135598.3 148141.1 267511.9 245588.7 222526.1      0.0      0.0      0.0      0.0      0.0      0.0   192311.8
1946    43788.5  48671.9  64966.1  61983.6  90800.2 176023.0      0.0      0.0      0.0      0.0      0.0      0.0    81038.9
1947    44342.5 499231.1 517420.7 371727.6 337324.2 255287.2      0.0      0.0      0.0      0.0      0.0      0.0   337555.5
1948    43510.2  51156.8  85638.9  57167.3      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    39578.9
1949    50696.8 348145.0 493046.8 415517.7 289522.0 253070.3      0.0      0.0      0.0      0.0      0.0      0.0   308333.1
1950    93281.9 271646.9 282506.6 335574.2 290257.8 345754.6      0.0      0.0      0.0      0.0      0.0      0.0   269837.0
1951    18291.9  23028.8  41374.1      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    13782.5
1952    42694.7  35113.5  21112.7      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    16486.8
1953    38463.8  93404.5  63586.4 184575.0 134900.3  33390.4      0.0      0.0      0.0      0.0      0.0      0.0    91386.7
1954    73545.4 429019.5 331859.2 198305.4  72923.3      0.0      0.0      0.0      0.0      0.0      0.0      0.0   184275.5
1955    50047.3 230403.1 349931.7 265509.6 150470.3 278568.6      0.0      0.0      0.0      0.0      0.0      0.0   220821.8
1956        0.0  18123.3      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     3020.6
1957   570240.0 570240.0 570240.0 569015.4 495698.4 486654.8      0.0      0.0      0.0      0.0      0.0      0.0   543681.4
1958   100461.0 292840.3 293991.0 430397.8 298582.0 333842.3      0.0      0.0      0.0      0.0      0.0      0.0   291685.8
1959    35611.9  57764.3 208561.1 195674.7  73594.2      0.0      0.0      0.0      0.0      0.0      0.0      0.0    95201.0
1960    57316.6  39307.9  24829.2 151905.1  25403.4      0.0      0.0      0.0      0.0      0.0      0.0      0.0    49793.7
1961    45954.2  49607.2 296338.1 514852.1 404396.8 449727.3      0.0      0.0      0.0      0.0      0.0      0.0   293479.3
1962    42776.5  20208.9 275866.5 276088.3 153011.7 460144.8      0.0      0.0      0.0      0.0      0.0      0.0   204682.8
1963   137403.0 128740.3 202807.5  60392.9      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    88223.9
1964    39932.1      0.0      0.0      0.0      0.0  18932.3      0.0      0.0      0.0      0.0      0.0      0.0     9810.7
1965    81684.8 447745.0 451039.8 418346.5 417660.7 327264.2      0.0      0.0      0.0      0.0      0.0      0.0   357290.2
1966   274305.7 463406.9 456538.4 310870.9 288341.4 570240.0      0.0      0.0      0.0      0.0      0.0      0.0   393950.5
1967    79068.8  79640.6  75067.6  96804.4      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    55096.9
1968   154333.4 202016.2 264566.6 296123.9 273759.5 246238.4      0.0      0.0      0.0      0.0      0.0      0.0   239506.3
1969   104609.2 560260.8 564085.2 413423.0 356512.7 423750.0      0.0      0.0      0.0      0.0      0.0      0.0   403773.5
1970    99128.5 179183.2 167197.3 134009.9 104301.8  59645.2      0.0      0.0      0.0      0.0      0.0      0.0   123911.0
1971    29497.1      0.0      0.0      0.0 179251.5 207712.1      0.0      0.0      0.0      0.0      0.0      0.0    69410.1
1972    23617.2  72707.5      0.0      0.0  37122.5  23647.0      0.0      0.0      0.0      0.0      0.0      0.0    26182.4
1973   109643.9 107217.6 130817.0 130425.6 110567.5 106453.7      0.0      0.0      0.0      0.0      0.0      0.0   115854.2
1974    69584.0  57254.3  11516.3      0.0      0.0 198939.7      0.0      0.0      0.0      0.0      0.0      0.0    56215.7
1975    62453.0 152165.2 233015.7 258939.1 269199.3 278846.3      0.0      0.0      0.0      0.0      0.0      0.0   209103.1
1976    54211.8  66505.2  44906.8  37266.9  31774.6  82480.5      0.0      0.0      0.0      0.0      0.0      0.0    52857.6
1977    97858.1 140960.4 154116.2 130138.5 101024.3  80522.7      0.0      0.0      0.0      0.0      0.0      0.0   117436.7
1978    16104.5      0.0      0.0      0.0 462808.3 415167.9      0.0      0.0      0.0      0.0      0.0      0.0   149013.5
1979    57319.1 114479.0 165887.9 165507.5 161255.9 138060.5      0.0      0.0      0.0      0.0      0.0      0.0   133751.6
1980    41164.8 183927.6 187881.2  48818.1      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    76965.3
1981    86659.2  96118.5 203148.9 182677.5 164902.3 149469.0      0.0      0.0      0.0      0.0      0.0      0.0   147162.6
1982    45093.2 570240.0 570240.0 570240.0 440685.9 314850.2      0.0      0.0      0.0      0.0      0.0      0.0   418558.2
1983    45352.6 111295.4 124245.3  66991.2   4082.5      0.0      0.0      0.0      0.0      0.0      0.0      0.0    58661.2
1984    11040.2      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     1840.0
1985   143268.7 241723.3 251244.1 133018.0   9041.2      0.0      0.0      0.0      0.0      0.0      0.0      0.0   129715.9
1986    43589.2  47559.6 183133.4 225859.8 213958.8 279962.1      0.0      0.0      0.0      0.0      0.0      0.0   165677.1
1987    84344.0 196137.6 440490.5 453054.9 429612.7 417652.1      0.0      0.0      0.0      0.0      0.0      0.0   336882.0
1988    42920.2      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     7153.4
1989    41195.3 225872.4 411916.9 384889.7 387514.1 433731.3      0.0      0.0      0.0      0.0      0.0      0.0   314186.6
1990   570240.0 570240.0 570240.0 552810.5 494902.5 489191.4      0.0      0.0      0.0      0.0      0.0      0.0   541270.8
1991    45867.5 160156.5 570240.0 458238.6 419044.9 479124.7      0.0      0.0      0.0      0.0      0.0      0.0   355445.4
1992   109348.5 177937.0 570240.0 570240.0 570240.0 567072.9      0.0      0.0      0.0      0.0      0.0      0.0   427513.1
1993    70046.6  79450.6 108635.9  85813.4  67921.3  56298.2      0.0      0.0      0.0      0.0      0.0      0.0    78027.7
1994    41658.1 329213.2 318443.2 302719.6 170540.5  62714.0      0.0      0.0      0.0      0.0      0.0      0.0   204214.8
1995    48117.6  62754.6 124717.4 114300.9 215641.1 230869.5      0.0      0.0      0.0      0.0      0.0      0.0   132733.5
1996    26437.9      0.0      0.0      0.0      0.0 212244.0      0.0      0.0      0.0      0.0      0.0      0.0    39780.3
1997   102231.6 184487.7 308448.9 326857.4 315360.5 288916.2      0.0      0.0      0.0      0.0      0.0      0.0   254383.7
MEAN    95217.2 184108.5 235951.5 221711.5 195539.5 208170.3      0.0      0.0      0.0      0.0      0.0      0.0   190116.4
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END-OF-PERIOD STORAGE (AC-FT) FOR RESERVOIR Belton

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-------------------------------------------------------------------------------------------------------------------------------
YEAR        APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC      JAN      FEB      MAR        MEAN
-------------------------------------------------------------------------------------------------------------------------------
1940     61664.3  51666.9 133702.7 158698.5 144386.4 126100.0      0.0      0.0      0.0      0.0      0.0      0.0    112703.1
1941    163676.1 457600.0 457600.0 457600.0 457600.0 457600.0      0.0      0.0      0.0      0.0      0.0      0.0    408612.7
1942    322472.7 457600.0 457600.0 408034.8 402257.7 457600.0      0.0      0.0      0.0      0.0      0.0      0.0    417594.2
1943     62309.8  66642.9  46792.8      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     29290.9
1944     99450.5 457600.0 457600.0 338807.6 304563.1 294440.3      0.0      0.0      0.0      0.0      0.0      0.0    325410.2
1945    433077.8 457600.0 457600.0 457600.0 440390.2 428425.2      0.0      0.0      0.0      0.0      0.0      0.0    445782.2
1946     75309.0 205891.6 233875.1 129954.3  13281.5  22069.4      0.0      0.0      0.0      0.0      0.0      0.0    113396.8
1947     74129.6 114581.5 106369.1  87835.7  58623.8  40862.7      0.0      0.0      0.0      0.0      0.0      0.0     80400.4
1948     38643.3  51687.8  43341.7  28649.3      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     27053.7
1949    116369.4 173245.2 201876.6 178623.6 146285.0 118287.0      0.0      0.0      0.0      0.0      0.0      0.0    155781.1
1950     44822.2  70187.2  75621.8  67327.5  37176.7  50415.0      0.0      0.0      0.0      0.0      0.0      0.0     57591.7
1951         0.0      0.0   9292.3      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      1548.7
1952     59554.0 110432.7 100835.7      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     45137.1
1953     37959.3 180525.3  63899.7  41872.8  12255.2      0.0      0.0      0.0      0.0      0.0      0.0      0.0     56085.4
1954     31702.4  21647.4      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      8891.6
1955     52951.4 116925.7 132785.7 104115.0  76298.0  49262.9      0.0      0.0      0.0      0.0      0.0      0.0     88723.1
1956      2230.0  96257.6      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     16414.6
1957    358716.4 457600.0 457600.0 457600.0 437029.7 336424.5      0.0      0.0      0.0      0.0      0.0      0.0    417495.1
1958     84183.0 249879.5 254500.8 235746.7 204561.1 188909.3      0.0      0.0      0.0      0.0      0.0      0.0    202963.4
1959     35499.8  23162.4  55145.1  52074.0  43807.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     34948.1
1960     58514.5  57933.4  45335.2  27231.5      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     31502.4
1961     63695.3  56398.0 136844.3 218416.3 209393.8 203113.9      0.0      0.0      0.0      0.0      0.0      0.0    147976.9
1962     34880.0  27462.1  26207.2   8277.2      0.0  30162.6      0.0      0.0      0.0      0.0      0.0      0.0     21164.8
1963     36038.9  53322.4  24973.4      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     19055.8
1964     12071.1  13088.2      0.0      0.0      0.0  33778.9      0.0      0.0      0.0      0.0      0.0      0.0      9823.0
1965     61125.0 457600.0 457600.0 354412.6 342738.1 340259.8      0.0      0.0      0.0      0.0      0.0      0.0    335622.6
1966    120689.1 204934.5 227495.9 214910.8 240071.3 299529.3      0.0      0.0      0.0      0.0      0.0      0.0    217938.5
1967     43784.4  47207.4  54512.4  29226.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     29121.7
1968    149319.2 367456.7 436041.9 457600.0 399638.3 384821.4      0.0      0.0      0.0      0.0      0.0      0.0    365812.9
1969    141373.9 241844.5 232499.0 208713.7 192818.4 174451.6      0.0      0.0      0.0      0.0      0.0      0.0    198616.9
1970    120554.8 173035.1 202338.8 140397.1   5965.8  22106.8      0.0      0.0      0.0      0.0      0.0      0.0    110733.1
1971         0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0         0.0
1972     39511.9  46392.5   7778.3      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     15613.8
1973     97850.7 122873.6 153284.3 157272.9 134137.3 119136.1      0.0      0.0      0.0      0.0      0.0      0.0    130759.2
1974     36835.3  26366.3   7731.3      0.0      0.0  77848.7      0.0      0.0      0.0      0.0      0.0      0.0     24796.9
1975    132905.8 213981.9 235119.7 232183.8 219503.0 201369.5      0.0      0.0      0.0      0.0      0.0      0.0    205844.0
1976     60706.7  72481.7  78940.3 181070.9 160523.6 101276.2      0.0      0.0      0.0      0.0      0.0      0.0    109166.6
1977    284014.3 410233.4 434856.3 340831.3 211882.2 136998.2      0.0      0.0      0.0      0.0      0.0      0.0    303136.0
1978     34905.5      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      5817.6
1979     73653.7 174333.3 285692.2 285145.8 275494.6 257282.0      0.0      0.0      0.0      0.0      0.0      0.0    225266.9
1980     43492.6 170778.1 128398.8  94042.6      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     72785.4
1981     41879.6  31984.0 167991.7 150723.7 114881.9 103470.3      0.0      0.0      0.0      0.0      0.0      0.0    101821.9
1982     48688.4 100115.3 133326.4 130536.3 113625.5  94078.5      0.0      0.0      0.0      0.0      0.0      0.0    103395.1
1983     39294.5  46305.6  32716.7  11366.8      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0     21613.9
1984         0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0         0.0
1985     56089.6  65441.2  79907.8  59135.8  37662.9      0.0      0.0      0.0      0.0      0.0      0.0      0.0     49706.2
1986     36634.8  98727.4 321081.4 207156.1  85460.9 162445.5      0.0      0.0      0.0      0.0      0.0      0.0    151917.7
1987     63204.8 156006.5 365707.9 402504.9 383585.4 371308.2      0.0      0.0      0.0      0.0      0.0      0.0    290386.3
1988     25820.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      4303.3
1989     50438.4 143918.8 246935.9 243922.5 226370.9 201923.2      0.0      0.0      0.0      0.0      0.0      0.0    185585.0
1990    316474.3 457600.0 457600.0 365663.5 353973.8 346571.2      0.0      0.0      0.0      0.0      0.0      0.0    382980.5
1991     46822.6  65732.4  75089.3  60237.3  59895.9  58042.6      0.0      0.0      0.0      0.0      0.0      0.0     60970.0
1992    138240.0 312375.7 436955.2 457600.0 457600.0 457600.0      0.0      0.0      0.0      0.0      0.0      0.0    376728.5
1993    124271.4 175767.3 195706.5 177451.7 140470.9  26878.9      0.0      0.0      0.0      0.0      0.0      0.0    140091.1
1994     35252.2 216711.3 255023.9 136564.6 110172.3  89727.2      0.0      0.0      0.0      0.0      0.0      0.0    140575.2
1995    243035.2 358805.1 422402.5 312475.5 387992.7 394766.3      0.0      0.0      0.0      0.0      0.0      0.0    353246.2
1996     38269.8      0.0      0.0      0.0      0.0  62728.0      0.0      0.0      0.0      0.0      0.0      0.0     16833.0
1997    250718.9 452457.9 457600.0 457600.0 450777.7 416914.0      0.0      0.0      0.0      0.0      0.0      0.0    414344.8
MEAN     92341.0 162765.6 182236.8 160814.0 139537.1 133430.8      0.0      0.0      0.0      0.0      0.0      0.0    145187.5
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Options for Assigning Probabilities to the Simulation Sequences

The preceding example illustrates the default relative frequency approach. The 58 alternative simulations are each weighted the same in the frequency and reliability computations. Each of the 58 six-month long sequences of naturalized flows and net evaporation rates represent one possible occurrence of hydrologic conditions. Each sequence is implicitly treated as having a probability of occurrence of 1/58. Some sequences have extremely low or extremely high flow volumes and net evaporation rates, representing infrequent drought or flooding conditions, while other sequences reflect more normal hydrologic conditions. Relatively few of the hydrologic sequences reflect infrequent extremes. Many more sequences are representative of more normal conditions that occur the majority of the time. The probabilistic nature of river basin hydrology is captured by the frequency of occurrence of the range from low to high natural stream flows and net reservoir evaporation less precipitation rates. The 58 hydrologic simulation sequences provide a sample of 58 occurrences which are adopted as being representative of the frequency characteristics of the continually varying hydrologic conditions in the river basin.

In the preceding example, the hydrology represented by each sequence is not treated as being equally likely, but the sequences are equally-weighted in the sense of each being counted once. The CRM approach of simply applying Eqs. 2.2−2.6 with each of the N simulation sequences considered one time is called the *relative frequency option*. In the *probability array option* outlined by the remainder of this section, each sequence is explicitly assigned both an exceedance probability and incremental probability that typically vary between sequences. The summation of the incremental probabilities total to 1.0.

The computational procedures activated by the *TABLES 2REL*, *2FRE*, *2FRQ*, and *2RES* records provide reliability and frequency estimates based on Equations 2.2, 2.3, and 2.4. The *2FRE* records contains options to apply the normal or log-normal probability distributions with Eqs. 2.7 and 2.8 for either CRM or conventional non-CRM applications. The relative frequency option provides valid estimates of frequencies and reliabilities and may often be the best choice for particular CRM applications. However, improvements in accuracy of the frequency and reliability estimates may be achieved in some applications by sets of other *TABLES* options based on more sophisticated computational methods for assigning probabilities to each of the multiple simulation sequences. The remainder of this chapter outlines sets of computational options incorporated in *TABLES* for assigning probabilities to each of the multiple hydrologic sequences. The *SIM* CRM simulation is not affected by these methods for assigning probabilities to the *SIM* generated simulation sequences. Likewise, the general format of the tables in the TAB file generated by *TABLES* is not affected.

The options for improving probability estimates assigned to each of the simulation sequences are based on two basic concepts.

1. The likelihood of the hydrologic sequences may be correlated to various degrees with preceding reservoir storage levels.
2. The log-normal probability distribution may model the probability distribution of naturalized flow volumes and the flow ratio R defined later by Eq. 2.8 more accurately than simple relative frequency.

Alternative Probability Estimation Strategies

Reliability and frequency estimates vary depending on the approach adopted in *TABLES* for assigning probabilities to each of the multiple hydrologic sequences generated by the *SIM/SIMD* simulation. *TABLES* provides alternative options for various tasks associated with assigning probabilities to each of the multiple CRM simulation sequences. The alternative strategies are outlined as follows.

1. The *relative frequency option* is based on weighting each of the hydrologic sequences the same in applying the simple relative frequency concepts expressed in Equations 2.2, 2.3, 2.4, 2.5, 2.6, and 2.7.

2. The *probability array option* assigns probabilities to each hydrologic sequence with alternative sets of methods that may either ignore or consider preceding reservoir storage contents.

    a. The *flow-frequency (FF) relationship option* is based on assigning exceedance probabilities directly to naturalized flow volumes using either the log-normal probability distribution or Weibull formula. Preceding storage may be either incorporated into the determination of probability distribution parameters by using only sequences with preceding storage falling within a specified range or simply ignored.

    b. The *storage-flow-frequency (SFF) relationship option* is based on probabilistically representing deviations in naturalized flow volumes from the amounts indicated by a regression relationship between preceding reservoir storage volume and naturalized streamflow volume.

The relative frequency option involves no special features in *TABLES*. The computations associated with the *2REL*, *2FRE*, *2FRQ*, and *2RES* records and Eqs. 2.2−2.7 are the same for a CRM application with the relative frequency option and a conventional non-CRM application. The *2FRE* record also includes an option that allows use of a probability distribution function for use with either CRM or non-CRM applications. This generic *2FRE* record probability distribution option is separate from the CRM probability array option described below and may be applied in combination with the CRM relative frequency option.

The CRM probability distribution option also uses the same computational routines associated with the *2REL*, *2FRE*, *2FRQ*, and *2RES* input records but incorporates an exceedance probability (FF or SFF) relationship that is used to assign an incremental probability to each simulation sequence. These incremental probabilities vary between sequences and sum to 1.0. If the incremental probability (IP) array happens to contain equal probabilities for all hydrologic sequences, the probability distribution option yields the same reliability and frequency analysis results as the equally-weighted option.

The CRM probability distribution option assigns probabilities to each of the hydrologic sequences. Either a flow-frequency (FF) or storage-flow-frequency (SFF) relationship is developed for use in developing the incremental probability (IP) array. The SFF relationship option incorporates preceding storage in more detail in assigning of flow probabilities. With the probability distribution option for performing CRM reliability and frequency analyses, an array assigning a probability to each of the hydrologic sequences produced in the *SIM/SIMD* simulation is developed by *TABLES* in two steps.

1. A FF or SFF relationship is developed from sequences of monthly naturalized flow volume and preceding storage volume read from a *SIM/SIMD* output file for a conventional single long-term *SIM/SIMD* simulation as specified by a *5CR1* record.
2. The array of naturalized flow volumes for each simulation sequence read from a CRM execution of *SIM/SIMD* for a given initial storage condition is combined with the FF/SFF relationship of step 1 above to develop an array of incremental probabilities (IP array) for the hydrologic sequences as specified by a *5CR2* record.

The *5CR1* record controls development of a flow-frequency (FF) or storage-flow-frequency (SFF) relationship from a single conventional long-term *SIM/SIMD* simulation using either annual or monthly cycles to define flow segments. The *5CR2* record develops an array assigning an incremental probability (IP) to each simulation sequence of a CRM analysis. The FF or SFF relationship developed by the *5CR1* record is used in the routines controlled by the *5CR2* record to develop the IP array.

The model-user may specify lower and upper limits defining a reservoir storage range on the *5CR1* record. Only those naturalized flow sequences with the preceding storage falling within the specified range are used in building the FF or SFF relationship. For example, assume that a CRM analysis is being performed for an initial storage content of 50 percent of the storage capacity. The model-user may choose to build the FF or SFF relationship using only flow sequences that follow storage contents falling in the range of 20 to 80 percent of capacity. For the FF option, the storage limits provide the only mechanism for relating naturalized flow volume to preceding storage. The FF option may also be applied without specifying storage limits and thus without relating naturalized flow volume to preceding storage.

Relationship between Naturalized Streamflow and Preceding Storage

The SFF option for assigning probabilities to each of the multiple simulation sequences as a function of preceding reservoir storage pivots around the storage-flow-frequency (SFF) relationship. The SFF relationship relates exceedance probabilities to the random variable R.

$$R = \frac{Q}{Q_S} \tag{2.8}$$

where Q is the naturalized flow volume over one or more months observed in the *SIM/SIMD* CRM simulation results, and Q_S is the corresponding expected value of the naturalized flow volume determined from a regression equation reflecting preceding storage volume. The naturalized flow volume is the total summed for the months specified by the parameter FM on the *5CR1* record which defaults to the CR1 months from the *CR* record.

The flow ratio R measures the amount of flow observed in the model relative to that expected from relating flow to preceding storage. The magnitude of R expresses the deviation of the flow volume from the expected value of the flow volume conditioned on preceding storage volume as modeled by a regression equation.

Regression Methods

The following exponential (Eq. 2.9), power (Eq. 2.10), linear (Eq. 2.11), and combined (Eq. 2.12) forms of regression equations may be used to relate the naturalized flow volume Q_S in Eq. 2.8 to preceding storage volume S.

$$Q_S = a \times e^{S/b} \tag{2.9}$$

$$Q_S = b\,S^c \tag{2.10}$$

$$Q_S = a + b\,S \tag{2.11}$$

$$Q_S = a + bS^c \tag{2.12}$$

Eq. 2.9 is the default option, where e is the base of the natural logarithms. The parameters a, b, and c are determined by applying least-squares regression to the naturalized flow volumes and preceding reservoir storage volumes from a long-term *SIM* simulation. An option allows forcing the y-intercept to be zero (a=0) for Eqs. 2.11 and 2.12. If the coefficient c is 1.0, Eq. 2.12 reduces to Eq. 2.11. With a value for c other than 1 and a coefficient a of zero, Eq. 2.12 reduces to Eq. 2.10.

A 732-month 1940-2000 simulation comparing a 3-month naturalized flow volume to the preceding storage volume will have either 60 or 61 (annual option) or 729 (monthly option) pairs of values of S_i and Q_i. The storage S_i is the volume content of one or more specified reservoirs at the beginning of each 3-month sequence. The flow Q_i is the total volume of the naturalized streamflow at one or more control points over each 3-month sequence. Application of regression analysis to the pairs of S_i and Q_i results in the parameters a, b, and c for the alternative Eqs. 2.9, 2.10, 2.11, or 2.12.

Standard least-squares linear regression methods outlined in statistics and numerical methods textbooks are used.

$$E(Y\,|\,x) = a + bx \tag{2.13}$$

$$b = \frac{n\,\Sigma\, x_i y_i - (\Sigma x_i)(\Sigma y_i)}{n\,\Sigma\, x_i^2 - (\Sigma x_i)^2} \tag{2.14}$$

$$a = \overline{y} - b\,\overline{x} \tag{2.15}$$

$E(Y\,|\,x)$ denotes the conditional expectation of Y given x, and $\overline{y}$ and $\overline{x}$ are the means of y and x. Eqs. 2.13, 2.14, and 2.15 are applied with x = S and y = Q to determine values for the coefficients a and b in Eq. 2.11, which represent the y-intercept and slope of a straight line plot.

The linear regression equations (Eqs. 2.13−2.15) are applied to transformed variables to obtain the coefficients a, b, and c for Eq. 2.9 and Eq. 2.10. For the exponential model of Eq. 2.9, the natural logarithm of Q_S is regressed with S, with resulting the y-intercept and slope of a straight line plot being represented by ln a and b, respectively. For the power function of Eq. 2.10, the log Q_S is regressed with log S, with resulting the y-intercept and slope of a straight line plot being represented by log b and c, respectively. The coefficients b and c for Eq. 2.12 are set in two steps. The exponent c in Eq. 2.12 is fixed based on the power function regression, and then S^c and Q are regressed to obtain the coefficients a and b.

Correlation Coefficients

The *5CR1* record results in computation of the regression (a, b, c in Eqs. 2.9-2.12) and correlation coefficients (r and r_r of Eqs. 2.14 and 2.15) for the selected regression equation along with a SFF relationship table. The *5COR* record develops correlation coefficients (Eqs. 2.17 and 2.18) for the various optional forms of the regression equation. Correlation coefficients are indices of the goodness-of-fit of the regression relationships. While Eq. 2.11 is based on a linear relationship between S and Q_S, Eqs. 2.9, 2.10, and 2.12 are based on a linear relationship between variables that are nonlinear functions of S and Q_S. The linear correlation coefficients of Eqs. 2.17 and 2.18 are indices of the linear correlation between the previously noted transformed variables. In comparing regression equations, the storage versus flow data should be transported to MS Excel and plotted for visual inspection along with comparison of the *5CR1* or *5COR* record computed r^2 and r_r^2 values.

The correlation coefficient r is the square root of the coefficient of determination r^2.

$$r = \sqrt{r^2} \tag{2.16}$$

The standard linear correlation coefficient r is computed as Eq. 2.17.

$$r = \frac{n\,\Sigma\,x_i y_i - (\Sigma x_i)(\Sigma y_i)}{\sqrt{n\,\Sigma\,x_i^{\,2} - (\Sigma x_i)^2}\,\sqrt{n\,\Sigma\,y_i^{\,2} - (\Sigma y_i)^2}} \tag{2.17}$$

Spearman's rank correlation coefficient is also computed as supplemental information. The rank correlation coefficient does not depend upon the actual values of x and y (Q_S and S) but rather their relative rank. The ranks of the two variables in the paired data set are correlated rather than the actual magnitudes. For a set of paired data, (x_i, y_i), i = 1, 2, ... , n, the x_i and y_i are ranked separately with the highest value having rank 1 and the lowest value rank n. The ranks are correlated with Eq. 2.17, which may be algebraically converted to Eq. 2.18. In correlating ranks, the rank correlation coefficient r_r is expressed as Eq. 2.18 where d_i is the difference between the ranks assigned to x_i and y_i for each of the n pairs of values.

$$r_r = \frac{6\,\Sigma\,d_i^2}{n(n^2 - 1)} \tag{2.18}$$

The correlation coefficient r provides a measure of the degree of linear correlation between the variables x and y. The rank correlation coefficient r_r provides a measure of the degree of linear correlation between the ranks of the variables x and y. Values of the correlation coefficient can range between –1.0 and 1.0.

$$-1.0 \le r \le 1.0 \quad \text{and} \quad -1.0 \le r_r \le 1.0$$

A value for r of 1.0 indicates a perfect linear correlation. A plot of x versus y would be a perfect straight line, increasing with increasing magnitudes of x and y. A value for r of –1.0 indicates that x and y are inversely correlated with y decreasing with increasing x. A value for r of 0.0 indicates no linear correlation between x and y. With r near zero, a plot of x versus y would show either random scatter or a highly nonlinear relationship.

The *5COR* correlation coefficient record may be used to compute the correlation coefficient of the sum of naturalized flows at specified control points and reservoir storage at specified reservoirs or control points, without actually developing the *5CR1* record *SFF* or *FF* relationship. The *5COR* record is designed primarily as an aid in determining whether the correlation of flow volume to preceding storage is strong enough to warrant adoption of the storage-flow-frequency (SFF) option and in selection of the control points and reservoirs to be used in developing SFF relationships. Again, a graphical comparison external to WRAP will typically be combined with the correlation coefficients.

Probability Distributions

The exceedance probability is the estimated probability of equaling or exceeding particular values of the random variable X. Restating in terms of frequency, the exceedance frequency is the relative frequency of equaling or exceeding particular values of X. In developing a FF relation, the random variable X is the naturalized flow volume for a specified length of time. In developing a SFF relation, the random variable X is the R defined by Eq. 2.8. The naturalized flow volumes are the sum of the monthly amounts during the period of months specified by the parameter FM on the *5CR1* record which defaults to CR1 from the *CR* record. The *TABLES 5CR1* record activates two alternative options for computing exceedance probabilities that are based on either the log-normal probability distribution or Weibull formula.

The first option for modeling the probability distribution of X representing either naturalized flow volumes for a FF relationship or the ratio R for a SFF relationship is to apply the log-normal probability distribution using Eq. 2.7 with z derived from the normal distribution.

$$\log X = \overline{\log X} + z\, S_{\log X} \tag{2.19}$$

The mean $\overline{\log X}$ and standard deviation $S_{\log X}$ of the logarithms of X are computed. The frequency factor z is entered by linear interpolation into a normal probability built into *TABLES* to obtain cumulative probability (1-P) which is converted to the exceedance probability (P).

Naturalized stream flow ranges upward from a lower limit of zero, with no defined upper limit. Likewise, the Eq. 2.8 ratio R, representing deviations, has a lower limit of zero and no upper limit. The log-normal models the skewed distribution for these types of random variables.

The other option for assigning exceedance probabilities for a SFF or FF relationship involves ranking the flow ratio (R) or flow volume series and applying the Weibull formula:

$$P = \frac{m}{N+1} \tag{2.20}$$

where P denotes exceedance probability, m is the rank of the values (m = 1, 2, 3, ... ,N), and N is the total number of sample values of the random variable. The flow sequence with the greatest flow ratio R or flow volume is assigned a rank of 1, and the smallest is assigned a rank of N. The Weibull relative frequency formula weights each flow sequence (and associated flow volume or Eq. 2.8 flow ratio R) equally in developing the SFF or FF relationship. The algorithm in *TABLES* extends the SFF or FF relationship by assigning an exceedance probability of 1.0 to a flow of zero. If a flow volume in a *5CR2* record application exceeds the highest flow included in the *5CR1* record FF or SFF array, the relation is linearly extrapolated using the highest two flows, subject to the limiting restriction that the probability can not be less than zero.

The probability option with a FF relationship developed using the Weibull formula is conceptually similar to the equally weighted option. The computational algorithms differ. The Weibull formula (Eq. 2.20) is applied explicitly to flow volumes at one or more specified control points. Eq. 2.20 can be compared with Eqs. 2.2 and 2.4 upon which the relative frequency option is based. In either case, the concept of relative frequency is applied with each of N sample hydrologic sequences treated as being equally-likely. Each simulation is assigned the same incremental probability. Relatively few sequences reflect infrequent extremely wet or dry conditions. A larger number of sequences reflect more normal flow conditions that are expected to occur more often. Thus, the computational methods model the probability distribution of stream flow volumes representing hydrologic conditions.

The accuracy of probability estimates based on direct application of relative frequency concepts reflected in Eqs. 2.2, 2.4, and 2.20 is limited by the sample size set by the number of hydrologic sequences. The log-normal probability distribution may improve modeling accuracy by providing a general form for the probability distribution considered representative of either stream flow volumes or the Eq. 2.8 ratio R representing deviations from the flow volumes indicated by regression with preceding storage.

Flow-Frequency (FF) and Storage-Flow-Frequency (SFF) Relationships

The sole purpose of a *TABLES 5CR1* record is to develop either a FF or SFF relationship for use later by a *5CR2* record.

- A flow-frequency (FF) relationship is between naturalized flow volume over a specified number of months versus exceedance probability developed based on either the log-normal probability distribution or Weibull frequency formula.
- A storage-flow-frequency (SFF) relationship is between the flow ratio R defined by Eq. 2.8 versus exceedance probability developed based on either the log-normal probability distribution or Weibull frequency formula.

The SFF relationship is developed by assigning exceedance probabilities to values of the flow ratio R defined by Eq. 2.8 and either Eqs. 2.9, 2.10, 2.11, or 2.12. Exceedance probabilities are assigned to the naturalized flow sequences as an expression of the relative likelihood of departures of flow volumes from those expected based on relating flow to preceding storage. The basic premise of the SFF option is that naturalized streamflows are correlated to some extent with preceding storage content. Low reservoir storage contents imply dry conditions during preceding months with a high likelihood of continued low naturalized flows. Full reservoirs imply high precipitation during the preceding months with an increased likelihood of continued high flows during subsequent months. Naturalized streamflows are assumed to exhibit some degree of autocorrelation. The likelihood of flows being high during a particular time period is greater if the flows were high in preceding months. Reservoir storage contents are dependent upon flows in preceding months.

The *5CR1* record routines develop either a FF or SFF relationship. Pairs of flow and storage volumes are obtained from the results of a long-term *SIM* simulation. The flow volumes are for naturalized streamflow over a specified number of months at one or more control points. The storage volumes are the storage contents of one or more reservoirs at the beginning of the period over which the naturalized flows occur. Either annual or monthly cycle options may be adopted to define the flow sequences.

Storage limits may be specified on the *5CR1* record such that the only flow sequences considered in developing the SFF or FF array are those with preceding storage falling within the specified range. For example, if lower and upper storage volume limits equal to 25% and 90% of reservoir storage capacity are defined on the *5CR1* record, the set of flow sequences included in the FF and SFF relationship computations include only those flow sequences with preceding storage volume within the range of 25% to 90% of the reservoir capacity.

A flow-frequency (FF) array is based on applying the log-normal probability distribution or Weibull probability formula directly to the naturalized flow volumes. The array assigns exceedance probabilities to flows without considering preceding storage other than through the option that limits the flow sequences included in the computations to a specified storage range.

A storage-flow-frequency (SFF) relationship relates exceedance probability to a flow ratio expressing the deviation of flow volume from that expected based on a given preceding storage volume. The *TABLES 5CR1* record routines perform the following tasks resulting in production of the SFF array.

1. The main *SIM/SIMD* output file resulting from a conventional single long-term simulation is read by *TABLES* to obtain the beginning storage and naturalized flow for each simulation sequence.

2. The initial storage at specified control points or for specified reservoirs is summed for each simulation sequence to obtain the total storage amounts used in the analysis. Likewise, naturalized flows during specified months at specified control points are summed to obtain the total flow amounts used in the analysis.

3. Regression analyses are performed to relate flow volume to preceding storage volume in the form of either Eq. 2.9, Eq. 2.10, Eq. 2.11, or Eq. 2.12.

4. The expected value of flow conditioned on storage is computed for each simulation sequence using the regression equation derived from step 3 above. The corresponding values of the flow ratio R are determined with Eq. 2.8.

5. The storage-flow-frequency (SFF) relationship is developed by connecting exceedance frequencies to R using either Eq. 2.19 or Eq. 2.20. The mean and standard deviation of the logarithms of R are computed as the parameters for the log-normal distribution option. Alternatively, an array of R versus exceedance probability is developed using the Weibull formula.

The product of this process activated by a *TABLES 5CR1* record is a SFF relationship connecting exceedance probabilities to values of the flow ratio R. The SFF relationship is input to the *TABLES* routine outlined next, which is activated by the *5CR2* record to assign probabilities to each simulation sequence in a CRM application.

<u>Incremental Probability (IP) Array for the CRM Simulation Sequences</u>

After the FF or SFF relationship has been established by the *5CR1* record based on the results from a single long-term *SIM/SIMD* simulation, the next task is for the *5CR2* record to develop the IP array by assigning incremental probabilities to each of the multiple simulation sequence of a CRM execution of *SIM/SIMD*. Whereas the *5CR1* record FF and SFF relationships connect the random variable (flow volume or Equation 2.8 flow ratio R) to exceedance probabilities, the *5CR2* record computes incremental probabilities for these variables that are assigned to the corresponding hydrologic simulation sequences. The incremental probabilities for all simulation sequences sum to 1.0.

The flow-frequency (FF) option is based on assigning frequencies to naturalized flow sequences without considering reservoir storage contents. With the FF option, *TABLES* assigns probabilities to each of the simulation sequences as follows.

1. The main *SIM/SIMD* output file (filename root.CRM) resulting from a CRM simulation is read by *TABLES* to obtain the naturalized flow in each month for each simulation sequence.

2. Naturalized flow volumes during specified months at specified control points are summed to obtain the total flow amounts used in the analysis.

3. The naturalized flow volume for each hydrologic sequence is combined with the previously established FF relationship to obtain an exceedance probability for each CRM hydrologic simulation sequence. Linear interpolation is used to obtain exceedance probabilities from either the normal probability table using the FF log-normal probability distribution parameters or the FF Weibull exceedance probability array.

4. The exceedance probabilities are ranked in order and converted to incremental probabilities. The incremental probability for each flow sequence is computed based on the half-way

points between the exceedance probabilities of the next larger flow volume and next smaller flow volume. The incremental probability is the difference between the two exceedance probabilities.

The storage-flow-frequency (SFF) option considers preceding storage contents in assigning probabilities to the hydrologic simulation sequences. With the SFF option, *TABLES* assigns probabilities to each of the simulation sequences as follows.

1. The main *SIM/SIMD* output file (filename root.CRM) resulting from a CRM run is read by *TABLES* to obtain the naturalized flow in each month for each simulation sequence.

2. The initial storage for each pertinent reservoir or control point is read from either a *5CR2* record or *SIM/SIMD* beginning reservoir storage (filename root.BRS) file.

3. The initial storages at specified reservoirs or control points are summed for each simulation sequence to obtain the total storage amounts used in the analysis. Likewise, naturalized flows during specified months at the specified control points are summed to obtain the total flow amounts used in the analysis.

4. The expected value of flow conditioned on preceding storage is computed for each simulation sequence using either Eq. 2.9, Eq. 2.10, Eq. 2.11, or Eq. 2.12. The corresponding values of the flow ratio R are determined with Eq. 2.8.

5. The value of R for each hydrologic sequence is combined with the previously established SFF relationship using linear interpolation to obtain an exceedance probability for each CRM hydrologic simulation sequence.

6. The exceedance probabilities are ranked in order and converted to incremental probabilities. The incremental probability for each R is computed based on the half-way points between the exceedance probabilities of the next larger R and next smaller R. The incremental probability is the difference between the two exceedance probabilities.

The product of this process activated by a *TABLES 5CR2* record is an IP array assigning incremental probabilities to each of the simulation sequences included in the *SIM/SIMD* CRM results. The IP array is used in the reliability and frequency routines activated by *2REL*, *2FRE*, *2FRQ*, and *2RES* records.

Reliability and Frequency Analyses

The probability distribution option is activated by inserting a *5CR2* record in the *TABLES* input file. Without a *5CR2* record, the relative frequency option is adopted by default. The relative frequency option signaled by a *5CRM* record remains in effect until a *5CR2* record is read in the sequence of input records. The incremental probability array created by a *5CR2* record is applied for all subsequent *2REL*, *2FRE*, *2FRQ*, and *2RES* records. The routines activated by these records adopt the last *5CR2* record probability array created during the *TABLES* execution.

With activation of the probability distribution option by a *5CR2* record, all subsequent *2REL*, *2FRE*, *2FRQ*, and *2RES* records incorporate the IP array that assigns incremental probabilities to the CRM simulation sequences. The reliability and frequency analysis computation routines are modified to reflect varying probabilities for the multiple sequences for the probability distribution option. The modifications to the computations are based on counting each simulation sequence multiple times with the count totaling to 1,000,000. The number of times N_S that each simulation sequence is repeated is proportional to incremental probability P_S as follows.

$$N_S = 1{,}000{,}000 \; P_S \tag{2.21}$$

The procedure is illustrated with an example. A water supply diversion CRM reliability table is being constructed for water rights of interest for some selected month of interest, say July, and also for the entire annual simulation period. Frequency tables are being constructed for regulated and unappropriated flows and end-of-month storage contents for a selected month of interest. A 1940-2000 period-of-analysis is divided into 61 annual simulation sequences for the CRM analysis. The *5CR2* record incremental probability array assigns probabilities to each of the 61 simulation sequences as shown in the second column of Table 2.9. The counts from Eq. 2.21 are shown in the last column of the table.

Table 2.9
Example of Applying Probability Array in
Reliability and Frequency Counts

Simulation Sequence	Incremental Probability	N_S Count
1	0.019254	19,254
2	0.025347	25,347
3	0.007469	7,469
4-59	not shown	
60	0.011528	11,528
61	0.017862	17,862
Totals	1.000000	1,000,000

For this example, reliability and frequency analyses for a conventional long-term simulation are based on data from 61 years of simulation results. Likewise, reliability and frequency analyses for a CRM application assuming equally-likely sequences are based on data from 61 simulation sequences. Each sequence is given equal weight and counted one time. However, reliability and frequency analyses for a CRM application using the SSF option is based on data from 61 simulation sequences that are counted as 1,000,000 simulation sequences. The first simulation sequence is counted 19,254 times as shown in the third column of the table above. The second simulation sequence is counted 25,347 times. Thus, the simulation sequences are weighted or counted in proportion to the *5CR2* record probability array.

The reliability and frequency analysis computational routines in *TABLES* are basically algorithms that count the frequency or number of times that specified magnitudes of specified variables are equaled or exceeded. The algorithms are essentially the same for either conventional simulation, CRM relative frequency option, or CRM probability array option. However, the counts are increased in proportion to incremental probabilities for the CRM probability array option.

CRM Probability Array Option Example

A CRM analysis based on the relative frequency option is presented earlier in Tables 2.2-2.8 for the system shown schematically in Figure 2.1. This example is switched to the probability array option as follows.

As long as the parameters on the *CR* record are not changed, the same *SIM* CRM output file is used regardless of the relative frequency probability array options. However, the SFF option requires OUT file simulation results from a convention long-term *SIM* simulation. SIM is executed twice, once to generate the CRM results stored in a CRM output file and again to derive the conventional long-term simulation results stored in an OUT output file. The two simulations with and without the *CR* record reflects the same water management and use requirements. The *CR* record is the only difference between the *SIM* input datasets for the two executions to generate the OUT and CRM output files.

The probability array option is activated by adding *5CR1* and *5CR2* records at the beginning of the *TABLES* input TIN file. The *5CRM* record is no longer needed. The *5CR1* and *5CR2* records are as follows.

Summary of CRM Options

Reliabilities associated with meeting water supply diversion, hydroelectric power generation, and environmental instream flow targets over the next several months and the amount of water contained in storage at the end of the next several months depend on both the:

1. amount of water currently available in reservoir storage
2. hydrology that occurs over the future several-month period of interest as represented by naturalized flows and net reservoir evaporation rates

Beginning reservoir storage and naturalized stream flow represent the two sources of available water. The relative importance of these two sources in determining supply reliabilities and end-of-period storage frequencies depends upon their relative magnitude. Beginning reservoir storage is specified by the model-user. The CRM options outlined in the latter half of this chapter focus on the hydrology, particularly on relating the probabilistic characteristics of the multiple sequences of naturalized streamflows to specified known beginning storage conditions.

The final results of CRM analyses are organized in the format of reliability and frequency tables created by *2REL*, *2FRE*, *2FRQ*, and *2RES* records. Other auxiliary tables may be created as well. The format and content of these tables displaying CRM results are the same regardless of the options adopted to perform the computations. Of course, the numerical values of the reliability and frequency estimates will vary depending on the computational techniques chosen. The choices of computational options are outlined in Table 2.10.

Table 2.10 Outline of CRM Computational Options

1. Relative Frequency Option
    - ∗ choice of annual or monthly cycle options (*CR* record)
2. Probability Array Option (*CR* record, *5CR1* and *5CR2* records)
    - Flow-Frequency (FF) Relationship Option
        - ∗ choice of annual or monthly cycle options
        - ∗ selection of control points for naturalized flows
        - ∗ upper and lower limits defining reservoir storage range
        - ∗ choice of log-normal or Weibull (Eq. 2.19 or Eq. 2.20)
    - Storage-Flow-Frequency (SFF) Relationship Option (Eq. 2.8)
        - ∗ choice of annual or monthly cycle options
        - ∗ selection of control points for storages and flows
        - ∗ upper and lower limits defining reservoir storage range
        - ∗ choice of regression equation (Eq. 2.9, 2.10, 2.11, or 2.12)
        - ∗ choice of log-normal or Weibull (Eq. 2.19 or Eq. 2.20)

Choice of Annual or Monthly Cycle Options

CRM is based on repeating the *SIM/SIMD* simulation with many sequences of naturalized flows and net evaporation rates, starting each simulation with the same initial storage condition. The *CR* record that activates the CRM mode of simulation is the only *SIM/SIMD* record associated with conditional reliability modeling. The annual versus monthly cycle options are set by the *CR* record entries listed in Table 2.1. With the annual cycle option, the multiple simulations all reflect the same seasonal sequencing. The annual cycle option has the advantage of capturing seasonality, but the disadvantage of limiting the number of simulations to the number of years in the total period-of-analysis. The monthly cycle option allows up to 12 times more simulations than the annual cycle option. The accuracy of reliability estimates depends both on properly modeling seasonal characteristics of hydrology and maximizing the number of hydrologic sequences used in the CRM analysis. The choice of which option to adopt for a particular application depends upon the relative importance of these two considerations.

The annual cycle option limits the simulation period to 12 or fewer months. The monthly cycle option places no limits on the simulation period, allowing it to exceed 12 months.

Choice of Relative Frequency or Probability Array Options

All of the hydrologic simulation sequences may be weighted the same in the reliability and frequency analysis computations, or probabilities may be assigned to each simulation sequence that may vary between sequences depending upon preceding storage. The default relative frequency option simplifies the CRM computations and reduces requirements for the model-user to select further sub-options. If the relative frequency option is adopted, the only CRM input is the *SIM/SIMD CR* record. However, the relative frequency option ignores the correlation of natural streamflows and net reservoir evaporation rates to preceding reservoir storage. The probabilistic characteristics of river basin hydrology may possibly be estimated more accurately using the probability array option.

The random variable defined in probability array methodology is naturalized stream flow volume at a single control point or the sum of flows at selected multiple control points. The flow volumes are for a specified length of time. Flow volumes are related to storage volumes in one or more selected reservoirs. Thus, the method is defined in terms of specific locations in the river/reservoir system and specific time periods for aggregating flow volumes. The enhanced accuracy of the probability array option is most applicable if focused on one or a few reservoirs and diversion sites. In this regard, the relative frequency option may be advantageous if many reservoirs and diversion sites scattered over a large river basin are being investigated. For example, in the preceding example, the relative frequency option facilitated the analysis of six reservoirs and diversions at 11 locations at both the end of June and September based on a single execution of *SIM* and *TABLES*. Multiple runs of *TABLES* with CRM parameters varied depending on location and timeframe of interest will typically be required to best achieve the potential enhancements in probability estimation offered by the probability array methodology.

Hydrology may be modeled in *TABLES* with the log-normal probability distribution with or without relating flow probabilities to preceding storage contents. The incorporation of the log-normal distribution in the CRM probability array methodology may enhance probability estimates over the relative frequency option, either with or without consideration of storage.

The optional methods in *TABLES* are designed to further improve estimates of the probabilities associated with each of the multiple hydrologic sequences based on the information provided by a known fixed preceding storage condition. High storage levels result from past wet conditions that are more likely to be followed by continued wet conditions. Severe reservoir draw-downs imply dry weather that may be followed by continued dry conditions.

The improvements in probability estimates provided by the probability array option relative to the relative frequency option depend largely on the degree of correlation that exists between preceding storage and naturalized flow volumes. The correlation for a short period will typically be greater than for a longer period. The naturalized flow volume during a month has a greater correlation with reservoir storage at the beginning of the month than the correlation of the flow volume during a year to the reservoir storage at the beginning of the year. For typical river systems, the correlation of natural flow to preceding storage may not necessarily be high. The validity or accuracy of CRM is not highly dependent on there actually being a significant correlation. However, if a significant correlation does exist, the modeling the effect of preceding storage on flow probabilities should enhance the CRM analysis. The correlation coefficients provided by the *5COR* and *5CR1* records provide useful indices for assessing the degree of correlation. Graphical analyses of flow versus storage performed external to the WRAP programs are also useful.

Water availability depends upon both beginning-of-simulation reservoir storage and naturalized stream flow. Beginning reservoir storage is specified by the model-user. If water supply is dominated by releases or withdrawals from storage in a large reservoir, the accuracy of water supply reliability estimates may be relative insensitive to the accuracy of estimates of the probability of naturalized stream flows.

If the relative frequency option is adopted, the discussion stops here. The *TABLES 5CR1* and *5CR2* records are not applicable to the relative frequency option. The remainder of this section addresses options specified on the *5CR1* and *5CR2* records.

SFF or FF Probability Distribution Options

The probability distribution options consist of a set of computational methods in *TABLES* organized into two major tasks controlled by the *5CR1* and *5CR2* records, respectively. The *5CR1* record develops a relationship between exceedance probability and either naturalized flow or the flow ratio defined by Eq. 2.8. These two alternative relationships define the flow-frequency (FF) option and the storage-flow-frequency (SFF) option. The *5CR2* record uses the FF or SFF relationship to build an incremental probability (IP) array assigning probabilities to each of the multiple hydrologic simulation sequences.

The model-user may specify lower and upper limits defining a reservoir storage range on the *5CR1* record. Only those naturalized flow sequences with a preceding storage falling within the specified range are used in building the FF or SFF relationship. Thus, the FF or SFF relationship may be built using only flow sequences that follow storage contents that are reasonably representative of the initial storage that will be considered in the analysis.

With the FF option, the reservoir storage range provides the only mechanism for incorporating storage in the assigning of probabilities to hydrologic sequences. The SFF option is based on the flow ratio of Eq. 2.8, which explicitly incorporates preceding storage in the assigning of probabilities. The random variable is naturalized flow volume with the FF option and the Eq. 2.8 flow ratio with the SFF method. Thus, the SFF option is more detailed than the FF option in modeling the correlation between flows and preceding storage. The FF option is applicable if there is little or no correlation. With little correlation between flow and storage, the FF option may still be advantageous over the relative frequency approach by allowing flow volumes to be modeled with the log-normal probability distribution. Again, the correlation of flow volume to preceding storage volume depends upon the length of the time period over which the flows occur. Plots and correlation coefficients provide information that is useful in evaluating the degree of correlation, but choices are based largely on judgment.

Either the FF or SFF relationship may be modeled with either the log-normal probability distribution or Weibull relative frequency equation. The Weibull formula is based on assuming that all of the sequences used to develop the FF or SFF relationship are equally likely to occur. With an extremely large number of hydrologic sequences, the Weibull equation would accurately capture the actual probability distribution of the flow volumes. With a limited sample size, the log-normal distribution provides the advantage of contributing additional information by adopting a probability distribution that reasonably characterizes flow volumes. The log-normal distribution is widely applied in hydrology to model various hydrologic variables including flow volumes. It provides a smooth exceedance frequency curve. The log-normal distribution option is also advantageous over the Weibull probability equation in extrapolating probabilities values for flow volumes in the IP array that fall outside the range of volumes used in building the FF or SFF relationship. The Weibull formula may be most applicable for developing a SFF relationship using the monthly cycle option with several hundred sequences. In most other situations, the log-normal distribution is probably preferable.

The sum of naturalized flow volumes at any number of control points covering a defined number of months is correlated with the sum of the preceding reservoir storage volume at any number of control points or in any number of reservoirs. The model-user selects the control points and reservoirs that are most applicable to the particular application. The time period over which flow volumes are defined for purposes of building the SFF or FF relationship and IP array is also user-specified and is not restricted to CR1 on the *CR* record that defines the length of the simulation sequences, though CR1 is the default. The correlation coefficient tables developed using the *5COR* record supplemented by Microsoft Excel plots provide information that is useful in evaluating the degree of correlation related to various alternative choices of time periods and control points. However, these choices are governed largely by logical judgments regarding physical relationships inherent in river basin hydrology. Sensitivity analyses may be performed to evaluate the effects of various options on CRM results.

CHAPTER 3
SUB-MONTHLY TIME STEP FEATURES

WRAP allows each of the 12 months of the year to be divided into any integer number of computational time steps. The term *daily* is used in this manual synonymously with the term *sub-monthly* since the day is the sub-monthly interval expected to be adopted most often. With the default daily time step, each month is subdivided into 31, 30, 29 (leap year), or 28 days.

A conventional monthly time step simulation may be performed with *SIMD* with the same input datasets used with *SIM*. Supplemental input is added to apply the *SIMD* sub-monthly features. Naturalized river flows generate the daily or sub-monthly variability in the simulation. Flow forecasting and routing are incorporated in the computations to simulate lag and attenuation effects. All simulation result variables are computed by *SIMD* for each time step, but the sub-monthly amounts may be summed to monthly values. *TABLES* organizes *SIMD* simulation results and develops frequency and reliability tables using either daily or other sub-monthly computational time step *SIMD* results or aggregated monthly amounts.

Hoffpauir (2006) describes development of the sub-monthly features of WRAP and explores advantages and disadvantages of daily versus monthly time step modeling for various types of applications. The sub-monthly features of the WRAP programs *SIMD*, *TABLES*, and *DAY* include:

- routines in *SIMD* for setting the number of sub-monthly computational time steps contained in each month and uniformly subdividing monthly net evaporation depths, water use requirements, and other quantities to the smaller time steps
- options in *SIMD* for varying diversion, hydropower, and instream flow targets over the sub-monthly time steps within each month
- option in *SIMD* for reading an input file of sub-monthly naturalized flows
- alternative options in *SIMD* for disaggregating naturalized monthly flows to sub-monthly time intervals that range in complexity from a linear interpolation routine that requires no additional input data to methodologies that reproduce the sub-monthly variability exhibited by sequences of flows or flow patterns provided as model input at sub-monthly time intervals
- flow forecasting in *SIMD*
- adaptation of Muskingum method for routing of flow adjustments in *SIMD*
- aggregation of *SIMD* sub-monthly simulation results to monthly values and recording of simulation results at sub-monthly and/or monthly time steps
- options in *TABLES* for developing reliability indices and frequency relationships using sub-monthly time step simulation results
- disaggregation methods in *DAY* for developing sequences of naturalized flows or flow patterns for input to *SIMD*
- routines in *DAY* for calibration of flow routing parameters for use in *SIMD*

Monthly Versus Sub-Monthly Time Steps

Most reservoir/river system models use either a monthly or daily time step (Wurbs 2005). The effects of computational time step choice on simulation results vary with different modeling applications (Hoffpauir 2006). Flow averaging over longer time intervals tends to over-estimate capabilities for meeting requirements for water supply, environmental instream flow, hydroelectric power, and flood control. Accurate modeling of flood control operations is particularly difficult with a time step much greater than a day due to the extreme fluctuations in flow rates over short time spans associated with flood events. The effects of adopting a time interval of finite length on model results related to capabilities for meeting water supply, hydropower, and environmental instream flow requirements depend largely on the reservoir storage capacities available for mitigating flow fluctuations. Choice of time interval tends to affect reliability estimates for run-of-river diversion and instream flow targets much more than if there is reservoir storage to mitigate flow fluctuations. However, simulation results for systems with large reservoirs may also be significantly affected by the choice of time interval.

A monthly interval provides adequate modeling accuracy for many common applications, while facilitating development and management of input datasets. A daily time step may improve the accuracy of a simulation, but greatly increases the difficulty of compiling and managing input data. A daily interval greatly increases the effort required to develop multiple-decade-long sequences of naturalized stream flows at numerous locations. Flow forecasting and routing considerations are modeled in greater detail and correspondingly greater complexity with a daily time step, requiring specification of forecast periods and routing parameters.

The following considerations are addressed in this section.

- Flow rates that vary continuously over time in the real world are modeled as volumes occurring during discrete time intervals. Thus, comparisons of stream flow rates with water management/use targets in the model are based on total volumes during finite time intervals rather than instantaneous rates at points in time.

- In a monthly time step model, the effects of reservoir releases and water management/regulation/use actions on stream flows at downstream locations are assumed to propagate through the system within the same month, precluding flow forecasting and routing computations. However, flow forecasting and routing are important in typical modeling applications based on a daily time step.

Instantaneous Flow Rate versus Mean Flow Rate for a Time Interval

A hydrograph of instantaneous stream flow rates at a location on a river over a six-month period is plotted in Figure 3.1. A constant target flow rate is also plotted. This target could be either a minimum instream flow requirement or a diversion demand. The flow rate above which flood damages begin to occur is also shown. The river flow, instream flow or diversion target, and maximum non-damaging flood level are instantaneous flow rates that could be expressed in m^3/s, ft^3/s, or any other units of discharge. The flow volume during any specified time interval is represented by the area under the flow plot. For example, the total river flow during the six-month period may be computed as the area under the stream flow hydrograph during January through June. Likewise, the total volume of the target during the six-month period is represented by the rectangular area under the plot of the instantaneous target discharge rate extending from January through June. A volume occurring during a specified time interval may be expressed as a mean flow rate during the interval in units such as m^3/s, thousand m^3/day, thousand m^3/month, million m^3/year, ft^3/s, acre-feet/day, acre-feet/month, or acre-feet/year.

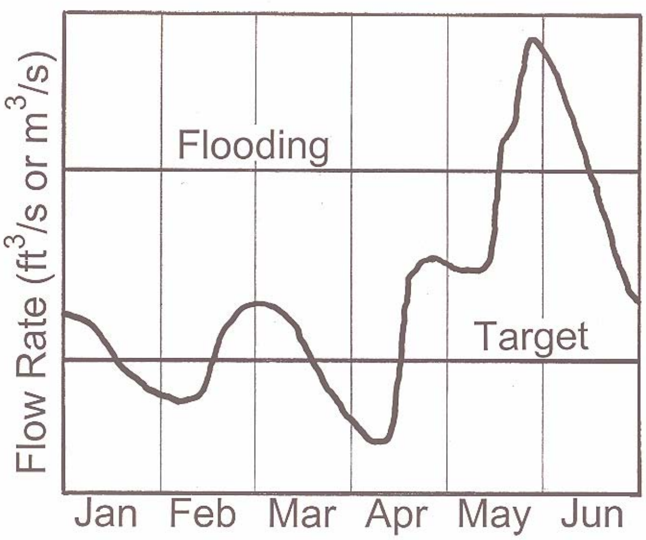

Figure 3.1 Stream Flow Hydrograph and Water Management Targets

Figure 3.1 illustrates the significance of adopting a daily versus monthly time interval. Assume that the target plotted in Fig. 3.1 is a constant minimum instream flow requirement. The stream flow hydrograph is the regulated flow at that location. If a monthly time interval is adopted, both the instream flow target and stream flow are expressed in terms of flow volume (area under the plots) in each month. The stream flow volume exceeds the instream flow target in each of the six months, with no failures to meet the target. However, results change significantly if a daily time step is adopted. Failures to meet the instream flow target occur during the last 15 days of January and first 15 days of February and during the last 14 days of March and first 15 days of April. With a monthly time interval, the instream flow target is satisfied 100 percent of the time during this six-month period. With a daily time interval, the instream flow target is satisfied 67 percent of the time.

Now assume that the target is a water supply diversion right and the stream flow hydrograph is the stream flow available to the diversion right. For a run-of-river diversion, the period reliability is 100 percent and 67 percent, respectively, for a monthly and daily time interval. If the diversion target is supplied by stream flow supplemented as necessary by releases from one or more reservoirs located upstream, the amount of water withdrawn from reservoir storage will vary depending on the time step adopted. For a monthly time step, the entire demand is met from stream flow with no releases from reservoir storage. With a daily time step, portions of the demand during January, February, March, and April are met by releases from storage leaving less water in storage for future months. If the water supply diversion is lakeside directly from a reservoir, the choice of monthly versus daily time step is less significant. The reservoir storage mitigates the effects of flow fluctuations during the month, storing excess stream flow and supplying the diversion target as necessary. A similar effect occurs during months in which the reservoir is empty for a portion of the month.

The flood level shown in Fig. 3.1 is the river flow level above which damages to properties or structures occur. With a monthly time interval, the mean stream flow rate each month is less the mean monthly non-damaging flood discharge for each of the six months. A monthly time interval indicates no flooding. With a daily time step, the non-damaging flood level is exceeded during 30 days in May-June. Reservoir operations for flood control are based on storing inflows as necessary to prevent flows from exceeding the maximum non-damaging flow limits at downstream locations. Thus with a flood control reservoir, a daily time interval results in storage of flood waters, but a monthly time interval does not.

The Fig. 3.1 example illustrates the approximations involved in averaging flow rates over a monthly time interval. River flows may fall well below instream flow requirements for several days even though high flows in other days of the month result in the mean monthly stream flow being above the instream flow target. Reservoir storage plays a significant role in mitigating the effects of alternative choices of time interval. Although this discussion focuses on monthly versus daily time intervals, flow fluctuations during a day may also be significant. Flood flows may vary greatly over a period of an hour or several hours. However, the day and month are probably the two alternative time intervals that are most pertinent for most typical WRAP applications. The impacts of the choice of computational time interval on the accuracy of the model depend on the circumstances of the modeling application.

Flow Forecasting and Flow Routing

In a real-world river basin, time is required for the effects of diversions, return flows, and reservoir refilling and releases at an upstream location to propagate to downstream locations. River flows diverted or stored by a particular water user today may diminish the flows available to other water users located further downstream tomorrow or several days in the future. Likewise, flow travel times for reservoir releases or diversion return flows to reach other downstream locations may be several days, perhaps a week or longer. Thus, water supply capabilities are affected by earlier upstream activities. Flood control reservoir operations are based on making no releases that contribute to flows exceeding maximum non-damaging flow limits at downstream gages that may be located several days of flow travel time below the dam.

The timing of flows or flow adjustments cascading downstream through a river/reservoir system is reflected in two aspects of modeling, flow forecasting and flow routing. Forecasting and routing considerations are typically not explicitly addressed in modeling with a monthly computational time step but may be quite significant with smaller time steps. Pertinent effects of stream flow depletions and inflows propagating through a river/reservoir system typically occur over time scales of less than a month. Translating effects of actions occurring late in one month to the early part of the next month is not possible if the model is based on lumped monthly volumes. The WRAP simulation program *SIM* has no explicit features for either forecasting or routing because it is limited to a monthly time step. *SIMD* provides optional capabilities for flow forecasting and routing for use with sub-monthly time steps.

In *SIM* or *SIMD*, a water rights priority loop is nested within a period loop. The simulation progresses sequentially through time. In each time step, computations are performed for each water right (set of water control and use requirements) in priority order. As each set of requirements is considered, the following tasks are accomplished within *SIM* and in an expanded form reflecting forecasting and routing in *SIMD*. Flow forecasting in *SIMD* is performed in conjunction with the first task. Flow routing is performed in conjunction with the fourth task.

1. The amount of water available to that water right is determined considering available stream flows at the control point of the water right and at all control points located downstream. In the *SIMD* simulation of flood control operations, the amount of channel flood flow capacity below maximum allowable (non-damaging) limits is determined at all pertinent control points.

2. The water supply diversion target, hydroelectric power generation target, minimum instream flow limit, or non-damaging flood flow limit is set.

3. Decisions regarding reservoir storage and releases, water supply diversions, and other water management/use actions are made; net evaporation volumes are determined; and water balance accounting computations are performed.

4. The stream flow array used to determine water availability and remaining flood control channel capacity at all downstream control points is adjusted for the effects of the water management actions.

Water control and use actions today both affect and are affected by future river flows. Forecasting addresses the issue of considering future flow conditions in current operating decisions. Task 1 listed above consists of determining the amount of water that is available to a water right. Water availability in *SIM* and *SIMD* is based on not allowing a water right to adversely affect the amount of water available to senior rights. This task requires consideration of water availability at all control points located downstream. Likewise, *SIMD* flood control operating decisions may affect flows at downstream locations one or more days into the future. In the monthly time step *SIM*, the water availability determination considers only the current month. Flow forecasting capabilities of *SIMD* allow the computational algorithms to look a specified number of days covering up to one month into the future in determining water availability and/or remaining flood flow capacities. The flow forecasting feature is based on performing the simulation twice at each monthly time step to allow a look forward at future stream flow conditions prior to making diversion and reservoir operation decisions.

Routing is performed in conjunction with task 4 outlined above where the flows at downstream control points are adjusted for diversions, return flows, and reservoir releases and refilling occurring upstream. Adjustments may also involve reservoir releases made for downstream uses. Meeting water right requirements today may affect flows at downstream locations from one to many days into the future. The effects of a stream flow depletion or return flow addition at an upstream location may require several days, perhaps a week or two, to propagate to the basin outlet. Flow travel times for extremely large river systems may be several weeks. However, for most river systems, flow times will typically be less than a month. Flow routing is typically not feasible with a monthly time step. An adaptation of the Muskingum routing technique is incorporated in *SIMD* for routing daily flow adjustments.

Computer Programs, Data Files, and Input Records

The programs *DAY, SIMD*, and *TABLES* contain features associated with modeling with a daily or other sub-monthly time step. Input and output files are listed in Table 1.2 of Chapter 1. Input records are described in Appendices B, C, D, and E.

WRAP-DAY

DAY is a utility program for developing *SIMD* daily stream flow input data. Monthly naturalized flows and net evaporation depths, common to both *SIM* and *SIMD*, can be developed using the hydrology program *HYD*. Program *DAY* performs various tasks in developing additional hydrology data for a daily simulation. Its primary functions are:

- disaggregation of monthly flows to sub-monthly time steps
- calibration of river routing parameters

Flows or flow patterns and river routing parameters developed by *DAY* are provided as input to *SIMD*. *DAY* is designed as an optional aid in developing *SIMD* input data but is not actually required for applying *SIMD*. The flow disaggregation routines in *DAY* are also incorporated in *SIMD*. Routing parameters may developed by other means for input to *SIMD*.

DAY has a main input file with the filename extension DIN that contains records controlling each flow disaggregation or calibration task. The input records are described in Appendix C. Program *DAY* reads monthly and daily flows from the same FLO and DCF input files read by *SIMD*. Results of the *DAY* computations are written to an output file with the filename extension DAY.

WRAP-SIMD

The original *SIM* simulation algorithms and input file architecture were preserved while adding sub-monthly time step features to create *SIMD*. All features of *SIM* are also included in *SIMD*. The following additional record types provide input for the *SIMD* sub-monthly time step features. The *JT* record is the only record required to activate sub-monthly features. The other records are optional, providing information that may be needed for various features.

- *JT* record controls time step, output, and forecasting aspects of the simulation.
- *TI* record specifies sub-monthly time intervals other than the default daily.
- *W2*, *C2*, *C3*, *G2*, and *R2* records control selection of sub-monthly interval output.
- *DW* record specifies target and forecast data related to individual water rights.
- *DC* record provides flow disaggregation and routing data for control points.
- *DF* record provides sub-monthly flows or flow patterns.

The *JT*, *TI*, *W2*, *C2*, *C3*, *G2*, *R2*, and *DW* records are added to the DAT file. The *DC* and *DF* records are stored in a separate file with the filename extension DCF and contain routing parameters, daily flows or flow patterns, and specifications controlling methods for disaggregation of monthly naturalized flows to daily time intervals. Descriptions of the input records for the DAT and DCF input files for program *SIMD* are provided in Appendix B.

SIMD writes simulation results at sub-monthly time intervals to a file with the filename extension SUB. The sub-monthly interval simulation results are aggregated by month within *SIMD* to create an output file with the filename extension OUT. The flood frequency analysis file with the filename extension FFA contains annual series of maximum naturalized flow, regulated flow, and reservoir storage. The three output files created by *SIMD* are optional; either or all may be used.

The OUT file developed by *SIMD* is indistinguishable in format from an OUT created by *SIM*. The user selects which water right, control point, and reservoir/hydropower records to write to the *SIMD* OUT file using the *JD* input record in the same manner as for a *SIM* simulation. The OUT file covers the entire simulation period.

The SUB file generated by *SIMD* contains water right, control point, and reservoir /hydropower records with the sub-monthly time step simulation results. These daily simulation results are also aggregated to form the monthly OUT file. The data selected for output to the SUB file are selected independently on the *JT* record in the DAT file from the data selected for the OUT file on the *JD* record. Thus, the user is able to obtain basin-wide output at the monthly time scale, while separately obtaining data for a select few locations at the sub-monthly time scale. Another output management option for the SUB file is selection of a sub-range from the entire simulation period-of-analysis. The user can select a starting month-year and ending month-year combination from within the entire simulation period. The selected sub-period does not have to begin and end with whole years. This option will not affect the full period of record simulation reporting that is sent to the OUT file. These features are designed to provide flexibility for the user to limit the potentially huge size of the SUB file.

The organization of the SUB file is outlined in Table 3.1. The number of control points, water rights, and reservoirs included in the sub-monthly SUB and monthly OUT output files are controlled similarly. Likewise, the water right, control point, and reservoir/hydropower output records in the *SIMD* SUB file have the same format as in the *SIM* or *SIMD* OUT file. The fifth line of the SUB file contains extra information not found on the monthly OUT file. Because the daily output file can be limited to any sub-range of the simulation period, the beginning year-month and ending year-month pair are stored in the SUB file. These dates are used by *TABLES* to process daily simulation results that need not span whole years. Output for the first year is not required to start with January nor the final year to end with December.

The sixth line of the SUB file contains information describing the number of time steps in each of the 12 months. The first entry is the parameter *NTI* from the *SIMD* input file *JT* record that flags the pattern of periods per month in array *NDAYS* as either user defined or the default calendar days. If *NTI* indicates that the array *NDAYS* follows a daily pattern, *TABLES* determines which years are leap years and assigns the value 29 for February in the array *NDAYS*.

Flood control reservoir operation features are described in Chapter 4. *SIMD* generates a file with the filename extension FFA that contains the maximum daily naturalized flow, regulated flow, and reservoir storage volume for each year of the simulation. The *TABLES* *7FFA* record activates a routine in *TABLES* that performs flood frequency analyses using the data in the *SIMD* FFA file.

Table 3.1
Organization of the *SIMD* SUB Output File

First Six Records of *SIMD* Output File

WRAP-SIMD (December 2005 Version) Output File
TITLE1
TITLE2
TITLE3
BEGYR BEGMON ENDYR ENDMON DAYS NCPO2 NWROUT2 NREOUT
NTI NDAY(1,…,12)

Definition of Variables on Fifth Record

BEGYR − first year in output file
BEGMON – first month in output file
ENDYR − last year in output file
ENDMON − last month in output file
DAYS – number of days (time steps) in output file
NCPO2 − number of control points in output file
NWROUT2 − number of water rights in output file
NREOUT2 − number of reservoirs in output file

Definition of Variables on Sixth Record

NTI – parameter (*JT* record) indicating calendar or user defined intervals in each month
NDAY(1,…,12) – number of time intervals used per month

Block of Records Repeated for Each Period (Month)

water rights output records (number of records = *NWROUT2*)
control point output records (number of records = *NCPO2*)
reservoir/hydropower output records (number of records = *NREOUT2*)

Total Number of Records in SUB File for Calendar Day Simulations

number of records = 6 + (12**NYRS**∑*NDAY*+(Number of Leap Years)) *
(*NWROUT2* + *NCPO2* + *NREOUT2*)

Total Number of Records in SUB File for User-Defined *NDAY* Simulations

number of records = 6 + (12**NYRS**∑*NDAY*)*(*NWROUT2* + *NCPO2* + *NREOUT2*)

Program TABLES

The monthly simulation results recorded in a *SIMD* OUT file have the same format as the results stored in a *SIM* OUT file. Program *TABLES* processes an OUT file from *SIMD* exactly the same as an OUT file from *SIM*. The SUB output file generated by *SIMD* containing sub-monthly time interval simulation results is also processed in essentially the same way by *TABLES*. The same *TABLES* TIN input file used for OUT file processing can be used for SUB file processing with minimal modification.

TABLES input records are described in Appendix E. The *TABLES* type 6 records with associated tables and data listings that are available for organizing the *SIMD* SUB file simulation results include:

- Sub-monthly time series records such as *6NAT*, *6REG*, *6UNA*, *6STO*, *6DIV*, etc., described in Appendix E are analogous to the monthly time series records *2NAT*, *2REG*, *2UNA*, *2STO*, *2DIV*, etc., which are described in the basic *Users Manual.*
- *6REL* and *6RET* reliability records are analogous to *2REL* and *2RET* records.
- *6FRE* and *6FRQ* frequency records are analogous to *2FRE* and *2FRQ* records.
- The *6RES* reservoir storage reliability and drawdown frequency record described in Appendix E is analogous to the *2RES* record described in the *Users Manual*.

The *SIMD* and *TABLES* flood control features covered in Chapter 4 use daily time steps. The flood frequency analysis computations activated by the *TABLES 7FFA* record using peak annual series of storage, naturalized flow, and regulated flow from the *SIMD* FFA file are described in Chapter 4.

Disaggregation of Monthly Amounts into Sub-Monthly Time Intervals

The sub-monthly *SIMD* simulation model is an extension of the monthly *SIM*. The computational algorithms of both *SIM* and *SIMD* are organized based on stepping through the hydrologic period-of-analysis month-by-month. *SIMD* allows each of the 12 months of the year to be divided into any integer number of intervals, thus increasing the number of computational time steps. The default sub-monthly time interval is one day, with each month except February having either 31 or 30 days. February has 28 days except for leap years with 29 days. Alternatively, each of the 12 months may be subdivided into any other integer number of intervals between 1 and 32 by use of the time interval *TI* record. For the sake of brevity, the terms *daily* and *sub-monthly* are used synonymously throughout this chapter.

The simulation computations are performed for each time step of the hydrologic period-of-analysis. Selected *SIMD* sub-monthly simulation results may be written to the SUB output file for each time step as specified by output control parameters included on the *JT*, *W2*, *C2*, *G2*, and *R2* records in the DAT input file. *SIMD* also totals the sub-monthly simulation results to aggregated monthly amounts which are recorded in the OUT file. The routines in *TABLES* handle the sub-monthly time step simulation results in a *SIMD* SUB output file or the monthly results in a *SIM* or *SIMD* OUT file in the same manner.

The process of subdividing monthly amounts into daily or other sub-monthly time intervals is referred to as disaggregation. The opposite process of summing daily values to monthly totals is called aggregation. Monthly values of input variables are disaggregated within *SIMD* to sub-monthly amounts as follows.

- *Naturalized flows* may be provided directly as input data on *DF* records at a daily or other sub-monthly interval. Alternatively, sub-monthly naturalized flows may be computed within the model by disaggregating monthly flows using the alternative options described later in this chapter.
- *Diversion and hydropower targets* may be uniformly distributed over the sub-monthly time intervals. Alternatively, options described later limit targets to a specified number of days or allow targets to vary across a month depending upon daily water availability.
- *Instream flow targets* may be uniformly distributed over the sub-monthly time intervals. Alternatively, an option limits targets to a specified number of days.
- The following monthly amounts are uniformly distributed over the sub-monthly time intervals. The monthly quantities are simply divided by the number of days in the month to obtain the daily amounts.
    - *Net evaporation depths* from *EV* records.
    - *Constant inflows* from *CI* records in DAT file.
    - *Flow adjustments* from *FA* records in a FAD file.

Diversion, Hydropower, and Instream Flow Targets

Monthly water supply diversion, hydroelectric power generation, and environmental instream flow requirements are set the same in either a monthly or daily time step simulation. The distribution of an annual target over the 12 months of the year followed by monthly target adjustments activated by the various target setting options described in the basic *Reference* and *Users Manuals* are the same whether or not months are divided into smaller time steps.

The global default daily target distribution option is set on the *JT* record. This default is overridden for individual water rights by options activated by the daily water right data *DW* record associated with each individual water right.

Monthly target volumes may be evenly divided into daily amounts. A monthly target is divided by the number of sub-intervals in each month to obtain amounts for each computational time step. With this option, a shortage occurs any time a daily target is not fully met.

Other options activated by the *JT* or *DW* records provide an alternative to the uniform distribution. An option is provided that allocates the monthly target to a specified number of days each month. The specified period begins with the first day of the month. This option may be combined with another option that allows shortages from preceding days to continue to be supplied in subsequent days of the same month.

The parameter *ND* is the number of days over which the monthly target is distributed. The daily target amount during the *ND* days is the monthly target divided by *ND*. The period of *ND* days always begins in the first day of the month. The *ND* option is applicable to either diversion, hydropower, or instream flow targets.

The *SHORT* option is applicable to diversion and hydropower targets but not to instream flow targets. The parameter *SHORT* on the *JT* or *DW* record is a switch that activates an option used in combination with the *ND* option that allows diversion or hydropower shortages to be met in subsequent days of the same month. If the target is fully met during each of the first *ND* days of the month, the target is zero for the remainder of the month with or without the *SHORT* option. However, with the *SHORT* option activated, a failure to meet the full target amount during the first *ND* days results in the shortages being supplied during subsequent days of the same month if sufficient water is available.

As an example of the *ND* daily target distribution option, agricultural irrigation practices might involve three 2-day irrigations during several selected months of the year. The entire monthly diversion occurs in just 6 days. A *ND* of 6 days sets the target at 1/6 of the monthly target in each of the first six days of the month. If this target is fully met, the target is zero for the remaining days of that month. With the *SHORT* option activated, shortages during the first 6 days and subsequent days are accumulated and treated as a daily target of up to 1/6 of the monthly target in the seventh and subsequent days of that month. The daily target is limited to not exceed 1/6 of the monthly target regardless of shortage to be made up from preceding days.

As another example, assume one day is entered for the parameter *ND* on the *DW* record associated with a particular water right *WR* record. The entire monthly target is met in the first day of the month if sufficient water is available. Any shortage in meeting the target in day one is supplied in day two. Any remaining shortage is supplied in day three and so forth throughout the remainder of the month. A water supply system with storage tanks providing storage capacity to deal with fluctuations in daily supply and demand may be modeled in this manner.

Monthly to Sub-Monthly Disaggregation of Naturalized Flows

The Texas WAM System contains datasets of monthly naturalized flows. Disaggregation options are adopted when applying daily time steps. In applying WRAP outside of Texas, the optimal daily time step modeling strategy will also often be to develop monthly naturalized flow sequences for use in combination with the *SIMD* disaggregation options. Disaggregation is a somewhat subjective process of making optimal use of available monthly and daily flow data. Historical gaged daily flow records and daily data related to past water control and use required to convert gaged flows to naturalized or unregulated flows may be limited in availability. Lag and attenuation effects complicate the process of naturalizing gaged flows and transferring them to ungaged sites. Converting gaged daily flows to naturalized daily flows at pertinent locations is difficult for extensively developed river basins.

SIMD reads monthly flow volumes from *IN* records for primary control points and distributes the flows to secondary control points using DIS file parameters just like *SIM*. These monthly flows are then disaggregated to daily amounts in *SIMD*. The alternative disaggregation methods all convert sequences of monthly naturalized flow volumes into daily flow volumes that preserve the monthly amounts.

Naturalized flows at daily or other sub-monthly time intervals may be input directly on *DF* records. If daily flows are provided on *DF* records for all primary (gaged) control points, the flow distribution options can be applied to transfer the daily flows to secondary (ungaged) control points using parameters from a DIS file in the same manner as monthly flows are distributed from gaged to ungaged locations. However, if monthly flow disaggregation at some control points is combined with reading daily flows directly from *DF* records at other control points, the flow distribution options associated with DIS file parameters are applied only to the monthly flows. However, the daily flows may be transferred to other locations with the disaggregation options outlined in this section.

Monthly-to-daily flow disaggregation computations are normally performed within *SIMD* as an integral part of a simulation. The naturalized flow disaggregation routines are also included in the utility program *DAY*. Sequences of river flows or flow patterns may be developed within program *DAY* and provided as input to *SIMD*.

Alternative Flow Disaggregation Methods

The alternative methods outlined in Table 3.2 for dividing monthly naturalized flow volumes between time steps within each month are activated by the *SIMD JT* and *DC* records. *JT* record field 11 sets a global default option. The default for this default setting option is to input daily flows on *DF* records without providing monthly flows. The global default defined by the *JT* record is applied to all control points unless overridden for individual control points by *DC* records. *DC* record field 5 is used to select a disaggregation method for an individual control point. Different methods may be adopted for different control points.

Daily flow *DF* records may contain either sub-monthly naturalized flow volumes or amounts that are used to represent flow patterns. In the case of flow amounts defining patterns, only the relative amounts, not the actual amounts, are relevant. Each set of *DF* record flow sequences may be repeated for any number of control points and applied with different disaggregation options for different control points. The *DF* input records do not have to include data covering the entire hydrologic period-of-analysis. The flows on the *DF* records are repeated as necessary within the *SIMD* simulation to extend over the hydrologic period-of-analysis.

The *uniform distribution* (option 1) and *linear interpolation* (option 2) methods require no additional data not already found in a monthly *SIM* simulation dataset. Options 1 and 2 may be adopted for use with existing Texas WAM System datasets without additional input data requirements. However, these methods tend to smooth out the extreme variability often exhibited by actual river flows.

Options 3 and 4 in Table 3.2 are based on reproducing the daily variability characteristics of available daily flow sequences. The *variability adjustment method* (option 3) is based on adjusting the flows computed by linear interpolation (option 2) to reflect greater more realistic variability. The *flow pattern method* (option 4) uses flows provided on *DF* records to establish a daily flow pattern. The daily flow sequences provided on *DF* records are used by *SIMD* in options 3 and 4 to set the pattern of variability and may be input for all or portions of the hydrologic period-of-analysis at any number of locations. The variability pattern derived from one or several years of daily flows may be repeated multiple times in disaggregating monthly flows covering a much longer simulation period-of-analysis. *DF* records developed for a particular location may be used to disaggregate monthly flow sequences to daily time steps at many different control points.

The flow pattern method (option 4) is based on entering a sequence of daily flows that are representative of flow variability. However, the pattern of daily flows derived from gaged flows at one particular location may not be representative of other sites with smaller or larger watersheds. For example the flows from a small upper-basin subwatershed may exhibit greater variability than the flows at a downstream gaging station with a much larger watershed. Options 5 and 6 listed in Table 3.2 are methods for transferring the flow pattern represented by *DF* record flows to other locations. An equation based on a drainage area ratio is used in option 5 to transfer a flow pattern from a source location to a destination location. The transfer equation of option 6 is based on regression coefficients. The pattern flows may also be lagged forward or backward in time in transferring them to upstream or downstream locations.

Table 3.2 Alternative Flow Disaggregation Methods

Daily Flows Input Without Monthly Flows

No Disaggregation − Daily flows are provided on daily flow *DF* records for use directly without disaggregating monthly flows. Monthly flows are not required.

Monthly Flows Disaggregated without Input of Daily Flows

1. *Uniform Distribution Option* − Monthly flow volumes are distributed evenly over the month with the same amount assigned to each daily time step.
2. *Linear Interpolation Option* − A linear spline interpolation routine is applied to the sequence of monthly flow volumes to assign a non-uniform daily flow distribution.

Monthly Flows Disaggregated Using Input Daily Flows or Flow Patterns

3. *Variability Adjustment Option* − The daily flow volumes computed with the linear interpolation routine (option 2 above) are adjusted to reflect the variability determined from daily flow sequences provided as input on daily flow *DF* records.
4. *Flow Pattern Option* − Daily flow amounts on *DF* records define a daily flow distribution pattern. Location adjustments are available with options 5 or 6 below.

Transferring Flow Patterns to Other Control Point Locations

5. *Drainage Area Ratio Transfer Option* − The daily flow pattern defined by the *DF* record flows are adjusted for location upstream or downstream with a nonlinear equation that is based a drainage area ratio.
6. *Regression Equation Transfer Option* − The daily flow pattern defined by the *DF* record flows are adjusted for location upstream or downstream with a nonlinear equation that is based regression coefficients.

Option 1 − Uniform Distribution

The uniform distribution option consists of computing daily flow volumes by simply dividing the monthly flow volume by the number of sub-intervals in the month.

Option 2 − Linear Interpolation

Linear spline interpolation may be applied to a sequence of monthly naturalized flows to obtain non-uniform daily amounts. The methodology is illustrated graphically in Figure 3.2. Instantaneous flows at the beginning, middle, and end of each month of the series are defined based on the flow volumes in the preceding, current, and subsequent months. The straight lines connecting these points are called linear splines. The splines represent instantaneous flow rates at points in time, and the areas under the splines represent flow volumes during intervals of time. The splines define areas representing monthly flow volumes which are dissected at sub-monthly intervals to disaggregate the monthly volumes into sub-monthly volumes.

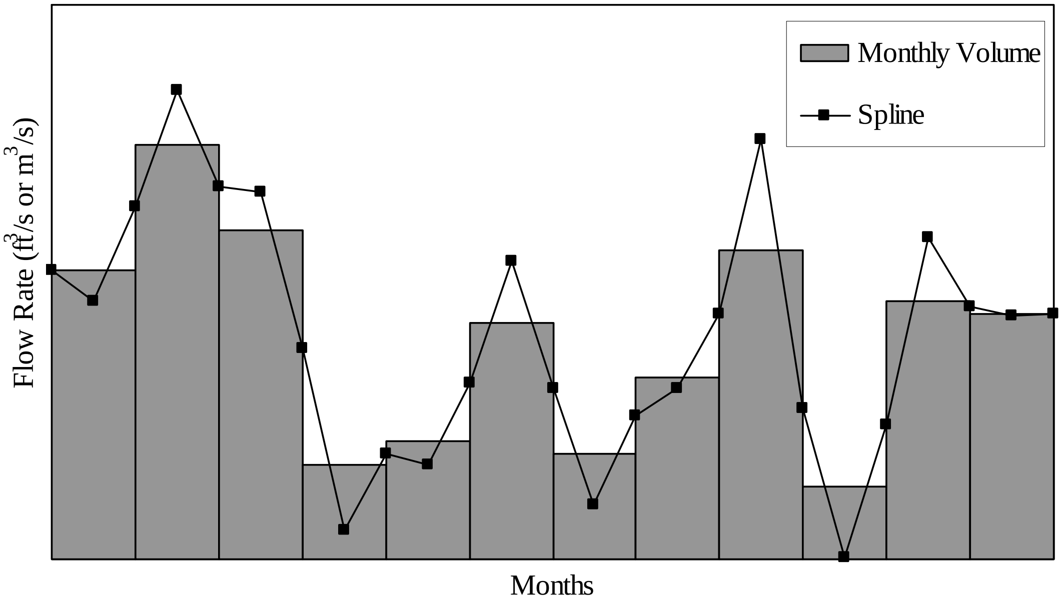

Figure 3.2 Linear Interpolation of Flow Volumes

The shaded bars in Figure 3.2 represent the monthly naturalized flow volumes that are to be disaggregated. The linear interpolation splines connect the beginning, middle, and ending points of each month. The end of one month is the beginning of the next month. The spline flows at the beginning and end of each month are set as the average of the mean instantaneous flow rates associated with the monthly volumes of adjoining months. Middle-of-month flow points are then set based on conserving the total monthly flow volume. The middle-of-month flow point is selected such that the monthly flow volume being disaggregated is represented by the area under the two linear splines spanning that month.

In some cases, with beginning/end-of-month flow points set as averages of adjacent mean monthly flows, the preservation of the monthly volume by defining a single middle-of-month point may result in negative middle-of-month flow rates. When such a negative flow occurs, two zero-flow points are set within the month defining a period of zero flow during the middle of the month that results in preservation of the total volume for the month without creating negative flows. A zero monthly volume results in a zero instantaneous flow rate for the entire month.

The accuracy of the linear interpolation approach is illustrated in Fig. 3.3 by comparing computed flows with corresponding known unregulated flows at a gaging station on the Brazos River. Known daily flows in second-feet-day ($ft^3/s \times day$) are aggregated to monthly totals which are then disaggregated back to daily flows by linear interpolation. Thus, flows determined by the linear interpolation methodology are compared with the corresponding actual flows from which they are derived. The hydrographs of both the unregulated daily flows and computed flows are plotted in Figure 3.3. Statistics from the actual versus interpolated daily flows are shown in Table 3.3. The actual and interpolated daily flows have the same mean, but their standard deviations vary greatly. The actual flow series exhibits much greater fluctuations, especially for high flows. The interpolated series is basically a smoothed version of the actual series.

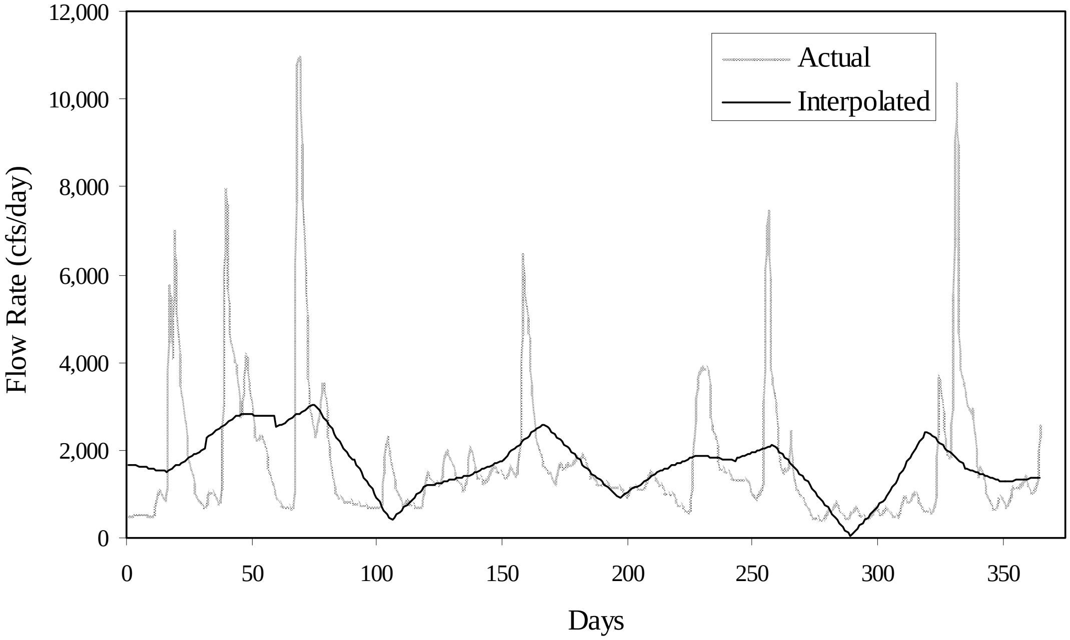

Figure 3.3 Comparison of Interpolated and Actual Daily Flow Hydrographs

Table 3.3
Mean and Standard Deviation of Daily Flows

Statistic of Daily Flow Volume	Actual ($ft^3/s \times day$)	Interpolated ($ft^3/s \times day$)
Mean	1,678	1,678
Standard Deviation	1,533	645

The plot of the serial correlation coefficient in Figure 3.4 further illustrates the dissimilarity between the linear interpolation versus actual flow series when sequencing of the fluctuations is considered. Measurable serial correlation is lost after about 10 days and 26 days in the actual flow series and interpolated flow series, respectively.

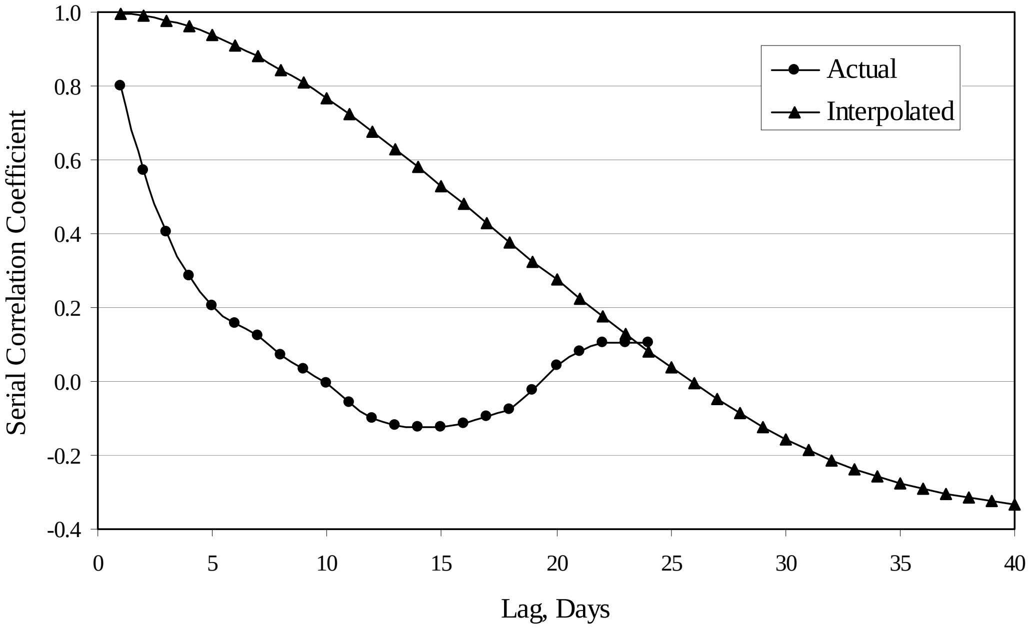

Figure 3.4 Comparison of the Serial Correlation Coefficient

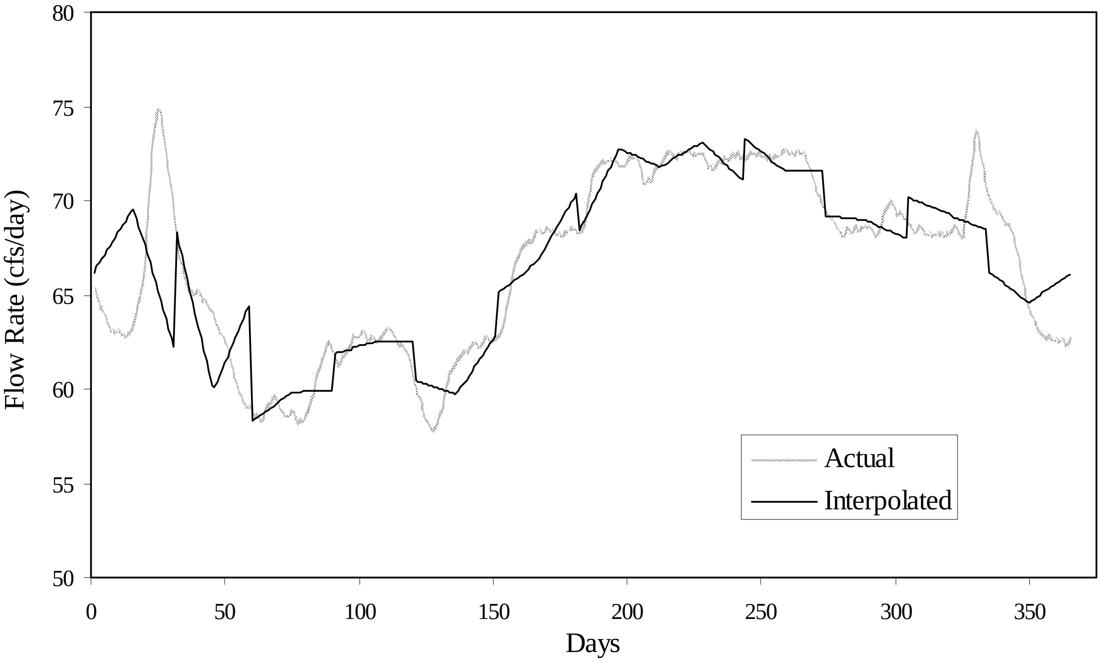

Figure 3.5 Daily Hydrographs for a Baseflow Dominated River Flow Regime

The linear interpolation method for disaggregating monthly flows to daily volumes results in smoother and more serially correlated daily flow sequences than the actual observed daily flows. Thus, the method may be best applied to streams that are base-flow dominated with lesser fluctuations. Figure 3.5 compares linear interpolation splines versus actual observed daily flows at a site on a base-flow dominated river characterized by gradually varying flows. Although stream flow is typically highly variable as illustrated by Figure 3.3, the linear interpolation method may still be a valid approach for normal and low-flow periods of the simulation, which are most important in assessing reliabilities in meeting water supply and instream flow requirements. Option 3 described next is designed to adjust daily flows resulting from the linear interpolation splines to add greater variability representative of actual daily flows.

Option 3 − Variability Adjustment

The linear interpolation method described in the preceding section requires no input data other than the sequences of monthly naturalized flows but tends to smooth out daily flow variations. Flow variability is modeled more realistically by incorporating information provided by input sequences of daily flows. The variability adjustment option methodology is based on using flow variation patterns from actual daily flows input on *DF* records to adjust the daily flows computed by the linear interpolation procedure. With all of the alternative disaggregation methods, the sum of the disaggregated daily flows is the original monthly amount.

The variability adjustment option is designed for the common situation in which a complete dataset of monthly naturalized flows are combined with limited available sequences of daily flows. Daily flow sequences for one or a few years at one or a few locations may be used to establish patterns which are then used in disaggregating monthly flows to daily flows for the complete period-of-analysis at all control point locations. Patterns of variability derived from limited sequences of daily flows are repeated for multiple time periods and multiple locations.

The combined linear interpolation with variability adjustment strategy consists of the tasks outlined in Table 3.4. The methodology is based on a daily pattern ratio (VR) defined as follows. The VR is computed for each day from daily flows (DF) provided on *DF* records and interpolated flows (I_{DF}) computed from the corresponding aggregated monthly volumes. If I_{DF} is zero or extremely small relative to DF, the methodology is not valid and thus the ratio VR is set at 1.0 meaning the variation between I_{DF} and DF is not considered.

$$VR = 1.0 \quad \text{if} \quad I_{DF} \leq (VRL)DF \tag{3.1}$$

Otherwise

$$VR = \frac{DF}{I_{DF}} \tag{3.2}$$

The I_{DF} for each day is computed by applying the linear interpolation method to the aggregated monthly sums of the daily flows (DF) read from the *DF* records. The sequence of daily variability ratios (VR) represents the pattern of variability in daily flows expressed as a ratio of the actual daily flow volume (DF) read from *DF* records to the daily flow volume (I_{DF}) computed by the linear interpolation methodology. The Eq. 3.2 ratio is undefined for an I_{DF} of zero, and VR may be unrealistically large for extremely small I_{DF}. Thus, VR is set at 1.0 if I_{DF} is either zero or very small relative to DF as defined by the limit VRL in the conditional statement of Eq. 3.1. By default, VRL is set at 0.10 unless otherwise specified on the *JT* record.

Table 3.4 Combined Linear Interpolation with Variability Adjustment Strategy

1. A sequence of variability ratios (VR) used to increase the variability of daily flows (I_Q) computed by interpolating monthly volumes (Q_M) is developed from daily flows (DF) read from *DF* records. The procedure includes the following tasks.
    - The daily flow (DF) sequence is converted to a monthly sequence. Daily flow volumes are summed for each month to obtain monthly flow volumes.
    - The aggregated monthly flow volumes are disaggregated to daily flows (I_{DF}) using the linear interpolation methodology outlined in the preceding section.
    - The ratio (VR) of *DF* record flows (DF) to interpolated flows (I_{DF}) is computed for each day.
2. The *SIMD* monthly flows (Q_M) are disaggregated to daily flows (I_Q) using the linear interpolation methodology outlined in the preceding section.
3. For each month, the sequence of daily variation ratios (VR) developed in task 1 are combined with the interpolated daily flows (I_Q) developed in task 2 to obtain first the daily pattern flows (P_D) and then the daily flows (Q_D) used in the simulation.
    - The sequence of daily deviation factors (VR) from task 1 is multiplied by the interpolated daily flow volumes (I_D) associated with the *SIMD* monthly flows (Q_M) for that particular month and location to obtain daily flows (P_D) defining a pattern of variability. Monthly totals (P_M) of P_D are computed.
    - The daily pattern flows (P_D) are scaled (Q_M/P_M) to obtain the sequence of naturalized flow volumes (Q_D) for each day of each month at that location which is adopted for the *SIMD* simulation.

VR is zero for each day that has zero flow on the *DF* record. Thus, the method reproduces the same percentage of days with zero flow for the daily flows (Q_D) adopted for the *SIMD* simulation as is found on the *DF* records.

The linear interpolation methodology is applied to the *SIMD* monthly flow volumes (Q_M) to compute daily flows (I_Q). Equation 3.3 combines the interpolated flows (I_Q) with the daily flow variability ratios (VR) computed with Eqs 3.1-3.2 to develop a sequence of flows (P_D) defining a flow pattern. The daily pattern flow volumes (P_D) are aggregated to monthly volumes P_M with Eq. 3.4. The daily flows (Q_D) adopted for the simulation are computed with Eq. 3.5.

$$P_D = I_Q(VR) \tag{3.3}$$

$$P_M = \sum P_D \tag{3.4}$$

$$Q_D = \left(\frac{Q_M}{P_M}\right) P_D \tag{3.5}$$

The disaggregated daily flows (Q_D) used in *SIMD* sum to the monthly *SIMD* volumes (Q_M) and have the same pattern of variability as the pattern flows (P_D).

Option 4 − Flow Pattern

A sequence of daily flow volumes defining a pattern of variability may be compiled external to *SIMD* and input on *DF* records. The *DF* record pattern flow sequences may cover the entire hydrologic period-of-analysis or some other period that may be much shorter. The flow pattern is repeated as necessary within the *SIMD* simulation to extend over the entire hydrologic period-of-analysis. The same flow pattern may be repeated for any number of control points.

A monthly naturalized flow volume (Q_M) is disaggregated into daily flows (Q_D) within *SIMD* using a sequence of daily pattern flows (P_D) read from *DF* records based on Eq 3.5.

$$Q_D = \left(\frac{Q_M}{P_M}\right) P_D \tag{3.5}$$

Each monthly volume (Q_M) is proportioned to daily volumes (Q_D) in the same ratio as the daily pattern flows (P_D) divided by their monthly total (P_M).

Naturalized flows reflect natural hydrology without human water resources development and use activities. The daily flows entered on *DF* records as input for either options 3 or 4 may be observed flows at a gaging station that have not been significantly affected by reservoir operations and water use. The observed flows may be recorded during an early pre-development period prior to reservoir construction and river basin development. Gaged daily flows may also be adjusted to remove the effects of water resources development and management. Alternatively, daily flows may be computed using a watershed precipitation-runoff model.

An option 4 flow pattern defined by a set of *DF* records may be applied to multiple locations. A lag option activated by *DC* record field 11 allows the daily flows to be shifted forward or backward in time for control points located upstream or downstream. The flows are simply translated a specified number of days to reflect timing. Options 5 and 6 described next change the relative magnitude of the flows to reflect watershed runoff differences between different control point locations.

Options 5 and 6 − Transferring a Daily Pattern to Other Locations

Monthly naturalized flow volumes are distributed from locations of gaged or known flows to ungaged control points in the same way in either *SIMD* or *SIM* using the same computational methods outlined in the *Reference* and *Users Manuals* with watershed parameter input data from a DIS file. Monthly flows at ungaged (unknown flow) control points are computed based on monthly flows at gaged (known flow) control points and watershed parameters. Monthly naturalized flow volumes at all control points are then disaggregated into daily amounts.

Daily flow variability patterns as well as total monthly volumes may vary with location. For example, daily flows at an ungaged upstream site with a relatively small watershed may exhibit greater variability than daily flows at a gaging station located downstream that has a much larger watershed. The flows provided on *DF* records are typically from a gaging station. The pattern of daily fluctuations derived from these flows may be applied to disaggregate monthly flows at other ungaged control point locations.

Options 5 and 6 listed in Table 3.2 are techniques for adjusting the daily flow pattern established with option 4 to reflect other locations in the river system with different watershed characteristics. Option 4 may be applied either with or without options 5 or 6 depending on whether the adjustment of flow variability patterns for watershed differences is considered significant and/or feasible. Options 5 and 6 are based on Equations 3.6 and 3.7, respectively. A related option activated by *DC* record field 11 allows the entire period-of-analysis daily flow pattern sequence to be lagged backward or forward in time any number of days to account for the routing lag between locations. Details of these techniques are addressed in Appendices B and C.

The option 5 transformation of the option 4 flow pattern from a source location to a destination location is based on a drainage area ratio and empirically determined exponent X.

$$P_{destination} = \left[P_{source} \left(\frac{DA_{destination}}{DA_{source}} \right) \right]^{X} \tag{3.6}$$

P denotes the daily flows defining the flow pattern, and DA denotes drainage areas from the DIS file. The exponent X will typically be greater than 1.0 when transferring a pattern from a downstream source control point to an upstream destination control point. Conversely, X will typically be less than 1.0 in transforming a flow pattern from upstream to downstream.

Option 6 is an alternative to option 5 for transferring an option 4 flow pattern from a source location to a destination location with different watershed characteristics. The flow pattern adjustment is based on the following non-linear regression equation with empirically determined regression parameters A, M, and X.

$$P_{destination} = A + M\,(P_{source})^{X} \tag{3.7}$$

The feasibility of applying Equations 3.6 or 3.7 to adjust variability patterns to reflect watershed differences is dependent upon the availability of daily flow data from either gage observations or watershed precipitation-runoff models with which to establish the coefficients A, M, and X. Investigation of parameter estimation procedures is a subject for further research.

Overview of Simulation Procedures

Flow forecasting and routing are described later in this chapter in the context of their role in the overall simulation. An overview of pertinent aspects of the *SIMD* simulation model is presented here prior to integrating flow forecasting and routing into the discussion.

Computations Repeated for Each Water Right at Each Time Step

The *SIMD* simulation steps through time. At each time step, computations are performed for each water right in priority order. As each set of water management and use requirements is considered in the water right priority loop, the computational tasks described in Table 3.5 are performed.

Table 3.5
Computations Repeated for Each Water Right at Each Time Step

Task 1: *Availability Determination*. – Using the control point flow availability array, the amount of water available to the right is determined considering available flows at the control point of the water right and at all control points located downstream. In simulating flood control operations, the amount of channel flood flow capacity below maximum allowable non-damaging limits is determined considering the control point of the flood control right and all pertinent downstream control points.

Task 2: *Target Set*. – The water supply diversion target, hydroelectric power generation target, minimum instream flow limit, or non-damaging flood flow limit is set.

Task 3: *Right Simulation*. – For the water right being considered, decisions are made regarding reservoir storage and releases, water supply diversions, and other water management/use requirements, and appropriate actions are taken. Net evaporation volumes are determined. Water balance accounting computations are performed.

Task 4: *Flow Adjustment*. – The control point flow availability array used to determine water availability and remaining flood flow channel capacity in Task 1 is adjusted for the effects of the Task 3 water management, control, and use actions associated with that particular water right.

Sequences of naturalized stream flows are established at the beginning of a *SIMD* simulation. These are cumulative total flows at each control point. Naturalized flows represent undeveloped natural conditions unaffected by the reservoirs, system operating practices, and water use requirements reflected in the water rights input dataset. A *SIMD* simulation consists basically of adjusting naturalized river flows to reflect the effects of all of the water rights incorporated in the model. Water rights are sets of information regarding constructed facilities, operating rules, and use demands associated with reservoir storage, flood control operations, water supply diversions, hydroelectric power generation, and environmental instream flow requirements.

A *control point flow availability array* is created in a *SIM* or *SIMD* simulation. At the beginning of a simulation time step, the control point flow availability array is populated with the naturalized flows. The amounts in the array are adjusted in the water rights computational loop nested within the time step loop to reflect the impacts of each right. At the end of the simulation time step, the array is used to determine regulated and unappropriated flows. During the water right simulation, the array is adjusted in Task 4 described in Table 3.5. The control point flow availability array represents available river flow amounts at that computational point in the simulation considering each control point location individually.

The availability determination, target setting, water right simulation, and flow adjustment computations performed for each right in the water rights priority loop are referred to as Tasks 1, 2, 3, and 4, respectively, in Table 3.5 and the following discussion. Flow forecasting is performed in conjunction with Task 1. Flow routing is performed with Task 4. Options for handling negative incremental flow situations in Task 1 are discussed next prior to exploring forecasting and routing methods. The role of negative incremental flow adjustments is closely connected to the roles of forecasting and routing.

Negative Incremental Inflow Options

Negative incremental naturalized flow adjustment options activated by *JD* record field 8 are described in the basic *Reference* and *Users Manual*. Negative incrementals found in comparing river flows at upstream and downstream sites are physically caused by time lag and attenuation effects as well as channel losses and other factors. Negative incremental flows are an important consideration in a conventional monthly *SIM* simulation and are an even greater concern with a daily time step *SIMD* simulation since opportunities for negative incrementals to occur increase with smaller time intervals.

Naturalized, regulated, and unappropriated flow volumes, other related variables, and *SIM/SIMD* algorithms are all based on cumulated total flows at each control point, rather than incremental local flows. However, the term *negative incremental flow* is applied to describe situations in which the naturalized flow volume for a particular time step at a control point is less than concurrent flows at control points located upstream. Negative incremental means the flow is decreasing in a downstream direction in that time interval. This discussion has no relevance for a naturalized flow dataset in which flows in each time step either remain constant or increase going downstream.

Negative incremental flow options 1, 2, 3, and 4 activated by *JD* record field 8 are similar for either a monthly or daily time step simulation. *SIMD* does not allow use of negative incremental flow option 5 in combination with sub-monthly time steps. Options 2 and 3 are seldom used for either a monthly or daily simulation. Options 1 and 4 are pertinent for a daily as well as monthly simulation.

The default option 1 involves no adjustments to deal with negative incremental flows. Option 1 may be overly conservative for water supply in that water availability may be over-restricted, reducing water supply reliability estimates. Option 1 may result in over-estimating flood control channel flow capacity allowing release of too much flood water from reservoir flood control pools. Since development of the option 4 adjustment array discussed below is computationally intensive, for large systems with many control points, option 1 may require significantly less computer run time than option 4.

Negative incremental option 4 is the recommended *JD* record field 8 option for either a monthly or daily simulation. As explained in Chapter 3 of the *Reference Manual*, option 4 involves a flow adjustment defined as the minimum amount of flow that must be added to the naturalized flow at a control point to alleviate all negative incremental naturalized flows at upstream control points. *SIM* computes these adjustments for monthly flows. *SIMD* similarly computes negative incremental flow adjustments for whatever time step is being used in the simulation. *SIMD* first determines daily naturalized flows at all control points and then uses the daily flows to compute adjustment amounts where negative incrementals are found to occur. *SIMD* applies daily negative incremental flow adjustments in Task 1 in the same manner that *SIM* applies monthly adjustments. In determining water availability and available flood flow capacity at a particular control point, the adjustment amounts are added to control point flows at downstream control points but not at the control point of the water right.

Flow Forecasting and Routing

Flow forecasting in *SIMD* is the process of considering future flows over a forecast period in determining water availability for *WR* record water rights and available flood flow channel capacity for *FC* record flood control rights. The forecast period in days for each *WR* record water right and *FF* record control point is the input parameter controlling forecasting.

Routing in *SIMD* is the process of modeling lag and attenuation effects as adjustments to river flows for upstream water control/use actions are propagated downstream over time. An adaptation of the Muskingum routing method is adopted. The Muskingum X and K routing parameters are provided as input at pertinent control points.

The relevance of flow forecasting and routing depends upon the relative magnitude of computational time steps and flow travel times between control point locations. The effects of reservoir operations and other water management and use actions usually propagate through a river/reservoir system in less time than a month. Forecasting and routing are typically not applied in a monthly time step simulation for even very large river systems. Forecasting and routing are typically appropriate for daily simulations of relatively large river systems. With time steps of one-fifth or one-fourth of a month, forecasting and routing may or may not be appropriate depending upon the flow travel times involved in the simulation.

Flow Forecasting

Forecasting addresses the issue of water control and use decisions today affecting regulated flows over the next several days from the perspective of the Task 1 availability determination described in Table 3.5. Since some lag time is required, perhaps several days, for flow changes to propagate downstream to the river system outlet, water supply diversions and return flows and multiple-purpose reservoir operations in the current time step affect regulated flows in subsequent time steps. The *SIMD* water right priority system protects senior rights from the actions of junior rights in the current and preceding days. As discussed in Chapter 4, reservoir operations for flood control are based on making no release today that contributes to downstream flooding today or during future days.

Flow forecasting in *SIMD* is defined as considering the control point flow availability array over a future forecast period (F_P) when determining water availability and flood flow capacity in conjunction with the previously described Task 1 accomplished for each individual water right in the priority-based water rights computation loop. Without forecasting, *SIMD* considers only the current time period in determining water availability and flood flow capacity. With forecasting, F_P future days are considered in the examination of available flows at downstream control points. Forecasting is not relevant for water rights at a control point that has no other control points located downstream. Forecasting for a water right refers to available flows in future time periods at control points located further downstream.

The forecast period (F_P) is the number of time steps into the future considered in determining water availability for a *WR* record right or remaining flood flow capacity for a *FC/FF* record right. This discussion often refers to the F_P in terms of number of days though the time steps may also be sub-monthly time intervals other than days. Forecasting is based on a F_P that may range from 1 to 32 time steps. A F_P of zero means no forecasting.

Forecasting may be applied with *WR* and *FC* record rights but not with *IF* record rights. Instream flow requirements specified by *IF* records affect the amount of water available for other *WR* record rights, but downstream water availability is not a factor in setting the instream flow requirements. Likewise, downstream water availability does not constrain hydropower releases. Forecasting is applied in determining water availability for diversions and refilling reservoir storage for *WR* record rights and in determining remaining flow capacity for *FC* record flood control releases.

Forecasting is activated by setting a forecast period (F_P). A F_P may be assigned to any, none, or all *WR* record water rights and flood flow *FF* record control points. Flood control is covered in Chapter 4. A global forecast period for all *WR* and *FC* record rights may be entered on the *JT* record. The global F_P is overridden for individual *WR* record rights by specifying a F_P on the *DW* record or for flood control rights on *FF* records. With no global or individual right F_P specified, the default is zero F_P meaning no forecasting.

Two-Month-Forecast/One-Month-Simulation

Forecasting in *SIMD* is accomplished through a two-month/one-month simulation procedure outlined in Table 3.6 that is repeated for each month of the hydrologic period-of-analysis. The flow forecasting strategy allows the computational algorithms to look F_P days into the future in determining water availability or remaining flood flow capacities for the individual rights. The iterative two-month/one-month simulation procedure is activated if at least one water right has a forecast period of at least one sub-monthly time step (one day).

The portion of daily water availability and flood flow capacity information covered by the F_P for each individual water right is used as each right in considered in the water rights priority loop. By repeating the two-month simulation at the beginning of each month, the daily water availability and flood flow capacity information always provides at least 28 days of forecasted daily values for use during each day of the second normal simulation. The initial two-month simulation provides forecast information covering up to 62 days, which includes at least 28 forecast days past the last day of the actual month being simulated. For a F_P of greater than 28 days, a portion of the F_P may not actually be considered in some days.

Table 3.6
Two-Month Forecast Daily Simulation Followed by One-Month Regular Daily Simulation

1. At the beginning of each month, the daily time step simulation is performed for a two-month period covering that month and the next month for the sole purpose of forecasting future flow conditions. The only results saved from this simulation are:
    - stream flow availability array for each *WR* record water right
    - flood flow capacity array for each flood flow *FF* record control point (see Chapter 4)
2. The normal daily time step simulation is performed for the one month.

The two-month forecast simulation and one-month normal simulation are identical except that the two-month forecast simulation contains no forecasting and, as discussed in Chapter 4, no flood control releases. In each day of the two-month simulation, water availability is determined considering only that day, without looking forward to future days. The only results saved are a water availability array and flood flow capacity availability array. These arrays allow forecasting to be incorporated into the subsequent one-month simulation.

The flood flow capacity array developed during the initial two-month simulation for use with flood control *FC* record rights is discussed in Chapter 4. The stream flow availability array developed during the initial two-month simulation for *WR* record rights contains the amount of stream flow available to each right in each day of the two month period.

As indicated by Table 3.5, in the time step, as each water right is considered in priority order, Task 1 consists of determining the volume of stream flow that is available to that water right. Without the forecasting option activated, stream flow availability for that day is determined from the control point stream flow availability array for that day only, considering the control point of the right and all other control points located downstream. With the forecasting option activated, the water availability in each of the next F_P days from the results of the preceding two-month simulation is also considered

For the particular water right being considered, a daily availability amount for each day of its forecast period (F_P) is read from the two-month long array. The stream flow availability for the current day is also considered. Two options are provided for applying the daily amounts for the F_P+1 days (forecast and current days).

1. The default option is to adopt the minimum daily amount of the F_P+1 days.
2. The second option is to adopt the mean of the daily amounts of the F_P+1 days.

If all of the days have an availability amount exceeding the right's diversion and storage refilling target, the target will be fully met regardless of the option selected. If all of the days have an availability amount of zero, the target will be completely shorted regardless. Otherwise, option 1 will provide a conservatively lower estimate of water availability than option 2 and thus a greater diversion shortage or less storage refilling. Due to the effects of routing, the impacts of a stream flow depletion on downstream flows during the current day and each day of a multiple-day forecast period are less than the stream flow depletion. Thus, the default option of adopting the minimum availability amount during the F_P+1 days may over-constrain the water right. The second option of adopting the mean of the daily amounts of the F_P+1 days is less restrictive.

Channel losses are incorporated in Tasks 1 and 4 of Table 3.5. Routing is included only in Task 4. The determination of flow availability (Task 1) does not include "backward" routing.

The forecasted flow availability amounts include only those control points that are located downstream of the control point of the water right. The control point of the right as well as downstream control points are considered for the current day. The negative incremental flow option 4 adjustments are added at downstream control points for the current and forecast days but not at the control point of the water right. Forecasting has no effect for rights located at a control point defining a basin outlet and thus having no downstream control points.

Applications and Approximations of Flow Forecasting

Forecasting of future river flows may be considered from the dual perspectives of actual forecasts in the real world and computational forecasts in the *SIMD* model. Both are characterized by uncertainties and inaccuracies. Forecasting can also be viewed from the dual perspectives of water supply and flood control. Forecasting in *SIMD* serves two purposes.

1. Prevention of rights from making appropriations of river flows that adversely affect senior rights located at downstream control points during the forecast period.
2. Prevention of flood control reservoirs from making releases that contribute during the forecast period to flows at downstream locations exceeding specified allowable limits.

Flood control reservoir operations are discussed in Chapter 4. From a water supply perspective, the sole purpose of forecasting in *SIMD* is to protect senior rights from having their water taken by other rights with junior priorities located upstream. The concern is that an appropriation by a junior right could affect downstream senior rights one or more days into the future. Forecasting allows limiting the amount of water available to the junior right. Forecasting is relevant only if junior rights are located upstream of senior rights. *SIM* and *SIMD* have a natural priority option that automatically sets priorities for rights in upstream-to-downstream order allowing appropriation of water without consideration of downstream water users. The priority numbers assigned on *WR* records may also be set to define priorities in upstream-to-downstream order. Forecasting is inappropriate in these cases.

In the real-world, administration of water right permit systems generally is not precise. Forecasting like other aspects of administering a permit system is necessarily highly subjective. In real-world water management, water users are legally obligated to curtail diversions and pass inflows through their reservoirs as necessary to accommodate downstream senior rights. However, forecasting capabilities as well as monitoring and other aspects of permit administration are not necessarily well established. Thus, flow forecasting is approximate in the real-world as well as in the *SIMD* model.

Real-world forecasting is often associated with another aspect of water supply operations that is not directly addressed in *SIMD.* Water supply diversions may be pumped from a river at sites located several days travel time below dams from which the water is released. A diversion today diverts water released from the reservoir several days ago. In making decisions regarding amounts to release today to meet diversion needs projected for several days into the future, water managers forecast the unregulated flows entering the river between the dam and diversion sites and the attenuation and channel losses associated with the reservoir release. *SIMD* does not apply forecasting in this sense.

SIM and *SIMD* allow diversions to be met by combinations of unregulated river flows and/or releases from reservoirs located any distance upstream. Channel loss and routing computations are applied to the reservoir releases to determine their contribution to regulated flows at control points between the dam and diversion site. Releases are increased to compensate for channel losses. However, releases are not increased to compensate for flow lag/attenuation. *SIMD* has no capabilities for forecasting the number of days in advance that a reservoir release must be made to meet a downstream water supply diversion requirement.

Routing of Flow Adjustments

Routing in *SIMD* propagates flow changes through river reaches connecting control points. The routing parameters K and X are entered on the *DC* record for the control point defining the upstream end of a river reach. Different K and X values may be entered for flow changes associated with flood control *FC* record reservoir operations and flow changes for *WR* and *IF* record rights. If routing parameters are assigned for a control point, Muskingum routing computations are performed resulting in lag and attenuation of flow adjustments originating at or passing through the control point. If routing parameters are not specified for a particular control point, flow adjustments originating at or passing through the control point are routed through the reach below the control point by simple translation without Muskingum routing computations and thus without lag or attenuation. Without Muskingum routing, outflow from a river reach in a time step equals the inflow in the time step less channel losses.

Channel losses are computed in both monthly *SIM* and daily *SIMD* simulations. Whereas channel loss computations are incorporated into both Tasks 1 and 4 of Table 3.5, Muskingum routing is limited to Task 4. In Task 4, routing computations are performed prior to channel loss computations. The routed flow adjustments are then further adjusted for channel losses.

Routing occurs at a control point if and only if Muskingum routing parameters K and X are specified as input data for that control point. Routing computations normally simulate flow attenuation/lag in the river reach below the specified control point. However, the model user may chose to lump attenuation/lag effects in multiple reaches in routing computations at a single control point. The model user selects the control points at which Muskingum routing is to be applied. In applications with significant flow travel times between control points, routing parameters will be provided for all control points, except the basin outlet. A *SIMD* model may include numerous control points, with the river reaches between many of them being too short to apply Muskingum routing in a daily time step model. The larger river basins in the Texas WAM System have hundreds of control points, many of which are too closely spaced for Muskingum routing. For complex datasets with numerous closely spaced control points, lag and attenuation effects may be aggregated to selected reaches.

Muskingum Routing

The Muskingum method has been applied in many models over many years to rout flows through river reaches (Wurbs and James 2002; McCuen 2005). The method dates back to a flood control study of the Muskingum River in Ohio by the Corps of Engineers in the 1930's. Muskingum routing has been applied most often for routing flood hydrographs, but has also been used for routing long-term sequences of daily flows. Given the discharge hydrograph at an upstream site, the corresponding hydrograph at a location further downstream is computed.

All hydrologic routing techniques are based on the continuity equation.

$$\frac{dS}{dt} = I(t) - O(t) \qquad (3.8)$$

S denotes the total volume of water stored in the river reach at an instant in time. The derivative of storage with respective to time (dS/dt) represents a rate of change in storage at that instant in time. I(t) and O(t) denote inflow and outflow rates at an instant in time. For computational purposes, Eq. 3.8 is rewritten as Eq. 3.9.

$$\frac{S_T - S_{T-1}}{\Delta t} = \left(\frac{I_{T-1} + I_T}{2}\right) - \left(\frac{O_{T-1} + O_T}{2}\right) \qquad (3.9)$$

The subscripts T-1 and T refer to the beginning and ending of the time interval Δt. Routing algorithms step through time with the inflow to the river reach known at both the beginning (I_{T-1}) and end (I_T) of each Δt. The storage (S_{T-1}) and outflow (O_{T-1}) at the beginning of Δt are also known from computations for the preceding time step. S_T and O_T are the unknowns computed at each time step. With two unknowns, a second flow versus storage relationship is required. Alternative hydrologic techniques differ in the second flow versus storage relationship that is combined with the continuity equation.

Muskingum routing is based on combining the continuity equation (Eq. 3.9) with a linear relationship between storage (S) in the river reach at an instant in time and a weighted instantaneous inflow (I) to the reach and outflow (O) from the reach.

$$S = K\,(X\,I + (1.0 - X)\,O) \tag{3.10}$$

The Muskingum routing equation (Eqs. 3.11a, 3.11b, 3.11c, and 3.11d) is derived by substitution of Eq. 3.10 for S_1 and S_2 into Eq. 3.9 and collecting and rearranging terms.

$$O_T = C_A I_T + C_B I_{T-1} + C_C O_{T-1} \tag{3.11a}$$

$$C_A = \frac{0.5\Delta t - KX}{K(1.0 - X) + 0.5\Delta t} \tag{3.11b}$$

$$C_B = \frac{0.5\Delta t + KX}{K(1.0 - X) + 0.5\Delta t} \tag{3.11c}$$

$$C_C = \frac{K(1.0 - X) - 0.5\Delta t}{K(1.0 - X) + 0.5\Delta t} \tag{3.11d}$$

$$C_A + C_B + C_C = 1.0 \tag{3.12}$$

Inflows (I) and outflows (O) in Eqs. 3.8, 3.9, 3.10, and 3.11 are defined at an instant in time. However, in applying Eq. 3.11, many models including *SIMD* treat I and O as flow volumes or mean flow rates during a finite time interval (Δt). K and Δt have the same units of time.

The routing parameters X and K are defined by Eq. 3.10 in which storage (S) is linearly related to a weighted combination of inflow and outflow ($XI+(1-X)O$). In general, K controls lag, and X controls attenuation in the Muskingum model of flow through a river reach. The parameter K represents flow travel time through the river reach and has units of time such as days. The dimensionless weighting factor X represents the relative influence of inflow versus outflow in determining the volume of water stored in the river reach at an instant in time.

Relating storage to a weighted inflow and outflow (Eq. 3.10) addresses the looped storage versus outflow relationship discussed in textbooks that is typically exhibited by flow in rivers. For a given flow rate (O) at the downstream end of a river reach, the volume of water stored in the reach is greater if the river stage at the downstream end is falling than if it is rising. Eq. 3.10 provides a simple means to represent control of storage by both inflow and outflow.

An X of zero implies that storage can be computed as a function of outflow only ($S=KO$) without considering inflow. The simpler convex routing method, also referred to in the literature as linear reservoir routing, is equivalent to Muskingum routing with a value of zero for X.

The parameter X by definition is a weighting factor ranging from 0.0 to 1.0. In actual application, X must range between 0.0 and 0.5 to simulate flow attenuation. Natural river reaches have been found to often be characterized by a value for X of about 0.2. Without calibration studies, $X=0.2$ has sometimes been adopted for particular applications. The parameter K represents flow travel time and has been approximated by various methods for estimating travel time through a river reach (McCuen 2005). Values for X and K are normally established by calibration based on observed flows, which is covered later in this chapter. Calibration routines for computing K and X are included in the program *DAY*.

Computational instabilities resulting in negative or otherwise unreasonable values for computed outflows are a problem with Muskingum routing if the river reach being modeled is too short long or too long. McCuen (2005) and others have suggested the following rule-of-thumb limits on K and X to avoid these problems.

$$2KX \le \Delta t \le 2K(1-X) \tag{3.13}$$

$$0.0 \le X \le 0.5 \tag{3.14}$$

With a Δt of one day and X of 0.2, these limits imply that K should range between 0.625 and 2.5 days. If a river reach is too short, outflow may be assumed equal to inflow without routing. If a river reach is too long, it may be divided into two or more reaches with the outflow from one reach becoming the inflow to another.

SIMD checks the input values of K and X and reports a warning message to the MSS file if the parameters violate the above criteria. K is the more critical parameter for routing accuracy. Parameter calibration is usually relatively insensitive to changes in X. A common practice is to assume most river reaches are modeled with an X of between 0.0 and 0.3. The value of X will decrease towards 0.0 as K increases to maintain numerical stability, and is physically related to increasing wave attenuation as travel time increases in the reach.

SIMD Adaptation of Muskingum Routing

SIMD is different than conventional routing applications because multiple incremental flow adjustment volumes rather than total flow rates are routed. For example, if 5.4 acre-feet of water is either stored or diverted from the river at a particular control point, the stream flow at that control point and downstream control points is reduced. As the effects of this 5.4 ac-ft stream flow depletion propagates to river flows at downstream control points, the 5.4 ac-ft adjustment may be modified by attenuation and lag effects modeled by Muskingum routing as well as channel losses modeled by the linear channel loss equation described in the *Reference Manual*. The 5.4 ac-ft flow appropriation affects flows at downstream control points in the same day as the appropriation and in subsequent days. Routing and channel losses affect only adjustments to flows at downstream control points, not the current day 5.4 ac-ft flow adjustment at the control point at which the 5.4 ac-ft stream flow depletion occurred. In order to maintain the priority system, incremental adjustments associated with each individual water right are routed separately.

Routed flow adjustments are used by *SIMD* to continually update the control point flow availability array in conjunction with Task 4 described in Table 3.5. As the simulation steps through time, at a particular time step, the routing of incremental stream flow adjustments is organized as follows.

1. Prior to the water rights computation loop, the control point flow availability array is adjusted for the effects of constant inflows from *CI* records, flow adjustments from *FA* records, and spills associated with seasonal rule curve reservoir operations. Muskingum routing is applied to these adjustments prior to simulating water rights.

Thus, the amount of water available to any or all water rights may be affected in current and future time steps.

2. Adjustments associated with individual water rights are routed within the water rights loop in order to prevent junior rights from affecting water availability for senior rights during either the current or future time steps. As each water right is simulated, the control point flow availability array is adjusted for the effects of reservoir releases, refilling storage, diversions, and return flows. Routing is applied separately for each individual right.

3. Flood control operations specified by the *FC* record are described in Chapter 4. Flow adjustments are associated with filling storage and subsequent releases from flood control pools. *JD* record field 11 controls whether flood flow adjustments affect the next-day flows at downstream control points at the beginning of the next-day simulation or within the priority loop computations.

The variables in Eqs. 3.9 and 3.10 are defined below from the perspective of routing in *SIMD* and are defined again later from the perspective of calibrating K and X in *DAY*.

Δt – day or other sub-monthly time interval
K – parameter input on *DC* record in same units as Δt
X – dimensionless parameter input on *DC* record, $0.0 \leq X \leq 0.5$
S_T – storage volume at the end of time step T (used in calibration only)

Muskingum is a linear routing method based on Equation 3.11. The coefficients C_A, C_B, and C_C for a particular river reach are computed from the parameters K and X entered on a *DC* record for the control point defining the upstream end of the reach.

$$O_T = C_A I_T + C_B I_{T-1} + C_C O_{T-1} \tag{3.11a}$$

The outflow (O) from a river reach is the inflow (I) to the next downstream reach. Stated another way, the outflow (O) computed for a particular control point is the inflow (I) or at least a component of the inflow (I) at the next downstream control point. The variables in Eq. 3.11a are defined as follows, where subscripts T-1 and T denote the preceding and current time steps.

I_{T-1} – volume of the adjustment entering the control point during the preceding time step
I_T – volume of the adjustment entering the control point during the current time step
O_{T-1} – volume of the adjustment leaving the control point during the preceding time step
O_T – volume of the adjustment leaving the control point during the current time step

Incremental adjustments associated with each individual water right are routed separately. A key fundamental concept of the *SIM/SIMD* simulation strategy is to start with total cumulative river flows and to make adjustments to the flows as each water right is modeled in priority sequence. Thus, incremental adjustments rather than total flows are routed. Routing of adjustments for individual rights separately allows senior rights to be protected in the current day from the actions of junior rights occurring in previous days.

Different values of Muskingum K and X parameters may be assigned on the *DC* record for adjustments associated with flood control *FC* record reservoir operations versus *WR* record water right operations. Flow velocities are greater and travel times shorter for flood flows.

Example Illustrating *SIMD* Daily Time Step Simulation Features

The following example is a daily time step version of the example presented in the *Fundamentals Manual* and modified in the chapters of this manual. The monthly naturalized flow volumes are preserved throughout the daily time step simulation. Figure 2.1 is a schematic of the river/reservoir system. The hydrologic period-of-analysis is 1940−1997. The daily time step example uses all of the input files of the original monthly example from the *Fundamentals Manual* with additional data added as needed.

Input Data

Four records are added to the DAT file shown in Table 3.7. The *JT* record is the only required record to trigger a *SIMD* simulation. The *C2*, *W2*, and *R2* records used in this example specify the information sent to the SUB file (Table 3.10) and are optional. These records are analogous to the *CO*, *WO*, and *RO* records used to specify monthly output. For this example, the *JT* record is set to send daily output data to the SUB file for a period corresponding to the drought of record in this river basin. The *JT* record also limits the SUB file output to the control point, water rights, and reservoir listed on the *C2*, *W2*, and *R2* records. All of the water rights, excluding instream flow requirements, are set to forecast water availability for 5 days into the future. The remainder of the DAT file is unchanged from that required to run a monthly simulation with *SIM*. Further information regarding routing and flow disaggregation is found in the DCF file of Table 3.8.

DC records are included to the DCF file (Table 3.8) to specify the reach parameters for each control point listed in the DAT file (Table 3.7). There are two categories of reach parameters on the *DC* record, those related to routing and those related to flow disaggregation.

Routing is considered to occur in the river reach below the control point listed in field 2 of the *DC* record. As seen in Table 3.10, not all of the reaches have routing. For example, the control points Whit and WacoL are too close to the next downstream point for a daily time step to capture the routing effects. If the basin were configured with a large number of these short reaches, some of the reaches could be designated to include the aggregated routing parameters for several upstream reaches.

The remaining fields on the *DC* record pertain to the flow disaggregation methods adopted for each control point. All of the control points, except PK and WacoL, obtain their daily flow patterns directly from patterns on the *DF* records. Control point WacoL uses the method of spline interpolation, and therefore does not require any more information on its *DC* record. Control point *PK* uses a combination of spline interpolation and *DF* record pattern.

All of the daily patterns identified in field 6 of the *DF* records are limited to data for the ten year period 1960−1969. Though it would be ideal to have daily patterns that are concurrent in space and time with each month of the naturalized flow record, it is often the case that only subsets of daily data are available. The monthly naturalized volume is preserved nonetheless. If all daily patterns used in the simulation are of the same subset period, then the timing of wave movement between control points will be maintained in the basin. When the chosen *DF* record patterns are shorter in period than the entire simulation, *SIMD* simply repeats the pattern over and over. In this example, the simulation starts with naturalized monthly data in the year 1940, and a ten year daily pattern starting in 1960 is used to disaggregate the monthly volumes. When the simulation arrives at the 1950's, the daily patterns from the 1960's are repeated again.

Control points PK, High, and George use daily patterns from sources other than collected in near proximity. Therefore, these control points shift the daily patterns forward or backward a number of time steps indicated by the final field on the *DC* record. The number of time steps to shift the pattern is related to the total Muskingum K value between the source and destination locations.

The remaining data in the DCF file are *DF* records which provide the daily flow patterns specified by field 6 on the *DC* record. Because of the daily pattern normalization, the units of the *DF* record data do not have to conform to the units of the monthly naturalized flow. Pattern normalization converts the *DF* record data to a dimensionless pattern in order to preserve the monthly naturalized flow volume units. The user may provide more data in the *DF* records than called by the *DC* records. For example, the user may have a very large daily data set spanning several decades at dozens of locations. All of this information can be converted into *DF* records by the optional program *DAY* and placed in the DCF file. The user can then select any subset of years and locations in the *DC* records. *SIMD* reads the *DC* records at the beginning of the simulation and scans the *DF* records to extract the necessary patterns and stores them in memory. This is done only once at the beginning of the simulation to minimize the time consuming process of reading a large data file.

Simulation Results

The first several records in the *SIMD* output files with filename extensions OUT and SUB are reproduced as Tables 3.9 and 3.10. The SUB file contains daily results, and the OUT file contains aggregated monthly results. Program TABLES input TIN and output TAB files are reproduced as Tables 3.11 and 3.12.

The reliability summary of the entire basin was produced from data in the OUT file. The OUT file contains monthly values aggregated from the daily values and covers the entire period of record of the simulation. This reliability summary of the entire basin is therefore comparable to the reliability summary contained in the original example in the *Fundamentals Manual*. The original example produced a basin-wide volume reliability of 93.68%. This *SIMD* example produces a basin-wide volume reliability of 81.36%. The reduced reliability is due to the factors discussed early in this chapter.

The DCF file contains data for the sub-range of years and months specified on the *JT* record in the DAT file. The tables constructed from the DCF file give the user information for the drought of record in this basin. The user could alternatively request daily data in the DCF file for the entire period of record, though the file size can become extremely large and increase the time of simulation. Creative use of the sub-range period for the DCF file gives the user a convenient tool to quickly tabulate statistics for particular flow events at a daily time step.

Table 3.7
Beginning of the DAT File for the *SIMD* Example

```
T1  File Example.DAT - WRAP-SIMD Input Data File for the Example Dataset
T2  WRAP Fundamentals Manual
T3  December 2005
**
**-----!-------!-------!-------!-------!-------!-------!-------!-------!
** JD Record Fields
**  NYRS    YRST  ICHECK   CPOUT   OUTWR   IDSET  ADJINC
JD    58    1940       1      -1      -2               4
JO     2
**
JT     0   0   0    1947   7    1957   1   0   0   0   5   0
**
**
RO    -1
**
C2     1   Camer
W2     3           WR-24            IF-1            IF-2
R2     1    Whit
**
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!
**       1         2         3         4         5         6         7         8         9         1
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!
**
**  Water Use Coefficient (UC) Records
**
UC  IND1   0.054   0.060   0.070   0.083   0.094   0.105   0.113   0.106   0.096   0.083   0.072   0.062
UC  IND2   0.058   0.077   0.087   0.097   0.107   0.124   0.128   0.124   0.078   0.041   0.038   0.041
UC  IRR1   0.005   0.007   0.017   0.033   0.092   0.163   0.267   0.235   0.117   0.044   0.014   0.007
UC  IRR2   0.005   0.008   0.018   0.032   0.075   0.189   0.304   0.253   0.079   0.022   0.008   0.007
UC  MUN1   0.065   0.063   0.068   0.072   0.085   0.093   0.118   0.114   0.095   0.087   0.071   0.069
UC  MUN2   0.065   0.063   0.066   0.069   0.082   0.105   0.111   0.106   0.100   0.089   0.074   0.069
UC POWER   2250.   2250.   2250.   2250.   2250.   3000.   6000.   6000.   3000.   2250.   2250.   2250.
**
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!
**
** Control Point (CP) Record Fields
**   2       3      4       5       6       7       8       9      10
** CPID1  CPID2   CPDT1   CPDT2  INMETH  CPIN    CPEV      EWA     CL
**-----!-------!-------!-------!-------!-------!-------!-------!-------!
**
CP    PK    Whit                                                   0.061
CP  Whit   WacoG                                                   0.009
CP WacoL   WacoG                                                   0.000
CP WacoG    High                                    none           0.010
CP  High   Bryan                                    none           0.014
CPBelton   Camer                                                   0.028
CPGeorge   Grang                                                   0.008
CP Grang   Camer                                                   0.015
CP Camer   Bryan                                    none           0.036
CP Bryan    Hemp                                    none           0.025
CP  Hemp                                            none
**
```

Table 3.8
Beginning of the DCF File for the *SIMD* Example

```
**
**  File Example.DCF - WRAP-SIMD Input Data File for the Example Dataset
**  WRAP Expanded Capabilities Manual
**  December 2005
**
*********************************************************************************
**
**  CPID      MK      MX     MKF     MXF MTH    DFID BEGYR  MT ENDYR  MT LAG
**
DC    PK     2.5     0.0     0.0     0.0   2  WHITNY  1960   1  1969  12  -3
DC  Whit     0.0     0.0     0.0     0.0   5  WHITNY  1960   1  1969  12
DC WacoL     0.0     0.0     0.0     0.0   1
DC WacoG     0.8     0.2     0.0     0.0   5  WACBRZ  1960   1  1969  12
DC  High     0.9     0.2     0.0     0.0   5  WACBRZ  1960   1  1969  12   1
DCBelton     1.6     0.2     0.0     0.0   5  BELTON  1960   1  1969  12
DCGeorge     0.6     0.0     0.0     0.0   5  GRANGR  1960   1  1969  12  -1
DC Grang     0.8     0.1     0.0     0.0   5  GRANGR  1960   1  1969  12
DC Camer     1.0     0.2     0.0     0.0   5   CAMRN  1960   1  1969  12
DC Bryan     1.3     0.1     0.0     0.0   5  BRYBRZ  1960   1  1969  12
DC  Hemp     0.0     0.0     0.0     0.0   5  HMPSTD  1960   1  1969  12
**
**
*********************************************************************************
**
**  Begin DF Record format daily flows for control points:
**          WHITNY  BELTON  GRANGR  WACBRZ   CAMRN  BRYBRZ  HMPSTD
**
*********************************************************************************
**
**
** DF Record format daily flows for location WHITNY
**
**   3653 time steps
**
** Staring from year 1960 and month  1
** Ending  with year 1969 and month 12
**
**
DF  WHITNY      1960         1         4
   2327.00   1710.00   1401.00   1992.00  10576.00   7301.00   7793.00   6770.00
   5261.00   4333.00   2836.00   2702.00   2655.00   3328.00   3898.00   6249.00
   6141.00   3333.00   2430.00   2108.00   2004.00   1691.00   1265.00   1018.00
   1405.00   1246.00   1599.00   1762.00    562.00   1427.00   1197.00
DF  WHITNY      1960         2         4
   1208.00   1079.00   3524.00   2567.00   1839.00   3544.00   3075.00   2389.00
   2567.00   1315.00   1192.00    721.00    927.00    816.00   1054.00   1418.00
   1206.00    376.00    261.00   1563.00   1133.00    551.00   2091.00    560.00
    491.00    407.00    982.00   1038.00   1070.00
```

Table 3.9
Beginning of the OUT File for the *SIMD* Example

```
  Program WRAP-SIMD (December 2005 Version) Output File
  File Example.DAT - WRAP-SIMD Input Data File for the Example Dataset
  WRAP Fundamentals Manual
  December 2005
  1940    58    11    30     6     0     0   1.000
IF   1      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1  333.13    0.00
IF   1      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2 11104.5   751.7
1940 1    0.000 3841.501    634.9 103992.1   1131.9    1131.9      0.0            WR-5WacoLake          1344.5
1940 1    0.000  637.000   2525.6 552127.2   1404.6    1404.6      0.0            WR-1      PK           223.0
1940 1    0.00013256.518   2524.7 551718.0    571.5     571.5      0.0            WR-2      PK             0.0
1940 1    1.823   56.500      0.0      0.0     54.7    7381.0      0.0           WR-14 Cameron             5.5
1940 1    5.565  172.500      0.0      0.0    166.9   32126.0      0.0           WR-20   Bryan             8.3
1940 1    8.000  248.000      0.0      0.0    240.0   32019.6      0.0           WR-22    Hemp             0.0
1940 1    5.210  161.500      0.0      0.0    156.3   11038.0      0.0           WR-16WacoGage             0.0
1940 1    7.226  224.000      0.0      0.0    216.8   20326.9      0.0           WR-17Highbank             0.0
1940 1   34.052 1055.600      0.0      0.0   1021.5    7326.3      0.0           WR-13 Cameron           510.8
1940 1   72.968 2262.001      0.0      0.0   2189.0   30035.0      0.0           WR-19   Bryan          1422.9
1940 1  248.777 5544.802      0.0      0.0   5296.0   28571.7      0.0           WR-21    Hemp             0.0
1940 1    0.000 5379.398   1125.5 442939.7    946.3     946.3      0.0            WR-8  Belton          2420.7
1940 1    0.000 5275.554   1125.3 442769.6      0.0       0.0      0.0            WR-9  Belton          1055.1
1940 1    0.000 1666.317    130.3  34754.7    143.1     143.1      0.0           WR-10  George           799.8
1940 1    0.000 2732.732    409.2  62412.0   1504.9    1504.9      0.0           WR-11 Granger          1093.1
1940 1    0.000    4.496    634.9 103992.0      0.0       0.0      0.0            WR-6WacoLake             0.0
1940 1    0.000 1170.000   1791.0 623996.8   4489.3    4570.2      0.0            WR-3 Whitney           468.0
1940 1   16.509  460.500      0.0      0.0    444.0    6451.4      0.0           WR-12 Cameron           155.4
1940 1  106.623 1652.653      0.0      0.0   1546.0   19517.5      0.0           WR-18   Bryan           618.4
1940 1    0.000 1352.000    869.8 189759.3      0.0       0.0      0.0            WR-7WacoLake           540.8
1940 1    0.000 5725.726      0.0      0.0   5252.3    5928.1    473.4           WR-15 Cameron          2004.0
1940 1   24.032  372.500      0.0      0.0    348.5   12170.6      0.0           WR-23    Hemp             0.0
1940 1    0.00058558.543      0.0      0.0  11822.1   11822.1  46736.4           WR-24    Hemp             0.0
1940 1-1510.888 2250.000   1790.7 623721.6    868.6     868.6      0.0            WR-4 Whit HP          9406.5
1940 1    0.000    0.000   2523.0 550898.8      0.0       0.0      0.0           WR-25      PK             0.0
1940 1    0.000    0.000   1124.7 442078.8      0.0       0.0      0.0           WR-26  Belton             0.0
1940 1    0.000    0.000    130.2  34699.1      0.0       0.0      0.0           WR-27  George             0.0
1940 1    0.000    0.000    408.8  62288.6      0.0       0.0      0.0           WR-28   Grang             0.0
    PK    0.00013893.512   2523.0 550898.9   1976.1     152.6      0.0   10094.0   33511.7   121. 1549. 25394.
  Whit    0.000 1170.000   1790.7 623721.6   5357.9     147.2    215.8   11746.0   26604.7    64.  198. 21781.
 WacoL    0.000 5197.995    869.8 189759.3   1131.9      34.1      0.0    1166.0      34.1     0.    0.     0.
 WacoG    5.210  161.500      0.0      0.0    156.3     228.0  11683.9   13511.0   38631.7    84.  335. 21585.
  High    7.226  224.000      0.0      0.0    216.8     568.8      0.0   14754.0   38316.3   118.  448. 20693.
Belton    0.00010654.949   1124.7 442078.8    946.3      17.1      0.0     996.0   21466.2    26.  600. 21416.
George    0.000 1666.317    130.2  34699.1    143.1       2.7      0.0     156.0    1737.3     1.   14.  1724.
 Grang    0.000 2732.732    408.8  62288.6   1504.9      47.0    799.8     502.0    5619.9    25.   95.  5544.
 Camer   52.383 7298.324      0.0      0.0   6772.5     236.7   4456.8    4226.0   26300.4   335. 1094. 25169.
 Bryan  185.155 4087.154      0.0      0.0   3902.0     554.9   2588.6   20668.0   60889.2   527. 1534. 42878.
  Hemp  280.80964723.875      0.0      0.0  17706.6     302.6   1980.6   31649.0   10655.3     0.    0.     0.
```

Table 3.10
Beginning of the SUB File for the *SIMD* Example

```
  Program WRAP-SIMD (December 2005 Version) Daily Output File
  File Example.DAT - WRAP-SIMD Input Data File for the Example Dataset
  WRAP Fundamentals Manual
  December 2005
  1947     7  1957     1  3503     1     3     1
     0    31    28    31    30    31    30    31    31    30    31    30    31
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1    10.7     0.0
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2   358.2   292.6
1947 7    0.000 3225.806      0.0      0.0      0.0       0.0   3225.8           WR-24    Hemp             0.0
 Camer  978.323 1404.548      0.0      0.0    110.8       0.0    244.1     441.4    3693.4    5.5 120.6 3062.3
  Whit      0.0    193.5    565.6 619998.2      0.0       0.0   1625.2       0.0   0.75600
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1    10.7     0.0
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2   358.2   242.7
1947 7    0.000 3225.806      0.0      0.0      0.0       0.0   3225.8           WR-24    Hemp             0.0
 Camer  978.323 1404.548      0.0      0.0    110.8       0.0    273.2     338.4    3887.5    4.3 130.1 3296.7
  Whit      0.0    193.5    564.4 618176.0    146.9       0.0   1404.7       0.0   0.75600
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1    10.7     0.0
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2   358.2    48.8
1947 7    0.000 3225.806      0.0      0.0      0.0       0.0   3225.8           WR-24    Hemp             0.0
 Camer  903.174 1404.548      0.0      0.0    186.0       0.0    273.2     367.9    5202.0    9.4 181.4 4722.7
  Whit      0.0    193.5    563.4 616462.2    146.0       0.0   1296.4       0.0   0.75600
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1    10.7     0.0
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2   358.2    48.3
1947 7    0.000 3225.806      0.0      0.0    287.5     287.5   2938.3           WR-24    Hemp             0.0
 Camer  349.626 1404.548      0.0      0.0    821.0       0.0    273.2     654.8    3497.8   36.5 136.8 3483.6
  Whit      0.0    193.5    562.4 614513.4    638.2       0.0   2024.5       0.0   0.75600
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1    10.7     0.0
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2   358.2    66.5
1947 7    0.000 3225.806      0.0      0.0   1537.9    1537.9   1687.9           WR-24    Hemp             0
 Camer  777.416 1404.548      0.0      0.0    311.7       0.0    273.2    1191.9    3358.9   27.7 103.7 2564.1
  Whit      0.0    193.5    561.2 612274.2    347.8       0.0   2025.9       0.0   0.75600
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1    10.7     0.0
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2   358.2    59.1
1947 7    0.000 3225.806      0.0      0.0   2121.5    2121.5   1104.3           WR-24    Hemp             0.0
 Camer  794.095 1404.548      0.0      0.0    295.0       0.0    273.2    1743.6    3292.9   32.7  86.4 2084.5
  Whit      0.0    193.5    559.9 609899.7    212.7       0.0   2027.3       0.0   0.75600
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-1    10.7     0.0
IF   7      0.0      0.0      0.0      0.0      0.0       0.0      0.0            IF-2   358.2    39.8
1947 7    0.000 3225.806      0.0      0.0   1767.0    1767.0   1458.8           WR-24    Hemp             0.0
 Camer  794.095 1404.548      0.0      0.0    295.0       0.0    273.2    1949.6    3154.9   29.5  70.9 1652.2
  Whit      0.0    193.5    558.5 607481.1    168.5       0.0   2028.6       0.0   0.75600
```

Table 3.11

TABLES Input TIN File for the *SIMD* Example

```
**  TABLES Input File for the Example Dataset
**
****---!---!---!---!---!---!---!---!---!---!---!---!---!
**  Frequency tables developed from the monthly OUT file
2FRE   1   0   1   Camer
2FRE   2   0   1   Camer
2FRE   3   0   1   Camer
2FRE   6   0   2            IF-1            IF-2
****---!---!---!---!---!---!---!---!---!---!---!---!---!
**  Reliability table for monthly OUT file
2REL   0   0   1
****---!---!---!---!---!---!---!---!---!---!---!---!---!
**  Reservoir storage developed from the monthly OUT file
2RES   2   0   1    Whit
2RES             627100.
2RES             379000.
****---!---!---!---!---!---!---!---!---!---!---!---!---!
**
**
****---!---!---!---!---!---!---!---!---!---!---!---!---!
**  Frequency tables developed from the daily SUB file
6SUB
2FRE   1   0   1   Camer
6SUB
2FRE   2   0   1   Camer
6SUB
2FRE   3   0   1   Camer
6SUB
2FRE   6   0   2            IF-1            IF-2
****---!---!---!---!---!---!---!---!---!---!---!---!---!
**  Reliability table developed from the daily SUB file
6SUB
2REL   0   0   1   0   1           WR-24
****---!---!---!---!---!---!---!---!---!---!---!---!---!
**  Reservoir storage developed from the daily SUB file
6SUB
2RES   2   0   1    Whit
2RES             627100.
2RES             379000.
**
ENDF
```

Table 3.12
TABLES Output TAB File for the *SIMD* Example

FLOW-FREQUENCY FOR NATURALIZED STREAMFLOWS

```
-------------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD       PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION  100%      99%      98%      95%      90%      75%      60%      50%      40%      25%      10%  MAXIMUM
-------------------------------------------------------------------------------------------------------------------------
Camer   109858.4 170466.      0.0    494.4   1249.0   2706.4   5440.0  15032.0   28988.   44799.   65294.  130473.  290433.1403136.
-------------------------------------------------------------------------------------------------------------------------
```

FLOW-FREQUENCY FOR REGULATED STREAMFLOWS

```
-------------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD       PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION  100%      99%      98%      95%      90%      75%      60%      50%      40%      25%      10%  MAXIMUM
-------------------------------------------------------------------------------------------------------------------------
Camer    88253.6 133519.      0.0    145.9    284.2    608.4   2043.1  18896.6   32271.   44518.   59410.   97395.  215468.1393361.
-------------------------------------------------------------------------------------------------------------------------
```

FLOW-FREQUENCY FOR UNAPPROPRIATED STREAMFLOWS

```
-------------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD       PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION  100%      99%      98%      95%      90%      75%      60%      50%      40%      25%      10%  MAXIMUM
-------------------------------------------------------------------------------------------------------------------------
Camer    72960.7 136696.      0.0      0.0      0.0     25.1    240.8   2050.8    9110.   18248.   32992.   79962.  212480.1393060.
-------------------------------------------------------------------------------------------------------------------------
```

FREQUENCY VERSUS INSTREAM FLOW SHORTAGES FOR SPECIFIED WATER RIGHTS

```
------------------------------------------------------------------------------------------------------------------------
 WATER               STANDARD    PERCENTAGE OF MONTHS WITH SHORTAGE EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 RIGHT           MEAN DEVIATION 100%      99%      98%      95%      90%      75%      60%      50%      40%      25%      10%  MAXIMUM
------------------------------------------------------------------------------------------------------------------------
IF-1              5.2    27.6      0.0      0.0      0.0      0.0      0.0      0.0       0.       0.       0.       0.       8.     333.
IF-2            518.2  1040.8      0.0      0.0      0.0      0.0      0.0      0.0       2.      50.     177.     633.    1626.    9972.
  ------------------------------------------------------------------------------------------------------------------------
```

Table 3.12
TABLES Output TAB File for the *SIMD* Example (continued)

RELIABILITY SUMMARY FOR SELECTED WATER RIGHTS

```
--------------------------------------------------------------------------------------------------------------------------------
               TARGET       MEAN   *RELIABILITY*| +++++++++ PERCENTAGE OF MONTHS +++++++++|------- PERCENTAGE OF YEARS -------
   NAME      DIVERSION   SHORTAGE  PERIOD VOLUME|  WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT
            (AC-FT/YR)  (AC-FT/YR)   (%)    (%) | 100%   95%   90%   75%   50%   25%   >0% | 100%   98%   95%   90%   75%   50%
--------------------------------------------------------------------------------------------------------------------------------
WR-5           59100.0     522.47   98.28  99.12| 98.3  98.7  98.9  98.9  99.0  99.4 100.0| 96.6  96.6  96.6  98.3  98.3 100.0
WR-1            9800.0    1382.48   60.63  85.89| 60.6  64.5  67.4  78.4  89.4  96.1 100.0| 36.2  39.7  50.0  56.9  75.9  91.4
WR-2          245000.0   67907.09   57.61  72.28| 57.6  58.3  59.2  62.6  68.8  78.3 100.0| 34.5  34.5  36.2  46.6  58.6  72.4
WR-14          11300.0    1265.60   39.08  88.80| 39.1  83.9  85.5  91.7  95.8  98.1 100.0|  0.0   5.2  56.9  70.7  86.2  93.1
WR-20          34500.0    3009.61   36.93  91.28| 36.9  87.6  88.9  94.1  97.8  99.3 100.0|  0.0   1.7  65.5  75.9  91.4  98.3
WR-22          49600.0    3876.97   34.77  92.18| 34.8  92.7  93.7  95.4  96.8  99.4 100.0|  0.0   3.4  82.8  86.2  89.7  98.3
WR-16          32300.0    6522.39   31.47  79.81| 31.5  67.2  72.7  85.2  92.5  96.4 100.0|  0.0   1.7  27.6  50.0  75.9  86.2
WR-17          44800.0    7829.88   34.34  82.52| 34.3  78.0  81.0  88.9  94.1  96.4 100.0|  0.0   1.7  37.9  55.2  79.3  87.9
WR-13          18200.0    2315.44   32.76  87.28| 32.8  76.1  79.0  86.8  92.0  95.4 100.0|  0.0  20.7  46.6  62.1  86.2  94.8
WR-19          39000.0    3812.10   31.18  90.23| 31.2  80.5  82.9  90.5  94.7  97.7 100.0|  0.0  20.7  46.6  74.1  89.7  98.3
WR-21          95600.0    8203.55   26.44  91.42| 26.4  83.9  86.4  91.7  95.0  97.4 100.0|  0.0  22.4  60.3  75.9  89.7 100.0
WR-8           82760.0   18821.01   67.67  77.26| 67.7  68.8  69.7  73.3  77.6  82.2 100.0| 43.1  46.6  50.0  53.4  62.1  81.0
WR-9           97500.0   25184.71   66.81  74.17| 66.8  67.4  68.4  70.1  74.0  77.2 100.0| 43.1  46.6  46.6  48.3  60.3  74.1
WR-10          25610.0    7096.38   64.66  72.29| 64.7  66.1  66.8  68.1  71.4  76.9 100.0| 44.8  44.8  46.6  48.3  55.2  70.7
WR-11          42000.0    9351.65   68.39  77.73| 68.4  70.4  71.1  73.3  77.6  83.8 100.0| 44.8  44.8  46.6  51.7  60.3  82.8
WR-6             900.0       7.29   98.28  99.19| 98.3  98.4  98.6  98.7  98.9  99.0 100.0| 96.6  98.3  98.3  98.3  98.3 100.0
WR-3           18000.0    2763.15   81.03  84.65| 81.0  81.2  81.8  82.6  84.9  86.9 100.0| 62.1  65.5  70.7  70.7  81.0  86.2
WR-12          92100.0   44983.45   28.74  51.16| 28.7  49.7  52.4  65.5  74.1  84.2 100.0|  0.0   0.0   1.7   8.6  19.0  51.7
WR-18          25400.0    4939.08   30.60  80.55| 30.6  60.2  63.5  76.7  87.2  93.1 100.0|  0.0   6.9  13.8  37.9  72.4  91.4
WR-7           20800.0     233.29   98.28  98.88| 98.3  98.4  98.6  98.7  98.9  99.0 100.0| 96.6  96.6  96.6  96.6  98.3  98.3
WR-15          88000.0   18200.28   70.55  79.32| 70.5  71.8  72.4  76.0  79.9  84.6 100.0| 46.6  46.6  50.0  56.9  62.1  84.5
WR-23          74500.0   18080.88   30.46  75.73| 30.5  71.4  74.9  81.3  90.1  96.0 100.0|  0.0   0.0  17.2  27.6  62.1  87.9
WR-24         899999.9  139611.59   70.69  84.49| 70.7  74.1  75.7  79.2  85.2  91.5 100.0| 44.8  50.0  53.4  62.1  75.9  91.4
WR-4           36000.0    3412.29   85.78  90.52| 85.8  86.2  86.4  87.2  90.2  94.4 100.0| 60.3  60.3  69.0  81.0  84.5  91.4
WR-25             This water right has no diversion target.
WR-26             This water right has no diversion target.
WR-27             This water right has no diversion target.
WR-28             This water right has no diversion target.
--------------------------------------------------------------------------------------------------------------------------------
Total        2142770.0  399332.66          81.36
-------------------------------------------------
```

RESERVOIR STORAGE DRAWDOWN-DURATION SUMMARY

```
--------------------------------------------------------------------------------------------------------------
                MEAN        BOTTOM       TOP         NUMBER OF PERIODS WITH DRAWDOWNS EQUALING OR EXCEEDING PERCENT
NAME          STORAGE      OF ZONE     OF ZONE                         OF ZONE STORAGE CAPACITY
              (AC-FT)      (AC-FT)     (AC-FT)       0%       2%       5%      10%      25%      50%      75%      90%     100%
--------------------------------------------------------------------------------------------------------------
Whit        512773.47      379000.     627100.     696.     560.     536.     511.     427.     307.     195.     155.     117.
--------------------------------------------------------------------------------------------------------------
```

FLOW-FREQUENCY FOR NATURALIZED STREAMFLOWS
Daily Data Ranging From July, 1947 Through January, 1957

```
--------------------------------------------------------------------------------------------------------------
CONTROL          STANDARD        PERCENTAGE OF DAYS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION    100%      99%      98%      95%      90%      75%      60%      50%      40%      25%      10% MAXIMUM
--------------------------------------------------------------------------------------------------------------
Camer     992.8   6504.4      0.0      0.0      0.2      4.5     16.2     57.2    137.1    233.4    397.0    853.4   2299.2 75399.4
--------------------------------------------------------------------------------------------------------------
```

Table 3.12
TABLES Output TAB File for the *SIMD* Example (continued)

FLOW-FREQUENCY FOR REGULATED STREAMFLOWS
Daily Data Ranging From July, 1947 Through January, 1957

```
-----------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD      PERCENTAGE OF DAYS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION   100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10% MAXIMUM
-----------------------------------------------------------------------------------------------------------------------
Camer      783.4  5631.9     0.0     0.0     0.0     0.0     5.5    10.7    19.7    78.1   192.0   653.2  2121.4 73746.9
-----------------------------------------------------------------------------------------------------------------------
```

FLOW-FREQUENCY FOR UNAPPROPRIATED STREAMFLOWS
Daily Data Ranging From July, 1947 Through January, 1957

```
-----------------------------------------------------------------------------------------------------------------------
CONTROL         STANDARD      PERCENTAGE OF DAYS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT     MEAN DEVIATION   100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10% MAXIMUM
-----------------------------------------------------------------------------------------------------------------------
Camer      528.3  5307.1     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0   124.1  1194.2 64616.3
-----------------------------------------------------------------------------------------------------------------------
```

FREQUENCY VERSUS INSTREAM FLOW SHORTAGES FOR SPECIFIED WATER RIGHTS
Daily Data Ranging From July, 1947 Through January, 1957

```
-------------------------------------------------------------------------------------------------------------------------
 WATER                  STANDARD   PERCENTAGE OF DAYS WITH SHORTAGE EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 RIGHT              MEAN DEVIATION 100%     99%     98%     95%     90%     75%     60%     50%     40%     25%     10%  MAXIMUM
-------------------------------------------------------------------------------------------------------------------------
IF-1                 0.7     5.2     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.6    10.7
IF-2                37.1   175.6     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     1.5    26.6   156.7   370.1
-------------------------------------------------------------------------------------------------------------------------
```

RELIABILITY SUMMARY FOR SELECTED WATER RIGHTS
Daily Data Ranging From July, 1947 Through January, 1957

```
----------------------------------------------------------------------------------------------------------------------
                  TARGET       MEAN     *RELIABILITY*| ~~~~~~~~~ PERCENTAGE OF DAYS ~~~~~~~~~~~|+++++++++ PERCENTAGE OF MONTHS +++++++++|
    NAME        DIVERSION    SHORTAGE   PERIOD VOLUME|  WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT
               (AC-FT/YR)   (AC-FT/YR)    (%)    (%) | 100%   95%   90%   75%   50%   25%  >0% | 100%   95%   90%   75%   50%   25%  >0% |
----------------------------------------------------------------------------------------------------------------------
WR-24           902937.6  395169.66   47.10  56.24| 47.1  47.8  48.5  50.0  55.5  63.2 100.0| 22.6  32.2  35.7  44.3  55.7  70.4  99.1|
----------------------------------------------------------------------------------------------------------------------
Total           902937.6  395169.66          56.24
-------------------------------------------------
```

RESERVOIR STORAGE DRAWDOWN DURATION
Daily Data Ranging From July, 1947 Through January, 1957

```
---------------------------------------------------------------------------------------------------------------
              MEAN         BOTTOM        TOP           NUMBER OF PERIODS WITH DRAWDOWNS EQUALING OR EXCEEDING PERCENT
NAME        STORAGE       OF ZONE      OF ZONE                               OF ZONE STORAGE CAPACITY
             (AC-FT)       (AC-FT)      (AC-FT)        0%       2%       5%      10%      25%      50%      75%      90%     100%
---------------------------------------------------------------------------------------------------------------
Whit      399495.53       379000.      627100.     3503.    3503.    3500.    3494.    3477.    3325.    2607.    2351.    2083.
---------------------------------------------------------------------------------------------------------------
```

Calibration of Routing Parameters with Program *DAY*

Muskingum K and X values determined by *DAY* from naturalized daily flows are used by *SIMD* for routing incremental adjustments to these flows. Routing parameters for selected river reaches are entered in the *SIMD DC* records for the control points defining the upstream ends of the reaches. The control points for which Muskingum routing is to be applied must be selected, and values for the parameters K and X must be developed. Various methods have been applied over many years to calibrate Muskingum routing parameters in conjunction with other models. These methods could be used to develop parameter values for input to *SIMD*. However, calibration methodologies incorporated into the program *DAY* are designed specifically for use with *SIMD* and will normally be applied in WRAP modeling studies.

Other Non-WRAP Approaches

Muskingum routing has been incorporated in many models since its original development during the 1930's. Various calibration approaches have been reported for estimating K and X based on known inflow and outflow hydrographs for a river reach (McCuen 2005). Muskingum routing has been applied most often to flood hydrographs. Calibration studies have often focused on developing K and X using observed hydrographs for well-defined flood events. Parameter values determined for several representative storms are typically averaged.

The parameters K and X are defined by the previously discussed Equation 3.10.

$$S = K\,(X\,I + (1.0 - X)\,O) \tag{3.10}$$

McCuen (2005) and other hydrology textbooks describe a common graphical method based on plotting the S versus (XI+(1−X)O) terms of Eq. 3.10 for an assumed value of X. An optimal X is selected by trial-and-error based on minimizing the loop in the plotted relationship. The slope of a straight line fitted through the S versus (XI+(1−X)O) plot provides an estimate for *K*. The direct option methodology in *DAY* outlined in the next section is conceptually the same as this approach though linear regression computations rather than plots are used.

The Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) contains a parameter calibration method that is applied in determining the Muskingum routing parameters as well as parameters for other types of hydrologic models (Hydrologic Engineering Center 2001). The HEC-HMS calibration methodology uses either of two optional gradient search optimization algorithms that minimize an objective function representing the summation of squared deviations between computed and observed hydrograph ordinates. HEC-HMS may be applied to develop Muskingum K and X values for input to *SIMD*. The optimization option in *DAY* uses a genetic search algorithm rather than the gradient search approach of HEC-HMS.

General Considerations in Applying WRAP Calibration Methods

Instructions for developing input records for *DAY* are provided as Appendix C. Calibration routines in *DAY* are based on computing X and K for reaches between control points based on the known naturalized flows at the control points. The calibrated X and K values are then input to *SIMD* on *DC* records for use in propagating incremental changes in flows. A *SIMD* simulation begins with naturalized daily river flows covering the entire hydrologic period-of-analysis. These daily flows at the control points defining the upstream and downstream ends of selected routing reaches are used by *DAY* to calibrate values for X and K. The routing parameters are determined in *DAY* from these total flows and then applied in *SIMD* to adjustments or changes to the flows. Program *SIMD* allows two sets of K and X values, one set for use with flow adjustments associated with flood control reservoir storage and releases and a different set for all other flow adjustments.

Any number of various types of jobs may be performed in a single executive of *DAY*. A calibration job consists of computing routing parameters for a single river reach or for multiple reaches ending at the same downstream control point. Two control points define the upstream and downstream end of a reach. *DAY* has an optimization option that simultaneously calibrates two or more reaches that share a common downstream confluence. Multiple jobs may be included in a *DAY* dataset to determine routing parameters for any number of routing reaches. Appropriate control points are defined for each individual calibration job.

Program *DAY* reads naturalized monthly flows from *IN* records in a FLO file and sub-monthly (daily) flows or flow patterns from *DF* records in a DCF file. All other *DAY* input is read from a DIN file. File extensions are listed in Table 1.3. Programs *SIMD* and *DAY* may read the same FLO and DCF files. *DAY* reads flow data for only those control points that are pertinent to that execution of *DAY*.

Routing parameters may be developed for every control point included in the *SIMD* simulation except the river system outlet. Alternatively, routing parameters may be provided for selected control points of which some may represent the aggregation of multiple river reaches.

Parameter values may be calibrated for selected reaches and transferred based on user judgment to other reaches. The parameter K represents flow travel time through a river reach. The parameter X tends to be similar in different reaches. X may assumed to be the same for multiple reaches, and K may be estimated based on proportioning travel time. Distance may serve as a surrogate for travel time in proportioning K to reaches of varying length. The values of K for the selected reaches determined by calibration computations may be transferred to other reaches based on reach lengths. Reaches selected for the actual *DAY* calibration computations might be those at gaging stations defining reaches of optimal lengths with little local or tributary inflows. Optimal reach lengths based on maintaining computational stability are defined by rule-of-thumb criteria such as Eqs. 3.13 and 3.14.

The entire hydrologic period-of-analysis or any sub-portion thereof may be used to determine K and X for any user-selected control points. The user may define sequences of flows used in the *DAY* calibration computations by specifying the beginning and ending dates. For example, flood events may be selected for calibrating parameters for flood flows.

DAY also provides an option for specifying the range of flow to be used in the calibration. Flow range criteria are specified in terms of flow magnitude at the upstream control point. Although K is assumed to be a constant, it represents flow travel time which actually varies significantly with flow. Flood flows have a short travel time through a river reach and corresponding small K. Low flows through the same reach will be slower and may have a much longer travel time and thus longer K. The parameters may be determined with *DAY* based on using only flows falling within any user-specified range for the calibration.

Parameter calibration is complicated by flow gains and losses between the upstream and downstream ends of the routing reach. Channel losses include seepage, evapotranspiration, and unaccounted diversions. Precipitation runoff from local incremental watersheds as well as subsurface flows may enter the river along the routing reach. The same control point may be the downstream limit of two or more tributary streams. Multiple tributaries may enter the river reach at various locations between its upstream and downstream ends. Calibration is more accurate for river reaches with minimal change in volume between the upstream and downstream ends.

The *DAY* parameter calibration routines include an option for adjusting the downstream outflow hydrograph to contain the same total volume during the overall calibration period-of-analysis as the upstream inflow hydrograph. The daily outflows (O_T) at the downstream control point are adjusted based on mean volumes of inflow (I_{mean}) and outflow (O_{mean}) as follows.

$$\text{Adjusted } O_T = O_T \left(\frac{I_{mean}}{O_{mean}} \right) \tag{3.15}$$

With this volume adjustment approach, the hydrograph at the downstream control point is viewed as being composed of two components: (1) flows from the upstream control point(s) and (2) flows entering the reach downstream of the upstream control point(s). The two component hydrographs are assumed to have the same pattern as the combined flows at the downstream control point and are separated in proportion to total volume summed over the entire calibration period. The calibration may be performed either with or without the volume adjustment option.

Program *DAY* provides two alternative approaches for performing calibration computations. Calibration features described in the preceding paragraphs are the same with either of the two alternative computational options, except for simultaneous calibration of multiple reaches sharing a common downstream confluence.

1. The *direct option* consists of determination of K from linear regression for assumed values of X based on the Equation 3.10 definition of K and X.
2. The *optimization option* uses a genetic search algorithm that determines K and X based on repeating the routing numerous times in a search for the K and X that minimize the sum of squared deviations between computed and known outflows.

The direct option listed first above and described first below is applicable for an individual river reach defined by a downstream control point and one upstream control point. Reaches sharing a common downstream control point (confluence) are calibrated independently of each other except for volume balance adjustments of Eq. 3.15. The optimization option allows simultaneous calibration for two or more reaches defined by a common downstream control point and a different upstream control point for each river reach entering the confluence. The optimization option allows use of either the Eq. 3.15 option or an objective function option described later to account for lateral inflows in balancing the total inflow and outflow volumes.

Direct Option for Calibration of K and X

The direct calibration method consists of computation of K for assumed X based on the fundamental definition of the parameters K and X reflected in Equation 3.17.

$$\frac{S_T - S_{T-1}}{\Delta t} = I_T - O_T \tag{3.16}$$

$$S_T = K\left[X\, I_T + (1.0 - X)\, O_T\right] \tag{3.17}$$

The variables are defined as follows.

Δt – day or other sub-monthly time interval
K – parameter to be determined, same units as Δt
X – dimensionless parameter to be determined, $0.0 \leq X \leq 0.5$
S_{T-1} – storage volume at the end of day T-1
S_T – storage volume at the end of day T
I_{T-1} – inflow volume during day T-1
I_T – inflow volume during day T
O_{T-1} – outflow volume during day T-1
O_T – outflow volume during day T

The subscripts T-1 and T refer to successive time steps such as days. Storage (S) and (XI+(1.0−X)O) are computed stepping through time with the subscripts T and T-1 serving as moving indices. The parameter X represents a relative weighting of inflow (I) and outflow (O) in determining storage volume (S) in a river reach. K is the constant of proportionality or slope term in the linear function (Eq. 3.17) relating S to weighted I and O.

S denotes the volume of water stored in the river reach at an instant in time. However, storage changes rather than absolute magnitudes are of concern in the calibration procedure. The slope, not the intercept, of the S versus (XI+(1-X)O) relationship is of concern. S may be defined as the cumulative total storage volume above an arbitrary storage reference datum, typically taken as the unknown storage that existed at the beginning of the time series of inflows and outflows used in the calibration computations. Thus, S is the cumulative storage volume at an instant in time cumulated since a defined time zero.

The change in storage volume in a river reach occurring between two points in time equals the summation of inflow less outflow volumes during each incremental time interval spanning these two points in time. Change in storage (ΔS) during a time step of size Δt is computed as follows.

$$\Delta S = \sum (I\,\Delta t - O\,\Delta t) \tag{3.18}$$

The total volume of storage (S_T) at time T that has accumulated since the beginning of the computations at time zero is as follows.

$$S_T = \sum \Delta S \tag{3.19}$$

DAY provides a parameter calibration routine based on computing K from a known time sequence of I_T and O_T with Eqs. 3.16, 3.17, 3.18, and 3.19 with an assumed value of X. K is defined by Eq. 3.17 which can be rewritten as Eq. 3.20.

$$K = \frac{S_T}{\left[X\, I_T + (1.0 - X)\, O_T\right]} \tag{3.20}$$

K is the slope of the relationship between

$$S_T \quad \text{and} \quad \left[X\, I_T + (1.0 - X)\, O_T\right]$$

Paired sequences of I_T and O_T are converted to paired sequences of $(XI_T+(1.0\text{-}X)(O_T))$ and S_T, with S_T computed with Eqs. 3.18 and 3.19. K is determined by applying linear least-squares regression (Chapter 2 Eqs. 2.13, 2.14, 2.15) to this paired series. K is the slope of the regression line. The computation of K is repeated for different values of X. The optimal values of X and K are those with the linear correlation coefficient (Eq. 2.17) being closest to 1.0.

The computations are based on sequences of reach inflows (I_T) and outflows (O_T) over some time span that could range from a single flood event to an entire WAM hydrologic period-of-analysis. Although K is assumed to be a constant, it represents flow travel time which may actually vary significantly with flow. *SIMD* allows two sets of X and K values to be input on *DC* records. The first set is used for routing flow changes for *WR* record water rights which are typically associated with normal and low flows. The second set of values for K and X values on the *DC* records are for flow changes caused by flood control *FC* record reservoir operations.

DAY also has an option for computing K for a user specified range of flow. Flow range criteria are specified in terms of flow at the upstream control point. Equations 3.16, 3.17, 3.18, and 3.19 are applied to the hydrologic period-of-analysis daily naturalized flows at the two control points identically the same regardless of the flow range of interest specified by the user. However, in applying the regression analysis, only the pairs of S and (XI+(1.0−X)O) associated with upstream flows falling in the specified range are used.

The conceptual basis of the *DAY* computational methodology is the same as the graphical approach presented in hydrology textbooks such as McCuen (2005). Muskingum routing is based on the following premises, neither of which is strictly true but rather is approximately the case.

- There is a linear relationship between S and (XI+(1.0−X)O).
- The parameters K and X are constants for a particular river reach.

If these two premises were perfectly valid, a plot of S and (XI+(1.0−X)O) would be a straight line for a series of known inflows and outflows for the river reach. The optimal value of X results in the typical looped relationship being as close to a straight line or the correlation coefficient being close to 1.0 as possible. The parameter K is the slope of the line.

SIMD routes incremental flow changes, with the second premise being somewhat relaxed by allowing different K and X values for flood control operations versus normal flows. Other more conventional non-WRAP applications of Muskingum routing limit the method to modeling only flood events.

Optimization Option for Calibration of K and X

Program *DAY* provides another alternative calibration strategy that is based on repeatedly performing the routing computations with different values for K and X in an iterative search for the optimum values that minimize a defined objective function. For given values of K and X, the inflows (I_T) are routed with Eq. 3.11 to compute the outflows (O_T). An objective function is evaluated based on comparing known and computed outflows. The computations are repeated numerous times. The iterative search is organized as a genetic algorithm.

Various types of search algorithms are available for this type of optimization problem. The HEC-Hydrologic Modeling System has two alternative gradient search algorithms used for calibrating the Muskingum K and X routing parameters as well as for calibrating parameters for various watershed precipitation-runoff models (Hydrologic Engineering Center 2001). *WRAP-DAY* uses an optimization strategy based on a genetic search algorithm. Genetic algorithms are evolutionary search techniques based on the mechanics of natural selection (Goldberg 1989; Mitchell 1998; Ranjithan 2005). A genetic algorithm is a type of directed stochastic optimization strategy. Genetic search algorithms may have an advantage over gradient search driven deterministic optimization methods in that they are less likely to converge on local rather than global optima. The genetic search algorithm incorporated in *DAY* for parameter calibration is described by Hoffpauir (2006).

The optimization option allows simultaneous calibration for multiple reaches defined by a common downstream control point and a different upstream control point for each river reach entering the confluence. The Muskingum equation (Eq. 3.11) is applied to compute the outflows given the known inflow sequence for each of the river reaches. The outflows are summed to obtain the total outflows ($O_{computed} = \sum O_{reach}$) used in the objective function evaluation.

The model-user may place upper and lower limits on the values of K and X to be considered in the calibration. The user may also fix values of X and/or K in certain reaches while optimizing the X and/or K for the same or other reaches. Simulations may be performed with all parameters fixed in order to compare values of the alternative objective functions.

The optimum values for K and X for the one or more reaches are defined in terms of minimizing an objective function expressing criteria for measuring the closeness in reproducing known outflows. The objective function is computed from the results of the routing. Muskingum routing computations are performed with many different sets of values for K and X in a search for those K and X values that yield the optimum value of the objective function. *DAY* provides the following optional objective function formulations. The alternative objective functions described below (F_1, F_2, F_3, F_4, and F_5) all have dimensions of flow volume per time step. All are designed to be minimized in the optimization algorithm.

Option 1 is the least squares criterion based on minimizing the sum of the squares of the deviations between the known flows (O_{known}) at the downstream control point and the computed flows ($O_{computed}$). The objective (criterion) function (F) is expressed as Eq. 3.21, where N is the number of time steps (days) in the routing computations. The known flows (O_{known}) may reflect adjustments using Eq. 3.15 to account for net lateral inflows in the total volume balance.

$$F_1 = \frac{\sqrt{\sum_N \left(O_{\text{known}} - O_{\text{computed}}\right)^2}}{N} \tag{3.21}$$

By squaring the differences between the known and routed flows each period, larger deviations are magnified more in the weighting of daily deviations resulting in a more even distribution of deviation magnitudes over time. However, since larger differences tend to be associated with larger flows, larger flows will tend to have a greater influence on the optimization computations than smaller flows.

The second option is the absolute deviation criterion with the objective function defined identically to the first option except the deviations are not squared. Equation 3.22 is minimized. The absolute value (abs) converts negative differences to positive numbers in the summation.

$$F_2 = \frac{\sum_N \text{abs}\left(O_{\text{known}} - O_{\text{computed}}\right)}{N} \tag{3.22}$$

Equations 3.21 and 3.22 may be adopted either with or without adjusting the known flows (O_{known}) using Eq. 3.15. The Eq. 3.15 adjustments remove lateral inflows from the outflows, such that the total volume of inflows and outflows are the same over the total calibration period. Inherent in the Eq. 3.15 adjustment approach is the premise that the daily lateral inflows have the same daily flow pattern as the total daily outflows at the downstream control point. The third objective function formulation is designed to remove this assumption, allowing the daily flow pattern of the lateral inflows to be completely different than the daily flow patterns at either the downstream or upstream control points.

Objective function option 3 is based on computing the daily lateral inflows as the difference between the known outflows (O_{known}) and routed outflows (O_{computed}). Equation 3.15 is not applied.

The total flow volume over the total calibration period at the downstream control point is the sum of the flows at the one or more upstream control points plus the lateral flows entering the river reach between the upstream and downstream control points. The known total lateral flow volume (Q_{lateral}) over the entire calibration period is the total outflow less total inflow (Eq. 3.23).

$$\text{Total Lateral Flow Volume} = Q_{\text{lateral}} = \sum_N O_{\text{known}} - \sum_N I_{\text{known}} \tag{3.23}$$

The portion of the daily flow volume at the downstream control point in a given day attributable to net lateral inflow is the known daily outflow volume (O_{known}) less the routed daily outflow volume (O_{computed}) for that day.

$$\text{Daily Lateral Flow Volume} = O_{\text{known}} - O_{\text{computed}} \tag{3.24}$$

$$\text{Total Lateral Flow Volume} = \sum_N \text{Daily Lateral Flow Volumes} \tag{3.25}$$

The objective of the third criterion function option is to find values for K and X that minimize the difference between the two alternative summations (Eqs. 3.23 and 3.25) representing total lateral flow volume over the entire calibration period covering N sub-monthly (daily) time steps. The desired value is zero for the objective function (F_3) defined by Eq. 3.26. The search algorithm is driven by minimizing Eq. 3.26.

$$F_3 = \frac{Q_{\text{lateral}} - \sum_N \left(O_{\text{known}} - O_{\text{computed}}\right)}{N} \tag{3.26}$$

The relative advantage between the objective function Z_3 of Eq. 3.26 applied without the Eq. 3.15 adjustment versus either Z_1 or Z_2 (Eqs. 3.21 or 3.22) applied either with or without the Eq. 3.15 adjustment depends on the characteristics and relative magnitude of the lateral flows entering or leaving the reach between the upstream control point(s) and the downstream control point. Z_3 allows lateral inflows to be more accurately modeled in the calibration process without fixing the flow pattern as being the same as total outflows. Use of Eq. 3.15 with objective function Z_1 or Z_2 reflects a more approximate representation of lateral flows. However, the Z_1 or Z_2 options minimize the deviations between the daily computed and observed outflows. With only minimal lateral flows, Z_1 and Z_2 are clearly better objective functions than Z_3.

Objective function alternatives F_4 and F_5 address tradeoffs between the concepts outlined above by combining F_3 with either F_1 or F_2.

$$F_4 = (1.0 - W)\, F_1 + W\, F_3 \tag{3.27}$$

$$F_5 = (1.0 - W)\, F_2 + W\, F_3 \tag{3.28}$$

The weighting ($0.0 \leq W \leq 1.0$) factor W sets the relative influence of F_3. The value for W is rather arbitrary with a default W of 0.80 designed to assure that F_3 is forced to zero or at least very close to zero. Setting W equal to zero in Eqs. 3.27 or 3.28 has the same effect as adopting Eqs. 3.21 or 3.22 (F_1 or F_2).

The optimization algorithm searches for K and X values that minimize the objective function. Driving the F_3 component of F_4 or F_5 to zero maintains the volume balance for the overall calibration period (outflow = inflow at upstream control point(s) + lateral flow) while still allowing flexibility in the pattern of lateral flows. Minimizing the F_1 or F_2 component of F_4 or F_5 results in the routed outflows computed with Eq. 3.11 closely reproducing the general pattern of the known outflows. If the lateral flows are negligible, F_1 or F_2 should be used rather than F_4 or F_5. The Eq. 3.15 option for adjusting outflows to maintain the volume balance normally should not be used in combination with Z_3, Z_4, or Z_5.

DAY provides an option for computing K and X for a user specified range of flow. Flow range criteria are specified in terms of flow at the upstream control point. The Muskingum routing with Eq. 3.11 is applied identically the same regardless of the flow range of interest specified by the user. However, only the days with upstream flows falling in the specified range are used in computing values of the objective function.

Format of the Muskingum Routing Parameter Calibration Results

Program *DAY* will determine values for K and X for the single river reach defined by two control points using either the direct option or optimization option calibration strategies. The optimization option also allows simultaneous calibration of K and X for multiple reaches defined by the same downstream control point but different upstream control points. Any number of calibration jobs may be included in a *DAY* input dataset. *DAY* reads naturalized monthly flows from *IN* records in a *FLO* file and/or sub-monthly (daily) flows or flow patterns from *DF* records in a DCF file. All other *DAY* input is read from a DIN file. Programs *SIMD* and *DAY* may read the same FLO and DCF files. *DAY* reads flow data for only those control points specified in the DIN file that are pertinent to that execution of *DAY*.

Daily flows may be read by *DAY* from *DF* records in a DCF file. Alternatively, *DAY* can read monthly flows from *IN* records in a FLO file, and disaggregate the monthly flows to sub-monthly (daily) flows for use in the routing parameter calibration computations. Programs *DAY* and *SIMD* contain the same flow disaggregation capabilities.

Program *DAY* writes the values for K and X determined using either or both of the two alternative calibration strategies along with related input and computational results to a table contained in an output file with the filename extension DAY. The information included in a *DAY* calibration results table is listed in Table 3.13.

The *DAY* calibration may use the entire *SIMD* period-of-analysis reflected in the flow sequences found in the FLO or DCF files or any user-defined segment thereof. Upper and lower limits defining a range of flows to be used for the calibration may also be specified. As indicated by Table 3.7, the starting and ending dates adopted for the calibration and corresponding number of time periods are provided at the top of the results table. The flow limits are listed next.

The direct option based on Eqs. 3.15−3.20 computes K for assumed values of X ranging from 0.0 to 0.5. Alternatively, the user may specify a value for X. The fixed X and resulting K are output along with the linear correlation coefficient (R) defined by Eq. 2.17. The best estimate of X and corresponding K is indicated by the correlation coefficient (R) closest to 1.0.

The optimization option is based on the model-users choice of objective function F_1, F_2, F_3, F_4, or F_5, (Eqs. 3.21, 3.22, 3.26, 3.27, or 3.28). The results of the calibration consists of optimal values for K and X along with the corresponding value for the objective function. An optional table may be developed tabulating values for each of the five alternative objective functions for a user-specified set of values for K and X.

The output table ends with flow statistics which are provided for general information in better understanding the characteristics of the flows and calibration results. Statistics are tabulated for the flows at the upstream and downstream control points used in the calibration. Lateral flow volumes are shown. Serial correlation coefficients for a range of lags are listed. The parameter K is related to travel time or the lag between outflows and inflows. The lag with the greatest correlation coefficient provides an approximation for K.

Table 3.13
Format of Program *DAY* Routing Parameter Calibration Results

```
*** TIME STEPS FOR ROUTING CALIBRATION ***
START YEAR
START MONTH
END YEAR
END MONTH
FLOW RANGE
TIME STEPS

*** UPSTREAM FLOW LIMITS ***
LOWER LIMIT
UPPER LIMIT

*** DIRECT OPTION CALIBRATION RESULTS ***
CONTROL POINT    K    R
X = 0.00
X = 0.10
X = 0.15
X = 0.20
X = 0.25
X = 0.30
X = 0.40
X = 0.50

*** OPTIMIZATION OPTION LIMITS***
OBJECTIVE FUNCTION OPTION
CONTROL POINT
LOWER LIMIT K
UPPER LIMIT K
LOWER LIMIT X
UPPER LIMIT X

*** OPTIMIZATION OPTION CALIBRATION RESULTS ***
CONTROL POINT
OPTIMIZED K
OPTIMIZED X
OBJECTIVE FUNCTION

*** LATERAL FLOW VOLUME
COMPUTED LATERAL INFLOW VOLUME
PERCENT OF ACTUAL OUTFLOW VOLUME
ACTUAL LATERAL INFLOW
PERCENT OF ACTAL OUTFLOW VOLUME

*** STATISTICS OF GAGED FLOWS ***
CONTROL POINT
TOTAL VOLUME
PERCENT OF OUTFLOW VOLUME
AVERAGE FLOW
STANDARD DEVIATION
90TH PERCENTILE
50TH PERCENTILE
10TH PERCENTILE

*** LINEAR CROSS-CORRELATION BETWEEN GAGED INFLOW AND GAGED OUTFLOW ***
CONTROL POINT
TIME STEPS, LAG =  0
            LAG =  1
            LAG =  2
               ...
            LAG = 10
```

CHAPTER 4
FLOOD CONTROL RESERVOIR OPERATIONS

Flood control reservoirs are modeled in *SIMD* as *FC* record water rights. Operation of multiple-reservoir systems with any number of reservoirs may be based on flood flow limits at any number of downstream control points. Storage in individual reservoirs may be governed by storage versus outflow relationships as well as downstream flow limits. The daily time step features described in the preceding Chapter 3 facilitate simulation of flood control operations. Most of the tables created with program *TABLES* are generally applicable to organizing *SIMD* results irrespective of whether flood control operations are included in the simulation. *TABLES* also has options for frequency analyses of annual peak flow and storage based on the log-Pearson type III probability distribution that are designed specifically for flood studies.

Operation of Flood Control Reservoirs

Most of the large flood control reservoirs in Texas and throughout the United States were constructed and are operated by the U.S. Army Corps of Engineers (Wurbs 1996). Exceptions include International Amistad and Falcon Reservoirs on the Rio Grande operated by the International Boundary and Water Commission, the Tennessee Valley Authority System, and multiple-purpose reservoirs constructed by the Bureau of Reclamation in the western states for which the Corps of Engineers is often responsible for flood control operations. Most of the flood control storage capacity in Texas is contained in multiple-purpose federal projects that also provide water supply and recreation and in some cases hydroelectric power.

Releases from flood control reservoirs occur through spillways and other outlet structures that may be either uncontrolled with no gates or controlled by people opening and closing gates. *SIMD* can simulate either gated or ungated structures. The Natural Resource Conservation Service has constructed numerous flood control dams with ungated outlet structures in rural watersheds. The numerous small flood retarding structures constructed by local entities for stormwater management in urban areas are also typically ungated. Without gates, outflows are governed by the stage-discharge characteristics of the outlet structures. The large federal projects typically have gated outlet structures allowing people to make operating decisions. Uncontrolled spillways with a crest elevation at the top of the controlled storage may pass extreme flood flows while other gated outlet works are used for controlled releases from the conservation and flood control pools. The following discussion focuses on operations of reservoirs that are equipped with gated outlet structures that allow people to control releases.

Reservoirs may be operated solely for flood control, for only conservation purposes, or for both flood control and conservation. Conservation purposes include municipal and industrial water supply, agricultural irrigation, hydroelectric power, recreation, and environmental protection or enhancement. Multiple-purpose operations are based on dividing the storage capacity into conservation and flood control pools separated by a designated top of conservation pool elevation as illustrated by Figure 4.1. The top of the conservation pool is the bottom of the flood control pool. The allocation of storage capacity between pools may be constant or vary seasonally. The flood control pool remains empty except during and following flood events.

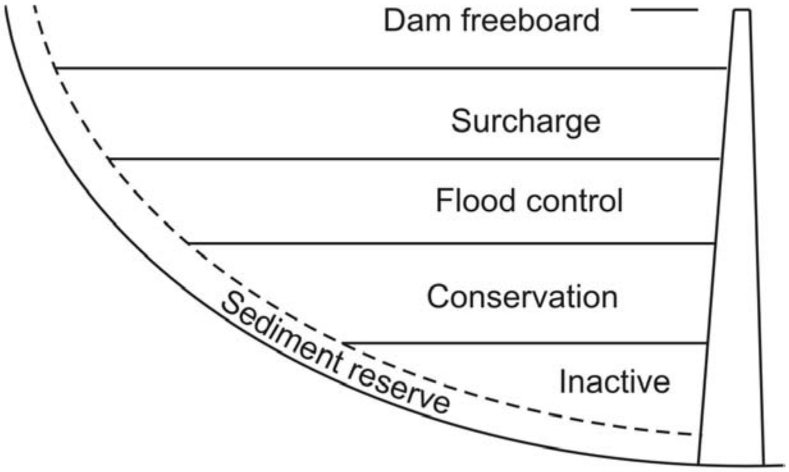

Figure 4.1 Reservoir Pools

Flood control operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding. Maximum allowable flow rates and stages at downstream control points are set based on bank-full river flow capacities, stages at which significant damages occur, environmental considerations, and/or constraints such as inundation of road crossings or other facilities. Releases are made to empty flood control storage capacity as quickly as possible without contributing to stream flows exceeding specified maximum allowable flow levels at the downstream gaging stations. When a flood occurs, the spillway and outlet works gates are closed. The gates remain closed until a determination is made that the flood has crested and flows are below the target levels specified for each of the gaged control points. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the downstream locations. The pool is emptied in preparation for the next storm producing flood inflows which will occur at some unknown time in the future.

Reservoir operations are based on flow limits at downstream locations as long as the flood control pool is not overtopped. During extreme flood events exceeding the flood storage capacity, flood waters may encroach into surcharge storage. With the flood control pool capacity exceeded, releases causing damages downstream are required to prevent the reservoir stage from exceeding a maximum design water surface level set based on protecting the structural integrity of the dam. If flood waters are expected to rise above the top of flood control pool, emergency operating procedures are activated with releases determined based on inflows and storage levels (Wurbs 1996, 2005). Uncontrolled spills may flow through emergency spillways.

In many cases, the allowable non-damaging channel capacity at a given river location is constant regardless of the volume of water in storage. However, operating rules may be formulated with the allowable flow rates at one or more operational control points varying depending upon the volume of water currently stored in the flood control pools. This allows stringently low flow levels to be maintained at certain locations as long as only a relatively small portion of the flood control storage capacity is occupied, with the flows increased to a higher level, at which minor damages could occur, as the reservoirs fill.

The gaged operating control points governing reservoir release decisions may be located significant distances below the dams. Uncontrolled local inflows from watershed areas below the dams increase with distance downstream. Thus, the impacts of reservoirs on flood flows at downstream locations decrease with distance downstream.

A reservoir may have one or more operational control points that are related only to that reservoir and several other control points that are shared with other reservoirs. For example, in Figure 4.2, gaging station 3 is used as a control point for both Reservoirs A and B, and gage 4 controls releases from all three reservoirs. Multiple-reservoir release decisions are typically based on maintaining some specified relative balance between the percentage of flood-control storage capacity utilized in each reservoir. For example, if unregulated flows are below the maximum allowable flow rates at all the control points, the reservoir with the greatest amount of water in storage, expressed as a percentage of flood control storage capacity, might be selected to release water. Various balancing criteria may be adopted. Flows at downstream control points depend upon releases from all reservoirs and runoff from uncontrolled watershed areas below the dams.

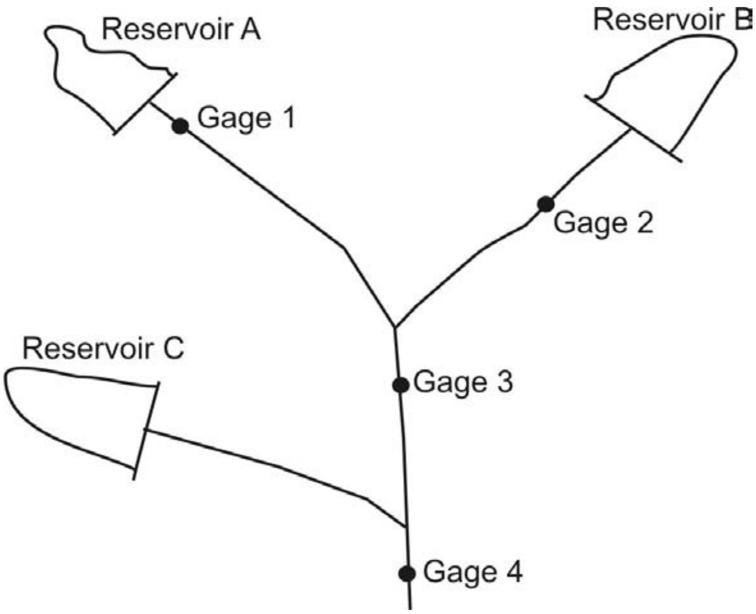

Figure 4.2 Multiple-Reservoir System Flood Control Operations

In order to minimize the risk of reservoir releases contributing to downstream flooding, operators are cautious about closing gates too late or making releases too soon. Outlet gates are opened only after some degree of confidence that flows are receding. Uncertainties regarding inflows from watershed areas below the dams and flow attenuation and travel times from the dams to the downstream control points are a key aspect of operations. Water released from a dam today may reach downstream control points several days from now. Releases combine with future unknown unregulated local inflows below the dams. Additional unexpected rainfall may occur during the time before water released from a dam reaches downstream sites on the river. Forecasting of future flows over the next several days is difficult. These uncertainties inherent in actual reservoir flood control operations are also important in *SIMD* modeling of operations.

Computer Programs, Data Files, and Input Records

The flood control *FC*, flood flow *FF*, flood volume *FV*, and flood outflow *FQ* records described in Appendix B are the only *SIMD* input records designed specifically for flood control. *FC* and *FF* records are used to model reservoir operations for flood control analogously to applying *WR*, *WS*, *OR*, and *IF* records to model operations for water supply, hydropower, and environmental instream flow requirements. The WRAP program *SIM* simulates water rights described by *WR*, *IF*, and other supporting input records, which are described in detail in the *Reference* and *Users Manuals*. *SIMD* has *FC* record rights as well as the basic *WR* and *IF* record rights. The auxiliary records that may be attached to the *WR* and *IF* records to activate target setting options are also applicable to setting the *FF* record flood flow target.

Reservoir outflows may also be specified as a function of storage. *FV* and *FQ* records provide a table of reservoir storage volume versus outflow volume that is linearly interpolated in *SIMD* in the same manner as *SV/SA*, *PV/PE*, and *TQ/TE* record tables input to either *SIM* or *SIMD*. The *FV/FQ* table is interpolated to determine outflow for a given storage volume.

SIMD creates an optional output file with the filename extension FFA with annual series of peak flood flows and storages. The maximum naturalized flow, regulated flow, and storage volume are listed for each year of the simulation at specified control points. The *SIMD* FFA file is read by *TABLES* to perform flood frequency analyses specified by a *7FFA* record.

The tables created by *TABLES* to organize simulation results are generally applicable either with or without flood control being considered. The flood frequency analysis table activated by the *7FFA* record is the only *TABLES* option designed specifically for flood control. The *7FFA* record develops frequency tables for reservoir storage, naturalized flow, and regulated flow based on applying the log-Pearson type III probability distribution to the annual series. The *7FFA* record is included in Appendix E and discussed later in this chapter.

Simulation of Flood Control Reservoirs

Any number of flood control reservoirs may be operated in *SIMD* to control flooding at any number of downstream control points. The reservoirs may be operated individually or as one or more multiple-reservoir systems. Flood control reservoir operations are treated in the model as a type of water right. In WRAP terminology, a water right is a set of water control requirements and associated reservoir facilities and operating rules. Flood control rights activated by *FC* records are modeled within a *SIMD* simulation along with all the other water rights activated by *WR/WS/OR* and *IF* records. Any number of *WR/IF/WS* record rights may be associated with the same reservoir as a *FC* record right.

The sub-monthly time step features of *SIMD* are applied in modeling reservoir operations for flood control. Relatively small computational time steps are required to accurately model flood control operations due to the great fluctuations in flow rates over short time spans that occur during floods. A daily interval is commonly used in flood studies for large river/reservoir systems. Small systems may require smaller time steps. Although discussions in this chapter refer to a daily time step, the sub-monthly time interval is actually a user defined variable.

<u>*Reservoir Pools*</u>

In *SIMD*, a reservoir consists of any or all of the four pools shown in Figure 4.3. *SIM* includes only the bottom two pools. In either *SIM* or *SIMD*, inactive and conservation pool storage capacities are specified on storage *WS* records associated with water right *WR* records. Additionally, *SIMD* allows controlled and uncontrolled flood control storage to be specified by *FC* records. A reservoir may contain any combination of one or more pools defined as follows.

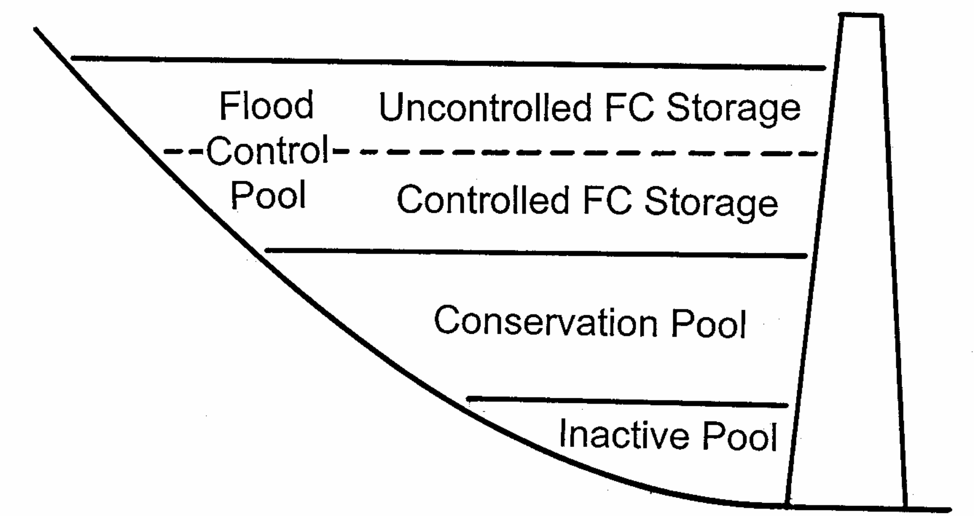

Figure 4.3 Reservoir Pools Defined by *SIMD WS* and *FC* Records

Flood Control Pool.− A flood control pool defined by *FC* record fields 7 and 9 may include zones with outflows through either controlled (gated) or uncontrolled (ungated) outlet structures. The zones are separated by the storage level entered in *FC* record field 8.

Uncontrolled Flood Control Storage.− Uncontrolled means that releases are controlled by the hydraulic design of outlet structures that have no gates operated by people. Outflow from an individual reservoir is specified as a function of storage level based on interpolation of a storage versus outflow table provided on *FV* and *FQ* records.

Controlled Flood Control Storage.− Controlled means that releases are through gated outlet structures with release decisions based on maximum allowable flows at downstream control points specified on *FF* records. Any number of reservoirs may be operated as a system to control river flows at any number of downstream control points. Flows during the current day and forecast period are considered.

Conservation Pool.− Releases or withdrawals from the conservation pool defined by a *WS* record are for water supply diversion, hydropower, and instream flow requirements.

Inactive Pool.− The only way that water can be removed from the inactive pool defined by a *WS* record is through evaporation occurring while the conservation pool is empty.

Reservoir Operations

Reservoir operations for either flood control or conservation purposes in *SIM* or *SIMD* consist of two separate operations: (1) storing inflows and (2) making releases. Filling storage and making releases are two related aspects of reservoir operations that are handled differently in defining operating rules and performing simulation computations.

From the perspective of storing inflows, the total storage capacity at the top of conservation pool and top of flood control pool are specified in *WS* record field 3 and *FC* record field 7, respectively. Storage is filled to these levels by *WR* and *FC* record rights, respectively. If a conservation pool is not full when a *FC* record impounds flood flows, the empty conservation space is filled as the storage level rises into the flood control pool. A *FC* record and any number of *WR/WS* record rights with different storage capacities may be assigned to the same reservoir. Junior rights must have storage capacities equaling or exceeding senior rights in the same reservoir. As *WR* or *FC* record rights are considered in priority order, reservoir storage is filled up to the specified storage capacity subject to the limitation of available stream flow.

The term *available stream flow* for filling storage refers to actual stream flows flowing into a reservoir less flow amounts that are passed through the reservoir or diverted from the reservoir to meet requirements of senior water rights. The *SIMD* simulation steps through time. Within each time step, each water right is simulated in priority order. Flood control *FC* record rights will normally be junior to water right *WR* record and instream flow *IF* record rights. The inflows available to fill storage in a particular *FC* record reservoir are stream flows after adjustments modeling the effects of all more senior *FC*, *WR*, and *IF* record rights.

The top of conservation pool shown in Figure 4.3 may vary between months of the year defining a seasonal rule curve operating plan. Thus, portions of the total storage capacity are reallocated between the conservation and flood control pools on a monthly or seasonal basis. Monthly varying conservation pool capacities are specified on monthly storage limit *MS* records described in the *Users Manual*.

Releases from conservation pool storage depend on operating rules specified by *WR*, *IF*, *WS*, and supporting records as described in the *Reference* and *Users Manuals*. Controlled releases from flood control pool storage are governed by operating rules defined by parameters entered on *FC* and *FF* records. Uncontrolled outflows through ungated outlet structures are specified by *FC*, *FV*, and *FQ* records.

Reservoir outflows associated with *FC* record rights model flows through spillways and other outlet structures that may be either uncontrolled (ungated) or controlled by opening and closing gates. *SIMD* computational algorithms for determining outflows are totally different for controlled versus uncontrolled flood control storage (with versus without operator decisions). Modeling uncontrolled outlet structures is much simpler than modeling operations of reservoirs with gated structures controlled by people. Outflows from an uncontrolled outlet structure depend only on storage and flow conditions at the reservoir for the current day. Operating rules for controlled flood control pools may depend upon storage in multiple reservoirs and flows at multiple control points during the current day and each day of various forecast periods.

Routing Flows Through River/Reservoir Systems

The *SIMD* algorithms for routing flood flows through reservoirs with either ungated or gated outlet structures are described in the following sections of this chapter. Routing through uncontrolled reservoir pools with ungated outlet structures is performed in two steps: (1) the inflow volume available for storage is determined and (2) the outflow is determined based on a storage-outflow relationship. Routing through flood control pools controlled by gated outlet structures is based on more complicated operating rules discussed later.

The *SIMD* algorithms implementing the Muskingum equation for routing flows through river reaches are described in the preceding Chapter 3. The *SIM/SIMD* linear channel loss equation is described in the *Reference Manual*. The Muskingum routing adaptation and channel loss methodology are used to adjust flows at downstream control points for the effects of streamflow depletions associated with storing flood waters and the effects of subsequent releases from flood control storage. Flow routing simulates lag and attenuation. Storing and subsequent releasing of inflows to flood control pools may affect regulated flows at downstream control points in future days as well as in the same day that the flood flows are stored or released.

Water rights are simulated in a priority loop that minimizes the effects of junior rights on senior rights. As discussed in Chapter 3, Muskingum routing of certain flow adjustments occurs before simulating individual water rights. Routing flow changes associated with individual *WR* record rights occur within the priority loop computations. The *SIMD* algorithm implementing Muskingum routing is designed to prevent stream flow depletions and other actions by junior water rights occurring in the current day from impacting senior rights in subsequent days.

An option switch on the *JT* record provides two alternatives for organizing the routing of flow adjustments from one day to the next. This feature is designed to help define the impact of flood control on *WR* record water rights. One option performs the routing of flow adjustments totally within the priority-based water rights simulation loop. Impacts of junior flood control operations on senior *WR* record water rights are minimized. The other option places flow adjustments routed from the preceding day at the beginning of the next-day simulation before the water rights loop. Senior rights may be affected by flood control activities occurring during preceding days. For example, *WR* record water supply diversion rights will have access to stream flows released from flood control pools. Storing flood waters may affect storage levels in conservation pools regardless of placement of routed flow adjustments in the simulation process.

Forecasting of Future Flows

The *SIMD* forecasting strategy previously described in Chapter 3 and outlined again in Table 4.1 is based on a two-month simulation to forecast flows followed by a one-month normal simulation. At the beginning of each month, the daily time step simulation is performed for a two-month period covering that month and the next month for the sole purpose of forecasting future flow conditions. The only results saved from this simulation are:

- flow availability array for each *WR* record water right as discussed in Chapter 3
- array of regulated flows without releases from flood pools for each flood flow *FF* record control point

The two-month simulation at the beginning of each month provides daily water availability and regulated flow arrays covering at least 28 days of forecasted future daily values for use during the second normal simulation, which may include forecast periods of one day to one month.

Table 4.1 Simulation of Controlled Reservoir Flood Control Operations

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Two-Month Forecast Simulation.− At the beginning of each month, an initial simulation is performed with a daily time step for the next two months with storage of flood waters but without releases from flood control pools. This initial forecast simulation provides forecasted estimates of future regulated flows without releases from flood control pools that are used to determine remaining non-damaging flow capacities at *FF* record control points.

One-Month Normal Simulation.− The daily time step simulation is repeated for one month with all features activated. Flood control operations are modeled as follows as the simulation steps sequentially through each day of the month.

1. For multiple-reservoir systems, reservoirs are prioritized based on beginning-of-day storage and parameters from the *FC* records. Each individual reservoir is assigned a relative priority, which may vary daily, that governs sequencing of operating decisions.

2. Flood waters are stored as each *FC* record right is considered in priority order. A yes or no decision is made regarding closing the outlet gates controlling the flood control pool.

    a. Flows at each pertinent *FF* record control point located at or downstream of the dam are checked. A flood is declared to be in progress or imminent if the regulated flow in the current day or flow estimate in any day of the forecast period at one or more control points exceeds the flow limit from the *FF* record.

    b. If a flood is declared, flood gates for the *FC* record right are completely closed, filling storage in the standard manner applied for all *WR* and *FC* record rights.

3. Flood control pools are emptied as flood waters recede. A decision is made regarding whether or not to release water and, if so, the amount to be released.

    As the flood control reservoirs are considered in turn, the release from each reservoir is based on the minimum flood flow capacity determined based on *FF* record limits for flows at each pertinent control point for the current day and each day of the forecast period and releases from other reservoirs. The flow capacity is reduced for releases made by preceding flood control reservoirs.

The forecast period F_P is the number of days into the future considered in the simulation in making reservoir/river system operating decisions. F_P is an input parameter entered on the *DW* or *FF* record. For flood control operations, for each day of the normal simulation, regulated flows for F_P future days at the *FF* record control points are obtained from the two-month array of regulated flows developed during the preceding forecast simulation.

As previously discussed, uncertainties and inaccuracies in forecasting future flow conditions are a major concern in both real-world reservoir operations and modeling of reservoir operations. Some time lag, perhaps many days, may be required for the effects of reservoir storage and releases to reach downstream control points. Storing flood water in a reservoir today may affect flows at downstream locations over the next several days or perhaps many days. Flood hydrographs attenuate as flows pass through river systems. The flows at a control point include local unregulated flows entering the river below dams as well as regulated releases from reservoirs located upstream.

Flood control operating procedures are designed to maintain flood control pools as empty as possible to provide storage capacity for future floods of unknown magnitude and timing while making no releases that contribute to flooding. The objectives are (1) to close gates in a timely manner at the beginning of a storm to store flood waters to minimize flooding and (2) to empty flood control pools expeditiously as flood flows recede without reservoir releases contributing to flows exceeding specified maximum non-damaging flow limits.

By adopting long forecast periods, the *SIMD* modeling approach generally provides a conservatively high estimate of the amount of water to be stored in flood control pools to assure that flow amounts above the flow limits during the forecast period are minimized to the extent possible. Due to approximations related to forecasting and routing, water may be stored in greater quantities and longer than absolutely necessary. However, future days extending past the forecast period are not considered in reservoir operating decisions. Routed reservoir releases could contribute to flooding at downstream control points in future days after the end of the forecast period. Approximations related to imperfect forecasting and routing are an issue in modeling of reservoir operations as well as in actual real-world reservoir operations.

Controlled Reservoir Flood Control Operations

The *SIM/SIMD* simulation process outlined in Figure 2.2 of the *Reference Manual* is organized based on a water rights priority loop nested within a period loop. A two-month/one-month simulation strategy for incorporating forecasting in *SIMD* is outlined in Table 3.6 of the preceding Chapter 3. Flood control operation features of *SIMD* defined by sets of *FC* and *FF* records are embedded within the overall simulation process as outlined in Table 4.1.

WR, *IF*, and *FC* record rights are considered in priority order in the water rights computational loop. The priorities on the *FC* records used to define flood control operations should normally be junior to all of the *WR* and *IF* record water rights in the dataset modeling the river/reservoir system. *FC* record rights have two priorities, one for storing flood flows and another for subsequent releasing of the flood water from the flood control pools. Multiple-reservoir system operations are based on varying release priorities between reservoirs based on their relative percentage depletion of storage capacity which may change daily.

Any number of reservoirs identified by *FC* records may be operated based on maximum non-damaging flow limits specified by *FF* records at any number of control points. Reservoirs with gated outlet structures are operated based on flow limits specified by *FF* records at the control points of the reservoirs and at downstream control points in the current day and all the days during the forecast period. *FC* and *FF* records define operating rules as follows.

- Flood flow *FF* records and supporting records set flow targets at pertinent control points defining the limits above which significant flooding occurs.
- Flood control *FC* records define rules for filling and emptying reservoirs that are based on the flow limits set by the *FF* records.
    1. Gates are closed whenever a flood is underway or imminent as defined by flows exceeding the limits set by the *FF* records.
    2. Flood control pools are emptied expeditiously without releases contributing to flows exceeding the limits set by the *FF* records.

Simulation of reservoir operations for flood control consists of the two separate tasks of storage and release that may occur at different points in the water rights priority loop.

1. Gates are closed if a flood is determined to be underway or imminent based on flows at *FF* record control points in the current day or forecast period. Reservoir storage is filled subject to the controlled flood control storage capacity specified on the *FC* record and computed flow availability in the standard manner applied to all *FC* and *WR* record rights. Storage in each reservoir is filled individually in a sequential order defined by priorities and multiple-reservoir ranking indices.
2. Releases are based on emptying flood control pools as expeditiously as practical without contributing to river flows exceeding *FF* record flow limits. Release decisions are based on flow estimates considering the current day and future days comprising the forecast period, which are subject to forecasting uncertainties. Operations are governed by *FC* record multiple-reservoir system operating rules and *FF* record flow limits at any number of control points.

Uncontrolled Flood Control Storage

The outlet structures of a flood control reservoir or flood retarding dam may be uncontrolled with no gates and thus no gate operations by people. Outflows are controlled by the hydraulic design of the outlet structure with no release decisions by human operators. The hydraulics are modeled with a storage-outflow table provided on *FV* and *FQ* records.

Reservoirs with controlled flood control pools and/or conservation pools with releases through gated outlet structures may also have uncontrolled spillways. With the controlled pools full of water, even with all gated outlets closed, spills may flow over an uncontrolled spillway. Uncontrolled spillways or gated spillways operated in accordance with emergency flood regulation plans may control surcharge storage in reservoirs that also have controlled flood control storage. Spills may also be routed through an uncontrolled spillway with a crest elevation at the top of conservation pool at a water supply only reservoir that has no actual flood control storage. Surcharge storage in the water supply reservoir occurs incidentally due to the limited outflow capacity of the spillway. These situations may also be modeled in *SIMD* with storage versus outflow relationships provided on *FV* and *FQ* records.

Routing of flood flows through reservoirs based on a *FV/FQ* record storage-outflow relationship is applicable to individual reservoirs but not to multiple-reservoir systems. Forecasting and *FF* records are not relevant for uncontrolled structures. Outflows are governed by storage and inflows at the reservoir in the current day.

With a set of *FV* and *FQ* records connected to a *FC* record right, whenever the storage contents exceed a specified volume, the outflow is determined by linear interpolation of the table of storage volumes versus outflow volume/period. As the *FC* record right is considered in the water rights priority loop, routing flow through the reservoir consists of the following two tasks.

1. The inflow volume available to fill storage is determined in the standard manner applied to all *FC* and *WR* record rights.
2. Outflows are computed by linear interpolation of the *FV/FQ* record storage-outflow table. An iterative algorithm determines the outflow during the day based on averaging beginning-of-day and end-of-day storage volumes.

Flood Flow Limits Defined by *FF* Records

A *FF* record is required for each control point location at which a flood flow limit is set. The *FF* record target represents a maximum non-damaging river flow level upon which flood control operations are based. A *FC* record reservoir is operated based on a particular *FF* record if the *FF* record control point is located downstream of the reservoir. The operation of a *FC* record reservoir may consider any number of *FF* record flow limits. Any number of reservoirs may consider the same *FF* record flow limit. Appendix B provides instructions defining variables entered in each of the fields of the *FF* record. The input data are also listed below.

Table 4.2 Flood Flow *FF* Record Input Variables

Field	Description
1	Record identifier (FF)
2	Control point identifier
3	Annual flood flow limit volume
4	Monthly distribution identifier, default = uniform
5	Forecast period, default = 0 (no forecast)
6	Flood index to connect to *DI/IS/IP* record

A *FF* record monthly flood flow limit is set similarly to an *IF* record instream flow target and *WR* record diversion and hydropower targets. An annual flow limit from a *FF* record is combined with monthly coefficients from *UC* records to obtain monthly volumes. A monthly target may be further adjusted by *DI/IS/IP*, *SO*, and *TO* record options described in the *Users Manual*. The flood index entered in *FF* record field 6 is connected to *IS* and *IP* records and applied identically as the drought index used with *WR* and *IF* records. The monthly target setting routines are essentially identical for *FF*, *IF*, and *WR* record targets. The resulting monthly volume is divided by the number of days in the month to obtain a daily volume.

The forecast period entered in *FF* record field 5 is defined the same as the forecast period entered on a daily water right data *DW* record connected to a water right *WR* record. However, the forecast period and associated forecasted regulated flows supporting flood control operations are connected to individual *FF* record control points. For *WR* record water rights, the forecast period and associated water availability estimates are defined for water rights.

The daily flood flow volume limit L_{FF} determined by adjustments to the annual volume entered on a *FF* record is used in the simulation computations to determine the remaining flood flow capacity C_{FF} at a control point for a given day defined by Eq. 4.1.

$$\begin{aligned} C_{FF} &= L_{FF} - Q_R \quad && \text{if } Q_R \text{ is less than } L_{FF} \\ C_{FF} &= 0 && \text{if } Q_R \text{ is greater than or equal to } L_{FF} \end{aligned} \tag{4.1}$$

where Q_R is the regulated flow at the control point that day, and L_{FF} is the daily flood flow limit set by a *FF*, *UC*, and other optional associated records. Q_R, L_{FF}, or C_{FF} are used in the simulation in conjunction with *FF* record control points to:

- determine whether or not to store flood waters
- determine whether or not to release water from flood control pools and, if so, the magnitude of the releases

Each *FC* record reservoir is considered in priority order to determine whether or not to store flood inflows. For each *FF* record control point located downstream of the reservoir, the regulated flow (Q_R) for the current day and each day of the forecast period are compared to the flow limit (L_{FF}). Q_R and L_{FF} are compared for the current day at the control point of the reservoir. The reservoir stores all available inflow up to its flood control pool storage capacity if Q_R exceeds L_{FF} in one or more days at one or more control points. Available reservoir inflow is actual inflow less flow that is passed through for downstream senior appropriations.

Each reservoir is considered in order as release decisions are made each day. The control point of the reservoir is considered for the current day C_{FF} but not for the C_{FF} for the future days in the forecast period. The controlling flow capacity CC_{FF} is determined as the minimum of:

1. the C_{FF} for the current day at the control point of the reservoir or at any downstream control point identified by *FF* records
2. C_{FF} for any day of the forecast period at any of the downstream control points.

As each reservoir is considered in a given day in turn in the priority sequence, the CC_{FF} is reduced by the volume of flood releases (R_{FF}) for that day from other reservoirs already considered.

$$\text{Adjusted } CC_{FF} = CC_{FF} - \sum R_{FF} \tag{4.2}$$

The reservoir release (R_{FF}) for that day for the reservoir being considered is then set at the adjusted CC_{FF}. End-of-period reservoir storage is adjusted for the release and also for net evaporation. The release is routed to the basin outlet, thus affecting regulated flows at downstream control points during that day and subsequent days.

Reservoir Operating Rules Defined by *FC* Records

A *FC* record defines operating rules for a flood control reservoir, which may be operated as an individual reservoir or as a component of a multiple-reservoir system. One *FC* record is required for each flood control reservoir. A *FC* record and any number of *WR/WS* records with various auxiliary records may be associated with the same reservoir. Appendix B provides instructions defining the variables entered in each of the fields of the *FC* record, which are also listed below in Table 4.3. Fields 10 through 15 are typically blank, with defaults adopted.

Table 4.3 Flood Control *FC* Record Input Variables

Field	Description
1	Record identifier (FC)
2	Reservoir identifier
3	Storage priority number
4	Release priority number
5	Number of *FF* record limits, default = all
6	Maximum release volume per time interval
	Storage Volumes
7	Maximum capacity for filling flood control storage
8	Storage capacity activating *FV/FQ* record table
9	Minimum storage capacity for controlled flood releases
10	Beginning-of-simulation storage contents
	Multiple-Reservoir System Balancing
11	Multiplier factor M, default = 1.0
12	Addition factor A, default = 0.0
	Storage-Area Relationship
13	Multiplier *A* for storage-area equation
14	Multiplier *B* for storage-area equation
15	Multiplier *C* for storage-area equation surface area = $A\ (\text{storage})^{B} + C$ *SV/SA* records are provided if fields 13-15 are blank.

Storage Levels

The storage capacities entered in *FC* record fields 7, 8, and 9 are total cumulative storage volumes below the pool levels shown in Figure 4.3. The capacities are defined as follows.

Field 7: Top of flood control pool – Upper limit to which flood waters can be stored. If the top of flood control pool is exceeded, outflow equals inflow. Flood control capacity in Equation 4.4 is the volume entered in field 7 or 8 minus the volume in field 9.

<u>*Field 8: Activation of FV/FQ record table*</u> – An entry in field 8 is required to activate routing with a *FV/FQ* record storage-outflow table. The *FV/FQ* record storage-outflow relationship governs outflows if the storage rises above this level. Otherwise, release rules control releases from controlled flood control storage.

<u>*Field 9: Bottom of controlled flood control pool*</u> – Controlled flood control releases are not made from storage below this level. This level could be the top of conservation pool, top of inactive pool, or any other pool level defining the lower limit of the storage range for flood control releases.

The beginning-of-simulation storage contents of a single-purpose flood control only reservoir may be entered in *FC* record field 10. *FC* record field 10 should be blank if one or more *WR* records are associated with the reservoir because the beginning-of-simulation storage will already be defined by *WR/WS* records. If field 10 is blank or zero for a single-purpose flood control reservoir without *WR* record rights attached, the storage contents will be zero at the beginning of the simulation.

<u>*Priority System for Sequencing of Simulation Computations*</u>

Reservoir operating decisions in *SIMD* are made in two stages:

1. closing the gates because a flood has been determined to be in progress or imminent (storage decision)
2. controlling the gates to make releases to empty or draw-down the flood control pool (release decision)

For each day of the simulation, first a decision is made of whether to keep the gates closed. If the answer is "yes keep the gates closed," storage capacity is filled by inflows, but releases are not considered. Otherwise, the release decision algorithm is activated. Thus, the storage priority should always be senior to the release priority, meaning the storage decision should precede the release decision in the simulation computations.

Storage and release priorities are entered in *FC* record fields 3 and 4, respectively. The priority numbers are key features for defining operating rules. Priorities control the sequential order in which rights (sets of water control facilities and operating practices) are considered in the computations. The organizing concept of a water rights priority loop nested within a period loop is fundamental to the modeling system. *FC* record rights will normally be assigned priorities that are junior to *WR* and *IF* record rights. Thus, the computations associated with operating flood control reservoirs will be performed last in the water rights computational loop.

As noted above, the release priority (field 4) for a particular reservoir should always be junior to its storage priority (field 3). An error message is activated by *SIMD* otherwise.

For controlled flood control reservoirs, the storage priority in field 3 defines the order in which flood control gates are closed. For uncontrolled reservoirs, the storage priority defines the order in which routing computations are performed. In either case, reservoirs will typically be assigned priorities listing them in upstream-to-downstream order. Gates are often operated to store flood waters as far upstream as possible. Routing through uncontrolled structures also naturally progresses from upstream to downstream.

The field 4 release priority sets the order in which each reservoir is considered in regard to releases from controlled flood control pools. Release priorities are used only with reservoirs for which operators make release decisions, not with uncontrolled flood retarding structures.

Multiple-Reservoir System Operations

All reservoirs having the same priority are treated as components of a multiple-reservoir system. Each *FC* record right has a priority for storing flood flows (field 3) and a separate priority (field 4) for the subsequent release of the stored flood waters. If multiple reservoirs share the same storage priority, these reservoirs are treated as a multiple reservoir system in making storage decisions. If multiple reservoirs share the same release priority, these reservoirs are treated as a multiple reservoir system in making release decisions.

> *Reservoirs with the same priorities entered in either FC record field 3 and/or field 4 are treated as a multiple-reservoir system. The rank index computed with Eq. 4.4 sets the order in which the reservoirs are considered in making operating decisions.*

At each time step, the ordering of reservoirs in a multiple-reservoir system for purposes of operating decisions is based on a ranking index. At the beginning of each day of the simulation, a rank index is computed with Equation 4.4 for each reservoir included in the system based on beginning-of-period storage.

$$\text{rank index} = (\text{multiplier factor}) \left[\frac{\text{storage content in FC pool}}{\text{storage capacity of FC pool}} \right] + \text{addition factor} \qquad (4.3)$$

Equation 4.3 can be written more concisely as Eq. 4.4.

$$\text{rank index} = \text{M} \left[\frac{\text{content}}{\text{capacity}} \right] + \text{A} \qquad (4.4)$$

The flood control pool capacity in Eq. 4.4 is the cumulative storage volume entered in field 8 or field 7 (if field 8 is blank or zero) minus the storage volume entered in field 9. The storage content is the beginning-of-period storage volume minus the field 9 storage volume. The ratio of storage content to capacity may exceed 1.0 if the storage falls between the fields 8 and 9 volumes but otherwise ranges between 0.0 and 1.0. The defaults are 1.0 for the multiplier factor *M* and 0.0 for the addition factor *A*. Fields 11 and 12 are used to enter values other than these defaults.

The rank indices computed each day for each multiple-reservoir system reservoir set the order in which operating decisions are made for the individual reservoirs.

- In making storage decisions, the reservoir with the smallest rank index is considered first, the reservoir with the second smallest index is considered second, and so forth.
- In making release decisions, the reservoir with the greatest rank index is considered first, the reservoir with the second largest index is considered second, and so forth.

Summary of Reservoir Operating Rules

As previously discussed, in each day of the simulation, flows at the *FF* record control points located at or downstream of each flood control reservoir are considered. If flows at one or more control points in the current or forecast days exceed flood limits, outlet gates are completely closed at that reservoir. Otherwise, if channel flow capacity is available, releases are made in an amount equal to the minimum flow capacity considering all pertinent control points and all pertinent days. As each reservoir makes releases, the channel flow capacity available to subsequent reservoirs is reduced. In a given day, the entire available channel capacity may be exhausted by the first reservoir considered, or perhaps two or more reservoirs may be able to make releases within available flow capacity.

FC record field 5 provides an option that allows operating decisions to be limited to consideration of only certain *FF* record control points located closest to the reservoir. The number of *FF* record control points to be considered in making operating decisions is entered in *FC* record field 5. With field 5 blank or zero, the default is for all *FF* record control points located at or below the reservoir to be considered. A 2 entered in field 5 means that only the two *FF* record control points at or downstream but closest to the reservoir are considered.

A maximum release rate may be entered in field 6 in dimensions of volume per daily or other sub-monthly time interval adopted. If the release rate computed based on *FF* record flow limits exceeds the field 6 maximum limit, the release is set at the limit. However, the *FC* record field 6 outflow limit does not override the *FV/FQ* record storage-outflow relationship.

Ordering of reservoirs is based on priorities and relative rank indices. Flood control operations for either a single reservoir operated alone or each individual reservoir operated as a component of a multiple-reservoir system include the following decision rules.

- Gates are closed, storing available inflows, if flood conditions are declared based on considering *FF* record flow limits at *FF* record control points located at or downstream of the reservoir. Inflows are stored subject to not exceeding the total storage capacity at the top of flood control pool specified in *FC* record field 7.

- Releases are governed by the *FF* record flow limits and operating rules previously discussed. *FC* record flood releases are not made if the storage level falls below the bottom of flood control pool defined in field 9. Releases are also constrained by the maximum release limit specified in field 6.

- If *FC* record field 8 is blank or zero, releases continue to be controlled by the *FF* record flow limits as long as the storage contents do not exceed the field 7 total storage capacity at top of flood control pool. Outflow equals inflow after the storage capacity is exhausted.

- If the *FC* record field 8 option is activated, the *FV/FQ* record storage-outflow hydraulics relationship controls outflows any time the storage reaches the level specified in field 8. An iterative algorithm determines the outflow volume during the day based on averaging beginning-of-day and end-of-day storage volumes.

Storage-Area Relationship

A relationship between storage volume and surface area is required for evaporation computations. The storage-area relationship for a reservoir is provided as a table entered on *SV* and *SA* records or as coefficients entered on a *WS* or *FC* record. Coefficients may be entered in *FC* record fields 13, 14, and 15. Blank *FC* fields 13-15 indicate that either *SV/SA* records are provided or coefficients were assigned by a previous water right. If multiple water rights are associated with the same reservoir, the storage-area relationship may be specified with the first right read. Thus, the storage-area relationship may be defined by either a previous *FC* record or a *WS* record associated with a *WR* record previously read for the reservoir.

Building a Flood Frequency Table with *TABLES*

The program *TABLES 7FFA* record routines are designed specifically for flood frequency analyses. However, other tables created by *TABLES* to organize simulation results are generally applicable either with or without flood control being considered. Other tables may be chosen along with *7FFA* record tables to organize the results of a simulation study of flood control operations. The flood frequency analysis *7FFA* record is included in Appendix E.

Table 4.4
Organization of the *SIMD* FFA Output File

First Six Records

WRAP-SIMD Flood Frequency Analysis File
TITLE1
TITLE2
TITLE3
YEAR CPID NAT-FLOW REG-FLOW STORAGE NYRS NCPTS

The first five records do not contain numeric data.
The first four records are equivalent to those found on the OUT and SUB files.
The fifth record gives the column headings for the remaining portion of the file.

Definition of Variables on the Sixth Record

NYRS – total number of years of data contained in the file
NCPTS – total number of control points reported for each year

Remaining Records

The remaining data is an annual sequential listing with each line containing the year, control point, naturalized flow, regulated flow, and storage peaks.

SIMD has an option to write annual series of maximum naturalized flows, regulated flows, and reservoir storages to an output file with the filename extension FFA. The peak daily naturalized flow, regulated flow, and storage volume are listed for each year of the *SIMD* simulation at specified control points. These series of annual peak daily volumes are input data for the *TABLES* flood frequency analysis *7FFA* record routines. The organization of the *SIMD* FFA file read by *TABLES* is outlined in Table 4.4. Peak annual series may be generated for all control points or for selected control points. If reservoir storage is not associated with a control point in the FFA output file, a value of -1 is inserted in the storage column.

Log-Pearson Type III Model of Annual Peak Flow and Storage

The *7FFA* record builds a table of daily flow or storage volumes corresponding to annual exceedance frequencies of 80, 50, 20, 10, 10, 4, 2, 1, and 0.5 percent, which correspond to recurrence intervals of 1.25, 2, 5, 10, 25, 50, 100, and 200 years. The relationship between annual exceedance probability P and recurrence interval T in years is:

$$T = \frac{1}{P} \quad \text{or} \quad P = \frac{1}{T} \tag{4.6}$$

The flood frequency analysis computations are based on applying the log-Pearson type III probability distribution in a standard manner outlined by Wurbs and James (2002), McCuen (2005), many other textbooks, and the Interagency Advisory Committee on Water Data (1982). The frequency factor table is reproduced as Table 4.5.

The random variable X is the maximum daily naturalized flow, regulated flow, or reservoir storage volume to occur in a year. The X corresponding to a given exceedance probability is determined from Equation 4.7 combined with Table 4.5 relating the frequency factor K to exceedance probability P and skew coefficient G.

$$\log X = \overline{\log X} + K\, S_{\log X} \tag{4.7}$$

The mean $\overline{\log X}$, standard deviation $S_{\log X}$, and skew coefficient $G_{\log X}$ of the logarithms of X are computed from an annual series of maximum daily flow or storage volumes X. The frequency factor K is obtained as a function of P and $G_{\log X}$ by linear interpolation of a Pearson type III probability table built into the program *TABLES* and reproduced as Table 4.5.

Equations for the sample mean, standard deviation, and skew coefficient are as follows.

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \tag{4.8}$$

$$S = \left[\frac{1}{n-1} \sum_{i=1}^{n} \left(X_i - \bar{X} \right)^2 \right]^{0.5} \tag{4.9}$$

$$G = \frac{n \sum_{i=1}^{n} \left(X_i - \bar{X} \right)^3}{(n-1)\,(n-2)\,S^3} \tag{4.10}$$

Table 4.5 Frequency Factor K for the Pearson Type III Distribution

Skew Coef G	Recurrence Interval (years)							
	1.25	2	5	10	25	50	100	200
	Exceedance Frequency (percent)							
	80	50	20	10	4	2	1	0.5
3.0	-0.636	-0.396	0.420	1.180	2.278	3.152	4.051	4.970
2.8	-0.666	-0.384	0.460	1.210	2.275	3.114	3.973	4.847
2.6	-0.696	-0.368	0.499	1.238	2.267	3.071	3.889	4.718
2.4	-0.725	-0.351	0.537	1.262	2.256	3.023	3.800	4.584
2.2	-0.752	-0.330	0.574	1.284	2.240	2.970	3.705	4.444
2.0	-0.777	-0.307	0.609	1.302	2.219	2.912	3.605	4.398
1.8	-0.799	-0.282	0.643	1.318	2.193	2.848	3.499	4.147
1.6	-0.817	-0.254	0.675	1.329	2.163	2.780	3.388	3.990
1.4	-0.832	-0.225	0.705	1.337	2.128	2.706	3.271	3.828
1.2	-0.844	-0.195	0.732	1.340	2.087	2.626	3.149	3.661
1.0	-0.852	-0.164	0.758	1.340	2.043	2.542	3.022	3.489
0.8	-0.856	-0.132	0.780	1.336	1.993	2.453	2.891	3.312
0.6	-0.857	-0.099	0.800	1.328	1.939	2.359	2.755	3.132
0.4	-0.855	-0.066	0.816	1.317	1.880	2.261	2.615	2.949
0.2	-0.850	-0.033	0.830	1.301	1.818	2.159	2.472	2.763
0.0	-0.842	0.000	0.842	1.282	1.751	2.054	2.326	2.576
-0.2	-0.830	0.033	0.850	1.258	1.680	1.945	2.178	2.388
-0.4	-0.816	0.066	0.855	1.231	1.606	1.834	2.029	2.201
-0.6	-0.800	0.099	0.857	1.200	1.528	1.720	1.880	2.016
-0.8	-0.780	0.132	0.856	1.166	1.448	1.606	1.733	1.837
-1.0	-0.758	0.164	0.852	1.128	1.366	1.492	1.588	1.664
-1.2	-0.732	0.195	0.844	1.086	1.282	1.379	1.449	1.501
-1.4	-0.705	0.225	0.832	1.041	1.198	1.270	1.318	1.351
-1.6	-0.675	0.254	0.817	0.994	1.116	1.166	1.197	1.216
-1.8	-0.643	0.282	0.799	0.945	1.035	1.069	1.087	1.097
-2.0	-0.609	0.307	0.777	0.895	0.959	0.980	0.990	0.995
-2.2	-0.574	0.330	0.752	0.844	0.888	0.900	0.905	0.907
-2.4	-0.537	0.351	0.725	0.795	0.823	0.830	0.832	0.833
-2.6	-0.499	0.368	0.696	0.747	0.764	0.768	0.769	0.769
-2.8	-0.460	0.384	0.666	0.702	0.712	0.714	0.714	0.714
-3.0	-0.420	0.396	0.636	0.660	0.666	0.666	0.667	0.667

Skew Coefficient

The skew coefficient G computed with Eq. 4.10 is particularly sensitive to extreme flood events due to the cube term. Estimates from small samples may be inaccurate. Therefore, Bulletin 17B of the Interagency Advisory Committee on Water Data (1982) provides a generalized skew map that is reproduced by Wurbs and James (2002), McCuen (2005), and other references. Depending on the number of years of gage record, regionalized skew coefficients are used either in lieu of or in combination with values computed from observed flows at the particular location of concern.

Equations 4.11-4.16 allow a weighted skew coefficient G_W for flood flows to be computed by combining a regionalized skew coefficient G_R and station skew coefficient G.

$$G_W = \frac{(MSE_R)(G) + (MSE_S)(G_R)}{MSE_R + MSE_S} \tag{4.11}$$

$$MSE_S = 10^{[A - B(Log_{10}(N/10))]} \tag{4.12}$$

$$A = -0.33 + 0.08|G| \quad \text{if} \quad |G| \leq 0.90 \tag{4.13}$$

$$A = -0.52 + 0.30|G| \quad \text{if} \quad |G| > 0.90 \tag{4.14}$$

$$B = 0.94 - 0.26|G| \quad \text{if} \quad |G| \leq 1.50 \tag{4.15}$$

$$B = 0.55 \quad \text{if} \quad |G| > 1.50 \tag{4.16}$$

The station skew G is computed from the logarithms of the observed flows using Eq. 4.10. The regional skew G_R is either developed from multiple stations following procedures outlined in Bulletin 17B or read from the generalized skew coefficient map also supplied by Bulletin 17B. The generalized regional skew coefficients G_R are for the logarithms of annual maximum streamflow. MSE_S denotes the mean square error of the station skew. MSE_R is the mean square error of the regional skew. Bulletin 17B sets the MSE_R at 0.302 if G_R is taken from the generalized skew map.

The *7FFA* record in *TABLES* provides options for determining the skew coefficient G for the logarithms of the annual peak naturalized and regulated flow and storage volumes. By default, the program computes G with Eq. 4.10. Alternatively, G may be computed external to the program and entered as input. As another option, the regionalized skew coefficient G_R may be entered as input and combined with G internally within the program based on Eqs. 4.11−4.16 to determine weighted skew coefficient G_W. The program uses a MSE_R of 0.302.

With a skew coefficient value of zero, the log-Pearson type III distribution is identical to the log-normal probability distribution. Thus, a frequency analysis based on the log-normal distribution may be performed by specifying a skew coefficient of zero. The values for K in Table 4.5 for a G of zero are the same as the values from normal probability tables.

Listing of Annual Peaks with Weibull Probabilities

The *7FFA* record will also create a tabulation of peak annual naturalized and regulated flows and reservoir storage with exceedance frequencies assigned by the Weibull formula. The Weibull formula estimates exceedance probabilities based on relative frequency as follows:

$$P = \frac{m}{N+1} \tag{4.17}$$

where P denotes annual exceedance probability, m is the rank of the values (m = 1, 2, 3, ... , N), and N is the total number of years in the data series. The greatest flow or storage volume is assigned a rank of 1, and the smallest is assigned a rank of N.

Example of Modeling Flood Control Reservoir Operations

CHAPTER 5
SALINITY SIMULATION

Salinity tracking components of WRAP consist of the program *SALT* and table building routines in the program *TABLES*. Program *SALT* combines water quantity data read from the *SIM/SIMD* simulation results file with concentrations or loads of inflows from a salinity input file. Loads and concentrations of water quality constituents in stream flows, reservoir storage, and diversions throughout the river system are computed. Options in *TABLES* organize the salinity simulation results and develop frequency statistics. The combined *SIM/SALT/TABLES* model is designed for simulating water quality throughout a river/reservoir system for alternative scenarios of water use, reservoir system operating policies, and salt control measures.

Salinity Aspects of Water Availability Modeling

Water supply capabilities depend upon water quality as well as quantity. The salinity modeling features of WRAP are designed primarily for computing concentration-frequency relationships at locations of interest throughout a river system for alternative water management plans. The spatial and temporal variability of salt concentrations represent another dimension in assessing water availability for various water users and types of use under specified water resources development and management scenarios.

Salinity refers to dissolved minerals and may be quantified in terms of the concentration of total dissolved solids (TDS) or concentrations of particular constituents such as chlorides or sulfates. Salinity plays an important role in water resources development and management throughout the world, particularly in relatively arid regions. In the United States, salinity is a particularly important consideration in the states located west of the Rocky Mountains as well as in Texas and neighboring states. In the Southwest, geologic formations underlying the upper watersheds of the Rio Grande, Pecos, Colorado, Brazos, Red, Canadian, and Arkansas Rivers in Texas, New Mexico, Oklahoma, Kansas, and Arkansas contribute large salt loads to the rivers. Primary salt source subwatersheds of these major river basins have streams with concentrations that sometimes exceed that of seawater. The salinity simulation features of WRAP are motivated by the natural salt pollution problems in Texas and neighboring states (Wurbs 2002).

Early research in incorporating salinity considerations in WRAP modeling are reported by Wurbs *et al*. (1994), Sanchez-Torres (1994), and Wurbs and Sanchez-Torres (1996). The current salinity modeling features of WRAP were developed during 2004-2005. Krishnamurthy (2005) presents a case study investigation of the new modeling capabilities performed during the developmental process.

Salt concentrations are an important consideration in assessing water supply capabilities. The U.S. Environmental Protection Agency secondary drinking water standards suggest limits for TDS, chloride, and sulfate concentrations of 500, 250, and 250 mg/l, respectively, based on health effects and taste preferences and because conventional treatment processes do not remove salinity. Salts also damage pipelines, equipment, household appliances, and industrial facilities. Salinity tolerance for different types of industrial water use varies greatly. Salinity greatly affects irrigated agriculture. Although plants can tolerate and even require minerals for growth, excessive salts within the root zone reduce or prevent plant growth. Tolerable maximum TDS limits for irrigation range from significantly less than 1,000 mg/l to greater than 10,000 mg/l depending on the crop, soil conditions, and proportion of soil moisture supplied by rainfall versus irrigation. Salinity is a major determinant of aquatic habitat. Many aquatic plants and animals are adapted to certain ranges of dissolved solids concentrations. Changes in salinity may significantly impact ecosystems. Dissolved solids affect saturation concentrations of dissolved oxygen and influence the ability of a water body to assimilate wastes. Eutrophication rates depend on TDS. Salts affect the mobility and transformation of other water quality constituents.

WRAP may be applied to assess the impacts of water management and use strategies on salt loads and concentrations throughout a river system. Measures for dealing with salinity may be evaluated. Salinity mitigation measures include blending water from multiple sources such as releases from multiple reservoirs on different tributaries of varying water quality, control of runoff from primary salt source subwatersheds, and desalination facilities.

Computer Programs, Data Files, and Input Records

A simulation study begins with development of the necessary input datasets. With all input files complete, a salinity simulation is performed in three steps.

1. A *SIM/SIMD* simulation is performed to determine water quantities.
2. A *SALT* simulation is performed to combine salinity data with the results of the *SIM/SIMD* simulation.
3. *TABLES* is used to develop tables that organize and summarize simulation results.

Program *SALT* reads the following three files produced by *SIM/SIMD*. The DAT and OUT file are required. The beginning reservoir storage BRS file is optional.

- The *CP* records are read from the *SIM/SIMD* input file (filename root.DAT) to assign the next downstream control point for each control point. The *CP* records establish the sequential organization of the *SALT* computations as well as the spatial connectivity of the river system. Constant inflow *CI* records are also read.
- The main *SIM/SIMD* simulation results file (root.OUT) provides streamflow, diversion, storage, and other pertinent quantities used in the salinity simulation.
- A *SIM/SIMD* BRS file provides beginning-of-simulation reservoir storage contents.

A monthly time step is used for the computations performed within *SALT*, but monthly-aggregated results from a *SIMD* simulation using a daily or other sub-monthly time step may be incorporated into the *SALT* simulation.

Program *SALT* reads salinity input data from a required SIN file and optional BRC file. The salinity input file with filename extension SIN contains the *JC*, *CO*, *CP*, *CC*, and *S* records described in Appendix D. The optional beginning reservoir concentration file (extension BRC) may be used to provide beginning-of-simulation storage concentrations. *SALT* also writes end-of-simulation reservoir concentrations to the BRC file (*JC* record field 8).

The control point *CP* records read by *SALT* from a *SIM/SIMD* input file establish the upstream-to-downstream sequential order in which the salt tracking computations are performed. The *TABLES 1CPT* record can be used to rearrange *CP* records with the proper sequencing. A *TABLES* execution controlled by the *1CPT* record reads the *SIM* input file and rearranges the *CP* records in an appropriate upstream-to-downstream order. The rearranged *CP* records are then inserted into a *SIM* input file to be read by both *SIM* and *SALT*.

Program *SALT* produces three output files.

1. The main simulation results output file with filename extension SAL is a table with each line containing the year, month, and control point and the following results for the control point: inflow volume, load, and concentration; end-of-month storage volume, load, and concentration; outflow volume, load, and concentration; and diversion target and shortage. The SAL file is read by program *TABLES*.
2. The message file with filename extension SMS provides a trace of the simulation, error and warning messages, an optional data listing of intermediate computation results, and a water volume and salt load balance summary table.
3. An optional beginning reservoir concentration file with filename extension BRC contains the final storage concentrations at the end of a simulation to be read by a subsequent execution of *SALT* as beginning-of-simulation storage concentrations.

The final *SALT* results to be read by *TABLES* are written to the SAL output file. Two optional tables for each constituent may be written to the message SMS file. A control point volume and load budget contains the values for essentially all of the variables included in the simulation. A summary water volume and salt load balance for the overall simulation is also provided as a much smaller table in the SMS file.

The program *TABLES* reads the program *SALT* output SAL file with the simulation results and the *TABLES* input TIN file with specifications regarding the tables to be created. *TABLES* develops the following tables summarizing the *SALT* simulation results.

8SAL records create tables of volumes, loads, and concentrations for control point inflow, storage, and outflow that are identical in format to the *2NAT*, *2STO*, and *2REG* record tables.

8FRE and *8FRQ* records create frequency tables of volumes, loads, and concentrations for control point inflow, storage, and outflow that are identical in format to the *2FRE* and *2FRQ* records

8SUM records provide control point summaries of volumes, loads, and concentrations.

8REL records create reliability tables that reflect limits on salt concentrations. In addition to the diversion shortages incurred in *SIM/SIMD* due to insufficient water volume, shortages are declared if concentrations exceed specified levels.

Instructions for preparing input records for programs *SALT* and *TABLES* are provided in Appendices D and E, respectively.

Spatial Configuration

The *SALT* computations are performed by control point in the sequence in which the *CP* records are read from the *SIM* or *SIMD* DAT file. The first control point considered is the most upstream control point on one of the stream branches. The computations proceed by control point in upstream-to-downstream order. Computations are performed for a particular control point only after completion of computations for all control points located upstream of that control point. This is necessary because the load of the regulated flows entering the control point from upstream must be included in the salt balance computations.

The *CP* records in a *SIM/SIMD* input file (filename extension DAT) may be in any order if a *SALT* simulation is not being performed. However, when *SIM/SIMD* is used in combination with *SALT*, the ordering of the *CP* records in the *SIM/SIMD* input file controls the order of the *SALT* computations. The *CP* records must be sequenced in accordance with the following rule.

> *For each control point, the CP records for control points located upstream must be entered in the SIM/SIMD input file before that control point.*

For example, for the system shown schematically in Figure 5.1, the computations may begin at either control point CP-1, CP-3, or CP5. One alternative correct sequencing of control points is as follows: CP-1, CP-2, CP-3, CP-4, CP-5, CP-6. Another of the several alternative acceptable sequences is: CP-5, CP-3, CP-1, CP-2, CP-4, CP-6.

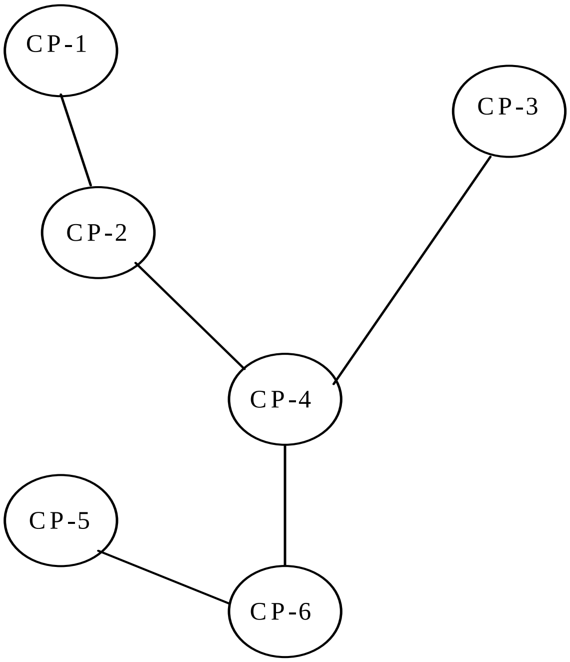

Figure 5.1 Control Point Configuration

The ordering of *CP* records is arbitrary for a *SIM* or *SIMD* simulation but must follow the rules outlined above for a *SALT* simulation. The *TABLES 1CPT* record routine is designed for rearranging *CP* records with the proper sequencing required for a *SALT* simulation. With a *1CPT* record, program *TABLES* reads the *SIM* input file and rearranges the *CP* records in an appropriate upstream-to-downstream order. The rearranged *CP* records may then inserted by the model user into a *SIM* input file to be read by both *SIM* and *SALT*.

Control point *CP* records are also included in the SALT input SIN file as well as in the *SIM* input DAT file. The SIN file *CP* records may be entered in any order. All control points with *CP* records in the SIN file must also have *CP* records in the *SIM* DAT file. However, all control points with *CP* records in the *SIM* DAT file do not necessarily have *CP* records in the SIN file. The information provided for a *CP* record control point in the SIN file may be repeated for any number of other control points located either upstream or downstream.

The concentrations of the local incremental inflows each month (SIN file) and the initial beginning-of-simulation reservoir storage concentrations (SIN or BRC file) are provided as input to *SALT*. Local incremental monthly concentrations and beginning-of-simulation storage concentrations read from the SIN file for a particular control point may be repeated for other control points. These data may be provided in the input file for any or all of the control points. However, the data must be included for either the most downstream control point or the most upstream control point on each branch for which salinity is modeled.

Options also allow upstream salinity boundary conditions to be defined at control points that are not upstream extremities. Salinity is not modeled by *SALT* at control points located upstream of a upstream boundary condition control point even though water quantities are computed in the *SIM* simulation.

Again using the Figure 5.1 example, if salinity is to be modeled at all control points, the *SALT* input SIN file must include *CP* records with pertinent salt information for either CP-6 or for CP-1, CP-3, and CP-5. If salinity at CP-1 is not of concern, CP-2 may serve as upstream boundary with CP-1 being omitted from the SIN file. With CP-2 defined as an upstream boundary, salt loads or concentrations for outflows at CP-2 are provided as input in the SIN file. SIM water quantities for CP-1 are read but salinity computations begin at CP-2.

Options in *SALT* also allow salinity data from the SIN file to be repeated for multiple control points. Assume that the *SIM* DAT file *CP* record sequence for the system of Figure 5.1 is CP-1, CP-2, CP-3, CP-4, CP-5, CP-6. Any or all but at least one of these control points must be included in the *SALT* SIN file. Repeat options activated by *JC* record field 10 allow data to be repeated for either upstream (option 1) or downstream (option 2) control points. With option 1, the input data are repeated for all upstream control points not included in the SIN file up to the next control point which is included in the SIN file. For example, with option 1, the concentration of local incremental flows and beginning-of-simulation reservoir storage concentration may provided as input in the SIN file for CP-6 and automatically repeated within *SALT* for all of the other control points. With option 2, CP-1, CP-3, and CP-5 could be included in the SIN file with repeats occurring as follows. Data input for CP-1 are repeated for CP-2. Input for CP-3 are repeated for CP-4. The data for CP-5 are repeated for CP-6.

Volumes, Loads, and Concentrations

The program *SIM* simulation results provide volume/month flow rates and end-of-month storage volumes. The program *SALT* input SIN file provides loads or concentrations for beginning-of-simulation reservoir storage and monthly incremental naturalized stream flows. *SALT* computes loads and concentrations for inflows, outflows, and storage at all control points except those located upstream of optionally defined upstream boundary control points. Program *TABLES* salinity routines build tables for volumes, loads, and concentrations for control point inflows, outflows, and storage. *TABLES* also has a routine for determining water supply diversion reliabilities constrained by maximum allowable salt concentration limits.

Units of Measure

Any consistent set of units may be adopted for storage volumes, volume/month flow rates, salt loads, and concentrations. A conversion factor may be entered in *JC* record field 14 that provides consistency for the units.

Concentration (C), load (L), and storage or flow volume (Q) are related as follows:

$$C = \frac{L}{Q} f_C \quad \textit{or} \quad L = \frac{C\,Q}{f_C} \tag{5.1}$$

where f_C is a conversion factor that is entered in *JC* record field 14, with a default of 735.48 that corresponds to units of milligrams/liter (mg/l) for C, tons or tons/month for L, and acre-feet or acre-feet/month for Q. The default factor reflects the following conversions.

$$\frac{\text{mg}}{\text{liter}} = \left(\frac{\text{tons}}{\text{ac-ft}}\right)\left(\frac{2{,}000\,\text{pounds}}{\text{ton}}\right)\left(\frac{453.59\,\text{g}}{\text{pound}}\right)\left(\frac{1{,}000\,\text{mg}}{\text{gram}}\right)\left(\frac{\text{ac-ft}}{43{,}560\,\text{ft}^3}\right)\left(\frac{\text{ft}^3}{28.316\text{ liters}}\right)$$

$$\frac{\text{milligrams}}{\text{liter}} = \left(\frac{\text{tons}}{\text{acre-feet}}\right)(735.48)$$

For units of mg/l, tons/day, and ft^3/s, the conversion factor f_C is 370.81.

$$\frac{\text{mg}}{\text{liter}} = \left(\frac{\text{tons/day}}{\text{ft}^3/\text{s}}\right)\left(\frac{2{,}000\,\text{pounds}}{\text{ton}}\right)\left(\frac{453.59\,\text{g}}{\text{pound}}\right)\left(\frac{1{,}000\,\text{mg}}{\text{gram}}\right)\left(\frac{\text{day}}{86{,}400\,\text{s}}\right)\left(\frac{\text{ft}^3}{28.316\text{ liters}}\right)$$

$$\frac{\text{milligrams}}{\text{liter}} = \left(\frac{\text{tons/day}}{\text{ft}^3/s}\right)(370.81)$$

The mean concentrations during a month entering the confluence of two tributaries are combined to obtain the mean concentration of flow leaving the confluence. Likewise, mean monthly concentrations are averaged to obtain mean annual concentrations. Discharge-weighted or volume-weighed mean concentrations C_M are computed as follows.

$$C_M = \frac{\Sigma L}{\Sigma Q} f_C \tag{5.2}$$

Components of Control Point Inflows and Outflows

The following volume and load balance equations are fundamental to the *WRAP-SALT* simulation computations.

$$\text{change in reservoir storage volume} = \text{inflow volume} - \text{outflow volume} \tag{5.3}$$

$$\text{change in reservoir storage load} = \text{inflow load} - \text{outflow load} \tag{5.4}$$

Equations 5.3 and 5.4 are applied at each control point for each month of the simulation. For control points with no reservoirs, storage volume and load are zero. For the volume and load balance summary table written to the SMS file, Eqs. 5.3 and 5.4 are applicable to the total river/reservoir system over the total period-of-analysis. The volume and load balances are actually applicable to any contiguous set of control points over any period of time.

From the perspective of volume and load balances at a control point, the inflow and outflow terms in Eqs. 5.3 and 5.4 consist of the summation of the inflow and outflow components listed in Table 5.1. Monthly volumes of naturalized flow, regulated flow, end-of-month reservoir storage, channel loss credits, channel losses, and return flows are read by *SALT* from the *SIM* output file and are defined in the *Reference* and *Users Manuals*. Monthly diversion targets and shortages are also read from the *SIM* output file, and diversion volumes are computed as their difference. Constant inflows input to *SIM* on *CI* records are not included as separate quantities in the *SIM* output file. Thus, *SALT* reads the *CI* records from the *SIM* input file along with the *CP* records.

The inflow and outflow volumes and loads written to the SAL output file are the totals for the component inflows and outflows listed in Table 5.1. The inflow and outflow concentrations are the volume-weighted means of the concentrations of each component. Each of the inflow components has a different concentration. Reservoir evaporation has zero load and concentration. The outflow components (regulated flow, diversions, and other releases) all have the same concentration in *SALT*, which is called the *control point outflow concentration.*

Salinity Simulation with Program SALT

The *WRAP-SALT* model computes salt loads and concentrations for each control point of a river/reservoir system for inflows and outflows during the month and end-of-month reservoir storage for each month of the hydrologic period-of-analysis, for given loads entering the system. Frequency statistics are developed with *TABLES* from the simulation results. The salt tracking algorithms are based on simple mass balance accounting. Water quality constituents are assumed to be conservative with no chemical or biological transformations. Multiple constituents such as total dissolved solids, chlorides, sulfates, etc., may be included in a single execution of *SALT*. Each constituent is simulated with the same mass balance algorithms, with no differentiation of different characteristics of different water quality constituents.

Table 5.1
Components of Control Point Inflows and Outflows

Control Point Inflows

incremental naturalized flows – Cumulative naturalized flow volumes are read from the *SIM* output file. Incremental volumes are computed by *SALT* by subtracting amounts at upstream control points. Either loads or concentrations are read from the SIN file.

upstream regulated flows – Monthly volumes are read from the *SIM* output file for all control points. Inflow loads are outflow loads from upstream control points computed earlier in the *SALT* simulation. For stream confluences, outflow volumes and loads at control points located immediately upstream on each tributary are summed.

channel losses and channel loss credits – Channel losses/credits associated with upstream control points are used to adjust the total inflows for the control point under consideration. For tributary confluences, volumes and loads at control points located immediately upstream of the site under consideration on each tributary are summed. Channel loss and loss credit volumes are read from the *SIM* output file. Concentrations are computed based on total outflow volumes and loads at each individual upstream control point, but are constrained by the minimum and maximum concentration limits specified on *CC* records in the SIN file.

return flows – Monthly volumes are read from the *SIM* output file. Concentrations are assigned based on options specified on SIN file *CC* records.

constant inflows – Monthly volumes are read from *CI* records in the *SIM* input file. Concentrations are assigned based on options specified on SIN file *CC* records.

Control Point Outflows

reservoir evaporation – Volumes are from *SIM* output file. Loads and concentrations are zero.

regulated flows – Monthly volumes are read from the *SIM* output file. Loads are computed by *SALT* through the procedures outlined in Figure 5.3 based largely on Eq. 5.4.

diversions – Diversion volumes are diversion targets less shortages read from the *SIM* output file. Diversion loads are computed along with regulated flow loads.

other reservoir releases – Monthly volumes for reservoir releases made specifically for hydropower or downstream instream flow requirements are computed by *SALT* based on the volume balance reflected in Eq. 5.3 with all terms except the *other releases* read from the *SIM* output file. The corresponding loads are computed by the simulation algorithms along with return flow and regulated flow loads.

The concentration is the same for the regulated flows, diversions, and other reservoir releases and is referred to as the control point outflow concentration.

Organization of the SALT Simulation

The *SALT* computations are performed within repetitive loops as illustrated in Figure 5.2. The simulation may be repeated for up to 15 different water quality constituents. For each salt constituent, the simulation steps through a monthly computational loop. The computations are repeated for each month of the hydrologic period-of-analysis. The volume, load, and concentration of the water stored in reservoirs at the end of a month become the beginning-of-month values for the next month. The reservoir lag option allows the concentration of reservoir releases to be determined based on storage concentrations in previous months. In a particular month, the computations are repeated for all control points. For each control point in turn, the inflow volumes and loads are first computed. Volumes, loads, and concentrations of outflows and reservoir storage at the control point are then computed. The simulation procedures are outlined in greater detail in Figure 5.3.

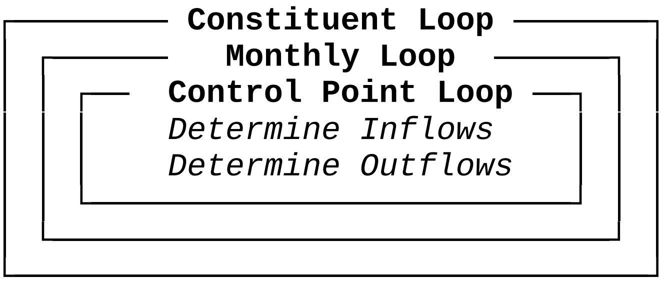

Figure 5.2 Organization of *SALT* Computations

Simulation results are written to the main *SALT* output file with filename extension SAL at the end of the control point loop for user-selected control points. The SAL file consists of a table for each water quality constituent that contains the following information written for user-selected control points for each month of the simulation.

- year and month
- control point identifier
- total volume and load and mean concentration of the inflows to the control point
- total volume and load and mean concentration of the outflows from the control point
- total volume and load and mean concentration of the storage at the control point
- total water supply diversion targets and shortages for the month at the control point

Inflows and outflows are totals or means during the month, and storage amounts are instantaneous values at the end of the month. The water supply diversion targets and shortages are the volumes read from the *SIM* output file and are included in the SAL file for use by *TABLES* in building a reliability table.

A volume and load balance summary table and optional additional detailed results table are written to the *SALT* message SMS file. The SMS file tables include the component parts of the total control point inflows and outflows as outlined in Table 5.1.

- Prior to beginning the three computational loops shown in Figure 5.2
    1. The required *SIM* input (DAT) and output (OUT) and *SALT* input (SIN) and output (SAL, SMS) files are activated.
    2. The optional beginning reservoir storage volume (BRS) and concentration (BRC) files are initiated after reading *JC* record specifications from the SIN file.
    3. The identifier of each control point and its next downstream control point are read from the *CP* records in the *SIM* DAT file to establish spatial connectivity.
    4. All data in the SIN file are read except the S records of time series of salt inflows.

- ***Beginning of Salt Constituent Loop***
    1. Salt concentrations or loads are read from the *S* records in the SIN file or constant concentrations from *CS* records are assigned if a SIN file control point has no *S* records.
    2. Beginning-of-simulation reservoir storage concentrations and loads are set.
    3. The initial concentrations are repeated at downstream *SIM* control points that are not included in the SIN file.

    - ***Beginning of Monthly Time Step Loop***
        1. Beginning-of-month reservoir storage volumes, loads, and concentrations are set at beginning-of-simulation values for the first month and thereafter at end-of-month values from the preceding month.
        2. Water quantities are read from the *SIM* simulation results OUT file.

        - ***Beginning of Control Point Simulation Loop***
            1. Lag is set and monthly lag index is updated if the lag options are activated.
            2. Volumes and loads entering the control point are determined.
            3. Concentrations of regulated flows and diversions leaving the control point and the end-of-month storage load and concentration are determined.
            4. Simulation results are written to the SAL and SMS files.
            5. Totals are accumulated for the SMS file total volume and salt balance table.

        - ***Control Point Simulation Loop is Repeated***

    - ***Monthly Time Step Loop is Repeated***

        Volume and load totals are written to the summary table in the SMS file.

- ***Salt Constituent Loop is Repeated***

    End-of-simulation storage concentrations are written to the optional BRC file.

Figure 5.3 Outline of the Salinity Simulation Performed by Program *SALT*

Volume and Load Accounting

Water quantities are provided by the *SIM/SIMD* simulation results. The control point output records of the *SIM* main output file are read by *SALT* for a given month at the beginning of the monthly time step loop shown in Figure 5.3. The quantities read for that month for each control point are listed in Table 5.2. The index cp implies the variable is stored as a control point array. The salt tracking computations include all control points. All control points included in the *SIM* input file must also be included in the *SIM* output file. *SALT* reads only the control point output records from the *SIM* output file. Water right and reservoir output records are skipped.

Table 5.2 Variables from SIM/SIMD Simulation Results

SIM Output Variable	CP Output Record Field	Fortran Variable
diversion shortage	2	DS(cp)
diversion target	3	DT(cp)
net evaporation-evaporation	4	EVAP(cp)
reservoir storage content	5	STO(cp)
return flow returned to cp	8	RET(cp)
naturalized flow	9	NAT(cp)
regulated flow	10	REG(cp)
channel loss credits	11	CLC(cp)
channel losses	12	CLO(cp)

Multiple water rights in *SIM* may be located at the same control point. *SIM* results used by *SALT* represent summations by control point. The total monthly diversion volume DIV is computed from the corresponding diversion target (DT(cp)) and shortage (DS(cp)) as:

$$\text{DIV} = \text{DT(cp)} - \text{DS(cp)} \tag{5.5}$$

The variable names used in the Fortran code are adopted in the following discussion. Variables with the cp array index are data stored in active memory as the iterative computations progress. Computed variables without indices are repetitively recomputed.

In the *SALT* model, salt loads enter the river/reservoir system in four ways.

1. Beginning-of-simulation reservoir storage loads represent the salt content of reservoirs at the beginning of the first month of the period-of-analysis.
2. Incremental local inflows represent the salt loads entering the river system with the incremental naturalized flows during each month of the simulation. At the most upstream control point on a stream branch, this is the total load associated with the total naturalized streamflow. Progressing downstream, additional local incremental loads at each control are associated with the additional incremental inflows.

3. An option allows a control point to be treated as an upstream boundary. The salinity tracking computations are not performed upstream of this boundary even though volumes are read from the *SIM* output file for all control points including those located above a *SALT* upstream boundary. Salinity loads or concentrations input for an upstream boundary represent outflows from that control point.

4. Salt may also enter the system through return flows or *CI* record constant inflows representing flows from outside of the river/river system from sources such as groundwater or interbasin transfers.

A *SALT* simulation consists of tracking or accounting for the movement of these salt loads through the river/reservoir system. Salt loads are tracked by control point in upstream to downstream order. A particular control point may or may not have reservoir storage. The water and salt accounting balances the flow volumes and loads entering and leaving the control point during the month and the change in volume and load in storage at the control point. At each control point, the simulation algorithms perform as the following two tasks.

1. Flows and loads entering the control point as defined in Table 5.1 are determined.
2. The loads and concentration of the outflows (Table 5.1) leaving the control point and loads and concentration of the reservoir storage contents at the end of the month are determined.

Storage Volumes and Concentrations at the Beginning of the Simulation

After the first month, the reservoir storage volume, concentration, and load at each control point at the beginning of a month of the simulation are equal the respective values at the end of the preceding month. Sequential months of the simulation are connected by reservoir storage volume and load. Reservoir storage volume and concentration for each control point must also be established for time zero at the beginning of the first month of the simulation.

The options for setting the beginning-of-simulation storage volumes are controlled by *JC* record field 7. Beginning-of-simulation storage volumes may be specified in the SIN file in *CP* record field 8. Another option is for *SALT* to read a beginning-reservoir-storage file with filename extension BRS created by *SIM/SIMD* as specified by *SIM JO* record field 6. A third option is for *SALT* to compute the beginning-of-simulation storage volumes BSS(cp) using end-of-month storage (ST), streamflow depletion (DEP), net evaporation-precipitation (EP), and diversion (DT-DS) volumes for the first month of the simulation read from the *SIM/SIMD* main output OUT file as follows.

$$\text{BSS(cp)} = \text{ST} - \text{DEP} + \text{EP} + \text{DT} - \text{DS} \tag{5.6}$$

In some cases the beginning-of-simulation storage may depend upon other reservoir releases not included in the *SIM* output file and Equation 5.6. Thus, this option may be approximate. The other option of creating a BRS file is advantageous in this regard, since the BRS file will always contain the exact beginning storages from *SIM*. The first option of entering the beginning-of-simulation storage for particular control points in SIN file *CP* record field 8 will over-ride the other options for a particular control point. The other options assign values for all control points including those not included in the SIN file.

Options for setting the beginning-of-simulation storage concentrations are selected by *JC* record field 8 and *CC* field 4. One option is to read the beginning concentrations from the *CC* records. Another option involves creation and application of a beginning reservoir concentration BRC file. The *CC* record option would typically be adopted if the beginning concentrations are known. The BRC file option is applied if the beginning concentrations are not known.

The *SALT* beginning reservoir concentration (BRC) file option is applied in combination with the *SIM* beginning-ending-storage (BES) file option based on the premise of cycling the hydrologic period-of-analysis. *SALT* is executed two or more times as necessary to match ending and beginning conditions. The end-of-simulation concentrations are written to a BRC file. The concentrations in the BRC file are read by subsequent executions of *SALT* as beginning-of-simulation concentrations.

In most applications, the beginning reservoir storage volumes and concentrations are unknown. A cycling premise involves setting beginning-of-simulation storage volumes and concentrations equal to end-of-simulation storage volumes and concentrations determined by previous executions of *SIM* and *SALT*. Since, ending values depend upon beginning values, multiple iterative simulations may be performed. The beginning-ending-storage (BES) options in *SIM* controlled by *JO* record field 5 facilitate applying this strategy to set the beginning storage volumes. The beginning-of-simulation concentration options in *SALT* controlled by *JC* record field 8 facilities applying the strategy for the concentrations.

Flows and Loads Entering a Control Point

The total monthly inflow volume (FIN) and load (LIN) that enters a control point is determined based on the following summations.

$$\text{FIN} = \text{FNAT} + \text{FREG} + \text{RET(cp)} + \text{CINF(cp,m)} + \text{FCLC} - \text{FCL} \tag{5.7}$$

$$\text{LIN} = \text{LNAT} + \text{LREG} + \text{LRET} + \text{LCIN} + \text{LCLC} - \text{LCL} \tag{5.8}$$

Using variable names from the Fortran code, the flow volumes (FIN) and salt loads (LIN) entering a control point include the following inflows described in Table 5.1.

FNAT, LNAT – monthly volume and load from incremental naturalized inflow

FREG, LREG – monthly volume and load from upstream regulated flows

RET(cp), LRET – monthly volume and load from return flows entering cp

CINF(cp,m), LCIN – monthly volume and load from *CI* record constant inflows

Since inflows include outflows from upstream control points, adjustments are made for:

FCLC, LCLC – monthly volume and load of channel loss credits

FCL, CLC – monthly volume and load of channel losses

Incremental naturalized flow volumes (FNAT) and upstream regulated flow volumes (FREG) are determined from NAT(cp) and REG(cp) read from the *SIM* simulation results (Table

5.2). Channel loss credits (FCLC) and channel losses (FCL) are also computed from CLC(cp) and CL(cp) amounts from the *SIM* output file associated with upstream control points. Return flows (RET(cp)) from the *SIM* output file are used directly without further manipulation.

The incremental naturalized flow (FNAT) entering a control point is computed as the cumulative flow (NAT(cp)) at that control point less the corresponding total flows at any control points located immediately upstream. If no control points are located upstream, the incremental (FNAT) and cumulative (NAT(cp)) naturalized flows are the same. Regulated flow (FREG) entering the control point is computed as the summation of regulated flows (REG(cp)) from upstream control points. Total inflow volumes originating at upstream control points are adjusted for channel loss credits (FCLC) and channel losses (FCL) that are likewise computed as summations of CLC(cp) and CL(cp) at upstream control points read from the *SIM* output file.

Salt loads and concentrations are either provided as input in the SIN file or computed within *SALT* based on combining volumes with concentrations or loads using Eq. 5.1 or Eq. 5.2. Loads and concentrations are determined as follows.

- Salinity concentrations of incremental naturalized flows are either read directly from the SIN input file or alternatively computed from loads read from the SIN file.

- If a control point is defined as an upstream boundary, concentrations of the regulated outflows are either read directly from the SIN file or alternatively determined from loads read from the SIN file. Otherwise, loads of entering regulated flows are based on regulated flow loads at upstream control points previously computed in the control point computational loop. The concentration of regulated flows at the control point under consideration in the control point loop is computed as the outflow concentration.

- Two options are provided by *CC* record field 5 for setting the salt concentration of the return flows entering the river system at this control point. A constant return flow concentration may be entered in the *CC* record field 5. Alternatively, the model may adopt the mean concentration of the outflows from upstream control points constrained by the limits specified in *CC* record fields 7 and 8.

- Two options are provided by *CC* record field 6 for setting the concentration of the *CI* record constant inflows entering the river system at this control point. A constant inflow concentration may be entered in the *CC* record field 6. Alternatively, *SALT* may use the mean concentration of the outflows from upstream control points constrained by the limits specified in *CC* record fields 7 and 8 in the same manner as for return flows.

- Loads of inflows originating from control points located upstream are adjusted for channel losses and loss credits based on concentrations at individual upstream control points determined from previously computed outflow volumes and loads. The limits from *CC* record fields 7 and 8 are applied. Estimating loads associated with channel losses/credits also includes application of an optional multiplier factor (CLF) from *CC* record field 11 that has a default value of 1.0. A CLF of 1.0 means that salt loads and stream flow volumes are lost to channel losses in the same proportion. CLF less than or greater than 1.0 increases or decreases the impact of channel losses on loads.

Outflow Volumes and Loads Leaving a Control Point

The total monthly flow volume (FOUT(cp)) and salt load (LOUT(cp)) that leaves a control point is defined by the following summations of outflows described in Table 5.1.

$$\text{FOUT(cp)} \;=\; \text{REG(cp)} + \text{DIV} + \text{FOTH} \tag{5.9}$$

$$\text{LOUT(cp)} \;=\; \text{REGL(cp)} + \text{LDIV} + \text{LOTH} \tag{5.10}$$

REG(cp), REGL(cp) – volume and load of regulated flows

DIV, LDIV – volume and load of diversions

FOTH, LOTH – volume and load of other reservoir releases for hydropower and instream flow requirements

FOUT(cp) is exclusive of the volume of net reservoir surface evaporation-precipitation (EVAP(cp)). The load and concentration of net evaporation are assumed to be zero. The concentration of the regulated flows (REGC(cp)), diversions (CDIV), and other reservoir releases (COTH) are assumed to be the same. The control point outflow concentration (COUT(cp)) is:

$$\text{COUT(cp)} \;=\; \text{REGC(cp)} = \text{CDIV} = \text{COTH} \tag{5.11}$$

Other Reservoir Releases

The flow volume (FOTH), load (LOTH), and concentration (COTH) of *other reservoir releases* refer to control point outflows other than net evaporation and the other terms in Eqs. 5.9 and 5.10. The *other releases* category includes releases made specifically for hydroelectric power generation or releases from storage for meeting instream flow requirements. Passing of reservoir inflows for downstream instream flow requirements and water supply releases that incidentally generate hydropower are not included in the category of *other releases*. The return flows in the *SIM* output file include the *other reservoir release* volumes to meet hydropower and instream flow requirements. Effects of return flows are reflected in the *SIM* regulated flow results. Return flows incorporating these *other reservoir releases* are included in *SALT* in the control point inflows and are reflected as inflows in the regulated flows. To maintain the volume balance, the *other reservoir releases* must also be included as separate identifiable quantities in the control point outflows.

The flow volume (FOTH) of the *other reservoir releases* leaving a control point is computed as follows based on a volume balance of inflows, outflows, and change in storage volume. FIN2 is a second estimate of inflows which is missing the amount of the *other releases*.

$$\text{FIN2} \;=\; \text{flow in} \;=\; \text{flow out} + \text{storage change} \tag{5.12}$$

$$\text{FIN2} \;=\; \text{REG(cp)} + \text{DIV} + \text{EVAP(cp)} + \text{STO(cp)} - \text{BSTO(cp)} \tag{5.13}$$

$$\text{FOTH} = \text{FIN2} - \text{FIN} \tag{5.14}$$

$$\text{LOTH} = \frac{\text{FOTH (COUT)}}{\text{CF}} \tag{5.15}$$

Computation of Outflow Loads and Concentrations

The final products of the *SALT* salinity accounting computations are the volume, load, and concentration of outflows leaving each control point during each month and the volume, load, and concentration of the end-of-month storage at each control point. These variables are listed below with their names from the Fortran code. The mean storage concentration (MC(cp)) is another related variable used in the computations discussed below.

FOUT(cp) – volume of the outflows leaving the control point
LOUT(cp) – load of the outflows leaving the control point
COUT(cp) – concentration of the outflows leaving the control point
STO(cp) – volume of the end-of-month storage at the control point
STOL(cp) – load of the end-of-month storage at the control point
STOC(cp) – concentration of the end-of-month storage at the control point
MC(cp) – mean concentration of the storage during a month

If a control point has no reservoir storage, complete mixing during the month is assumed. With reservoir storage, mixing over time is reflected by the lag parameter defined in the next subsection. Reservoir surface net evaporation-precipitation has volume but no salt load. The flow (FOUT(cp)) and load (LOUT(cp)) leaving a control point have the components summed in Eqs. 5.9 and 5.10 and described in Table 5.1.

For a control point with no reservoir or a reservoir that is empty at both the beginning and end of the month, the outflow concentration is determined as follows where CF is the conversion factor f_C in Eq. 5.1.

$$\text{COUT(cp)} = \frac{\text{LIN}}{\text{FOUT}}(\text{CF}) \tag{5.16}$$

$$\text{REGC(cp)} = \text{CDIV} = \text{COTH} = \text{COUT(cp)} \tag{5.17}$$

The total outflow load (LOUT(cp)) is the sum of the regulated flow load (REGL(cp)), diversion load (LDIV), and flow through hydropower turbines (LOTH) which are computed using Eq. 5.1.

$$\text{REGL(cp)} = \left(\frac{\text{REG(cp)COUT(cp)}}{\text{CF}}\right) \tag{5.18}$$

$$\text{LDIV} = \left(\frac{(\text{DIV})(\text{COUT(cp)})}{\text{CF}}\right) \tag{5.19}$$

$$\text{LOTH} = \left(\frac{(\text{FOTH})(\text{COUT(cp)})}{\text{CF}}\right) \tag{5.20}$$

$$\text{LOUT(cp)} = \text{REGL(cp)} + \text{LDIV} + \text{LOTH} \tag{5.21}$$

If the control point has storage, then loads and concentrations are determined for end-of-month storage as well as for outflows. The computational algorithms for determining the concentration of reservoir outflows vary with the options specified in *CP* record fields 5, 6, 7. Depending on TM(cp) selected in *CP* record field 5, outflow concentration (COUT(cp)) is set equal to either beginning-of-month storage concentration (BPC(cp)) or the mean storage concentration (MC(cp)) during the month. The total volume leaving the control point includes the reservoir water surface net evaporation-precipitation (EVAP(cp)) as well as FOUT(cp). The outflow load and concentration are determined based on Eqs. 5.17 through 5.21.

The minimum end-of-month storage concentration MINSC(I) entered in *CC* record field 9 sets a maximum concentration limit MAXCON for the outflow.

$$\text{MINSL} = \frac{\text{MINSC(I)} \times \text{STO(CP)}}{\text{CF}} \tag{5.22}$$

$$\text{MAXOUT} = \text{BSL(CP)} + \text{LIN} - \text{MINSL} \tag{5.23}$$

$$\text{MAXCON} = \left(\frac{\text{MAXOUT}}{\text{FOUT(CP)}}\right)\text{CF} \tag{5.24}$$

The outflow concentration (COUT(cp)) is set equal to either BPC(cp)) or MC(cp) if less than MAXCON. Otherwise, COUT(cp)) is set at the MAXOUT limit. This limit is determined with Eqs. 5.22-5.24 based on the load budget for the actual reservoir rather than the conceptual lag load budget described in the next subsection.

The option specified in *CP* record field 5 setting outflow concentrations to the mean storage concentration MC(cp) during the month is based on the following equations.

$$\text{LOUT} = \text{(FOUT)}\,\text{(MC)} \tag{5.25}$$

$$\text{STOL(cp)} = \text{BSL(cp)} + \text{LIN} - \text{LOUT} \tag{5.26}$$

$$\text{MC} = \left(\frac{\text{BSL(cp)} + \text{STOL(cp)}}{\text{BSTO(cp)} + \text{STO(cp)}}\right)\text{CF} \tag{5.27}$$

Eqs. 5.25, 5.26, and 5.27 are algebraically combined to obtain Eq. 5.28.

$$\text{MC} = \left(\frac{2 \times \text{BSL(cp)} + \text{LIN}}{\text{BSTO(cp)} + \text{STO(cp)} + \text{FOUT}}\right)\text{CF} \tag{5.28}$$

Depending on the CP record field 5 option selected, the outflow concentration COUT(cp) is set equal to either beginning period storage concentration (BPC(cp)) or mean concentration (MC) or maximum limit (MAXCON). The load budget is then completed as follows.

$$\text{LOUT(cp)} = \text{COUT(cp)}\,\text{FOUT(cp)} / \text{CF} \tag{5.29}$$

$$\text{STOL(cp)} = \text{BSL(cp)} + \text{LIN} - \text{LOUT(cp)} \tag{5.30}$$

In the *WRAP-SIM* simulation model, the volume of water leaving a reservoir includes diversions, regulated flow, other releases, and net evaporation. Net evaporation has no salt load in the *SALT* model. Thus, the salt load leaving reservoir storage consists of the loads of the diversions, regulated flow, and other releases. In both *SIM* and *SALT*, the regulated flow at a control point is the flow leaving the control point and entering the downstream river reach. Diversions typically represent withdrawals for water supply. Hydropower releases and releases from storage for instream flow requirements are treated in SIM similarly as diversions and in *SALT* as other releases. The storage concentrations computed by *SALT* are volume-weighted means for the total reservoir storage. The concentrations of the control point outflows are computed in *SALT* as the concentration of the reservoir storage either currently or during a specified past point in time.

Storage and outflow concentrations and loads for control points with reservoir storage are computed using combinations of Equations 5.21 through 5.28 and variations thereof. Algorithms in the model vary depending on whether the beginning-of-month versus mean storage concentration options are selected in *CP* record field 5 and on which reservoir outflow concentration lag options are selected in *CP* record fields 6 and 7.

Reservoir Lag Options

In the real-world, streams carry salt loads into the upper reaches of a reservoir, and mixing occurs over time. Inflows and their salt loads may require long periods of time to move through the reservoir and reach the outlet. Salt concentrations vary spatially, both horizontally and vertically, throughout a reservoir.

In the *WRAP-SALT* modeling strategy, the concentration of water supply diversions and spills and releases leaving reservoir storage is set equal to the concentration of the water in storage. The end-of-month storage concentration computed by *SALT* is a volume-weighted mean reflecting the total salt load and volume of the reservoir (Eq. 5.2). The *SALT* simulation procedures are based on the premise of complete mixing at each control point. However, the timing of the load inflows used to determine outflow concentrations is set by lag parameters entered in *CP* record fields 6, and 7. The following options are provided.

- If *CP* record fields 6 and 7 are left blank, the lag features are not activated for that control point. The simulation is based on complete mixing within each month at the control point.
- The lag options based on the variable LAG are controlled by LAG1(cp) and LAG2(cp) entered in *CP* record fields 6 and 7. A non-zero LAG1(cp) activates use of the LAG features. LAG2(cp) selects the manner in which LAG is determined.
    1. A negative one entered in *CP* field 7 for LAG2(cp) activates the option in which LAG is set equal to LAG1(cp) from field 6. Thus, the model-user sets a constant LAG that is applied during every month of the simulation.
    2. Otherwise, the variable LAG is computed in each month based on the concept of retention time. LAG2(cp) is a multiplier factor used in the computation of the retention time parameter.

The lag options are based on the premise that salt entering the reservoir in a particular month begins to reach the outlet LAG months later. Complete mixing occurs during the LAG months. Thus, the salt leaves the reservoir over a period of multiple months that begins LAG months after the month in which the quantity of salt entered the reservoir.

Salt load budgets result in end-of-month reservoir load for each month based on an accounting balance of inflow and outflow loads combined with the end-of-month storage load from the preceding month. With the lag features activated, two load budgets are maintained. The regular load budget maintained with or without the lag features reflect the actual total loads in storage with the corresponding volume-weighted mean storage concentrations. The second conceptual computational load budget based on lagged load inflows is maintained solely for the purpose of determining the outflow concentration each month. The timing of the load inflow to this *computational load-budget reservoir* is controlled by the LAG. With the exception of the timing of the salt load inflows, Equations 5.18-5.30 are applied in essentially the same manner for maintaining the salt load budgets both with and without the LAG.

The lag options are pertinent only for control points with significant reservoir storage. Without storage, complete mixing during the month without lag is the logical premise. Selection of the *CP* record reservoir lag parameters LAG1(cp) and LAG2(cp) are necessarily judgmental and may be somewhat arbitrary. They may be treated as calibration parameters in situations where observed data are available for calibration. Lag determined by calibration for reservoirs with observed data may be relevant to other reservoirs as well. The retention time option provides a conceptual basis that allows the model to be applied without calibration if necessary. Sensitivity analyses with alternative simulations with varying values for the lag may be made to investigate its effects on simulation results.

<u>*Computation of LAG Based on Retention Time*</u>

The variable LAG in months is computed based on retention time as outlined below. LAG1(cp) from *CP* record field 6 is a maximum upper limit on LAG. LAG1(cp) from *CP* record field 7 is a multiplier factor with a default of 1.0 that is incorporated in the computation of the retention time parameter.

Retention time is a representation of the time required for a monthly volume of water and its salt load to flow through a reservoir. Retention time is defined as follows.

$$\text{retention time in months} \quad = \quad \frac{\text{reservoir storage volume}}{\text{outflow volume per month}} \tag{5.31}$$

The computation of LAG is based on computing the parameter ZLAG for each cumulative set of L months from a L of 1 month to a L of MAXL=LAG1(cp) months, where L represents a time period extending backward from the current month.

$$\text{ZLAG} = \left(\frac{\big(\text{BSTO(cp)} + \Sigma\ \text{BSTO(cp,L)}\big)\,/\,(\text{L}+1)}{\Sigma\ \text{FOUT(cp,L)/L}} \right) \text{LAG2(cp)} \tag{5.32}$$

BSTO(cp) is the beginning-of-month storage for the current month. ∑BSTO(cp,L) and ∑FOUT(cp,L) are the summations for the preceding months L of the beginning-of-month storage and the outflow during the month. LAG2(cp) from *CP* record field 7 has a default of 1.0.

ZLAG is first computed for the month preceding the current month. Based on the results, either LAG is set or ZLAG is determined for a longer period of time.

If ZLAG < 1.0 then LAG = 0
If 1.0 ≤ ZLAG < 2.0 then LAG = 1 month

If ZLAG for one month is 2.0 or more, a second ZLAG is computed for the two month period preceding the current month.

If ZLAG < 3.0 then LAG = 2 months

Otherwise, ZLAG is computed for the three month period preceding the current month.

If ZLAG < 4.0 then LAG = 3 months

This procedure continues until the length of the preceding period reaches LAG1(cp) months. LAG is set equal to the limit LAG1(cp) from *CP* record field 6 if this limit is reached.

Incorporation of LAG in Load Budget Simulation

LAG may be treated as a monthly varying variable set based on retention time as outlined above. Alternatively, LAG may be a constant set by the model-user. LAG is applied in the same manner regardless of the option adopted for its determination.

A separate load budget for a conceptual computational reservoir is maintained for the sole purpose of computing the outflow concentration for the current month. The load inflow (ZLIN) for this load-budget for the current month is the actual load inflow (LIN) for the month that is LAG months earlier plus the inflow loads for any other months prior to LAG months ago that have not yet been activated. If LAG extends back to before the first month of the simulation, the load budget is based on setting the outflow concentrations equal to the storage concentration at the beginning of the current month and inflow load equal to outflow load.

Simplified Example

The lag represents physically the time required for salt entering the reservoir during a month to reach the outlet. The salt is assumed to be completely mixed during the lag time. The load entering the reservoir in a particular month leaves over multiple months beginning LAG months after entering.

The following hypothetical example illustrates the computational strategy by focusing on the salt load entering a reservoir in a single month. Several months are required for the *slug* of salt to pass through the reservoir. A constant inflow volume of 10,000 acre-feet/month and outflow of 10,000 acre-feet/month occur in every month of the simulation. The reservoir storage volume remains at a constant 50,000 ac-ft. The evaporation is zero. These quantities are provided by the *SIM* output file and of course typically unlike this example will vary monthly.

In month 1, the inflow has a concentration of 1,000 mg/l and load of

$$\text{LIN} = \frac{\text{FIN (CIN)}}{\text{CF}} = \frac{(10{,}000\text{ ac-ft})(1{,}000\text{ mg/l})}{735.48} = 13{,}597\text{ tons}$$

The inflow load of 13,597 tons in month 1 is the only salt entering the reservoir. The inflow concentration is zero in all other months of the simulation. The storage concentration is zero at the beginning of the simulation. Thus, this simplified hypothetical example is designed to demonstrate how the salt load in a particular month moves through the reservoir according to the model. Of course, in actual applications, salt inflow loads will be non-zero in every month. The parameters entered on the *CP* record for this example are as follows.

CP record field 5: Default results in use of mean concentration based on Eq. 5.28.
CP record field 6: Any integer greater than 5 for LAG1(cp) yields the same results.
CP record field 7: Default is a LAG2(cp) of 1.0.

The lag (LAG) computed by the repetitive algorithm based on Eq. 5.29 is 5 months. Beginning with L = 1 month, ZLAG = 5.0 which is greater than 2 months.

$$\text{ZLAG} = \left(\frac{\left(50{,}000 + 50{,}000\right)/(1{+}1)}{10{,}000\ /\ 1}\right)(1.0) = 5.0$$

After four more repetitions, L = 5 which is less than 6.0 and thus LAG = 5 months.

$$\text{ZLAG} = \left(\frac{\left(50{,}000 + 200{,}000\right)/(5{+}1)}{50{,}000\ /\ 5}\right)(1.0) = 5.0$$

With constant inflow volume, outflow volume, and storage volume, the retention time of 5 months and the LAG of 5 months are the same for every month of the simulation.

Simulation results are presented in Table 5.3. With no salt in the reservoir at the beginning and an inflow of 13,597 tons during month 1, the salt load at the end of month 1 is 13,597 tons, and the storage concentration is:

$$\text{STOC(cp)} = \left(\frac{\text{STOL(cp)}}{\text{STO(cp)}}\right)\text{CF} = \left(\frac{13{,}597\text{ tons}}{50{,}000\text{ ac-ft}}\right)735.48 = 200\text{ mg/l}$$

The end-of-month storage load and volume-weighted mean end-of-month storage concentration are tabulated in columns 3 and 4 of Table 5.3.

The lagged load budget to determine the outflow concentration is tabulated in columns 5 through 8. The mean outflow storage concentration (COUT(cp) = MC) computed with Eq. 5.28 is tabulated in column 8. The outflow load (Eq. 5.29) is shown in column 9. With a LAG of 5 months, the 13,597 tons of salt entering the reservoir in month 1 begins to affect the outflow concentration in month 6. The end-of-month storage load (column 2) decreases from 13,597 tons in month 5 to 1,112 tons in month 18, to 30 tons in month 36, and 2.7 tons in month 48.

Table 5.3
Simulation Results for the Example

				Computation of Outflow Concentration				
Month	Inflow Load (tons)	Storage Load (tons)	Storage Conc (mg/l)	Inflow Load (tons)	Storage Load (tons)	Storage Conc (mg/l)	Outflow Conc (mg/l)	Outflow Load (tons)
1	2	3	4	5	6	7	8	9
		0	0		0	0		
1	13,597			0			0	0
		13,597	200		0	0		
2	0			0			0	0
		13,597	200		0	0		
3	0			0			0	0
		13,597	200		0	0		
4	0			0			0	0
		13,597	200		0	0		
5	0			0			0	0
		13,597	200		0	0		
6	0			13,597		90.9	90.9	1,236
		12,361	181.8		12,361			
7	0			0		165.3	165.3	2,247
		10,113	148.8		10,113			
8	0			0		135.2	135.2	1,839
		8,274	121.7		8,274			
9	0			0		110.6	110.6	1,504
		6,770	99.6		6,770			
10	0			0		90.5	90.5	1,231
		5,539	81.5		5,539			
11	0			0		74.1	74.1	1,007
		4,532	66.7		4,532			
12	0			0		60.6	60.6	824
		3,708	54.5		3,708			
13	0			0		49.6	49.6	674
		3,034	44.6		3,034			
14	0			0		40.6	40.6	552
		2,482	36.5		2,482			
15	0			0		33.2	33.2	451
		2,031	29.9		2,031			
16	0			0		27.2	27.2	369
		1,662	24.4		1,662			
17	0			0		22.2	22.2	302
		1,360	20.0		1,360			
18	0			0		18.2	18.2	247
		1,112	16.4		1,112			
------	------	------	------	------	------	------	------	------
		36.7	0.54		36.7			
36	0			0		0.49	0.49	6.67
		30.0	0.44		30.0			

SALT Message File

The salt simulation results are written to two output files. The file with filename extension SAL is read by program *TABLES*. Additional information is provided in the message file, which has the filename extension SMS. The SMS file provides the following information that may be useful in tracking the simulation and dealing with various problems.

1. Trace messages track the simulation.
2. Error messages are written if errors or inconsistencies are detected in the input data. An error message is accompanied by termination of model execution.
3. Warning messages are activated by various situations that may be encountered during the simulation. For example, warning messages are written if the minimum or maximum concentration limits specified in *CC* record fields 7, 8, 9, and 10 are reached. Irregularities in input data may also generate a variety of warning messages.
4. A volume and load balance summary table is provided.
5. The components of detailed monthly control point volume and load balances are recorded as computed in the simulation if specified by *JC* record field 12.
6. A listing of control points with pertinent information is written if specified by *JC* record field 12.

The trace messages printed to the message (SMS) file during a successful execution of *SALT* are shown in Table 5.4. Some messages are printed only if certain options are activated, others are always found in the message file. The program contains routines that check the input data for blunders and inconsistencies. Numerous error and warning messages are possible. Program execution is terminated with an error message but continues with warning messages. The error and warning messages are inserted into the trace of Table 5.3 as problems are detected during model execution. The trace messages are designed primarily to track the reading of input data. The table discussed below tracks the simulation computations.

An option activated by *JC* record field 12 allows essentially any and all of the quantities computed during the simulation to be recorded in the SMS file. In a typical application, *TABLES* is used to organize results written by *SALT* to the SAL file without being concerned with this optional message SMS file table. However, the SMS file dataset with the variables listed in Tables 5.4 and 5.5 provides voluminous simulation results that may be useful to model users interested in tracking the computations in detail. The variables listed in Tables 5.5 and 5.6 are defined earlier in this chapter. These variables are components of the volume and load balances for a control point for a particular month of the simulation. For each month of the simulation, a set of three lines of data are written for each control point specified by *JC* record field 11 and *CO* records. The variables in the first line are listed in Table 5.5. The second and third lines of data consist of the volumes and loads listed in Table 5.6. The lengthy data listing is repeated for each salinity constituent.

Table 5.4 Trace Messages Written to SMS File

```
  WRAP-SALT Message File

** Starting to read input data.
** JC record from the SALT input file was read.
** Starting to read CP records from SIM input file.
** Read ___ CP records from SIM input file.
** Completed check of sequencing of CP records in SIM input file.
** Starting to read CO/CP/CC records from SALT input file.
** CO record from the SALT input file was read.
** Starting to read CO/CP/CC records from SALT input file.
** SALT CO/CP/CC records were read.
** Number of SALT CP records = ___
** Beginning-of-simulation storage is to be determined.
** Beginning storage was computed from data read from SIM output file.
** Beginning storage was read from BRS file.
** Beginning reservoir concentration was read from BRC file.
** Beginning the simulation for salt constituent ____
** Finished reading S_ records.
   (Last two messages are repeated for each salt constituent.)

***** Normal Completion of Program WRAP-SALT *****
```

Table 5.5 Variables in First Line of SMS File Data Set

	Description of Variable	Variable Name
1	year	YEAR
2	month (1, 2, 3, ... , 12)	M
3	control point identifier	CPID(cp,1)
4	naturalized flow from *SIM* output file	NAT(cp)
5	channel loss credits from *SIM* output file	CLC(cp)
6	channel losses from *SIM* output file	CL(cp)
7	concentration or load from SIN file	S(cp)
8	total load inflow	LIN
9	total flow inflow	FIN
10	inflow concentration	CIN=(LIN/FIN)CF
11	outflow concentration	COUT
12	beginning storage concentration	BPC(cp)
13	ending storage concentration	STOC(cp)
14	mean storage concentration	MC(cp)
15	lag time in months	LAG

Table 5.6 Monthly Volume and Load Budget by Control Point in SMS File Data Set

	Description of Variable	2nd Line Volume	3rd Line Load
1	incremental naturalized flows	FNAT	LNAT
2	regulated flow entering cp	FREG	LREG
3	return flows	RET(cp)	LRET
4	other inflows	CINF(cp,m)	LCIN
5	channel loss credits	FCLC	LCLC
6	channel losses	FCL	LCL
7	total inflows	FIN	LIN
8	regulated flows leaving outlet	REG(cp)	REGL(cp)
9	diversions	DIV	LDIV
10	hydropower and IF releases	FOTH	LOTH
11	net reservoir evaporation	EVAP(cp)	-0-
12	beginning-of-simulation storage	BSTO(cp)	BSL(cp)
13	end-of-simulation storage	STO(cp)	STOL(cp)
14	storage change = (13) – (12)	XSTO	XSTOL
15	inflows – outflows = (7) – (8) – (9) – (10) – (11)	XSUM	XSUML

Referring to variables listed at the bottom of Table 5.6, XSTO and XSUM should have the same values. XSTOL and XSUML should also be the same. These quantities are computed for volume and load balance comparisons as follows.

$$\text{storage change} = \text{ending storage} - \text{beginning storage} \tag{5.33}$$

$$\text{XSTO} = \text{STO(cp)} - \text{BSTO(cp)} \tag{5.34}$$

$$\text{XSTOL} = \text{STOL(cp)} - \text{BPL(cp)} \tag{5.35}$$

$$\text{storage change} = \Sigma\ \text{inflows} - \Sigma\ \text{outflows} \tag{5.36}$$

$$\begin{gathered}\text{XSUM} = \text{FNAT} + \text{FREG} + \text{RET(cp)} + \text{CINF(cp,m)} \\ + \text{FCLC} - \text{FCL} - \text{REG(cp)} - \text{DIV(cp)} - \text{FOTH} - \text{EVAP(cp)}\end{gathered} \tag{5.37}$$

$$\begin{gathered}\text{XSUML} = \text{LNAT} + \text{LREG} + \text{LRET} + \text{LCIN} \\ + \text{LCLC} - \text{LCL} - \text{REGL(cp)} - \text{LDIV(cp)} - \text{LOTH}\end{gathered} \tag{5.38}$$

Volume and Load Balance Summary Table in SMS File

A volume and load balance summary table providing the totals for the entire river basin system for the entire period-of-analysis is also provided in the *SALT* message file. All control points are reflected in this summary table regardless of the selection of control points for inclusion in the other *SALT* output. The variables listed in Table 5.7 are components of the volume and load balances expressed by Equations 5.39 through 5.46. The sum for all months of the incremental naturalized flow volumes (FNAT) and loads (LNAT) at all control points represent flows entering the system. Regulated flow volumes (REG(cp)) and loads (REGL(cp)) at the river basin outlet, or multiple outlets as defined by *SIM CP* records, represent river flows leaving the system. The other variables representing inflow and outflow or change in storage are also summed for all control points. The summation of all of the outflows and inflows for each month during the total period-of-analysis equals the change in reservoir storage contents, which is the total storage at the end of the simulation less the total storage at the beginning.

Table 5.7 SMS File Table of Total Volume and Load for the Entire River/Reservoir System and Period-of-Analysis

Description of Variable	Total Volume	Total Load
Incremental naturalized flows	Σ FNAT	Σ LNAT
Regulated flows at upstream boundary	Σ REG(cp)	Σ REGL(cp)
Return flows	Σ RET(cp)	Σ LRET
CI record constant inflows	Σ CINF(cp,m)	Σ LCIN
Channel loss credits	Σ FCLC	Σ LCLC
Channel losses	Σ FCL	Σ LCL
Regulated flows leaving river basin outlet	Σ REG(cp)	Σ REGL(cp)
Water supply diversions	Σ DIV	Σ LDIV
Other releases for hydropower and inst flow	Σ FOTH	Σ LOTH
Net reservoir evaporation	Σ EVAP(cp)	-0-
Summation of inflows minus outflows	Eq. 5.41	Eq. 5.42
Beginning-of-simulation storage	Σ BSTO(cp)	Σ BSL(cp)
End-of-simulation storage	Σ STO(cp)	Σ STOL(cp)
Change in storage	Eq. 5.43	Eq. 5.44
Volume and load balance differences	Eq. 5.45	Eq. 5.46
Negative inflows to control point	Σ FINNEG	Σ LINNEG
Negative incremental naturalized flows	Σ FNAT if < 0	–
Naturalized flows at river basin outlet(s)	Σ NAT(cp)	–

In general, volume and load balances may be expressed as Equations 5.37 and 5.38.

$$\text{change in storage} \;=\; \Sigma\ \text{inflows} \;-\; \Sigma\ \text{outflows} \tag{5.39}$$

$$\text{change in storage} \;=\; \text{total ending storage} \;-\; \text{total beginning storage} \tag{5.40}$$

The *SALT* simulation variables included in the SMS file summary table and listed in Table 5.7 are components of the volume and load balances reflected in the following equations.

$$\begin{gathered}\Sigma\ \text{inflow volume} - \Sigma\ \text{outflow volume} = \Sigma\text{FNAT} + \Sigma\text{RET(cp)} + \Sigma\text{CINF(cp,m)} \\ + \Sigma\text{REGL(boundary)} + \Sigma\text{FCLC} - \Sigma\text{FCL} - \Sigma\text{REG(cp)} - \Sigma\text{DIV(cp)} - \Sigma\text{FOTH} \\ - \Sigma\text{EVAP(cp)}\end{gathered} \tag{5.41}$$

$$\begin{gathered}\Sigma\ \text{inflow load} - \Sigma\ \text{outflow load} = \Sigma\text{LNAT} + \Sigma\text{LRET} + \Sigma\text{LCIN} + \\ \Sigma\text{REGL(boundary)} + \Sigma\text{LCLC} - \Sigma\text{LCL} + \Sigma\text{REGL(cp)} - \Sigma\text{LDIV(cp)} - \Sigma\text{LOTH}\end{gathered} \tag{5.42}$$

$$\text{change in storage volume} = \Sigma\ \text{STO(cp)} - \Sigma\ \text{BPSTO(cp)} \tag{5.43}$$

$$\text{change in storage load} = \Sigma\ \text{STOL(cp)} - \Sigma\ \text{BPL(cp)} \tag{5.44}$$

The volume and load balance differences in Table 5.6 represent losses or gains due to modeling approximations or failure to maintain perfect mass balances in the simulation.

$$\begin{gathered}\text{volume balance difference} = \\ [\Sigma\ \text{inflow volume} - \Sigma\ \text{outflow volume}] - [\Sigma\ \text{STO(cp)} - \Sigma\ \text{BPSTO(cp)}]\end{gathered} \tag{5.45}$$

$$\begin{gathered}\text{load balance difference} = \\ [\Sigma\ \text{inflow load} - \Sigma\ \text{outflow load}] - [\Sigma\ \text{STOL(cp)} - \Sigma\ \text{BPL(cp)}]\end{gathered} \tag{5.46}$$

Negative volumes and loads complicate the analysis. The physical or computational meaning of negative volumes and loads vary with different situations. The SMS file dataset represented by Table 5.7 includes the entry *negative inflows to control point*. Inflow volumes (FIN) and loads (LIN) are determined based on Eqs. 5.7 and 5.8. Negative values for FIN and LIN are recorded as the variables FINNEG and LINNEG. The summation of FINNEG and LINNEG for all control points and all time periods are included in the summary table. Options for dealing with negative control point total inflows are selected by *JC* record field 13.

Incremental naturalized flows (FNAT) are negative if the flows at upstream control points exceed the flow at the control point in question. The summation of negative incremental volumes is included in Table 5.7 for general information. The negative incremental naturalized flows generated in *SALT* may be different than the negative incremental flow adjustments in *SIM*. Whereas *SIM* looks at all control points located optionally either downstream or upstream in computing negative incremental naturalized flow adjustments, *SALT* considers only the upstream control point(s) located immediately adjacent to the control point being considered.

The last variable listed in Table 5.7 is naturalized flows at the one or more outlets. Outlets are defined by *SIM CP* records. The total naturalized flows NAT(cp) at outlets should be the same as the sum of the incremental flows ΣFNAT, which is the first entry in the table.

<u>*SALT Output SAL File*</u>

SALT writes its main final simulation results to a file with the filename extension SAL, which is read by *TABLES*. The *SIM* input and output files should contain exactly the same control points. The *SALT* computations are performed for all control points in the *SIM* files except those located above specified upstream boundary control points. However, only user-selected control points are included in the *SALT* output SAL file. The SAL file contains the data listed in Table 5.8. The volumes, loads, and concentrations are provided for each month of the hydrologic period-of-analysis for each user-selected control point.

Table 5.8 Variables in SAL File

Description of Variable	Variable Name
year and month	YEAR, M
control point identifier	CPID(cp,1)
total inflow volume to control point during month	FIN
total inflow load to control point during month	LIN
mean concentration of total inflow during month	CIN
end-of-month storage volume	STO(cp)
end-of-month storage load	STOL(cp)
end-of-month storage concentration	STOC(cp)
total outflow volume excluding evaporation	FOUT(cp)
total outflow load leaving control point during month	LOUT(cp)
concentration of outflow	COUT(cp)
total diversion target at control point during month	DT(cp)
total diversion shortage at control point during month	DS(cp)

Organizing Simulation Results with Program TABLES

Program *TABLES* reads the program *SALT* output file with filename extension SAL that contains the simulation results listed in Table 5.8. *TABLES* type 8 salinity routines organize these data and compute reliability indices and frequency relationships. The *8SUM* record develops a control point summary. The *8SAL*, *8FRE*, *8FRQ*, and *8REL* records described in Appendix E create salinity tables that are essentially identical in format to the corresponding type 2 record tables for water quantities described in the basic *Users Manual*. The *8SAL* record tabulates the variables listed in Table 5.8 in the same format as the tables created by *2NAT*, *2REG*, *2STO* and similar type 2 records. The data may be organized as tables with annual rows and monthly columns, tabulations to be read by Microsoft Excel, or HEC-DSS records to be read by HEC-DSSVue. *8FRE* and *8FRQ* records are analogous to *2FRE* and *2FRQ* records. The frequency computations are the same regardless of which variable is represented by the dataset.

The *8REL* record reliability table extends the *2REL* record table to consider a specified maximum acceptable concentration for each water quality constituent. The model-user specifies an allowable concentration limit for each constituent being considered. The water supply diversion target is considered met only if the concentration of each constituent is at or below its allowable limit. Volume and period reliabilities are shown in the *8REL* table both with and without consideration of the user-specified allowable salinity limits.

Salinity Simulation Example

The *Fundamentals Manual* presents a hypothetical example that deals only with water volumes. The following example adds salinity. The *SIM* input data and simulation results described in the *Fundamentals Manual* are adopted for the salinity example without change. The following discussion focuses on the salinity aspects of the modeling application added with the *SALT* simulation. The system schematic from the *Fundamentals Manual* is reproduced below as Figure 5.4 as well as earlier in Chapter 2 as Figure 2.1. The simulation period-of-analysis is 1940-1997.

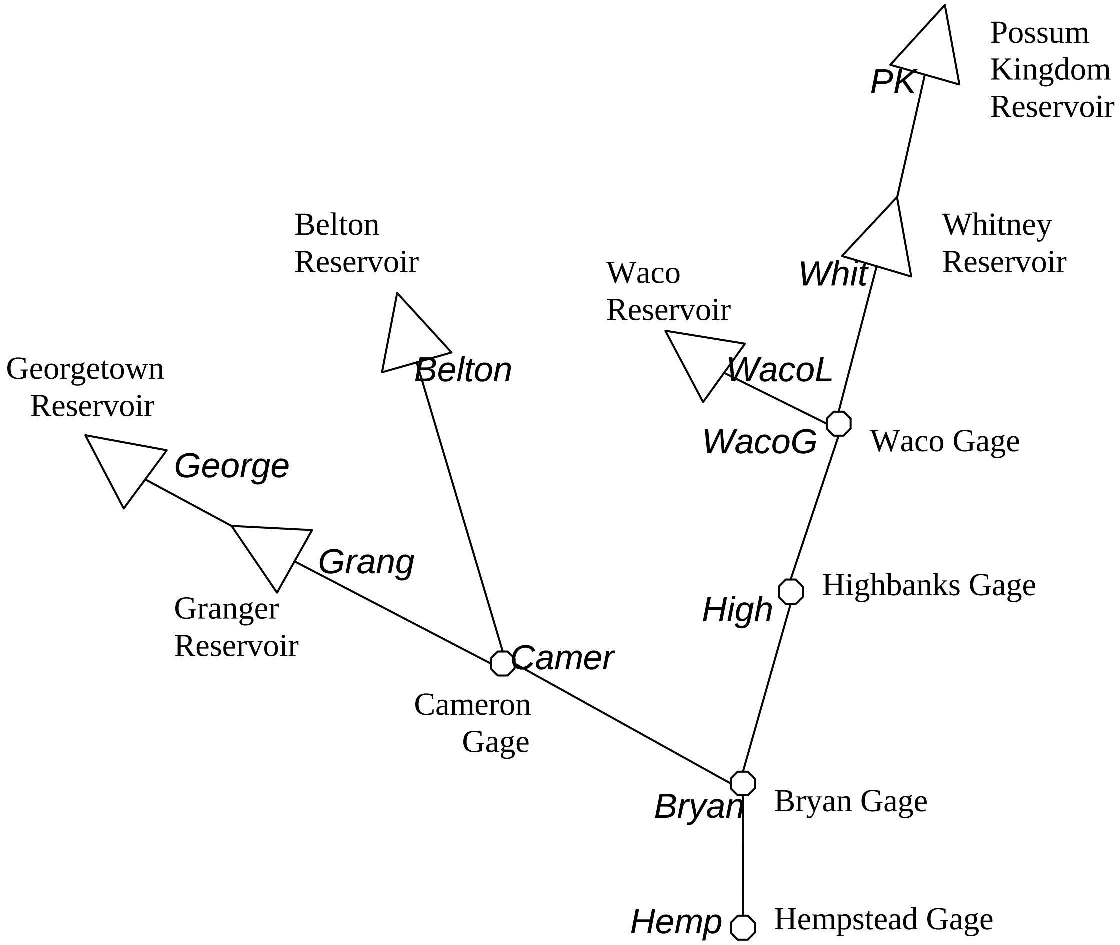

Figure 5.4 System Schematic for the Example

The river/reservoir system is represented spatially by the 11 control points shown in Figure 5.4. The *CP* records are entered in the *SIM* input file in the following upstream-to-downstream order: PK, Whit, WacoL, WacoG, High, Belton, George, Grang, Camer, Bryan, Hemp. The *SALT* computational algorithms require that the *SIM* output file include simulation results for all control points and that the results be organized by control point in upstream-to-downstream order.

The *SIM* input dataset and simulation results are described in the *Fundamentals Manual*. *SALT* reads the quantities listed in Table 5.2 from the main *SIM* output file. The beginning-of-simulation reservoir storage file generated by *SIM* and presented as Table 5.9 is also read by *SALT* to obtain initial storage volumes.

This example consists of tracking total dissolved solids (TDS) through the system. Salinity constituents such as chlorides and sulfates or other conservative water quality parameters may be modeled in exactly the same manner. Although this example is limited to the single water quality parameter TDS, multiple constituents may be included in a single input dataset and execution of *SALT* with each constituent being considered separately in turn within the model.

The majority of the total dissolved solids (TDS) load at the Hempstead gaging station (control point Hemp) representing the basin outlet originates from primary salt sources in the watershed above Possum Kingdom Reservoir (control point PK). The salinity SIN input file reproduced as Table 5.10 includes the following TDS input data.

- TDS loads of naturalized flows are provided on *S1* records for the PK control point. This represents a majority of the salt load entering the river/reservoir system.
- TDS concentrations of incremental naturalized flows at the Whit control point are entered as a constant 350 mg/l on a *CC* record.
- TDS concentrations of incremental naturalized flows at the Camer control point and all other control points located upstream are entered on *S1* records for the Camer control point.
- TDS concentrations of incremental naturalized flows at the Hemp control point and the Bryan, High, WacoG and WacoG control points located upstream are entered on *S1* records for the Hemp control point.
- Beginning-of-simulation storage TDS concentrations of 1,100 mg/l for Possum Kingdom Reservoir, 900 mg/l for Whitney Reservoir, and 300 mg/l for the four other reservoirs are entered in field 4 of the *CC* records.

The salinity input data provided by the *CC* and *J1* records for control point *Camer* are repeated internally within *SALT* for control points *Belton*, *George*, and *Grang*. The model also adopts the *CC* and *J1* record data entered for control point *Hemp* for the control points *Bryan*, *High*, *WacoG*, and *WacoL* located upstream.

Instructions for developing the SIN file are provided in Appendix D. The *SALT* message SMS file is presented as Table 5.11. With option 2 specified in *JC* record field 12, the total volume and load summary table described in Table 5.7 is included in the Table 5.11 SMS file, but the voluminous detailed listing outlined in Table 5.6 is not included. The beginning of the SAL file created by *SALT* and read by *TABLES* is reproduced as Table 5.12. Most of the lengthy SAL file is omitted from Table 5.12 for brevity.

TABLES input SIN, message TMS, and output TAB files are shown as Tables 5.13, 5.14, and 5.15. The TIN file input records for the salinity routines in *TABLES* are explained in

Appendix E. Table 5.15 illustrates the various formats into which *TABLES* organizes the SALT simulation results.

The summary activated by the *8SUM* record is the first table found in the TAB file of Table 5.15. The inflow and outflow volumes and loads for each control point are the 1940-1997 means of the 696 monthly quantities. The table also includes the 1940-1997 means of the end-of-month storage volumes and loads. The concentrations shown in the table are volume-weighted mean concentrations (Eq. 5.2) computed from the 1940-1997 total loads and volumes.

The frequency tables created by the *8FRE* and *8FRQ* records are based on the same computations regardless of the particular variable being analyzed. The means of the concentrations are the arithmetic averages of the N monthly mean concentrations, not volume-weighted mean concentrations like the *8SUM* record summary table. Option 2 in *8FRE* or *8FRQ* record field 4 specifies that months with zero volume are not counted in the frequency computations for concentrations. Thus, the total number of months (N) adopted may be less than 696 months for the 1940-1997 period-of-analysis. N is shown in the frequency tables.

A maximum tolerable TDS concentration of 1,000 mg/l is specified on the *8REL* record. The reliability table shows the volume and period reliabilities with and without considering the 1,000 mg/l TDS constraint. For example, monthly water supply diversion targets at the Hemp control point total to 1,119,703 acre-feet/year. Considering both water quality and quantity, diversion targets are fully met in 81.75 percent of the 696 months of the simulation. Considering only the diversion shortages determined in the *SIM* simulation, the period reliability is 85.34 percent. TDS concentrations exceed the 1,000 mg/l limit in 51 of the 696 months, resulting in a period reliability of 92.67 percent considering only water quality.

The *8SAL* record creates tables for any of the nine volume, load, or concentration variables for any or all control points. Tables with annual rows and monthly columns are included in the TAB file of Table 5.15. The means in the last row are arithmetic averages of 696 monthly quantities. Annual means of concentrations in the last column are arithmetic averages of 12 monthly concentration values. In additional to the table format shown in Table 5.15, *8SAL* record options also allow the data to be organized as columns for transport to spreadsheet programs or as HEC-DSS records for developing plots with HEC-DSSVue.

Table 5.9
Beginning Reservoir Storage BRS File for the Example

```
Beginning Reservoir Storage (BRS) File

             Control   Storage  Beginning
Reservoir     Point   Capacity   Storage

1      PK    1      PK  570240.0  570240.0
2    Whit    2    Whit  627100.0  627100.0
3   WacoL    3   WacoL  192100.0  192100.0
4  Belton    6  Belton  457600.0  457600.0
5  George    7  George   37100.0   37100.0
6   Grang    8   Grang   65500.0   65500.0
```

Table 5.10

SALT Input SIN File for the Example

```
**  SALT Input File Example.SIN
**
**       1         2         3         4         5
**345678901234567890123456789012345678901234567890
**     !   !   !   !   !   !   !   !   !   !   !
JC  1940  58   0   0   0   0   0   0   0   3   2
**
**       1         2         3         4         5         6         7
**3456789012345678901234567890123456789012345678901234567890123456789012
**     !       !       !       !       !       !       !       !       !
**   Possum Kingdom Dam on Brazos River
CP    PK       1       2       0       6
CC             0   1100.    -1.0    -1.0     0.0  20000.     50.  30000.
**   Whitney Dam on Brazos River
CP  Whit       2       0       0       6
CC          350.    900.    -1.0    -1.0     0.0  10000.     50.  30000.
**   Cameron Gage on Little River
CP Camer       1       0       0       3
CC             0    300.    -1.0    -1.0     0.0   5000.      0.   5000.
**   Hempstead Gage on Brazos River
CP  Hemp       1       0       0       3
CC             0    300.    -1.0    -1.0     0.0   5000.      0.   5000.
ED
**     !       !       !       !       !       !       !       !       !
**       1         2         3         4         5         6         7         8         9         1         11
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
**     !       !       !       !       !       !       !       !       !       !       !       !       !       !
S1    PK    1940     928   13016      21   31940   74062   81633   26291  265090   59279      36  108582   37860
S1    PK    1941    5090   40064  339660  670602 2205944  861018   31612    2883  104479 2332937  165265  101700
S1    PK    1942   40824   18429    7967  298351   30067   82899   31121   67624  270506  435414   87910   79669
S1    PK    1943   61421   17884   54729  161795  191282  493500   30514       0       0    1256    1201   18898
S1    PK    1944   27213   65211   41720    3363  154236   38514   79872    4685   37130   47885   24741   50523
S1    PK    1945   24836   21387   71149   33383    5843  118308  684240    7154   45659  215594    6021    6780
S1    PK    1946    7080    7647    3312    8738   38963  265481   47184   48007  242401  293137   33911  234635
S1    PK    1947   42578   12408   12278   20419 2443073  105948     499       1    3123   17184   19445   54909
S1    PK    1948    3669   44143   18983     766   35899  386343  217871   12140    4361   30934  131521    3337
S1    PK    1949   33868   57965   21043   28601  723565  682934   25212   16017  335150   61953   16603   20921
S1    PK    1950   16783   18758    2666   91378 1318480   68340  194072   73273  375972   75904   13640   20517
S1    PK    1951   18414   31842   15423    4212  225355  139462    5274  152288   22875       0    1407    2604
S1    PK    1952    4735   10351    7552   18656   63332   18786   33457     475     151       0    5564   11548
S1    PK    1953       0   20495   49610    5491   58325    3882  176571  224400    4121  441901   88202   34665
S1    PK    1954   23409   11400    3671  424353  835632   96876    3518       0      12       0    4797    6161
S1    PK    1955    5093   49184  253200    5000  592617  224832  169509   15138  768868 1319777   73766   59239
S1    PK    1956   51409   43294   10326    6749   93725   19806      54    7069       0    3576    1220    7371
S1    PK    1957    1347  166163   19999  332185  643879  888724  107817   45142   14461  167265  381142   29577
S1    PK    1958   32693   16692   38122   57833  484360   40314   42015   15762   46205   10621   27854    8091
S1    PK    1959    5432    5764    2018   43170   15142  200630  408259  103358    1723  467663   24610  209971
S1    PK    1960   80130   33150   21303   11163    9153   91760  749421    3700    1647  509406  143607  149282
S1    PK    1961   97961  109152  104393   47749  219187  980228  366383   42146   20809   12342   55694   23438
S1    PK    1962   17110   10040    7953   18521   13095  121264   29566   29030  389381   24831  178683  130492
S1    PK    1963   49546   31850   36065   53150  233097  317257   15689    2588   28697   16510   39630   30410
S1    PK    1964   16830   48320   13250    2840    6710   59280     170      30   60350   19330   16380    5500
S1    PK    1965    6070    4340    1590   54230  494990   90230    5450   78450   52750  312560   31100   15680
S1    PK    1966   25110   22700   49370  226110  261930   98510    1920  163120  766980  112390   41410   39480
S1    PK    1967   33690   19930   40340  337820   77660  268740  205770   28690   89830   27180    9590   11880
S1    PK    1968  133570   82910  182740  168590  130200  331330  198890   62370    7650    6860   16010   43710
S1    PK    1969    6550    8470   46260   26580  395070   78750    2630    2110  287810  155830  135760   58750
S1    PK    1970   67550   31290  236220   69610   60350   58120      72       1    3260   19770    2910    2000
S1    PK    1971    2260    2090    1510    1290  341610  105770    5380  214990  250800  170350  112850   94130
S1    PK    1972   39100   37420   38050   20640  106890   73480   51280  533220  434630  159000  211000  127000
S1    PK    1973  150000  163000  239000  133000   60200   94300   12300   13800   61600   26300   14100   13400
```

S1	PK	1974	11700	10600	15800	8810	46800	96600	343	23800	157000	137000	109000	63400
S1	PK	1975	63700	90600	46200	37200	140000	74800	134000	64000	110000	45900	67000	36400
S1	PK	1976	39400	22800	22300	83700	65700	11400	53000	41800	73200	108000	91000	50400
S1	PK	1977	55800	43400	28600	154000	222000	73200	18900	43300	16200	751	1170	2280
S1	PK	1978	5600	12300	14400	1000	50700	45900	3770	115000	105000	44400	31300	30400
S1	PK	1979	34500	31400	59200	45100	61300	126000	51100	90100	12600	132	18400	18000
S1	PK	1980	14900	28400	10800	7410	294000	102000	18300	31500	160000	95300	52100	72500
S1	PK	1981	52200	47200	97900	74700	82100	117000	7850	25400	10900	190000	66200	51500
S1	PK	1982	36500	51800	53100	19500	321000	295000	103000	44000	37800	18600	8190	24100
S1	PK	1983	46600	59600	37700	41300	177000	80800	24700	208	1490	299000	219000	114000
S1	PK	1984	84800	48300	50300	24900	19400	7000	747	24800	14300	53300	77900	91800
S1	PK	1985	96200	96200	120000	139000	188000	142000	63100	13100	11100	174000	88500	60200
S1	PK	1986	34700	38300	23700	44100	76400	131000	101000	90800	186000	649272	136590	159496
S1	PK	1987	133060	270576	231108	41784	730030	327723	18685	877	18642	20090	9632	20915
S1	PK	1988	28108	22048	14780	17678	11578	6854	72809	2965	149250	15714	18036	12700
S1	PK	1989	16483	93972	34142	18202	434472	509917	5108	4918	226595	30595	18098	23067
S1	PK	1990	84335	36701	217124	468536	322306	486212	36281	120387	39519	39339	36976	28784
S1	PK	1991	65618	55979	17710	20063	305765	893534	64250	151800	164138	85970	58653	316431
S1	PK	1992	198306	482375	355222	215773	303938	1026303	92713	10927	34226	8470	42374	72476
S1	PK	1993	73328	186155	162334	71136	81908	126835	273	4	7871	12000	5155	9227
S1	PK	1994	5749	10584	6943	2832	404972	30868	2974	3811	46540	20553	63227	31489
S1	PK	1995	29897	17577	39133	13242	337006	297611	25415	157531	94029	26090	32524	29047
S1	PK	1996	25009	15818	12880	12411	7044	18585	10253	67255	270391	42796	29800	38430
S1	PK	1997	14873	150834	47842	140626	274793	149690	13195	71108	17771	11995	9728	72015
S1	Hemp	1940	370	230	374	278	246	206	246	121	238	0	183	155
S1	Hemp	1941	131	183	144	0	75	0	0	4138	125	68	95	133
S1	Hemp	1942	68	221	315	163	72	215	122	164	76	66	191	172
S1	Hemp	1943	212	267	322	395	258	230	91	369	0	510	397	361
S1	Hemp	1944	330	246	107	50	73	40	3217	0	212	287	80	0
S1	Hemp	1945	266	327	0	207	243	205	251	203	169	253	259	174
S1	Hemp	1946	106	183	163	149	66	109	3	556	173	303	196	283
S1	Hemp	1947	168	189	156	244	262	284	54	8	184	2734	245	332
S1	Hemp	1948	310	355	144	126	79	0	0	207	0	0	344	885
S1	Hemp	1949	0	295	192	136	164	109	0	285	0	208	56	314
S1	Hemp	1950	202	130	108	0	501	110	279	324	133	280	368	348
S1	Hemp	1951	341	264	306	316	583	0	0	0	315	318	270	447
S1	Hemp	1952	449	234	626	266	144	255	299	178	575	471	204	250
S1	Hemp	1953	207	307	395	358	124	185	247	4	409	328	171	151
S1	Hemp	1954	411	379	0	386	366	361	162	282	604	505	514	336
S1	Hemp	1955	237	179	250	207	253	20	223	2412	252	0	186	0
S1	Hemp	1956	321	264	294	299	147	414	219	221	354	848	312	216
S1	Hemp	1957	446	175	262	211	114	70	0	0	420	163	84	0
S1	Hemp	1958	99	314	125	0	53	105	278	26	246	0	580	494
S1	Hemp	1959	152	167	196	117	0	106	572	410	446	300	225	155
S1	Hemp	1960	148	179	155	294	136	198	125	259	268	345	184	155
S1	Hemp	1961	208	161	163	64	250	119	29	140	306	154	134	162
S1	Hemp	1962	160	240	136	263	104	126	135	0	91	286	235	188
S1	Hemp	1963	282	222	336	239	405	127	417	239	312	0	307	326
S1	Hemp	1964	232	271	204	0	111	0	0	2734	147	107	120	135
S1	Hemp	1965	55	144	249	197	69	202	148	149	115	72	197	145
S1	Hemp	1966	240	199	270	328	161	228	99	325	0	424	405	416
S1	Hemp	1967	526	443	196	59	124	56	2043	0	267	298	87	0
S1	Hemp	1968	294	347	0	251	199	154	197	261	182	298	228	168
S1	Hemp	1969	138	187	176	123	77	142	3	415	0	369	289	297
S1	Hemp	1970	218	196	147	225	267	296	57	13	186	1658	232	416
S1	Hemp	1971	348	451	208	154	94	0	0	316	0	0	227	483
S1	Hemp	1972	0	293	243	201	152	122	0	266	0	345	55	359
S1	Hemp	1973	190	143	80	0	418	97	353	305	110	168	230	208
S1	Hemp	1974	170	166	231	301	281	0	0	0	168	198	123	239
S1	Hemp	1975	265	138	479	256	108	201	197	245	444	329	164	305
S1	Hemp	1976	281	327	454	224	135	134	141	3	423	167	162	129
S1	Hemp	1977	355	214	0	170	260	288	122	257	448	470	477	295
S1	Hemp	1978	171	176	194	291	238	19	248	1280	340	0	151	0
S1	Hemp	1979	172	189	169	158	95	181	277	107	172	361	243	162
S1	Hemp	1980	183	205	263	211	142	96	0	0	470	173	157	0
S1	Hemp	1981	153	457	175	0	68	70	237	26	263	0	398	453
S1	Hemp	1982	149	237	195	148	0	131	484	432	421	417	267	172
S1	Hemp	1983	177	162	128	253	122	214	155	221	205	330	320	243
S1	Hemp	1984	387	283	190	80	264	180	46	181	507	118	122	146
S1	Hemp	1985	136	202	98	203	103	126	129	0	162	261	140	147
S1	Hemp	1986	290	173	285	250	167	124	352	183	199	0	209	187

S1	Hemp	1987	151	208	156	0	101	0	0	3923	142	116	124	113
S1	Hemp	1988	60	205	249	247	122	300	170	166	121	76	306	224
S1	Hemp	1989	242	215	287	365	195	180	78	301	0	602	411	465
S1	Hemp	1990	481	323	121	55	87	46	3104	0	261	283	96	0
S1	Hemp	1991	250	316	0	236	240	220	279	257	201	420	223	142
S1	Hemp	1992	81	143	152	130	73	104	3	344	0	330	270	254
S1	Hemp	1993	173	161	147	203	222	218	42	12	233	1997	232	373
S1	Hemp	1994	287	303	144	132	66	0	0	348	0	0	232	438
S1	Hemp	1995	0	282	177	129	146	95	0	172	0	239	67	346
S1	Hemp	1996	265	214	142	0	769	221	492	341	91	266	368	230
S1	Hemp	1997	203	152	154	203	255	0	0	0	282	229	195	252
S1	Camer	1940	790	330	464	150	160	118	473	431	324	449	63	99
S1	Camer	1941	76	105	141	242	182	156	288	115	118	341	234	311
S1	Camer	1942	386	337	475	204	170	344	666	717	145	169	241	300
S1	Camer	1943	297	366	299	280	349	490	381	385	319	382	368	367
S1	Camer	1944	203	173	112	326	132	60	273	761	153	282	274	225
S1	Camer	1945	201	271	181	194	208	304	277	184	215	163	230	275
S1	Camer	1946	199	237	195	247	266	324	354	224	184	163	94	209
S1	Camer	1947	206	225	215	423	310	394	236	233	372	380	325	243
S1	Camer	1948	215	178	578	443	208	973	68	241	175	274	521	415
S1	Camer	1949	341	197	172	82	196	199	154	303	363	202	325	284
S1	Camer	1950	416	264	367	214	255	292	234	408	172	488	699	552
S1	Camer	1951	563	432	282	316	257	302	901	327	253	476	647	1025
S1	Camer	1952	1500	624	726	257	211	421	557	717	973	1276	387	268
S1	Camer	1953	250	243	254	223	200	307	420	377	243	156	314	207
S1	Camer	1954	471	498	402	347	523	1582	603	611	446	496	251	504
S1	Camer	1955	430	198	226	168	202	451	1983	322	214	187	341	464
S1	Camer	1956	347	315	444	540	203	655	0	507	0	649	369	309
S1	Camer	1957	425	321	168	84	117	270	480	260	159	97	130	118
S1	Camer	1958	153	106	93	81	56	141	819	405	185	209	294	274
S1	Camer	1959	323	201	213	228	262	120	281	159	268	108	169	110
S1	Camer	1960	124	126	200	203	224	293	274	254	310	95	153	159
S1	Camer	1961	110	93	70	71	2000	188	638	1653	388	89	190	155
S1	Camer	1962	145	142	240	226	391	174	231	332	238	18	180	216
S1	Camer	1963	550	278	337	213	194	199	1044	789	371	396	155	350
S1	Camer	1964	189	223	274	413	396	230	645	162	111	448	200	332
S1	Camer	1965	257	196	336	313	149	459	674	757	252	256	242	304
S1	Camer	1966	321	311	307	223	275	401	355	236	221	346	331	378
S1	Camer	1967	381	393	260	504	271	123	403	1376	204	301	278	344
S1	Camer	1968	187	329	202	283	194	335	254	224	240	303	285	350
S1	Camer	1969	339	340	272	233	309	450	466	213	284	176	167	262
S1	Camer	1970	312	231	195	453	318	359	238	250	247	256	342	290
S1	Camer	1971	239	254	806	590	273	1422	55	171	185	137	265	185
S1	Camer	1972	265	194	249	182	248	259	185	336	389	146	248	269
S1	Camer	1973	249	264	226	190	236	287	228	333	233	198	298	307
S1	Camer	1974	290	298	275	257	220	419	660	98	130	155	174	393
S1	Camer	1975	592	209	376	243	174	311	314	280	348	337	402	394
S1	Camer	1976	350	309	312	166	242	240	234	280	251	222	298	224
S1	Camer	1977	342	247	203	143	377	614	247	323	329	510	375	403
S1	Camer	1978	420	262	237	243	447	821	3063	468	388	331	232	387
S1	Camer	1979	180	196	140	223	181	290	191	280	398	424	478	339
S1	Camer	1980	283	218	191	193	168	542	855	457	205	319	334	223
S1	Camer	1981	296	264	151	122	99	103	766	427	199	165	269	281
S1	Camer	1982	329	250	204	242	197	127	342	239	549	393	384	270
S1	Camer	1983	291	182	218	262	187	252	324	237	378	279	371	507
S1	Camer	1984	327	307	134	150	2000	369	1910	4428	1099	92	252	168
S1	Camer	1985	131	117	178	235	364	202	310	482	569	17	177	186
S1	Camer	1986	506	208	308	234	177	120	920	466	197	187	86	105
S1	Camer	1987	83	128	162	319	230	127	325	119	135	503	228	285
S1	Camer	1988	350	315	430	413	403	439	853	883	387	444	513	575
S1	Camer	1989	377	354	303	331	243	296	290	278	382	451	458	533
S1	Camer	1990	365	349	149	238	159	79	264	709	189	300	322	439
S1	Camer	1991	215	340	278	280	205	335	338	189	193	176	184	143
S1	Camer	1992	138	147	154	217	222	241	228	135	179	167	138	227
S1	Camer	1993	256	180	188	385	259	274	167	211	297	220	240	226
S1	Camer	1994	188	155	495	491	155	671	66	221	156	111	228	160
S1	Camer	1995	210	161	132	82	164	157	119	149	201	143	309	286
S1	Camer	1996	364	367	381	292	377	300	291	208	135	262	294	199
S1	Camer	1997	217	135	127	99	130	165	284	97	210	239	280	286

Table 5.11
SALT Message SMS File for the Example

```
   WRAP-SALT Message File

 ** Starting to read input data.
 ** JC record from the SALT input file was read.
 ** Starting to read CP records from SIM input file.
 ** Read   11 CP records from SIM input file.
 ** Beginning-of-simulation storage is to be determined.
 ** Beginning storage was read from BRS file
 ** Starting to read CO/CP/CC records from SALT input file.
 ** SALT CO/CP/CC records were read.
 ** Number of SALT CP records =  4

 ** Beginning the simulation for salt constituent 1

 ** Finished reading S1 records.

Total Volume and Load Summary for Constituent 1

                                    Volume          Load    Concentration

Naturalized flows                310818880.     150458080.           356.
Regulated flows at boundary             0.             0.             0.
Return flows                      27026204.      23892158.           650.
CI record constant inflows              0.             0.             0.
Channel loss credits               6819712.       6416123.           692.
Channel losses                     2779890.       3005106.           795.
Regulated flows at outlet        206892992.      72600224.           258.
Diversions                       114416808.      87734784.           564.
Hydropower and IF releases        14551339.      17974328.           908.
Net evaporation                    6214698.             0.             0.
                                 ----------     ----------     ----------
Inflows - Outflows                 -190932.       -548081.             0.
                                 ----------     ----------     ----------
Beginning reservoir storage        1949640.       1927101.           727.
Ending reservoir storage           1758544.       1256870.           526.
                                 ----------     ----------     ----------
Change in storage                  -191096.       -670230.             0.
                                 ----------     ----------     ----------
Water balance difference               165.        122149.        544475.

Negative inflows to cpts             60833.         28916.           350.

Negative incremental nat flows     4060064.

Naturalized flows at outlet      310818816.

 ***** Normal Completion of Program WRAP-SALT *****
```

Table 5.12
First Portion of *SALT* Output SAL File for the Example

```
First year and number of years, control points and constituents:  1940   58   11    1   735.480

YearMon   CP    Flow In    Load In    Conc In    Storage   Sto Load   Sto Conc   Flow Out   Load Out   Conc Out Div Target   Shortage

Salinity constituent (IC) = 1

1940 1     PK   10094.00     928.00      67.62  497886.00  734121.19    1084.45   80013.70  119670.24    1100.00   13893.51       0.00
1940 1   Whit   64355.20   94566.45    1080.75  626401.81  784535.38     921.15   63257.39   77407.48     900.00    1170.00       0.00
1940 1  WacoL    1166.00     586.58     370.00  187198.70   76823.33     301.83    5198.00    2120.25     300.00    5198.00       0.00
1940 1  WacoG   62232.90   75722.16     894.90       0.00       0.00       0.00   62232.90   75722.16     894.90     161.50       0.00
1940 1   High   62829.30   75560.73     884.51       0.00       0.00       0.00   62829.30   75560.73     884.51     224.00       0.00
1940 1 Belton     996.00    1069.83     790.00  440913.41  180974.52     301.88   16545.69    6748.94     300.00   10654.95       0.00
1940 1 George     156.00     167.56     790.00   35304.70   14559.23     303.30    1817.40     741.31     300.00    1666.32       0.00
1940 1  Grang    1296.90     759.52     430.73   63147.10   26159.34     304.68    3229.80    1317.42     300.00    2732.73       0.00
1940 1  Camer   10071.90    5925.78     432.72       0.00       0.00       0.00   10071.90    5925.78     432.72    7298.33     460.50
1940 1  Bryan   66891.80   77257.41     849.45       0.00       0.00       0.00   66891.80   77257.41     849.45    4087.15    1652.65
1940 1   Hemp   74344.10   78706.14     778.63       0.00       0.00       0.00   74344.10   78706.14     778.63   64723.86     372.50
1940 2     PK   10172.00   13016.00     941.11  491928.09  724508.56    1083.21   15346.91   22628.65    1084.45   15346.86       0.00
1940 2   Whit   -2653.10    -420.84     116.66  603960.31  759013.00     924.30   20042.00   25101.55     921.15    1134.00       0.00
1940 2  WacoL    1315.00     411.23     230.00  183417.59   75166.22     301.41    5040.01    2068.34     301.83    5039.99       0.00
1940 2  WacoG    3197.30    2892.07     665.27       0.00       0.00       0.00    3197.30    2892.07     665.27     258.40       0.00
1940 2   High    6410.30    2223.78     255.14       0.00       0.00       0.00    6410.30    2223.78     255.14     358.40       0.00
1940 2 Belton    1663.00     746.17     330.00  432022.00  177174.66     301.62   11075.61    4546.02     301.88   11075.60       0.00
1940 2 George    1320.00     592.27     330.00   35123.30   14485.45     303.32    1615.10     666.05     303.30    1615.05       0.00
1940 2  Grang    3715.20    1638.42     324.35   64734.40   26700.34     303.36    2649.10    1097.42     304.68    2648.65       0.00
1940 2  Camer   20323.30    8944.76     323.70       0.00       0.00       0.00   20323.30    8944.76     323.70    7778.15       0.00
1940 2  Bryan   26064.50   10268.29     289.75       0.00       0.00       0.00   26064.50   10268.29     289.75    4880.80       0.00
1940 2   Hemp  131544.50   43017.78     240.52       0.00       0.00       0.00  131544.50   43017.78     240.52   65110.76       0.00
1940 3     PK     836.00      21.00      18.47  468528.19  698239.12    1096.07   17850.71   26290.41    1083.21   17850.77       0.00
1940 3   Whit    3858.10    2102.27     400.76  576762.50  731236.06     932.46   23775.41   29879.19     924.30    1224.00       0.00
1940 3  WacoL    1182.00     601.06     374.00  176488.59   73534.48     306.44    5448.40    2232.80     301.41    5448.48       0.00
1940 3  WacoG   24583.90   26605.44     795.96       0.00       0.00       0.00   24583.90   26605.44     795.96     581.40       0.00
1940 3   High   26138.40   26960.75     758.62       0.00       0.00       0.00   26138.40   26960.75     758.62     806.40       0.00
1940 3 Belton     989.00     623.94     464.00  417872.00  172686.06     303.94   12466.40    5112.54     301.62   12466.36       0.00
1940 3 George     464.00     292.73     464.00   33640.60   14080.37     307.84    1692.00     697.81     303.32    1691.95       0.00
1940 3  Grang    1845.10     985.75     392.93   15506.20    6893.70     326.98   50410.70   20792.39     303.36    2774.77       0.00
1940 3  Camer   54376.20   23032.11     311.53       0.00       0.00       0.00   54376.20   23032.11     311.53    9258.41       0.00
1940 3  Bryan   76555.30   48671.42     467.59       0.00       0.00       0.00   76555.30   48671.42     467.59    5692.08       0.00
1940 3   Hemp   81114.90   50431.45     457.27       0.00       0.00       0.00   81114.90   50431.45     457.27   70010.45       0.00
1940 4     PK   16772.00   31940.00    1400.62  461626.00  698762.06    1113.29   21081.29   31417.06    1096.07   21081.35       0.00
1940 4   Whit   25712.20   13510.21     386.45  580115.38  714429.00     905.77   23912.72   30317.24     932.46    1296.00       0.00
1940 4  WacoL   36755.00   13892.82     278.00  192100.00   78701.69     301.32   21646.79    8725.61     296.46    5782.47       0.00
1940 4  WacoG   64323.60   37022.58     423.32       0.00       0.00       0.00   64323.60   37022.58     423.32    1033.60       0.00
1940 4   High   87749.10   45747.54     383.44       0.00       0.00       0.00   87749.10   45747.54     383.44    1433.60       0.00
1940 4 Belton   29935.00    6105.20     150.00  433879.19  172708.53     292.76   14067.51    6082.73     318.02   14067.44       0.00
1940 4 George    4019.00     819.67     150.00   35883.20   14144.94     289.92    1768.90     755.10     313.96    1768.86       0.00
1940 4  Grang    9793.10    2193.71     164.75   22462.90    5294.82     173.36    2900.80    3792.59     961.59    2900.90       0.00
1940 4  Camer   70101.60   16615.72     174.33       0.00       0.00       0.00   70101.60   16615.72     174.33   11152.28       0.00
1940 4  Bryan  151132.69   61083.54     297.26       0.00       0.00       0.00  151132.69   61083.54     297.26    6641.35       0.00
1940 4   Hemp  113687.00   46889.28     303.34       0.00       0.00       0.00  113687.00   46889.28     303.34   75406.56       0.00
1940 5     PK  114403.00   74062.00     476.13  548220.31  736632.94     988.25   23909.09   36191.12    1113.29   23909.15       0.00
1940 5   Whit   24584.00   19198.30     574.36  577149.62  704181.88     897.36   23909.65   29445.43     905.77    1530.00       0.00
1940 5  WacoL       0.00       0.00       0.00  182267.20   76162.09     307.33    6874.20    2539.60     271.72    6874.22       0.00
1940 5  WacoG   17167.50   24577.09    1052.92       0.00       0.00       0.00   17167.50   24577.09    1052.92    2422.50       0.00
1940 5   High   42672.90   31631.73     545.18       0.00       0.00       0.00   42672.90   31631.73     545.18    3360.00       0.00
1940 5 Belton    6951.00    1512.16     160.00  421926.41  167450.55     291.89   16217.88    6770.15     307.03   16217.97       0.00
1940 5 George    4673.00    1016.59     160.00   37100.00   13914.85     275.85    3199.80    1246.68     286.55    2102.12       0.00
1940 5  Grang   12499.70    3086.73     181.62   31212.60    5277.68     124.36    3447.80    3103.87     662.11    3447.45       0.00
1940 5  Camer  102942.10   24204.65     172.93       0.00       0.00       0.00  102942.10   24204.65     172.93   16925.62       0.00
1940 5  Bryan  133123.00   52682.32     291.06       0.00       0.00       0.00  133123.00   52682.32     291.06    8845.38       0.00
1940 5   Hemp  227125.50   84000.85     272.01       0.00       0.00       0.00  227125.50   84000.85     272.01   93410.58       0.00
1940 6     PK  289797.00   81633.00     207.18  570240.00  460747.59     594.26  266073.91  357518.34     988.25   26687.95       0.00
1940 6   Whit  307173.50  356838.47     854.40  627100.00  747764.56     877.00  256745.42  313255.81     897.36    1674.00       0.00
1940 6  WacoL   61991.00   17363.01     206.00  192100.00   76525.04     292.99   53133.60   17000.06     235.32    7577.25       0.00
1940 6  WacoG  332645.72  327730.34     724.61       0.00       0.00       0.00  332645.72  327730.34     724.61    6104.70       0.00
1940 6   High  360924.50  332228.03     677.00       0.00       0.00       0.00  360924.50  332228.03     677.00    8467.20       0.00
1940 6 Belton   99398.00   15947.36     118.00  457600.00  159052.44     255.64   65379.80   24345.46     273.87   17954.70       0.00
```

Table 5.13
TABLES Input TIN File for the Example

```
COMM   TABLES Input File Example.TIN
**       1         2         3         4         5         6         7         8
**  56789012345678901234567890123456789012345678901234567890123456789012345678901234
**     !   !   !   !   !   !       !       !       !       !       !       !       !
8SUM
8FRQ   9   0  -1   7    Hemp    100.    200.    400.    600.    800.   1000.   2000.
8FRE   7
8FRE   8
8FRE   9   0  -1
8FRE   6   0  -1
8REL   0   0   0   1000.
8SAL   1   0   0   9   0   2      PK    Hemp
**     !   !   !   !   !   !       !       !       !       !       !       !       !
ENDF
```

Table 5.14
TABLES Message TMS File for the Example

```
  TABLES MESSAGE FILE

*** File was opened: example.TIN
*** File was opened: example.TAB
*** Identifiers for the 14 records in the TIN file were checked.
*** File was opened: example.SAL
*** Tables are being developed as specified by a 8SUM record.
*** Tables are being developed as specified by a 8FRQ record.
*** Tables are being developed as specified by a 8FRE record.
*** Tables are being developed as specified by a 8FRE record.
*** Tables are being developed as specified by a 8FRE record.
*** Tables are being developed as specified by a 8FRE record.
*** Tables are being developed as specified by a 8REL record.
*** Tables are being developed as specified by a 8SAL record.

    Program TABLES output is in file example.TAB

  ***** Normal Completion of Program TABLES *****
```

Table 5.15
TABLES Output TAB File for the Example

CONTROL POINT SUMMARY

```
----------------------------------------------------------------------------------------------
CONTROL   MEAN MONTHLY VOLUME (AC-FT)    MEAN MONTHLY LOAD (TONS)      MEAN CONCENTRATION (MG/L)
 POINT      Inflow   Outflow   Storage    Inflow   Outflow   Storage    Inflow   Outflow   Storage
----------------------------------------------------------------------------------------------
PK          66124.    63714.   382645.   109440.   109796.   599526.    1217.1    1267.3    1152.2
Whit        93795.    90399.   545641.    92848.    93400.   650135.     728.0     759.8     876.2
WacoL       29736.    28370.   170128.     7076.     7057.    67712.     175.0     182.9     292.7
WacoG      131271.   131271.        0.    99312.    99302.        0.     556.4     556.3       0.0
High       161414.   161414.        0.   104696.   104696.        0.     477.0     477.0       0.0
Belton      42105.    40996.   273198.    11571.    11587.   114958.     202.1     207.8     309.4
George       4827.     4747.    18424.     1346.     1315.     6898.     205.1     203.7     275.3
Grang       14802.    14507.    37313.     4121.     4044.    13405.     204.7     205.0     264.2
Camer       96480.    96480.        0.    26647.    26647.        0.     203.1     203.1       0.0
Bryan      278001.   278001.        0.   134791.   134791.        0.     356.6     356.6       0.0
Hemp       385613.   385613.        0.   157972.   157972.        0.     301.3     301.3       0.0
----------------------------------------------------------------------------------------------
```

CONCENTRATION FREQUENCY FOR OUTFLOWS FROM CONTROL POINT Hemp

```
------------------------------------------------------------------------------------------------------------------
     CONC  FREQ(%)      CONC  FREQ(%)      CONC  FREQ(%)      CONC  FREQ(%)      CONC  FREQ(%)      CONC  FREQ(%)      CONC  FREQ(%)
------------------------------------------------------------------------------------------------------------------
    100.0   97.70      200.0   83.48      400.0   40.66      600.0   20.69      800.0   11.35     1000.0    7.33     2000.0    0.43
------------------------------------------------------------------------------------------------------------------
```

VOLUME FREQUENCY FOR CONTROL POINT OUTFLOWS

```
-------------------------------------------------------------------------------------------------------------------------------
CONTROL           STANDARD         PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT   N     MEAN DEVIATION   100%     99%     98%     95%     90%     75%     60%     50%     40%     25%      10%   MAXIMUM
-------------------------------------------------------------------------------------------------------------------------------
PK     696   63714. 121000.       0.0    52.8  1208.6 13893.4  13894.  17851.  21228.  24498.  28897.  70562.  134966.  1806064.
Whit   696   90399. 179717.   -2822.1    -0.2   449.5 19317.0  23568.  24701.  26832.  34644.  58621.  80415.  196789.  2972162.
WacoL  696   28370.  51750.    5039.9  5040.0  5040.0  5198.0   5448.   5782.   7577.   8354.   9668.  22990.   77724.   531638.
WacoG  696  131271. 237851.   -2570.2  2367.5  3187.2  6418.2  20300.  33201.  46683.  61983.  76708. 119660.  305894.  3365316.
High   696  161414. 269593.    -351.9  3568.2  4743.9 11856.7  26109.  42673.  61456.  74125.  99046. 142451.  384858.  3585813.
Belton 696   40996.  65871.       0.0     0.0     0.0  1631.7  10655.  12466.  15309.  17241.  19790.  36201.  109511.   540670.
George 696    4747.   7852.       0.0     0.0    13.4    72.8    181.   1615.   1769.   2015.   2564.   2846.   13006.    67167.
Grang  696   14507.  23278.      -7.3    17.7   154.2   425.6   2014.   2901.   3590.   4204.   4944.  14698.   44455.   202749.
Camer  696   96480. 151175.      42.0  1249.0  1868.6  6941.2  11194.  19751.  29284.  39839.  60988. 108727.  229163.  1400337.
Bryan  696  278001. 431061.    5926.7 11889.3 20698.2 38334.3  51166.  74851. 106729. 125694. 144451. 278046.  679424.  4532039.
Hemp   696  385613. 538190.   11059.0 18823.5 27822.0 66950.7  75829. 104515. 138505. 155919. 220078. 469571.  980193.  5550107.
-------------------------------------------------------------------------------------------------------------------------------
```

LOAD FREQUENCY FOR CONTROL POINT OUTFLOWS

```
-------------------------------------------------------------------------------------------------------------------------------
CONTROL           STANDARD         PERCENTAGE OF MONTHS WITH LOADS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT   N     MEAN DEVIATION   100%     99%     98%     95%     90%     75%     60%     50%     40%     25%      10%   MAXIMUM
-------------------------------------------------------------------------------------------------------------------------------
PK     696  109796. 167161.       0.0     0.0  1160.4  8308.6  19360.  34511.  46719.  55215.  70872. 119670.  278706.  2565704.
Whit   696   93400. 150154.   -6537.0    -0.7     0.2 10603.0  20365.  31162.  42408.  53536.  65241.  99994.  200497.  2450901.
WacoL  696    7057.  12321.       0.0   892.5  1128.2  1466.5   1658.   2095.   2583.   2998.   3523.   6268.   18993.   218615.
WacoG  696   99302. 164430.       0.0  1303.9  2331.5  4299.2  12487.  29349.  40977.  50587.  68135. 109497.  227164.  2697715.
High   696  104696. 167160.       0.0  1144.0  2509.4  5974.8  14434.  32376.  44325.  58566.  76417. 109308.  250577.  2712608.
Belton 696   11587.  14344.       0.0     0.0     0.0     0.0   1318.   3846.   5433.   6414.   7855.  12803.   30292.   107001.
George 696    1315.   2047.       0.0     0.0     0.0    11.7     58.    288.    646.    838.    949.   1303.    3102.    20139.
Grang  696    4044.   5681.       0.0     0.0     0.0    65.2    262.   1019.   1606.   2029.   2591.   4737.   10195.    44867.
Camer  696   26647.  31370.       0.0   750.7  1260.3  3200.8   4813.   7440.  10728.  15077.  20352.  34543.   64183.   249402.
Bryan  696  134791. 185978.   -4910.8  5927.0 10228.0 20025.4  32567.  50593.  67248.  80471.  97378. 141666.  286029.  2820282.
Hemp   696  157972. 199209.  -10056.7  8623.7 12697.7 31053.7  41293.  60515.  79789.  95446. 115471. 177258.  345824.  2895318.
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CONCENTRATION FREQUENCY FOR CONTROL POINT OUTFLOWS

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CONTROL              STANDARD      PERCENTAGE OF MONTHS WITH CONCENTRATION EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT   N     MEAN DEVIATION   100%      99%      98%      95%      90%      75%      60%      50%      40%      25%      10%   MAXIMUM
------------------------------------------------------------------------------------------------------------------------------
PK      689   1879.   5402.      0.0     21.4     79.8    339.0     701.     997.    1240.    1415.    1639.    2050.    2872.  138417.
Whit    687   1001.    539.      0.0     94.3    223.7    394.2     496.     654.     803.     889.     978.    1199.    1687.    3732.
WacoL   696    252.    115.      0.0     26.7     51.0    101.8     142.     186.     218.     243.     263.     298.     389.    1098.
WacoG   693    719.    449.      3.5     82.8    134.7    216.3     272.     403.     545.     631.     743.     912.    1231.    3519.
High    695    623.    418.     11.8     82.1    135.7    181.8     227.     330.     448.     529.     610.     790.    1150.    2496.
Belton  673    260.    150.      0.0      0.0      0.0     67.5     108.     173.     224.     259.     288.     336.     398.    2000.
George  686    287.    243.      0.0      0.0      0.0     40.4      94.     176.     227.     261.     298.     372.     429.    4428.
Grang   690    313.    213.      0.0      0.0      0.0     33.5      84.     177.     243.     289.     329.     420.     521.    1910.
Camer   696    294.    240.      0.0     79.3     97.7    117.4     147.     199.     238.     261.     283.     330.     428.    4428.
Bryan   696    516.    377.   -133.4     85.2    139.8    177.3     203.     271.     345.     407.     482.     622.     959.    2738.
Hemp    696    457.    490.   -381.8     62.6     90.1    152.3     176.     232.     290.     339.     406.     539.     838.    9983.
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CONCENTRATION FREQUENCY FOR RESERVOIR STORAGE

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CONTROL              STANDARD      PERCENTAGE OF MONTHS WITH CONCENTRATION EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE
 POINT   N     MEAN DEVIATION   100%      99%      98%      95%      90%      75%      60%      50%      40%      25%      10%   MAXIMUM
------------------------------------------------------------------------------------------------------------------------------
PK      648   1077.    846.     50.0     50.0     50.0     50.0      50.     449.     743.     929.    1143.    1538.    2026.    4648.
Whit    696    868.    589.     50.0     50.0     50.0    132.7     232.     467.     616.     757.     891.    1138.    1747.    3297.
WacoL   696    294.    126.     45.5    132.8    140.1    150.3     194.     232.     249.     262.     284.     325.     422.    1111.
WacoG        There is no storage at this control point.
High         There is no storage at this control point.
Belton  633    778.  11070.      0.0     42.1    123.6    169.2     189.     243.     284.     313.     336.     363.     426.  278562.
George  517    259.    177.      0.0      0.0      0.0      0.0      35.     187.     234.     262.     293.     341.     386.    1992.
Grang   580    297.    601.      0.0      0.0      0.0      0.0       0.     124.     179.     211.     261.     337.     460.    9415.
Camer        There is no storage at this control point.
Bryan        There is no storage at this control point.
Hemp         There is no storage at this control point.
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RELIABILITIES WITH AND WITHOUT SALINITY CONSTRAINTS

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                    | Both Quantity & Quality |----- Quantity Only -----|+++++ Quality Only ++++++|Number Months
CONTROL   TARGET    |          *RELIABILITY* |          *RELIABILITY* |          *RELIABILITY* |Concentration
 POINT   DIVERSION  | SHORTAGE  |VOLUME|PERIOD | SHORTAGE  |VOLUME|PERIOD | SHORTAGE  |VOLUME|PERIOD |  is |exceeds
         (AC-FT/YR) |(AC-FT/YR)|  (%) |  (%)  |(AC-FT/YR)|  (%) |  (%)  |(AC-FT/YR)|  (%) |  (%)  | Zero| Limit
-----------------------------------------------------------------------------------------------------------
PK        254800.0   192985.86  24.26  22.99    10135.51  96.02  94.54   187270.81  26.50  25.86     11   516
Whit       18000.0     7126.29  60.41  59.48      958.69  94.67  94.68     6670.55  62.94  61.93      3   265
WacoL      80800.2      184.78  99.77  99.71        0.00 100.00 100.00      184.78  99.77  99.71      3     2
WacoG      32300.0     7921.60  75.47  78.16     2071.38  93.59  95.98     7026.92  78.24  80.60      3   135
High       44800.1    10440.78  76.69  84.63     3629.86  91.90  95.83     8305.76  81.46  87.21      1    89
Belton    180260.2    11923.77  93.39  91.67    11917.84  93.39  91.67      638.33  99.65  99.71     38     2
George     25610.0     4724.34  81.55  76.29     4721.70  81.56  76.29      287.30  98.88  98.99     26     7
Grang      42000.1     4263.99  89.85  85.49     4140.04  90.14  85.78      436.37  98.96  98.99     26     7
Camer     209599.8    35450.63  83.09  79.60    34236.55  83.67  79.89     3931.96  98.12  98.56      1    10
Bryan      98899.9    13157.07  86.70  85.06     4505.56  95.44  91.09    10449.78  89.43  91.24      1    61
Hemp     1119703.4   133777.84  88.05  81.75    57750.37  94.84  85.34    91066.98  91.87  92.67      1    51
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Total    2106773.8   421956.97  79.97          134067.50  93.64          316269.56  84.99
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OUTFLOW CONCENTRATION (MG/L) AT CONTROL POINT PK

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YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC          MEAN 
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1940     1100.     1084.     1083.     1096.     1113.      988.     1070.      871.      791.      918.     1059.     1109.         1024.
1941     1053.      977.      900.      756.      328.       21.        9.     2446.     4509.     2478.      738.     2250.         1372.
1942     3839.     3797.     3765.     2637.     1564.     1426.     1261.     1296.     1137.      758.     1033.     1505.         2002.
1943     1467.     1445.     1408.     1318.     1300.     1321.     1335.     1416.     1515.     1751.     2152.     3058.         1624.
1944     3754.     3666.     3284.     2925.     2581.     2230.     2052.     2047.     2077.     1902.     1899.     2050.         2539.
1945     2115.     2136.     1795.     1440.     1323.     1306.     1147.     1031.     1098.     1080.     1019.     1104.         1383.
1946     1630.     2048.     2049.     2214.     2310.     2183.     2088.     1977.     1503.     1056.      936.      995.         1749.
1947     1129.     1176.     1322.     1658.     1294.     2462.     4170.     4330.     4459.     4271.     4064.     3817.         2846.
1948     3613.     3572.     3435.     3331.     3213.     2680.     1986.     2184.     3392.     3687.     1524.      197.         2735.
1949     1834.     2787.      879.     1012.     2195.      830.      684.      670.     1482.     3695.     4698.     4629.         2116.
1950     4588.     4494.     4432.     3979.     2510.     1840.     1455.     1096.      894.      835.     1811.     2989.         2577.
1951     3262.     3585.     4483.     5723.     2295.     1534.      461.     1058.      681.        0.     2974.        0.         2171.
1952     7195.   138417.     6774.     1940.     2794.      988.     1710.       65.       21.        0.      894.     3566.        13697.
1953        0.    26170.     5477.     1296.     1678.      161.      873.     1226.       87.      470.     1485.     2677.         3467.
1954     2596.     2548.     1758.     2432.      502.      615.     1872.     3137.       50.        0.      187.        0.         1308.
1955      959.     6389.    11060.      246.     3322.     1283.     1116.     2127.     1684.      229.     1492.     2926.         2736.
1956     2922.     2923.     2927.     2949.     2713.     1706.       51.        0.        0.      395.       50.      263.         1408.
1957        0.     1679.      851.      725.      262.      199.     1085.     2043.     2005.     1794.     1485.     1314.         1120.
1958     1288.     1299.     1289.     1292.     1322.     1308.     1119.     1324.     1739.     1648.     1634.     1635.         1408.
1959     1673.     1725.     1787.     1855.     1788.     1384.     1049.      938.      934.      724.      602.      733.         1266.
1960     1077.     1323.     1343.     1618.     1912.     2058.     1892.     1632.     1674.     1877.     1935.     1859.         1683.
1961     1754.     1635.     1560.     1853.     2230.     1905.     1321.     2011.     2800.     2842.     2967.     2850.         2144.
1962     2816.     2836.     2871.     2867.     2907.     2270.     1510.     1329.     1004.      989.     1207.     1129.         1978.
1963     1092.     1085.     1076.      992.      953.      906.      864.     1226.     1850.      923.      422.     1446.         1070.
1964      912.     2218.      578.      142.      232.     1626.       51.        7.     1773.      708.      529.      299.          756.
1965      353.      242.      108.     1832.     2308.     1116.     1077.     1043.      958.      883.     1279.     1792.         1083.
1966     1876.     1945.     2049.     1805.     1390.     1143.     1157.     1136.      782.     1436.     2394.     2389.         1625.
1967     2469.     2548.     2532.     2370.     2201.     1979.     1535.     1299.     2173.     3297.     3315.     3453.         2431.
1968     2182.     1477.     1212.      961.      834.      740.      739.      840.     1024.     1286.     1517.     1870.         1224.
1969     2285.     2463.     2277.     1972.     1302.     1076.     1398.     1486.     1277.     1005.      924.      828.         1524.
1970      756.      723.      832.      994.     1036.     1060.     1148.     1240.     1507.     1826.     1985.     2143.         1271.
1971     2229.     2230.     2235.     1240.     2327.     1932.      829.     1545.      936.      874.      971.      926.         1523.
1972      893.      879.     1095.     1486.     1603.     1620.     1741.     1373.     1742.     2309.     2092.     2051.         1574.
1973     1897.     1714.     1504.     1402.     1533.     1665.     1736.     1901.     2156.     2318.     2387.     2515.         1894.
1974     2598.     2599.     2652.     2633.     2550.     2465.     2416.     1918.     1823.     1099.      756.      627.         2011.
1975      602.      540.      583.      744.      805.      764.      742.      784.      825.      857.      970.     1105.          777.
1976     1242.     1381.     1509.     1602.     1599.     1620.     1647.     1634.     1508.     1331.     1250.     1232.         1463.
1977     1250.     1285.     1272.     1247.     1237.     1220.     1252.     1336.     1404.     1575.     2004.     2431.         1459.
1978     2576.     2653.     2676.      557.      391.     1290.       84.      209.     1015.      385.     1283.     1154.         1189.
1979     1788.     1583.     1609.     1427.     1222.     1015.      951.      956.     1015.     1122.     1239.     1435.         1280.
1980     1616.     1757.     1858.     1863.     1438.     1144.     1141.     1192.     1005.     1041.      669.      901.         1302.
1981      684.      902.     1398.     1204.     1025.      891.      859.      930.     1047.      352.      446.      702.          870.
1982      965.      950.      964.      982.      621.      178.       60.      595.     1291.      237.      375.     1143.          697.
1983     1956.     1850.     1709.     1645.     1357.     1092.     1099.     1263.     1465.     1296.     2042.     3942.         1726.
1984     3639.      717.     2103.      732.     4456.        0.        0.     4751.     8565.     1674.     3038.     3120.         2733.
1985     1907.     1352.     1040.      803.      678.      644.      686.      828.     1196.     1756.     1812.     1785.         1207.
1986     1774.     1738.     1710.     1880.     2073.     1683.     1335.     1277.     1140.      751.     1222.     1832.         1534.
1987     1660.     1414.     1187.     1097.      941.      821.     1581.     2343.     2313.     2290.     2290.     2461.         1700.
1988     2608.     2571.     2556.     2566.     2567.     2524.     2433.     2382.     2203.      243.      768.      196.         1968.
1989     3913.     4477.     1417.     1307.     3605.     1217.     1038.      992.      823.      709.     1235.     2774.         1959.
1990     4372.     4509.     2883.     1124.      755.      938.     1251.     1504.     1323.     1183.     1132.     1097.         1839.
1991     1037.     1069.     1162.     1201.     1086.      692.     1259.     2109.     1757.     1518.     1397.      955.         1270.
1992      856.      879.      738.     1029.     1233.      889.     1281.     1991.     1951.     1978.     1950.     1877.         1388.
1993     1804.     1705.     1565.     1455.     1411.     1384.     1422.     1607.     1840.     1931.     1973.     2114.         1684.
1994     2182.     2150.     2118.     2107.     1531.     1109.     1096.     1099.     1095.     1374.     1547.     1475.         1574.
1995     1471.     1459.     1464.     1470.     1456.     1323.     1223.     1082.      957.      955.     1196.     1654.         1309.
1996     1892.     2021.     2211.     2270.     2280.     2298.     1322.     1792.     1713.     1104.      990.      893.         1732.
1997      849.      729.      765.      860.      784.      667.      591.      667.      794.      928.     1231.     1528.          866.
MEAN     1963.     4785.     2089.     1658.     1660.     1301.     1213.     1458.     1582.     1344.     1525.     1738.         1860.
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OUTFLOW CONCENTRATION (MG/L) AT CONTROL POINT Hemp

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YEAR       JAN      FEB      MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC         MEAN
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1940      779.     241.     457.     303.     272.     595.     315.     827.     690.     220.     268.     185.         429.
1941      149.     276.     186.     242.     204.      68.      77.    1256.     665.     870.     201.     686.         407.
1942     1218.    1226.    1172.    1036.     183.     537.     387.    1950.     175.    1062.     319.     297.         797.
1943      309.     572.     483.     486.     412.     411.     783.     371.     524.     677.     881.     373.         523.
1944      357.     274.     134.     180.     145.      59.    1135.     366.     355.     473.     164.      80.         310.
1945      266.     286.     166.     200.     244.     270.     429.     274.     241.     268.     320.     219.         265.
1946      158.     238.     198.     194.     125.     151.     117.     489.     457.     295.     215.     289.         244.
1947      192.     244.     223.     326.     436.     361.     996.      14.     692.     871.     750.     539.         470.
1948      703.     629.     365.     378.     290.     960.     782.    1123.     336.     926.     781.     453.         644.
1949      433.     456.     310.     181.    1084.     352.     498.    1041.     879.     226.     195.     372.         502.
1950      283.     168.     271.     121.     587.     146.    1053.     525.     483.     454.     625.     636.         446.
1951      693.     724.     642.     635.     869.     703.    1050.    1205.     415.    1257.    1557.    1663.         951.
1952     1798.    1272.    1199.     553.     383.     315.     477.     283.     570.     424.     443.     430.         679.
1953      296.     303.     405.     475.     139.     280.    1522.    1160.     786.     232.     304.     163.         505.
1954      408.     995.    1097.    1012.     419.     710.     601.     701.    1166.     563.     620.     360.         721.
1955      247.     191.     281.     214.     525.     917.    1205.    1285.    9983.     487.     650.     876.        1405.
1956      816.     264.    1126.    1462.     938.    1441.    1516.     491.    1585.    1839.    1446.    1393.        1193.
1957     2351.    2649.     281.     302.     223.      63.      17.     412.     405.     259.     439.     164.         630.
1958      234.     247.     220.     296.     273.     208.     834.     795.     240.     177.     656.     638.         401.
1959      460.     265.     500.     162.      90.     198.     793.     693.     220.     271.     189.     211.         338.
1960      261.     230.     213.     332.     199.     217.     241.     460.     499.     131.     182.     165.         261.
1961      213.     171.     187.     158.     769.     365.     310.     633.     386.     282.     302.     268.         337.
1962      290.     394.     457.     537.     339.     807.     987.     505.     593.     798.     634.     356.         558.
1963      573.     375.    1030.     296.    1350.    1326.     828.     338.     877.     834.     810.     380.         751.
1964      537.     562.     384.     553.     408.     427.    1121.    -382.     458.     457.     213.     329.         422.
1965      169.     158.     255.     229.     132.     209.     275.     317.     410.     326.     262.     217.         247.
1966      340.     241.     290.     287.     246.     339.     362.     517.     544.     464.     691.     408.         394.
1967      708.     444.     713.     230.     227.     459.     523.     636.     576.     396.     200.     215.         444.
1968      274.     381.     401.     349.     291.     222.     233.     463.     350.     482.     330.     228.         334.
1969      324.     243.     212.     175.     297.     168.     535.     371.    1349.    1002.     321.     341.         445.
1970      294.     286.     315.     345.     365.     324.     243.     653.     234.    1334.     400.     568.         447.
1971      534.     608.     568.     527.     355.     817.     291.     554.     695.     263.     233.     394.         487.
1972      179.     296.     477.     562.     181.     561.     217.     755.     769.     476.     104.     401.         415.
1973      236.     197.     127.     320.     413.     221.     429.     602.     233.     201.     262.     253.         291.
1974      204.     228.     337.     420.     311.     270.     715.     376.     166.     210.     201.     291.         311.
1975      455.     342.     425.     372.     176.     290.     245.     370.     519.     442.     333.     505.         373.
1976      654.     419.     542.     236.     171.     162.     182.     273.     469.     214.     237.     153.         309.
1977      356.     223.     287.     176.     239.     335.     395.     301.     578.     601.     597.     381.         373.
1978      304.     279.     293.     634.     802.     293.     806.     464.     438.     658.     154.     179.         442.
1979      178.     195.     179.     174.     181.     198.     255.     159.     188.     335.     226.     208.         206.
1980      194.     213.     241.     219.     164.     204.     160.     645.     565.     529.     397.     406.         328.
1981      523.     570.     192.     303.     172.      86.     320.     505.     396.     338.     312.     408.         344.
1982      363.     445.     326.     204.     296.     112.     175.     496.     878.     868.     325.     284.         398.
1983      264.     186.     166.     348.     159.     260.     280.     357.     227.     752.     658.     265.         327.
1984      574.     493.     196.     274.     351.     187.     208.     256.     510.     123.     208.     178.         297.
1985      174.     207.     132.     300.     209.     427.     533.     457.     542.     215.     160.     156.         292.
1986      382.     180.     372.     406.     188.     181.     260.     474.     322.     381.     235.     196.         298.
1987      227.     348.     269.     287.     499.     176.     131.    1420.     660.     843.     209.     263.         444.
1988      320.     430.     338.     473.     730.     291.     740.     258.     687.     543.     491.     686.         499.
1989      265.     343.     293.     365.     451.     354.     160.     430.     633.     703.     581.     573.         429.
1990      471.     362.     168.     282.      87.      39.    1333.    1691.    1418.    1164.     175.     539.         644.
1991      268.     373.     197.     263.     254.     904.     736.     693.     281.     794.     556.     273.         466.
1992       62.     188.     254.     274.     337.     412.     230.     530.     532.     621.     461.     319.         352.
1993      231.     243.     262.     260.     242.     237.      97.     332.     708.    1736.     396.     509.         438.
1994      438.     354.     262.     324.     357.     142.     176.     512.     444.      11.     445.     403.         322.
1995       84.     296.     262.     219.     272.     209.     232.     346.     284.     294.     234.     368.         258.
1996      333.     478.     233.     364.     637.     257.     495.     267.     204.     339.     559.     295.         372.
1997      212.     272.     187.     227.     277.     197.     140.     229.     445.     372.     321.     273.         262.
MEAN      424.     410.     375.     363.     362.     369.     520.     578.     706.     558.     421.     391.         457.
---------------------------------------------------------------------------------------------------------------------------
```

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APPENDIX A
DISPLAY OF SIMULATION RESULTS WITH ARCGIS

As discussed in Chapter 1 of the basic *Reference Manual*, various auxiliary software products are used with WRAP for developing input datasets and organizing and displaying simulation results. Microsoft Windows/Office programs are routinely applied with WRAP for editing and other pre- and post-simulation data management tasks. HEC-DSSVue is used to develop time series plots of simulation results. Geographic information system (GIS) software is used to compile and display data for which spatial considerations are important.

ArcGIS is geographic information system software developed and marketed by the Environmental Systems Research Institute, Inc. (http://www.esri.com/). Applications of ArcGIS for developing WRAP input datasets are cited in Chapter 1 of the *Reference Manual*. The present Appendix A describes a recently formulated application of ArcGIS to display WRAP simulation results in the format of a map/schematic-based spatial display or alternatively as time series plots. The procedure described here for displaying WRAP simulation results within ArcGIS represents a general strategy that may be further expanded in the future to handle more complex river basin systems and provide more detailed data displays.

The spatial display methodology is applied using a dynamic link-library (DLL) file with the filename Display.DLL that was developed with Visual Basic and is available with the WRAP software package. A set of files distributed with WRAP as a zip file with the filename DisplayTS.zip is required for developing time series plots. The *WRAP-SIM/SIMD* simulation results to be displayed are read from OUT and BES files. Most of the data is found in the main *SIM* or *SIMD* output file with filename extension OUT. The *SIM/SIMD* beginning/ending storage file (filename extension BES) provides reservoir storage capacities.

The following information is displayed within ArcGIS on a river/reservoir system schematic or map with color-coded symbols representing control points and reservoirs.

- reservoir storage as a percent of capacity
- water supply diversion as a percent of target requirement
- volume reliability
- period reliability

The program Display.DLL computes the reliabilities and other percentages within ArcGIS using simulation results from the OUT file created by *WRAP-SIM/SIMD*. The color coding of the control points and reservoirs represents ranges of percentages (<50%, 50%-70%, 70%-90%, 90%-95%, 95%-100%). The storage and diversion percentages are for a specified period of time which could be a particular month, year, or other period of multiple months or years defined by the model user. GIS is uniquely suited to these types of spatial displays of simulation results.

Time series plots may also be created with ArcGIS as well as with Microsoft Excel or HEC-DSSVue. Time series plots covering user-specified control points and periods of time may be created for naturalized flows, regulated flows, unappropriated flows, reservoir storage, streamflow depletions, and percent of diversion target supplied. The files contained in DisplayTS.zip are required along with Display.DSS.

The ArcGIS Desktop contains three basic programs: ArcMap, ArcCatalog, and ArcToolbox. ArcMap provides the means to display, analyze, and edit spatial data and data tables. ArcCatalog is used to manage files similarly to Windows Explorer. ArcToolbox provides access to various GIS data manipulation and analysis functions.

The following guidelines describe basic concepts and procedures for displaying *WRAP-SIM/SIMD* simulation results in ArcMap using the Display.DLL program. The following topics are covered.

- How to load Display.DLL and the files from DisplayTS.zip into ArcGIS.
- How to create a shapefile either manually or from X-Y coordinates.
- How to add fields to a shapefile.
- How to create reaches.
- How to label features.

The example from the *Fundamentals Manual* is used to illustrate the procedure for displaying simulation results.

Loading the WRAP Display Tools Into ArcMap

The first step is to open ArcMap within the ArcGIS menu structure by activating the ArcGIS and ArcMap selections as shown in Figure A.1. Select create a new empty map and save it to the preferred location.

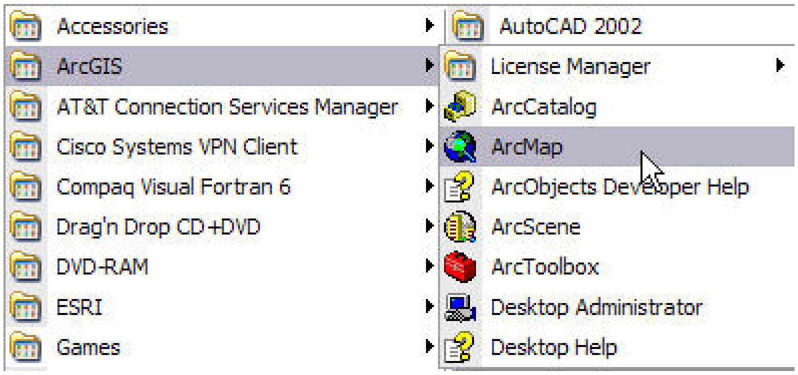


Figure A.1 Opening ArcMap

To load the file Display.DLL, right click on the standard toolbar and select **customize**. Next select **add from file** and browse to the location of the Display.DLL file. A new toolbar named **WRAP_DISPLAY** is added to the list. Check it and close the window. A new toolbar called **WRAP** is added to the screen as shown in Figure A.2.

The library for plotting time series is contained in the file DisplayTS.zip. If time series plots are of interest, the contents of the DisplayTS.zip file should be extracted into the following location or equivalent:

c:\windows\system32

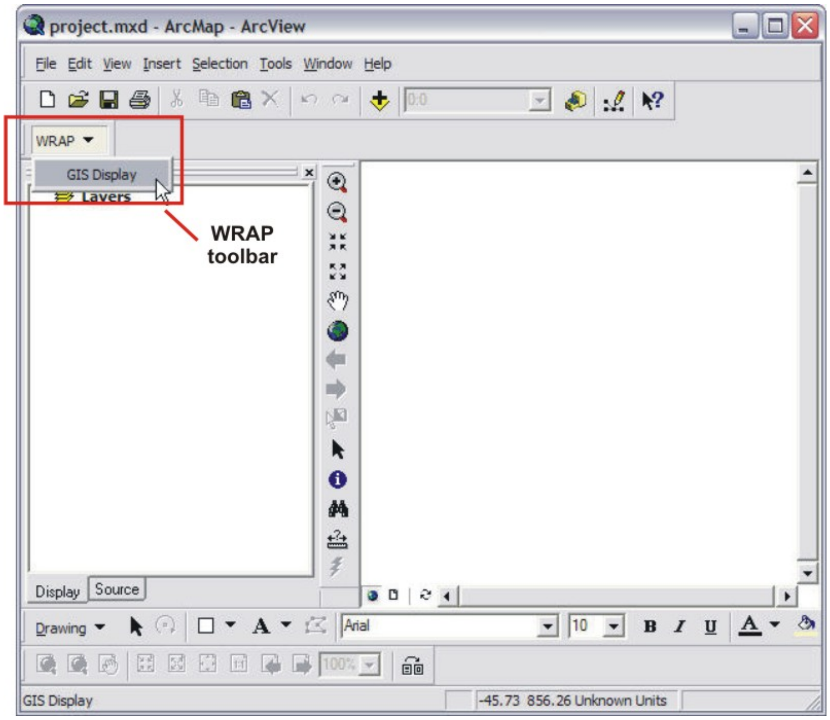


Figure A.2 WRAP toolbar added to the screen

Creating a Shapefile

The two alternative methods for creating a point shapefile are by manually drawing the features or by loading a text file containing the x-y coordinates.

Manually Drawing the Features

The first step is to open ArcCatalog which is located in the same menu as ArcMap as shown in Figure A.3.

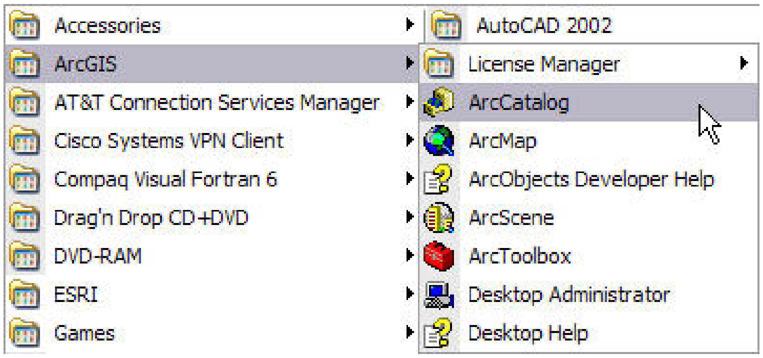
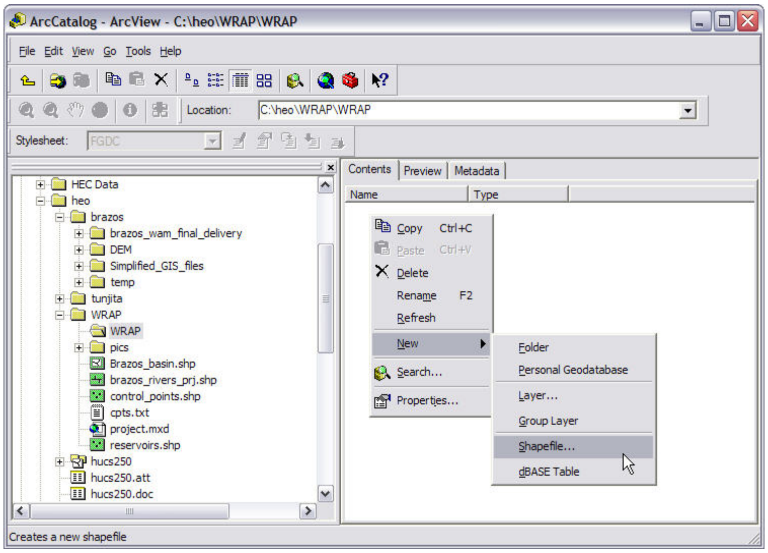


Figure A.3 Opening ArcCatalog

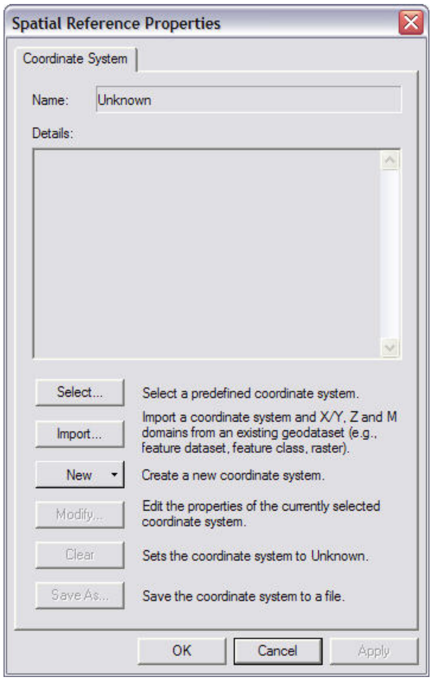
Browse to the folder where the shapefiles are to be stored; click on the contents screen, and select new, shapefile as shown in Figure A.4.



Creates a new shapefile

Figure A.4 Creating a new shapefile

The create shapefile window appears. Select a name without blank spaces and select the point feature type. In order to assign a spatial reference, click on **edit** to activate the spatial reference properties window shown in Figure A.5.



Name: Unknown

Details:

Select a predefined coordinate system.

Import a coordinate system and X/Y, Z and M domains from an existing geodataset (e.g., feature dataset, feature class, raster).

Create a new coordinate system.

Edit the properties of the currently selected coordinate system.

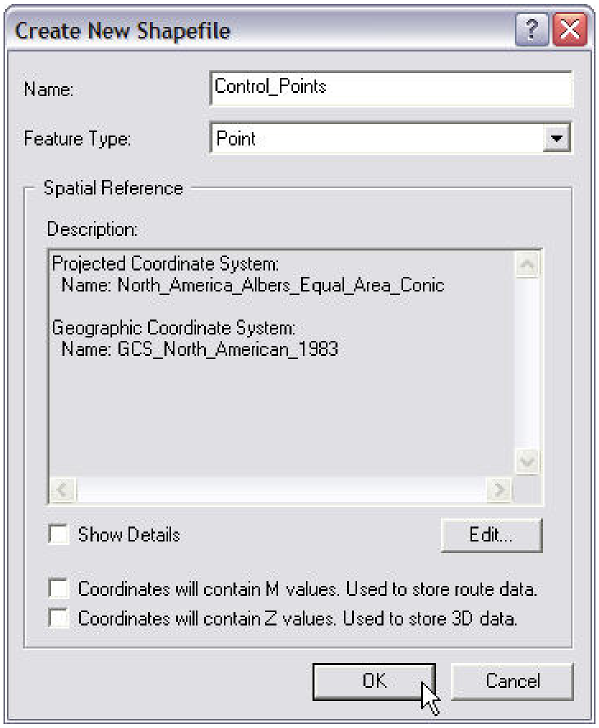
Sets the coordinate system to Unknown.

Save the coordinate system to a file.

Figure A.5 Spatial reference properties

The window shown in Figure A.5 provides three options to define a spatial reference: (1) select a predefined coordinate system, (2) import a coordinate system from an existing shapefile, or (3) create a new coordinate system.

If the coordinate system is predefined, click the **select** button and select it from the available options. After selection, any modifications to the predefined values can be performed by selecting the **modify** button. An existing shapefile with the desired coordinate system can be selected with the **import** button. When a new coordinate system is desired, click on the **new** button and enter all the necessary parameters. After assigning the coordinate system click **OK** (Figure A.6), and an empty shapefile will be created at the selected location.



Name: Control_Points

Feature Type: Point

Projected Coordinate System:
Name: North_America_Albers_Equal_Area_Conic

Geographic Coordinate System:
Name: GCS_North_American_1983

☐ Show Details

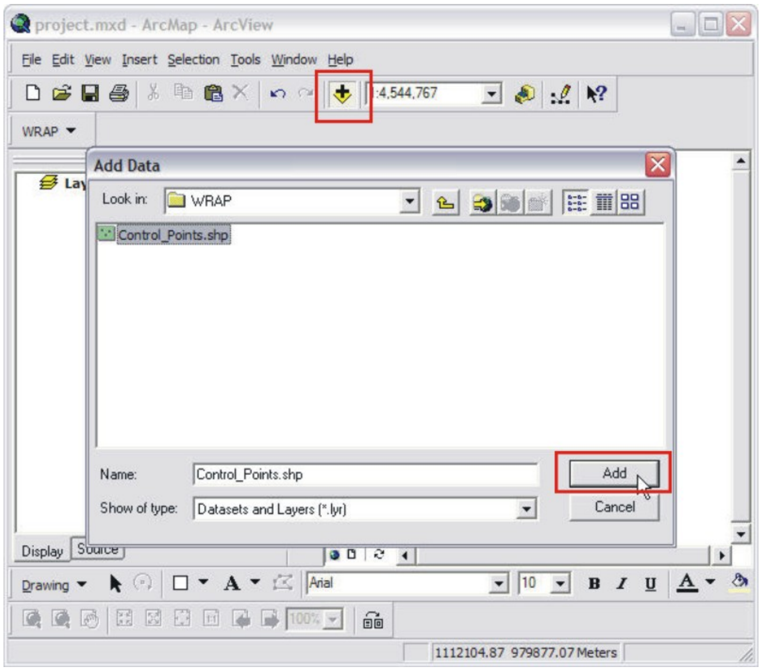
☐ Coordinates will contain M values. Used to store route data.

☐ Coordinates will contain Z values. Used to store 3D data.

Figure A.6 New point shapefile

From ArcMap add the new empty shapefile by selecting **File**, **Add data**, or by clicking on the button shown in Figure A.7. Browse to the location of the shapefile and click **Add**.

After the shapefile has been loaded, new fields can be added. In this case, a field containing the identifier used within WRAP is necessary. In order to create a new field, open the shapefile attribute table by right clicking it in the table of contents and selecting **open attribute table**. An empty table appears. Now click on **options** and select **Add field**. On name, type **CP_ID** or **RES_ID** for the control point or reservoir shapefile; and on type select **text** with a length of **6 characters** as shown in Figure A.8. A new field has been added to the attribute table. More fields can be added following the same procedure.



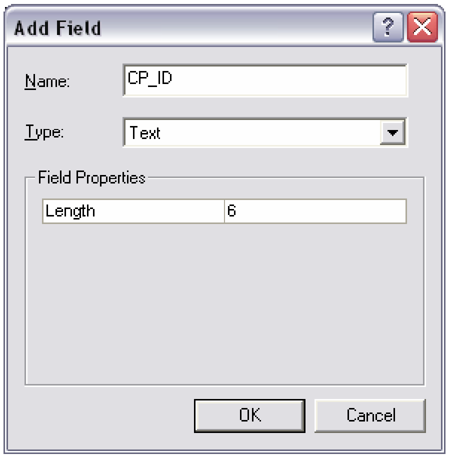
Look in: WRAP

Control_Points.shp

Name: Control_Points.shp

Show of type: Datasets and Layers (*.lyr)

Figure A.7 Adding a shapefile to ArcMap



Name: CP_ID

Type: Text

Length 6

Figure A.8 Creating a new field to a shapefile

In order to be able to create features, it is necessary to add the **editor toolbar**. Right click on the standard toolbar and select **editor** as shown in Figure A.9. The editor toolbar is added to the screen. In order to activate its buttons, it is necessary to start an editing session. Click on editor and select start editing. The buttons in the toolbar become active as shown in Figure A.10.

On the **task** list, select **Create New Feature**, in **target** select the target shapefile and click on the **attributes** button to display the attributes window. This will allow inputting attribute's information while drawing the features.

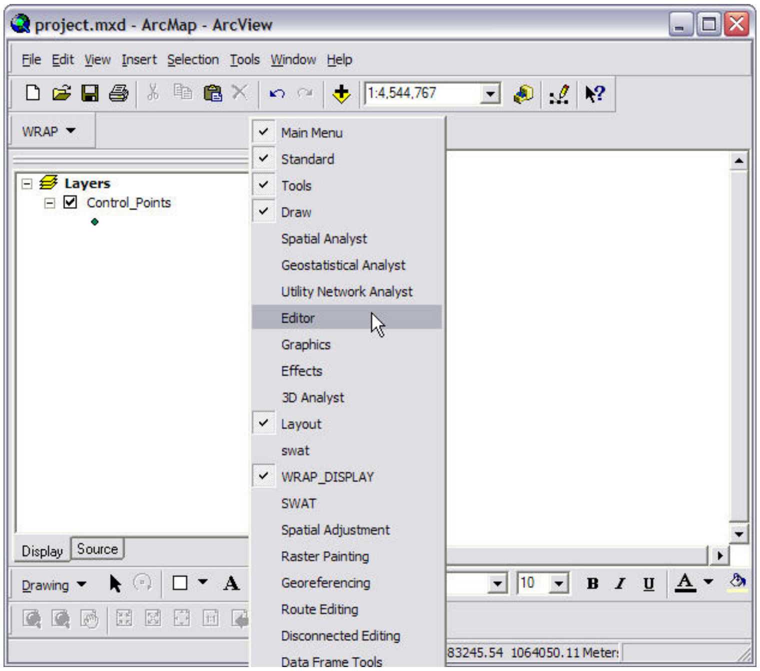
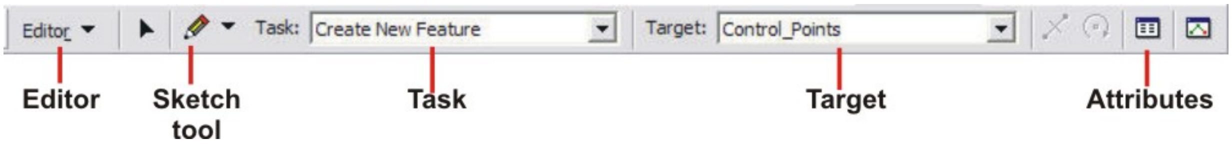


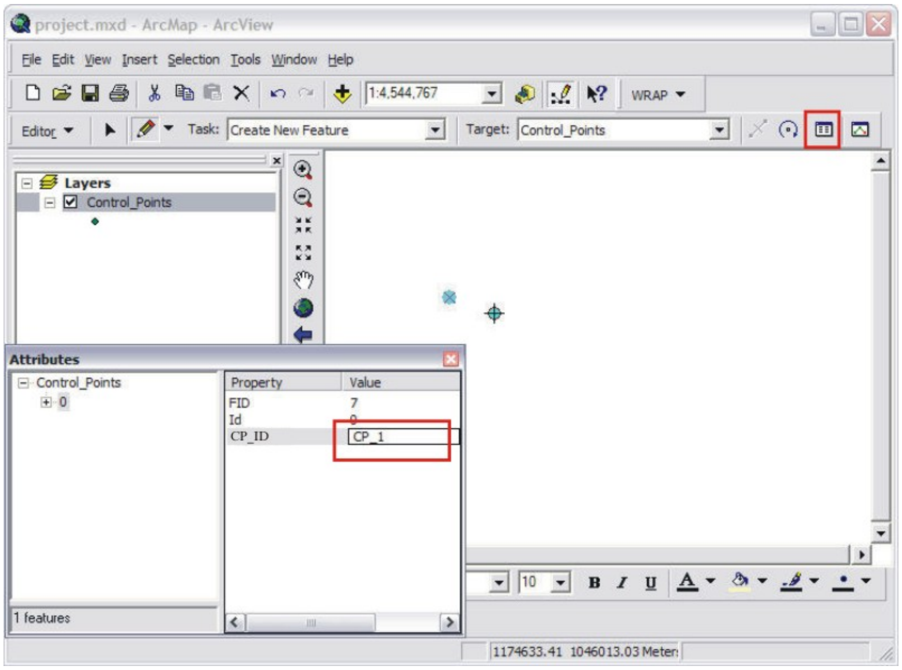
Figure A.9 Loading the editor toolbar



Task: Create New Feature

Target: Control_Points

Figure A.10 Editor toolbar



Task: Create New Feature

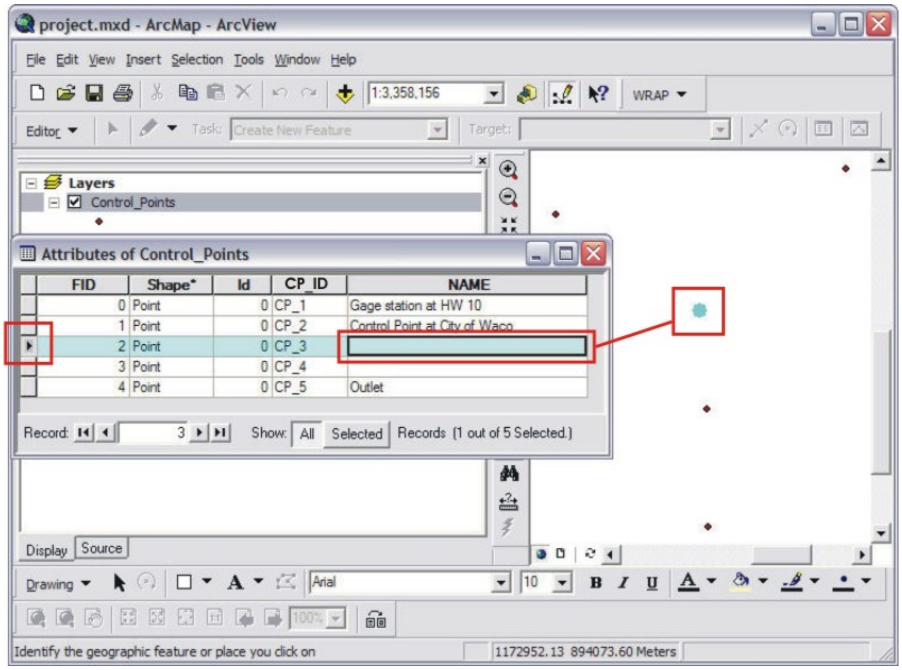
Target: Control_Points

Property	Value
FID	7
Id	0
CP_ID	CP_1

Figure A.11 Entering attributes for a feature

To start drawing the features, select the sketch tool and draw a point at the desired location by using the left button. The attribute window will display the attributes for the current feature. It is possible to define the **CP_ID** name or any other information while drawing the points, just enter the information under the value column as shown in Figure A.11.

Another option to enter attributes is to type them within the attribute table. Open the attribute table and type the attribute information. By selecting the far left button in each record, the corresponding feature will become selected in the map display as shown in Figure A.12. Make sure the information written in the attribute table corresponds to the correct feature.



FID	Shape*	Id	CP_ID	NAME
0	Point	0	CP_1	Gage station at HW 10
1	Point	0	CP_2	Control Point at City of Waco
2	Point	0	CP_3	
3	Point	0	CP_4	
4	Point	0	CP_5	Outlet

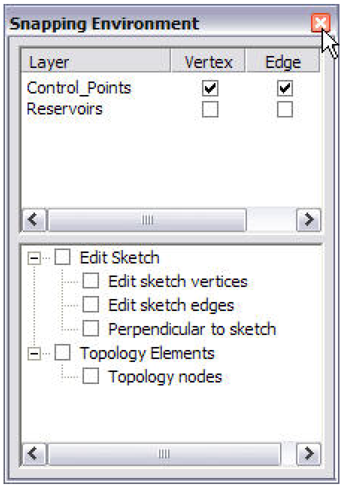
Record: 3 Show: All Selected Records (1 out of 5 Selected.)

Figure A.12 Adding attributes in the attribute table

To delete a feature, select it by using the **edit tool** button located at the left of the **sketch button**, then right click it and select **delete**. The edit tool will also allow changing the location of a feature.

After all the features have been drawn and all the attributes included, the edit session has to be closed. Click on **editor** and select **stop editing** and **save the edits**.

This process has to be followed when creating the control points and reservoirs shapefiles. If when drawing a feature, it is desired to snap it to an existing feature from another shapefile, for example a reservoir that has the same location of a control point, it is necessary to activate the snapping option by clicking **editor** and selecting **snapping**. The snapping environment window appears as shown in Figure A.13. Select both the **vertex** and **edge** of the existing shapefile and close the window. To modify the snapping tolerance, select **options** under **editor** and on the **general tab** modify the snapping tolerance as needed.



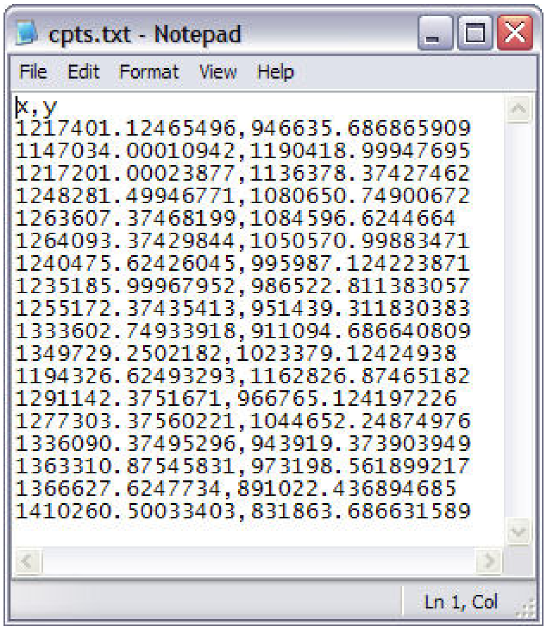
Layer	Vertex	Edge
Control_Points	☑	☑
Reservoirs	☐	☐

- ☐ Edit Sketch
  - ☐ Edit sketch vertices
  - ☐ Edit sketch edges
  - ☐ Perpendicular to sketch
- ☐ Topology Elements
  - ☐ Topology nodes

Figure A.13 Snapping environment window

Creating a Shapefile from X-Y Coordinates

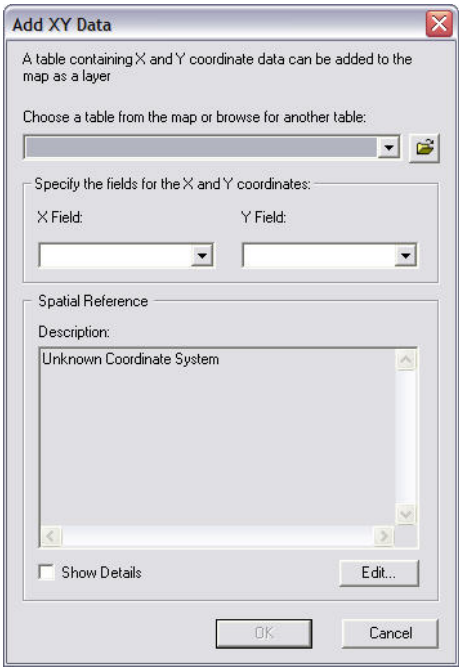
In order to create a point shapefile from X-Y coordinates, it is necessary to have a text file containing the coordinates, separated by commas and with the first line showing the label for each column as shown in Figure A.14.



```
x,y
1217401.12465496,946635.686865909
1147034.00010942,1190418.99947695
1217201.00023877,1136378.37427462
1248281.49946771,1080650.74900672
1263607.37468199,1084596.6244664
1264093.37429844,1050570.99883471
1240475.62426045,995987.124223871
1235185.99967952,986522.811383057
1255172.37435413,951439.311830383
1333602.74933918,911094.686640809
1349729.2502182,1023379.12424938
1194326.62493293,1162826.87465182
1291142.3751671,966765.124197226
1277303.37560221,1044652.24874976
1336090.37495296,943919.373903949
1363310.87545831,973198.561899217
1366627.6247734,891022.436894685
1410260.50033403,831863.686631589
```

Figure A.14 Text file containing X-Y coordinates

To create the shapefile, go to **tools**, **add XY Data**. The Add XY Data window appears as shown in Figure A.15. Click on the **folder** button and browse to the text file containing the coordinates. On the X field, select the field that contains coordinates in the horizontal direction, and for the Y field the correspondent for the vertical direction.



A table containing X and Y coordinate data can be added to the map as a layer

Choose a table from the map or browse for another table:

Unknown Coordinate System

Figure A.15 Add XY data window

As done previously when manually creating a shapefile, a coordinate system has to be defined for the new shapefile. The same options described earlier apply to this case. After the coordinate system has been selected, press **OK**. A new layer is added to the table of contents as shown in Figure A.16.

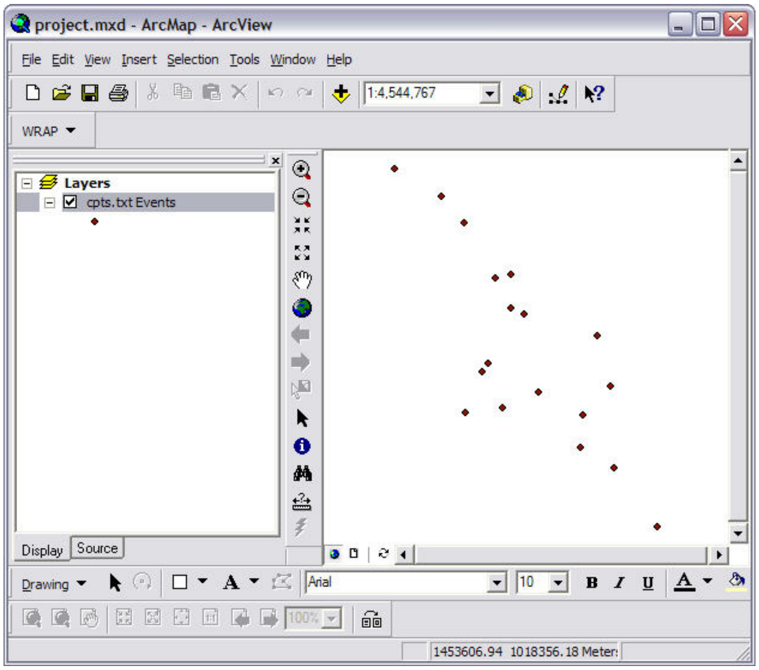
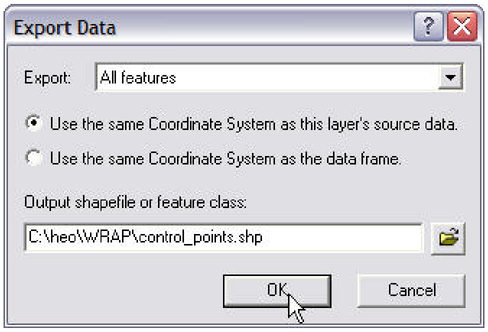


Figure A.16 Points located using XY coordinates

In order to save the file as a shapefile, right click the name on the table of contents and select **Data**, **Export Data**. The **Export Data window** will emerge as shown in Figure A.17. Select **All features** and use the same coordinate system as the source layer. Finally type a name for the new shapefile and click **OK**. Add the file to the view and remove the previous layer by right clicking it and selecting **remove**.



Export: All features

● Use the same Coordinate System as this layer's source data.

○ Use the same Coordinate System as the data frame.

Output shapefile or feature class:

C:\heo\WRAP\control_points.shp

Figure A.17 Exporting the points created from XY coordinates into a new shapefile

After building the shapefile containing control points and the shapefile containing reservoirs, the display view will look like Figure A.18. Two text files containing coordinates for control points and reservoirs (cpts.txt and reserv.txt) are included with this guideline; the coordinate system is defined by any of the provided shapefiles.

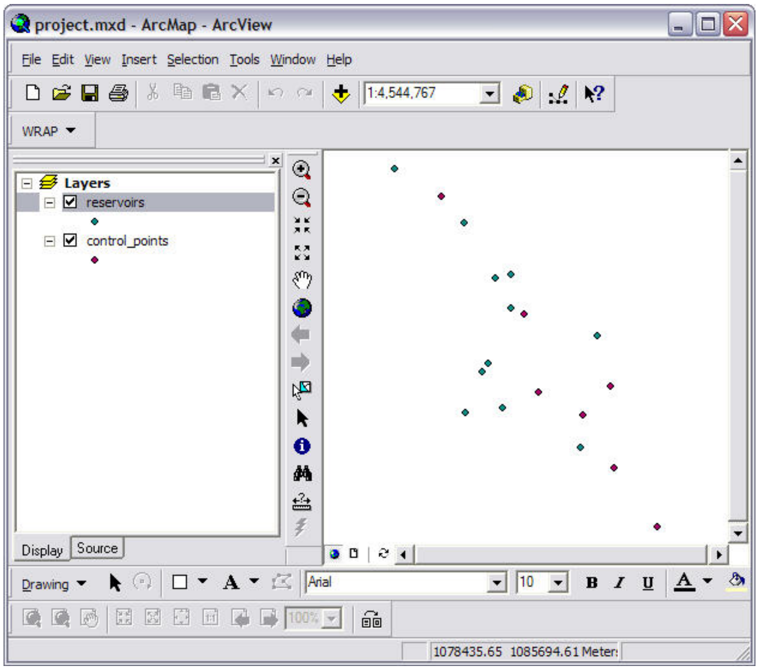


Figure A.18 Control points and reservoirs

Finally, it is necessary to add the **CP_ID** or **RES_ID** fields containing the control point or reservoir identifiers used in WRAP by following the procedure described earlier when manually creating features.

Creating Reaches

River reaches between control points are useful to visualize the system. Reaches can be created manually or by using a shapefile that contains streams.

Manually Creating Reaches

A new shapefile containing polylines can be created following the procedure described for a point shapefile. The coordinate system must match that used for control points or reservoirs. Use of snapping when drawing reaches is recommended. To draw a reach, an editing session has to be initialized. The reaches are drawn by using the **sketch tool** and setting the **target** to the reaches shapefile. Click on the first point and click for any intermediate vertex, double click on the ending point to finish the sketch. After drawing all reaches, open the **attribute table** and input any pertinent information if desired. **Close** the editing session and **save the changes**. Figure A.19 shows reaches connecting all control points.

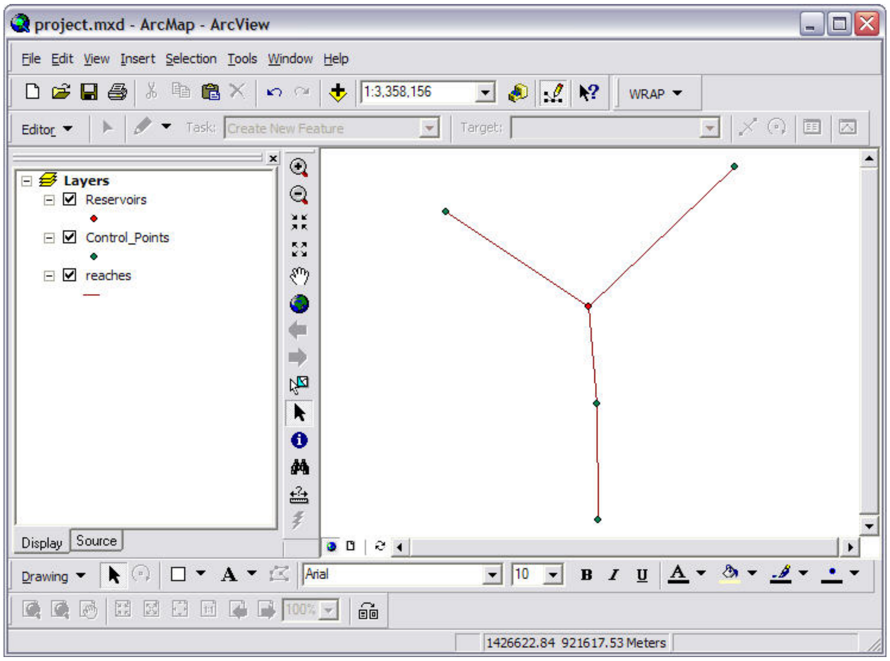


Figure A.19 Reaches drawn manually

Loading a Shapefile Containing Streams

A shapefile containing the streams may be loaded by selecting **File**, **Add Data** and browsing to the location of the shapefile. A shapefile named **brazos_rivers** is provided with this guideline and superimposes the control points and reservoirs created from X-Y coordinates. Any other additional shapefile can be included, such as a polygon representing the river basin.

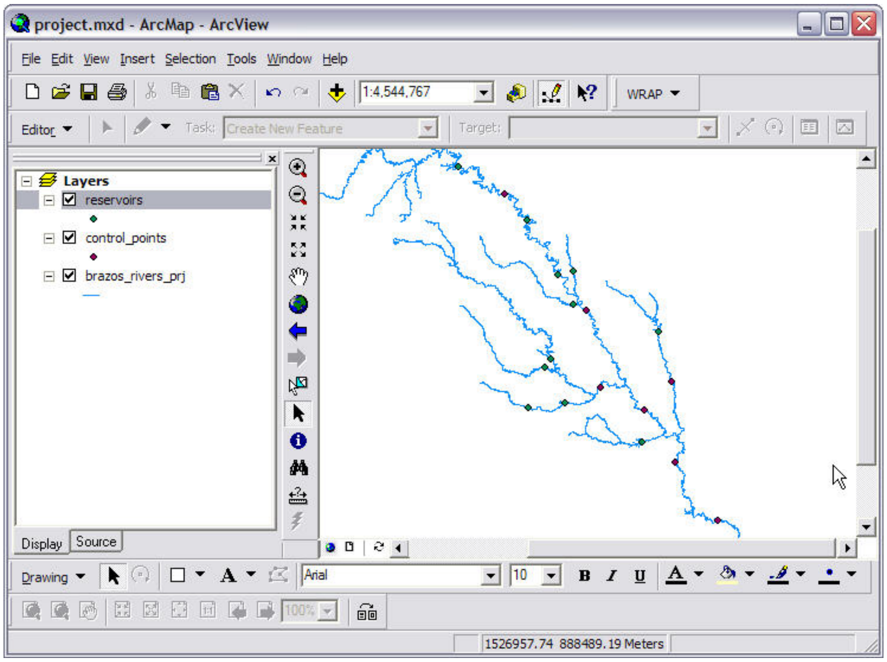


Figure A.20 Shapefile containing streams

Labeling Features

In order to label features on a shapefile, double click the shapefile name in the table of contents and select the **labels tab**. Activate the **label features in this layer** box and in the **label field**, select the field that contains the labels. If it is desired to modify the font or color of the labels, select **symbol**, and modify the options as needed. Click **OK** and the features for the selected shapefiles will be labeled.

ArcMap/WRAP Example

An WRAP simulation example with eleven control points and six reservoirs is presented in the *Fundamentals Manual* and adapted in the preceding chapters of this report. The procedure for displaying simulation results is applied to the *Fundamentals Manual* example as follows. Displaying *WRAP-SIM* simulation results within ArcMap includes the following tasks.

1. The *WRAP-SIM* simulation is performed with the results written to OUT and BES files providing data for the ArcMap display.

2. ArcMap is opened and the Display.DDL file and the files in DisplayTS.zip are loaded if not already loaded.

3. Shapefiles are loaded or developed, and the project is saved.

4. Features in the different shapefiles are labeled.

5. Open the WRAP display tool under the WRAP toolbar and click the define files and layers button as shown in Figure A.21.

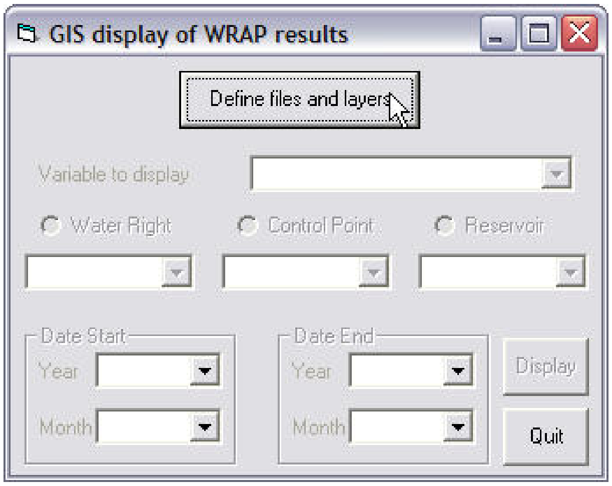
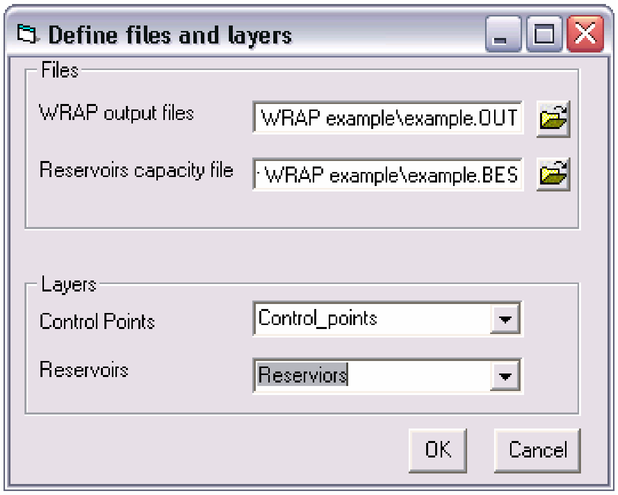


Figure A.21 Opening the GIS display tool

6. Browse to the location of the different files and select the layers for control points and reservoirs. After defining the files and shapefiles, press **OK**.



WRAP output files: WRAP example\example.OUT

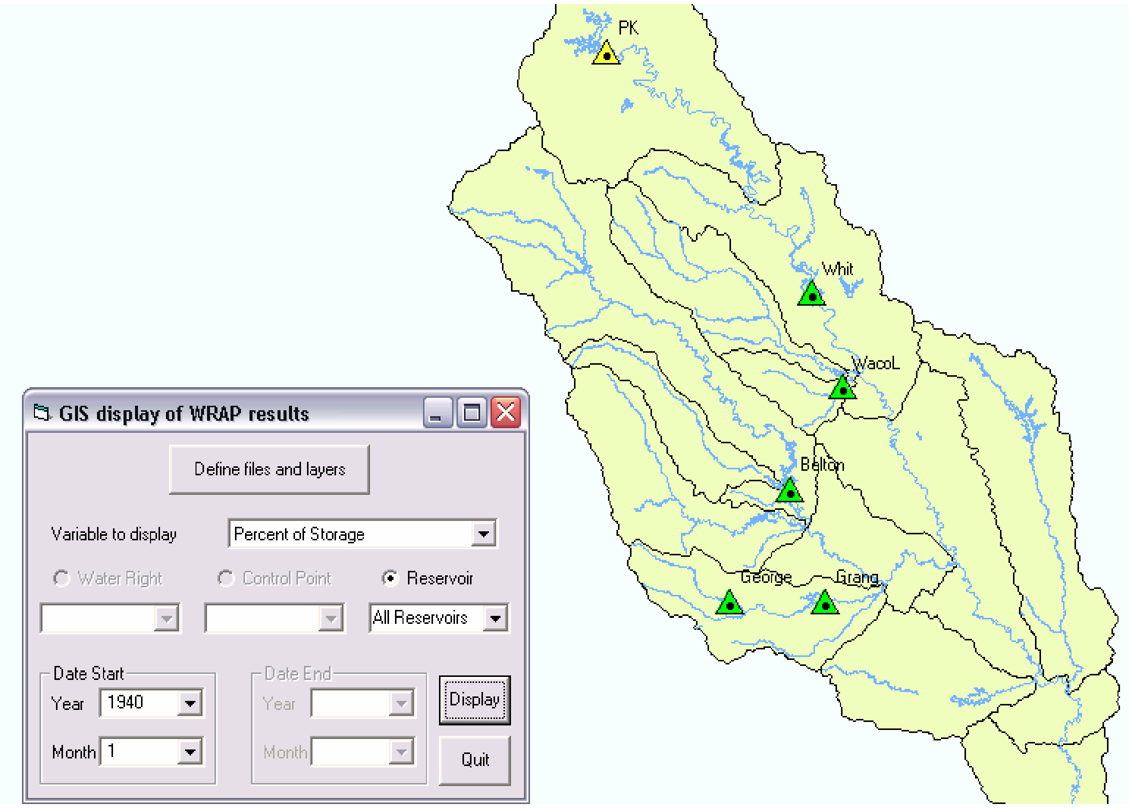
Reservoirs capacity file: WRAP example\example.BES

Control Points: Control_points

Reservoirs: Reserviors

Figure A.22 Defining files and layers

7. Select the percent of storage variable from the list and display the results for January 1940 by setting the appropriate date and clicking **OK.** The symbol representing reservoirs is modified to a triangle, and the different colors represent the storage level shown in the table of contents. Figure A.23 shows the results.



GIS display of WRAP results

Variable to display: Percent of Storage

○ Water Right ○ Control Point ● Reservoir

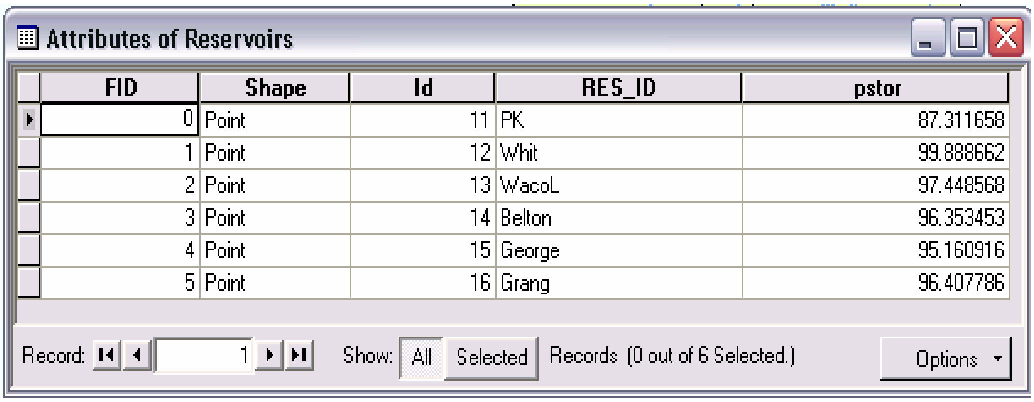
All Reservoirs

Date Start
Year 1940
Month 1

Date End
Year
Month

Figure A.23 Percent of storage for January 1940

Open the attribute table for reservoirs, notice that a new field called **Pstor** is created. This field stores the current value being displayed; if the date is modified, these values are updated (Figure A.24).


Attributes of Reservoirs

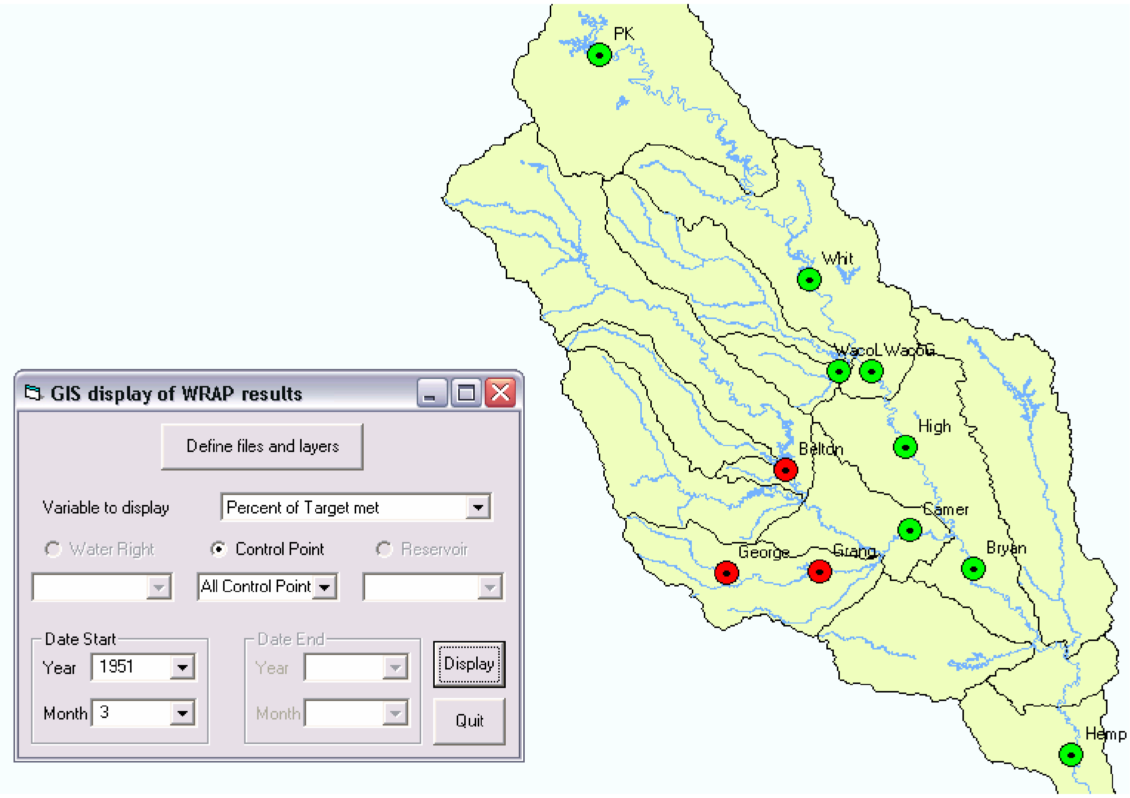
FID	Shape	Id	RES_ID	pstor
0	Point	11	PK	87.311658
1	Point	12	Whit	99.888662
2	Point	13	WacoL	97.448568
3	Point	14	Belton	96.353453
4	Point	15	George	95.160916
5	Point	16	Grang	96.407786

Record: 1 Show: All Selected Records (0 out of 6 Selected.)

Figure A.24 Attribute table for reservoirs after displaying Percent of Storage

8. Display the **percent of target met** for March 1951, by selecting the second variable in the list and setting the date. The reservoirs shapefile disappears and the control point shapefile

becomes active, the symbol changes to a circle with the color representing the percent of the target met at the specified month. Figure A.25 displays the results.



Variable to display: Percent of Target met

○ Water Right ● Control Point ○ Reservoir

All Control Point

Date Start

Year: 1951

Month: 3

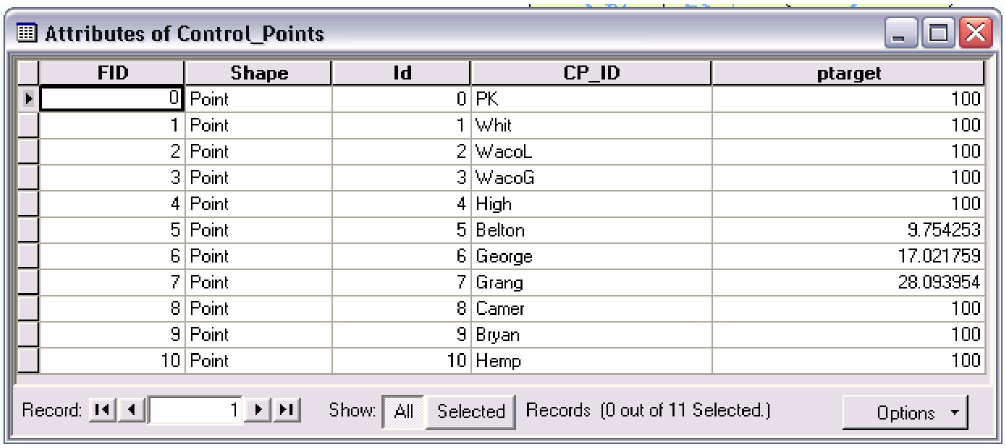
Date End

Year:

Month:

Figure A.25 Percent of target met for March 1951

Open the attribute table for control points, notice that a new field called **Ptarget** is created and the values stored correspond to the percent of target values for the displaying date. Figure A.26 shows the attribute table.

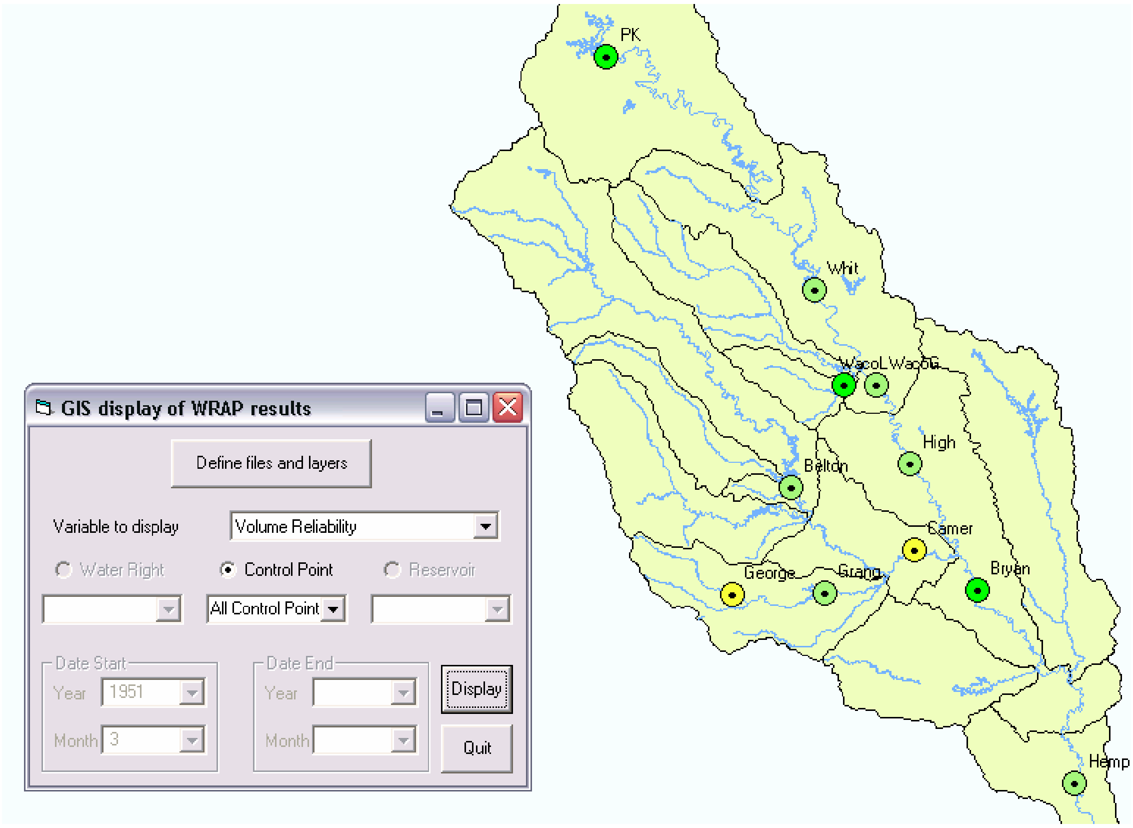


FID	Shape	Id	CP_ID	ptarget
0	Point	0	PK	100
1	Point	1	Whit	100
2	Point	2	WacoL	100
3	Point	3	WacoG	100
4	Point	4	High	100
5	Point	5	Belton	9.754253
6	Point	6	George	17.021759
7	Point	7	Grang	28.093954
8	Point	8	Camer	100
9	Point	9	Bryan	100
10	Point	10	Hemp	100

Record: 1 Show: All Selected Records (0 out of 11 Selected.)

Figure A.26 Attribute table for control points after displaying percent of target met

9. Volumes and period reliabilities for each control point can also be displayed by using the third and fourth variables respectively. In this case, in order to compute reliabilities, all the period of analysis is used, so it is not possible to select a date. These variables add two new fields to the control points attribute table, Volrel and Perrel. Figures A.27 and A.28 show results for volume and period reliabilities respectively, and Figure A.29 shows the attribute table for the control point shapefile. Again, different ranges of reliabilities are represented by different colors of the circles.


GIS display of WRAP results

Variable to display: Volume Reliability

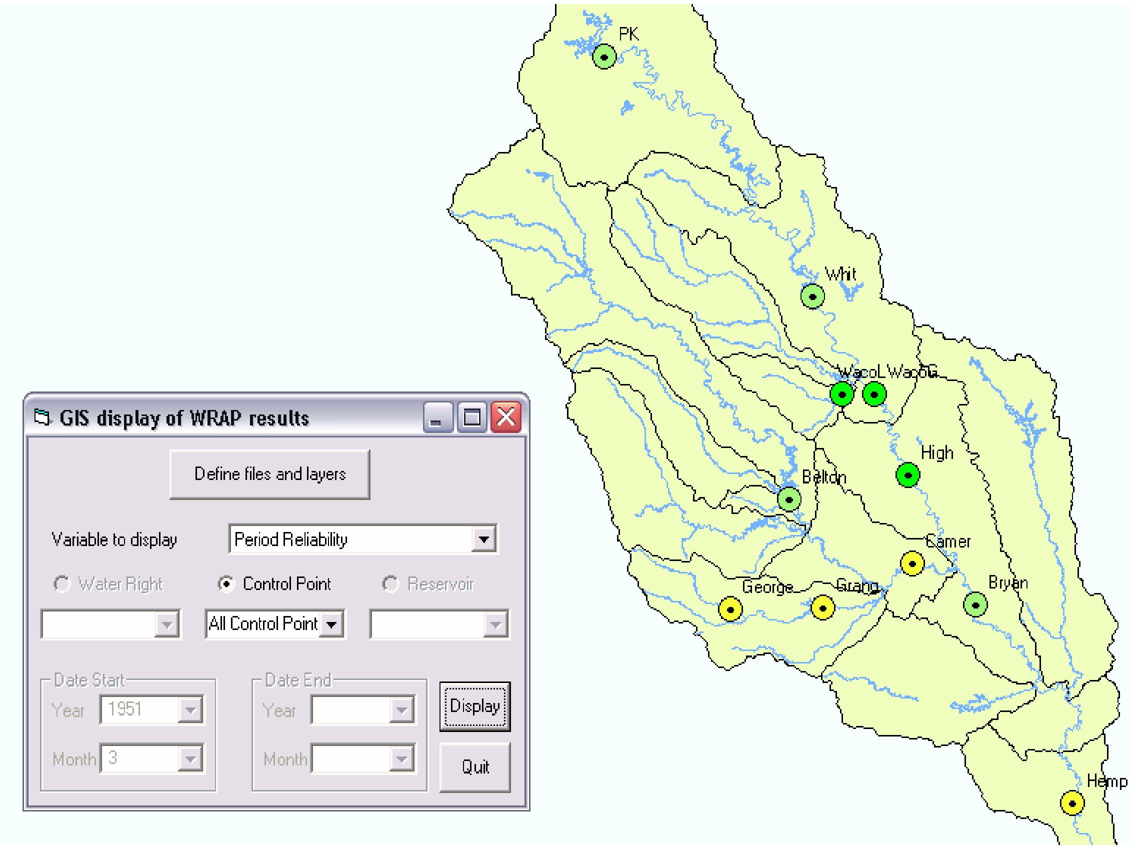
○ Water Right ● Control Point ○ Reservoir

All Control Point

Date Start: Year 1951, Month 3

Date End: Year, Month

Figure A.27 Volume reliability for all control points



Variable to display: Period Reliability

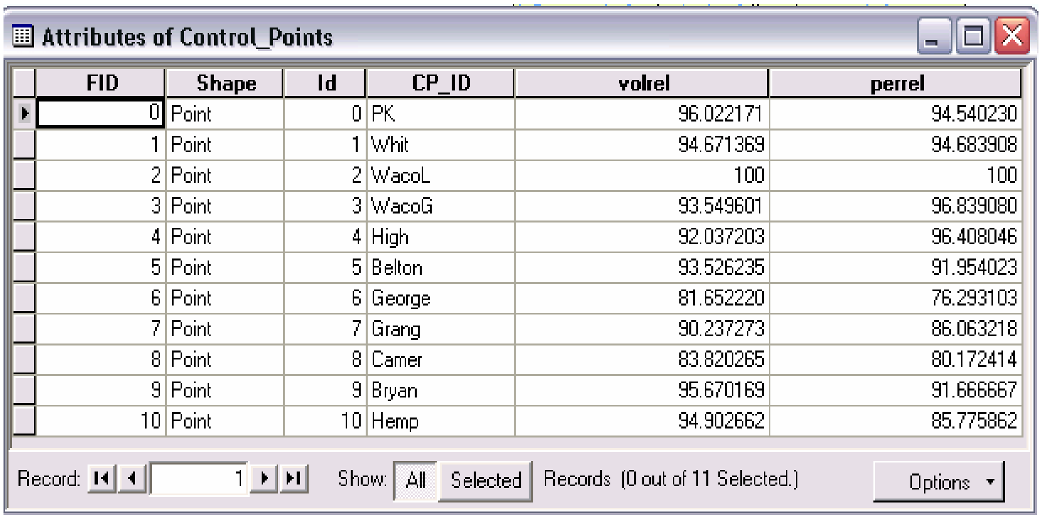
○ Water Right ● Control Point ○ Reservoir

All Control Point

Date Start: Year 1951, Month 3

Date End: Year, Month

Figure A.28 Period reliability for all control points



FID	Shape	Id	CP_ID	volrel	perrel
0	Point	0	PK	96.022171	94.540230
1	Point	1	Whit	94.671369	94.683908
2	Point	2	WacoL	100	100
3	Point	3	WacoG	93.549601	96.839080
4	Point	4	High	92.037203	96.408046
5	Point	5	Belton	93.526235	91.954023
6	Point	6	George	81.652220	76.293103
7	Point	7	Grang	90.237273	86.063218
8	Point	8	Camer	83.820265	80.172414
9	Point	9	Bryan	95.670169	91.666667
10	Point	10	Hemp	94.902662	85.775862

Figure A.29 Control point attribute table after calculating volume and period reliabilities

10. The remaining variables in the variables list display different time series, including naturalized flows, regulated flows, unappropriated flows, reservoir storage, percent of target met and streamflow depletions. These variables are associated with individual control points and reservoirs, with the possibility of plotting total storage in the entire river basin. In addition to the chart being displayed, a text file containing the time series is written to the same folder as the other WRAP files. This file is useful for plotting the time series with a different software package, such as Microsoft Excel. Figure A.30 shows a 1940-1997 monthly naturalized flow time series for a control point at the Hempstead Gage.

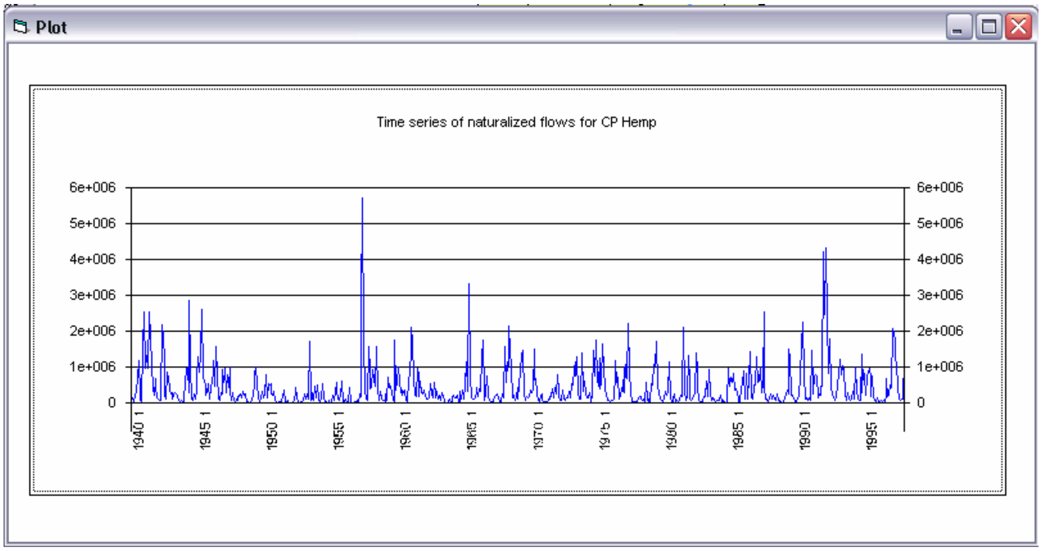


Figure A.30 Naturalized monthly flows from 1940 to 1997 at the Hempstead gage control point

The size of the WRAP output file that can be used for displaying purposes is limited by the computer memory. Therefore, display results for shapefiles containing an extremely large number of features (control points or reservoirs) combined with a long time period of analysis may not be feasible.

APPENDIX B
INSTRUCTIONS FOR PREPARING *SIMD* INPUT RECORDS

SIM input records are described in Chapter 3 of the *Users Manual*. All of the input records used for *SIM* are also applicable for *SIMD.* Additional input records associated with *SIMD* features not included in *SIM* are covered in this appendix.

The *DC* and *DF* records are stored in the *SIMD* sub-monthly input file which has a filename with the extension DCF. The other *SIMD*-specific input record types listed in the table below are included in the DAT file along with all of the other records that are common to both *SIM* and *SIMD.*

SIMD Input Records Described in Appendix B

Record Identifier	Type of Information	Page Number
	Sub-Monthly Time Step Features (DAT File)	
JT	Sub-Monthly Time Step Job Control Data	196
TI	Sub-Monthly Time Intervals	198
W2	Water Right Output in SUB File	199
C2	Control Point Output in SUB File	199
C3	Control Point Output in FFA File	199
G2	Water Right Group Output in SUB File	200
R2	Reservoir/Hydropower Output in SUB File	200
DW	Daily (Sub-Monthly) Water Right Data	201
	Flood Control Operations (DAT File)	
FC	Flood Control Reservoir Operations	202
FF	Flood Flow Limits	203
FV	Reservoir Storage Volume	204
FQ	Reservoir Outflow	204
	Sub-Monthly Time Step Data (DCF File)	
DC	Daily (Sub-Monthly) Control Point Data	205
DF	Daily (Sub-Monthly) Flow or Flow Pattern Data	207

JT Record – Sub-Monthly (Daily) Job Control Data

field	columns	variable	format	value	description
1	1-2	CD	A2	JT	Record identifier
					Number of Sub-Monthly Time Intervals
2	3-8	NTI	I6	Blank,0	Default number of days in each month.
				+	Constant number of intervals in each month.
				-1	Varying number of intervals specified on *TI* record.
					Data Written to SUB file
3	9-12	CPOUT2	I4	-1	Control point data is output for all control points.
				-2	Control point data is output only for cpts with *IN* records and plus those listed on *C2* records.
				+	Control point output is limited to first *CPOUT2* control points plus those listed on *C2* records.
				Blank,0	Control point output is specified only by *CO* records, with no CP output without a *C2* record.
4	12-16	OUTWR2	I4	-1	Water rights data is output for all rights.
				+	Water right output is limited to first *WROUT2* rights plus those listed on *W2* and *G2* records.
				blank,0	Water rights output is specified by *W2* and/or *G2* records, with no WR output without these records.
					Time Block for Output to SUB File
5	17-20	BEGYR	I4	+	Beginning year.
				blank,0	*BEGYR* is assumed equal to *YRST*.
6	21-24	BEGMON	I4	1,+	Beginning month of *BEGYR*.
				blank,0	*BEGMON* is assumed equal to 1.
7	25-28	ENDYR	I4	+	Last year to report.
				blank,0	*ENDYR* is assumed equal to *YRST+NYRS-1*
8	29-32	ENDMON	I4	1,+	Last month of *ENDYR*.
				blank,0	*ENDMON* is assumed equal to 12.
					CRM and FFA Files
9	36	CRMD	I4	1,+	CRM file, if created, contains daily results.
				blank,0	CRM file, if created, contains monthly results.
10	40	FFA	I4	1	FFA file is created and includes all control points.
				-1	FFA file is created for control points on C3 record.
					Next-Day Placement of Routed Flood Flow Changes
11	44		I4	blank,0,1	Routed *FC* record flows are placed in priority loop.
				2	Routed *FC* record flows at beginning of time step.
					Default Forecasting Parameters
12	45-48	FRCST	I4	blank,0	Default is zero forecast period. No forecasting.
				+	Forecast period.
13	52	FVAL	I4	blank,0,1	Default is to use minimum flow to assess availability.
				2	Average flow is used to assess *WR* right availability.

JT Record – Sub-Monthly (Daily) Job Control Data (Continued)

field	columns	variable	format	value	description
					<u>*Default Monthly Flow Disaggregation Option*</u>
14	56	DFMETH	I4	blank,0	No disaggregation. Daily flows are input on *DF* records.
				1	Uniform distribution option
				2	Linear interpolation option
				3	Variability adjustment option
				4	Flow pattern option
15	57-64	VRL	F8.0	Blank,0	Default = 0.10 for limit used with option 3.
				+	Limit VRL from Equation 3.1 used with option 3.
16	65-72	DFMULT	F8.0	Blank,0	Default = 1.0
				+	Multiplier for flows from *DF* records.

The *JT* record is required to incorporate a daily or other sub-monthly time step in a *SIMD* simulation. A blank *JT* record activates all defaults. The *JT* record is placed in the DAT file following the *JD* and *JO* records.

<u>Explanation of JT Record Fields</u>

<u>***Field 2***</u>: Each month may be divided in an interval number of intervals ranging from 1 to 32. For example, entering 5 for *NTI* results in constant time steps of 1/5 month throughout the year. The default is to divide February into 28 or 29 (leap year) days and the other 11 months into either 30 or 31 days. Entering –1 in *JT* field 2 means that 12 integers varying between months are entered on a *TI* record.

<u>***Fields 3 and 4***</u>: *CPOUT2* and *OUTWR2* on the *JT* record and *W2*, *C2*, *R2*, *G2* records control sub-monthly time step output written to the SUB file in the same manner as *CPOUT* and *OUTWR* on the *JD* record in combination with the *WO*, *CO*, *RO*, *GO* records control monthly output written to the OUT file.

<u>***Fields 5-8***</u>: The data written to the SUB file covers the period extending from the beginning year and month through the ending year and month defined in fields 5, 6, 7, and 8.

<u>***Field 9***</u>: Conditional reliability modeling with a resultant *CRM* file is activated by a *CR* record with either a monthly or daily time step simulation. For a daily time step simulation, simulation results written to a CRM file may be either daily or aggregated monthly amounts. The default is to write monthly amounts to the CRM file. Optionally, *JT* field 9 allows daily values to be recorded in the CRM file.

<u>***Field 10***</u>: The annual series of maximum daily naturalized and regulated flow and reservoir storage may be written to a FFA file to be read by *TABLES* to perform flood frequency analyses. The default (blank field 10) is to not create a FFA file. A one in field 10 creates a FFA file containing all control points. A −1 indicates that only the control points listed on a C3 record are included in the FFA file.

Field 11: Next-day results of Muskingum routing of *FC* record storage effects and releases may be placed either at the beginning of the next-day simulation or inserted in the water rights priority loop.

Field 12: The global forecast period in days (sub-monthly time interval) is applied for all water rights unless over-ridden for individual rights by the forecast period in *DW* record field 4 or *FF* record field 5.

Field 13: Water availability is determined based on either the minimum or the average of amounts from each day of the forecast period. *JT* field 13 sets a default that may be overridden by *DW* record field 5.

Field 14: Daily flows may be computed within *SIMD* by disaggregating monthly naturalized flows using the various optional methods described in Table 3.2. The global default approach set in *JT* record field 14 may be over-ridden for individual control points by *METH* in *DC* record field 7. The option selected in *JT* field 14 is used for all control points that have no other option activated by *DC* record field 7.

Field 15: Equation 3.1 in Chapter 3 defines an upper limit (VRL) on the variability ratio (VR) used with flow disaggregation option 3. The default of 0.10 may be replaced by entering a value in field 15.

Field 16: The flow quantities on the *DF* records may be multiplied by a factor entered in field 16. If monthly flows are disaggregated to sub-monthly flows, units of flow on the *DF* records are irrelevant. However, if the daily flows from the DF records are used directly without activating monthly disaggregation options, DFMULT in field 16 may be a unit conversion factor used to convert the units of the DF record flows to be consistent with the other simulation quantities.

TI Record – Sub-Monthly Time Intervals

field	columns	variable	format	value	description
1	1-2	CD	A2	TI	Record identifier
2	3-8	NDAY(1)	I8	+	Number of time steps in first month.
3-13	9-92	NDAY(I) I=2,12	11I8	+	Number of time steps in 2nd through 12th months.

A *TI* record is required if *NTI* in *JT* record field 2 is less than zero. The *TI* record is placed in the DAT file after the *JT* record and before the *WO*/*CO*/*GO*/*RO* and/or *W2*/*C2*/*G2*/*R2* records. *NTI* and *NDAY*(*I*) can not exceed a maximum of 32 sub-monthly time steps, which is also the maximum number of data fields available per *DF* record.

W2 Record – Water Rights Output Records to be Included in SUB File

field	columns	Variable	format	value	description
1	1-2	CD	A2	TI	Record identifier
2	3-8	NWOUT2	I6	+	Number of water right identifiers on *W2* records. *NWOUT2* is entered only on the first *W2* record.
				blank,0	*W2* records are ignored if *NWOUT2* is zero.
3-7	9-88	WROUT2(J) J=1,5	5A16	AN	Water right identifiers for rights included in SUB file.

C2 Record – Control Point Output Records to be Included in SUB File

field	columns	variable	format	value	description
1	1-2	CD	A2	C2	Record identifier
2	3-8	NCPOUT2	I6	+	Number of control point identifiers. *NCPOUT2* is entered only on the first *C2* record.
				Blank,0	*C2* records are ignored if *NCPOUT2* is zero.
3-7	9-48	CPOUID2(J) J=1,5	5(2x,A6)	AN	Control point identifiers of control points included in the SUB file.

C3 Record – Control Point Output Records to be Included in FFA File

field	columns	variable	format	value	description
1	1-2	CD	A2	C3	Record identifier
2	3-8	NCPOUT3	I6	+	Number of control point identifiers. *NCPOUT3* is entered only on the first *C3* record.
				Blank,0	*C3* records are ignored if *NCPOUT3* is zero.
3-7	9-48	CPOUID3(J) J=1,5	5(2x,A6)	AN	Control point identifiers of control points included in the FFA file.

G2 Record – Groups of Water Right Output Records to be Included in SUB File

field	columns	variable	format	value	description
1	1-2	CD	A2	G2	Record identifier
2	3-8	NGOUT2	I6	1-5	Number of water right identifiers on *G2* records. *NGOUT2* is entered only on the first *G2* record.
				blank,0	*G2* records are ignored if *NGOUT2* is zero.
3-7	9-48	GROUP2(J) J=1,5	5A8	AN	Group identifiers for water rights included in SUB file.

R2 Record – Reservoir/Hydropower Output Records to be Included in SUB File

field	columns	variable	format	value	description
1	1-2	CD	A2	R2	Record identifier
2	3-8	NREOUT2	I6	1-5	Number of reservoir identifiers on *R2* records. *NREOUT2* is entered only on the first R2 record.
				blank,0	*R2* records are ignored if *NREOUT2* is zero.
				-1	All reservoirs are included in the output.
3-7	9-48	REOUID2(J) J=1,5	5(2x,A6)	AN	Reservoir identifiers for reservoir/hydropower projects included in SUB file.

W2, *C2*, *C3*, *R2* and *G2* records are placed in the DAT file following the *JC/JO/JT* records or *WO*/*CO*/*GO*/*RO* records.

The *C3* controls which if any control points are included in a flood frequency analysis FFA output file. *W2*, *C2*, *G2* and *R2* records control the selection of data to be output to the SUB file.

W2, *C2*, *G2* and *R2* records specifying daily or other sub-monthly output data are analogous to the *WO*, *CO*, *GO*, and *RO* records which control monthly output data. Each of the records provides sets of identifiers used to select data to include in the simulation results, with up to five identifiers per record. All *C2* records are grouped together. All *C3* records are grouped together. All *R2* records are grouped as a set. Likewise, all *W2* are grouped together, and all *G2* records are grouped together. All are optional. It does not matter which of the four sets of records precede or follow the others. However, the complete set of *W2*/*C2*/C3/*G2*/*R2* records, if used, should follow after the complete set of *WO*/*CO*/*GO*/*RO* records, if used.

DW Record – Daily (Sub-Monthly) Data for a Water Right

field	columns	variable	format	value	description
1	1-2	CD	A2	DW	Record identifier
					Variation in Daily Targets During Month
2	3-8	ND	I6	+	Number of days or other sub-monthly time steps.
				Blank,0	Option is not activated.
3	9-16	SHORT	I8	+	Shortages are supplied in subsequent days.
				Blank,0	Option is not activated.
					Flow Forecast Parameters
4	17-24	FRCST	I8	Blank,0	Default is set by *JT* record field 12.
				+	Forecast period in days or sub-monthly time steps.
5	25-32	FVAL	I8	Blank,0	Default is set by *JT* record field 13.
				1	Minimum flow is used to assess availability.
				2	Average flow is used to assess availability.

The optional *DW* record is included within the group of records that follow a water right *WR* or instream flow *IF* record and provide supporting information regarding that water right. The *DW* record may be placed anyplace within the group of *SO*, *TO*, *TS*, and *WS/HP/OR* records that follow a *WR* or *IF* record.

Explanation of DW Record Fields

Field 2: If field 2 is left blank, the diversion, hydropower, or instream flow target specified on the *WR* or *IF* record is uniformly distributed over each day (sub-monthly time interval) of the month. A positive integer entry for *ND* activates an option in which the monthly target is uniformly distributed over the first *ND* days of the month. The *ND* option can be applied for either diversion, hydropower, or instream flow targets.

Field 3: The *SHORT* option can be activated by field 3 only if the *ND* option is activated in field 2. The *SHORT* option allows shortages to be supplied in subsequent days of the same month. If field 3 is blank, diversion and hydropower targets are met only during the first *ND* days of the month, with shortages declared if the targets can not be met. The *SHORT* option is applicable to either diversion or hydropower targets but is not applicable to instream flow targets.

Field 4: A global forecast period in days (sub-monthly time steps) may be set in *JT* record field 12 for use with all water rights except those rights with an individual forecast period provided in *DW* field 4. *DW* record field 4 over-rides the *JT* record field 12 default. The forecast period is applicable to *WR* record water rights and *FC* record flood control rights.

Field 5: The amount of stream flow available to a water right depends upon flow availability determined for the current day and each day of the forecast period (F_P). Optionally, either the minimum or average of the amounts in the F_P+1 days may be adopted to set the flow availability for a water right. The global default option set by *JT* record field 13 may be overridden for individual rights by DW record field5.

FC Record – Flood Control Reservoir Operations

field	columns	variable	format	value	description
1	1-2	CD	A2	FC	Record identifier
2	3-8		I6	A6	Reservoir identifier
3	9-16		I8	+	Storage priority number
4	17-24		I8	+	Release priority number
5	25-32		I8	+	Number of *FF* record limits, default is all *FF* records.
6	33-40		F8.0	+	Maximum release volume per time interval.
					Storage Volumes
7	41-48		F8.0	+	Total storage capacity at top of flood control pool.
8	49-56		F8.0	+	Storage capacity activating *FV/FQ* record table.
9	57-64		F8.0	+	Storage capacity at bottom of flood control pool.
10	73-80		F8.0	+	Beginning-of-simulation storage contents.
					Multiple-Reservoir System Balancing Index
11	81-88		F8.0	+	Multiplier factor M, default = 1.0
12	89-96		F8.0	+	Addition factor A, default = 0.0
					Storage-Area Relationship
13	97-104	EVCFA	F8.0	+	Multiplier A for storage-area equation.
14	105-112	EVCFB	F8.0	+	Multiplier B for storage-area equation.
15	113-120	EVCFC	F8.0	+	Multiplier C for storage-area equation.

Explanation of FC Record Fields

Field 2: The *FC* record right is for the reservoir with this identifier.

Fields 3 and 4: Storage and release priorities control the order in which the water right simulation computations are sequenced. Low priority numbers are senior to larger numbers.

Field 5: The default is for operation of the reservoir to be based on all *FF* record control points at and downstream of the reservoir. An integer in field 5 limits the number of *FF* record control points considered. The control points nearest the reservoir are considered.

Field 6: Daily release volumes from controlled flood control storage are constrained to not exceed this maximum limit.

Field 7: The top of flood control pool is the maximum cumulative storage volume to which inflows can be stored. If this level is exceeded, outflow equals inflow.

Field 8: An entry in field 8 is required to activate routing with a *FV/FQ* record storage-outflow table. The *FV/FQ* record storage-outflow relationship governs outflows if the storage rises above this level. Otherwise, release rules control releases from controlled flood control storage.

Field 9: Controlled flood control releases are not made if storage contents falls below this level.

Field 10: *FC* record field 10 is blank if one or more *WR* records are associated with the reservoir because the beginning-of-simulation storage is already be defined by *WR/WS* records. If field 10 is blank or zero for a single-purpose flood control reservoir without *WR* record rights attached, the storage contents will be zero at the beginning of the simulation.

Fields 11 and 12: The rank index is used to sequence simulation of each reservoir of a multiple reservoir system. Multi-reservoir system reservoirs have the same priority in fields 3 and/or 4.

$$\text{rank index} = M \left[\frac{\text{content}}{\text{capacity}} \right] + A$$

Fields 13, 14, 15: The storage-area relationship is defined by the first *WR/WS* or *FC* record in the dataset associated with a reservoir. *SV/SA* records are provided if *FC* fields 13-15 are blank and A, B, and C for the storage-area equation has not been defined by a preceding *WS* record.

$$\text{surface area} = A\,(\text{storage})^{B} + C$$

FF Record – Flood Flow Limit

field	columns	variable	format	value	description
1	1-2	CD	A2	FF	Record identifier
2	3-8	CP	I6	A6	Control point identifier
3	9-24	AMT	F16.0	+	Annual flood flow limit volume.
4	25-32	USE	2x,A6	blank,0 +	Default is uniform based on number days in month. Monthly distribution identifier (*UC* records).
5	33-40		I8	blank,0 +	Default is no forecast period. Forecast period in days or number of time steps.
6	40-48	DINDEX(wr)	I8	blank,0 +	Default is to not apply flood (drought) index. Flood index to connect to DI/IS/IP records.

Explanation of FF Record Fields

Field 2: The *FF* record limit is applied to flows at this control point.

Field 3: The annual equivalent volume from which the daily flow limits are computed are entered in the 16-character field 3. Annual volume is converted to monthly, then daily.

Field 4: The default is to distribute the monthly limit uniformly of the days of the month. A use identifier in field 4 connects to monthly coefficients on *UC* records. Monthly volumes are uniformly distributed to daily volumes.

Field 5: The forecast period is time steps, such as days, applied to flows at this control point.

Field 6: A flood index on a *FC* record is the same as a drought index on a *WR* record and connects the flow limit to a *DI/IS/IP* record storage-percentage target table.

FV Record – Reservoir Storage Volume for Storage versus Outflow Table

field	columns	variable	format	value	description
1	1-2		A2	FV	Record identifier
2	3-8		I6	A6	Reservoir identifier
3	9-104		F16.0	+	Reservoir storage volumes corresponding to outflows in same fields of *FQ* record.

FQ Record – Reservoir Outflow for Storage versus Outflow Table

field	columns	variable	format	value	description
1	1-2		A2	FV	Record identifier
2	3-8		I6	A6	Reservoir identifier
3	9-104		F16.0	+	Reservoir outflows corresponding to volumes in same fields of *FV* record.

DC Record – Daily (Sub-Monthly) Information for a Control Point

field	columns	variable	format	value	description
1	1-2	CD	A2	DC	Record identifier
2	3-8	CPID	2x,A6	AN	Control point identifier corresponding to *CP* record.
					Muskingum Routing Coefficients for Normal Flows
3	9-16	MK(cp)	F8.0	blank,0 +	Routing is not performed in the reach below CP. Muskingum *K* for the stream reach below CP.
4	17-24	MX(cp)	F8.0	+	Muskingum *X* for the stream reach below CP.
					Muskingum Routing Coefficients for Flood Flows
5	25-32	MKF(cp)	F8.0	blank,0 +	MK(cp) in field 3 is also applicable to flood flows. Muskingum *K* for flood flows in reach below CP.
6	33-40	MXF(cp)	F8.0	blank,0 +	MX(cp) in field 4 is also applicable to flood flows. Muskingum *X* for flood flows in reach below CP.
					Method for Disaggregation of Monthly Volume
7	41-48	METH	I8	blank,0 1 2 3 4 5 6	Default is specified in *JT* record field 14. Uniform distribution option Linear interpolation option Variability adjustment option Flow pattern option Drainage area ratio transfer option Regression equation transfer option.
					Source and Temporal Range of Explicit Pattern
8	49-56	DFID	2x,A6	AN Blank	Control point identifier on *DF* records of source gage. Default is *CPID* in *DC* record field 2
9	57-64	BEGYR	I8	+ blank,0	Beginning year of the pattern. Default = first year of simulation
10	65-72	BEGMT	I8	+,blank,0	Beginning month of the pattern. Default = 1
11	73-80	ENDYR	I8	+ blank,0	Ending year of the pattern. Default = last year of simulation
12	81-88	ENDMT	I8	blank,0,+	Ending month of the pattern. Default = 12
					Flow Lag Option
13	89-96	LAG	I8	+,-	Phase shift in units of time steps. Default = 0
					Coefficients for DFMETH Options 5 and 6
14	97-104	X	F8.0	+,blank,0	Exponent for *METH* options 5 and 6. Default = 1.0
15	105-112	M	F8.0	+,blank,0	Multiplicative coefficient for option 6. Default = 1.0
16	113-120	A	F8.0	+,blank,0	Additive coefficient for *METH* option 6. Default = 0.0

A *DC* record is required if routing occurs in the reach below the control point, thus requiring the MK and MX parameters in fields 3 and 4, or if a flow disaggregation method other than the default is used. The complete set of all *DC* records is placed in the DCF file before the complete set of *DF* records.

Explanation of DC Record Fields

Field 2: The data provided on the *DC* record is for the control point with this identifier.

Fields 3 and 4: The Muskingum X and K parameters [MK(cp) and MX(cp)] are for the reach downstream of this control point. *MX*(*cp*) is a dimensionless coefficient. Units for *MK*(*cp*) correspond to the time step. For example, for a daily time step, *MK* is an integer number of days.

Fields 5 and 6: The Muskingum X and K parameters [MKF(cp) and MXF(cp)] for *FC* record flood releases and filling of flood control pools may be different than the X and K for normal flows. Flow travel times during floods or high flows are typically shorter than for normal flows.

Field 7: Sub-monthly flows may be input on *DF* records, with no monthly flows provided. Alternatively, monthly flows may be disaggregated using various optional methods. Alternative flow disaggregation options are outlined in Table 3.2. If field 7 is blank, the default option defined in *JT* record field 11 is adopted for the control point.

Fields 8-12: Disaggregation options 3, 4, 5, and 6 are based on flow amounts from *DF* records. *DC* record fields 8-12 define the flow sequences from the *DF* records that are used to develop flow patterns for use in the disaggregation computations.

Field 13: Disaggregation options 4, 5, and 6 activated by *METH* in field 5 are based on a pattern established using flows from *DF* records. *LAG* in field 13 is used to shifting the time series forward or backward in time. *LAG* > 0 is used for transferring a pattern to a downstream destination from an upstream source. The time series at the upstream source is shifted forward in time, with the value at time step *T* at the source becomes the value at time step *T+LAG* at the destination. Likewise, *LAG* < 0 is used for transferring a downstream source pattern to an upstream destination by shifting the pattern earlier in time. The pattern is first checked for the need to repeat. Then during shifting, the values at the trailing end of the shift in the array are set equal to the last value of the trailing end. Values at the leading end of the shift in the array are lost.

Fields 14-16: Disaggregation options 5 and 6 activated by *METH* in field 7 are based transferring a pattern established using flows from *DF* records from a source control point to a destination control point using one of the following equations with parameter values provided in fields 14-16.

$$P_{\text{destination}} = \left[P_{\text{Source}} \left(\frac{\text{Area}_{\text{destination}}}{\text{Area}_{\text{source}}} \right) \right]^{X}$$

$$P_{\text{destination}} = A + M \left(P_{\text{source}} \right)^{X}$$

DF Record – Daily (or sub-monthly) Flow Record

field	columns	variable	format	value	description
1	1-2	CD	A2	DF	Record identifier
2	3-8	DFID	A6	AN	Identifier of the source location for the flow pattern. *DFID* is entered on the first *DF* record only.
3	9-16	YEAR	2x,A6	+	Year for the *DFLOW* values.
4	17-24	MONTH	2x,A6	+	Month for the *DFLOW* values.
5	25-32	NUM	I8	blank,0	By default, *NUM* is set to 4 to accommodate the default calendar day daily simulation.
				+	Number of *DFLOW* data records to follow. *NUM* is an integer between 1 and 4.

NUM lines of sub-monthly flow data covering one month following each *DF* record. Each line is in the following format.

1-8	1-80	DFLOW(J) J=1,8	8F10.0	+	Flow or flow pattern for sub-monthly time steps. Up to 8 flow values are entered across each line.

An example of a *DF* record for one month is as follows.

```
DF    CP-1      1974        12         4
     236.0     238.0     237.0     228.0     212.0     208.0     407.0     943.0
     421.0     286.0     958.0     734.0     459.0     316.0     265.0     244.0
     217.0     191.0     176.0     241.0     393.0     375.0     456.0     465.0
    1096.0    1618.0    1713.0    1647.0    1241.0     837.0     880.0     712.0
```

DF records are placed in the DCF file after the complete set of *DC* records. *DFLOW* values can be either actual sub-monthly naturalized flow volumes or amounts used to define a pattern for the flow disaggregation options. For defining a sub-monthly flow pattern, only the relative magnitude, not the actual magnitude, of the data entries is relevant.

APPENDIX C
INSTRUCTIONS FOR PREPARING *DAY* INPUT RECORDS

Any number of flow disaggregation and routing parameter calibration jobs may be specified in a Program *DAY* input file with the filename extension DIN using the input records described in this appendix. The results are written to an output file with the filename extension DAY.

Programs *DAY* and *SIMD* read the same FLO and DCF files. Monthly flows (*IN* records) and daily flows (*DF* records) are read from files with filename extensions FLO and DCF, respectively. The format of the *IN* records described in the *Users Manual* and the *DF* records described in the preceding Appendix B are the same for *DAY* and *SIMD*. Program *DAY* reads *IN* and *DF* records from the FLO and DCF files for only those control points specified in the *DIN* file. Records not needed are skipped.

Program *DAY* can also read sub-monthly flows in columnar format from a file with the filename extension DCF. The flows may be written to a file with filename extension DAY in the standard *DF* record format. The DAY file can be renamed with the DCF extension for use as a Program *DAY* or *SIMD* input file. The flows read as columns may also be used directly in the Program *DAY* disaggregation or parameter calibration computations.

Program *DAY* Input Records in a DIN File

Record Identifier	Type of Information	Page Number
	Records for Monthly Flow Disaggregation	
JOBDIS	Monthly to Daily Flow Disaggregation Job	210
NUMDAY	Sub-Monthly Time Intervals	212
RANGES	Input Data Time Range	212
	Records for Muskingum Parameter Optimization	
JOBMSK	Muskingum Parameter Optimization Job	215
KLOWER	Lower Constraints for *K*	215
KUPPER	Upper Constraints for *K*	215
XLOWER	Lower Constraints for *X*	216
XUPPER	Upper Constraints for *X*	216
RANGES	Input Data Time and Flow Range	217

** Record − Comments

field	columns	variable	format	value	description
1	1-2	CD	A2	**	Record identifier

Comment ** records are ignored by the computer program. Comment lines can be inserted between any records throughout the *DAY* input DIN file.

Records For Flow Disaggregation

JOBDIS Record − Monthly to Sub-Monthly (Daily) Flow Disaggregation Job

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	JOBDIS	Record identifier
					Number of Sub-Monthly Time Intervals
2	9-16	NTI	I8	blank, 0	Days per month are used as the time interval for producing the output daily flow time series. Leap year days are computed automatically.
				+	Constant number of intervals in each month.
				−1	User defined time intervals per month to be given in the *NUMDAY* record.
					Method for Disaggregation
3	17-24	METH	I8	1	Uniform distribution option
				2	Linear interpolation option
				3	Variability adjustment option
				4	Flow pattern option
				5	Drainage area ratio transfer option
				6	Regression equation transfer option.
				blank, 0	Flows are read and output with disaggregation.
4	25-32	VOL	I8	blank,0	Monthly and daily input data required for *DFMETH* 5 and 6.
				1	Only daily input data is used for methods 5 and 6.
					Daily Flow Lag Option
5	33-40	LAG	I8	blank,0,+,−	Number of time steps to shift output daily pattern.
					Coefficients for DFMETH Options 5 and 6
6	41-48	X	F8.0	+,blank,0	Option 5: Exponent, Default = 1.0 Option 6: Exponent, Default = 1.0
7	49-56	M	F8.0	+,blank,0	Option 5: Destination Area, Default = 1.0 Option 6: Multiplicative Coefficient, Default = 1.0
8	57-64	A	F8.0	+,blank,0	Option 5: Source Area, Default = 1.0 Option 6: Additive Coefficient, Default = 0.0
					Format of Daily Flows Read from DCF File
9	65-72		I8	blank, 0	Flows are read in standard DF record format.
				1	Flows are read in columnar format.
					Identifier and Formatting for Daily Flow Pattern
10	73-80	OUTFORM	I8	0	Columns of daily flows
				1	Rows of daily flows
				2	*SIMD DF* record formatted daily flows
11	81-88	ID(J) J=I,N	2x,A6	AN	Identifier for the output daily flow pattern. N=1 when METH > 0. N=ABS(METH) when METH < 0.

A JOBDIS record results in generation of a sequence of flows with a daily or other sub-monthly time step at single control point. Any number of flow disaggregation jobs may be included in a DIN file. For each job, the JOBDIS record may be followed by optional NUMDAY and RANGES records as needed. The disaggregated flows may be written to a DAY file and/or saved in memory for use in a subsequent JOBMSK record parameter calibration job.

Explanation of JOBDIS Record Fields

Field 2: Each month may be divided into any number of intervals ranging from 1 to 32. Alternatively, calendar days can be selected and the program will automatically compute days per month. Leap years are considered. Entering –1 in field 2 means that 12 integers varying between months are entered on a *NUMDAY* record.

Field 3: Disaggregation methods 1 through 6 are used to create an output daily flow pattern from the data contained in the input file. Field 3 may be left blank if flows being simply read from the DCF file and written to the DAY file in a different format as specified in fields 9 and 10 without performing disaggregation. In this case, fields 4-8 of are ignored.

Field 4: Only monthly data is required in the input file for field 3 *METH* 1 and 2. Method 3 requires both monthly and daily input data. Method 4 and only requires daily data. Methods 5 and 6 can use either a combination of monthly and daily input data or simply daily input data. This is equivalent to the use of variable *JTMETH* on the *JT* record. If monthly input volumes are used for *METH* 5 or 6, then the monthly input data controls the total volume and the daily input data is used as a pattern.

Field 5: *LAG* is used to shift the output daily flow pattern forward or backward a number of time steps. *LAG* > 0 would be used if the output corresponds to a location downstream of the input data. *LAG* < 0 would be used for shifting earlier in time, common for output corresponding to a location upstream of the input data.

Field 6-8: Disaggregation options 5 and 6 activated by *METH* in field 3 are based transferring a pattern established using flows from the source location in the input file to a destination location using one of the following equations with parameter values provided in fields 6-8.

$$\mathrm{P_{Destination}} = \left[\mathrm{P_{Source}} \left(\frac{\mathrm{Area_{Destination}}}{\mathrm{Area_{Source}}} \right) \right]^{\mathrm{X}}$$

$$\mathrm{P_{Destination}} = \mathrm{A} + \mathrm{M} \left(\mathrm{P_{Source}} \right)^{\mathrm{X}}$$

Field 9: The sub-monthly flows may be read in the standard *DF* record format or alternatively as columns of flow. Flows may be read from the DCF file in the format specified in field 8 and written to the DAY file in the format specified in field 10.

Field 10: The read or disaggregated flows may be written to the DAY file in three alternative formats. Alternatively, the flows may be used in a subsequent routing parameter calibration job without being written to the DAY file.

Field 11: The identifier *ID* is used to label the daily flow pattern written to the output DAY file.

NUMDAY Record − Sub-Monthly Time Intervals

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	NUMDAY	Record identifier
2-13	9-104	NDAY(I) I=1,12	12I8	+	Number of time steps in months 1 through 12.

Record *NUMDAY* is only used when *NTI* is equal to -1 on the *JOBDIS* record. The number of time steps *NDAY(I)* in each month can be set to any integer from to 1 through 32.

RANGES Record − Format and Time Range of the Input Data

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	RANGES	Record identifier
					<u>*Formatting for the Input File*</u>
2	9-16	INFORM	I8	blank,0	Columnar monthly flows followed by columnar daily flows if needed (*METH* > 1)
				1	Rows of monthly flows followed by rows of daily flows if needed
				2	Monthly flows in *SIM IN* format followed by columnar daily flows if needed
				3	Monthly flows in *SIM IN* format followed by *SIMD DF* format daily flows if needed
				−1	Multiple columnar daily flow hydrograph. This format is only used when *METH* < 0.
					<u>*Time Range to Use from the Input Data*</u>
3	17-24	MBEGYR	I8	+	First year for reading monthly data input.
4	25-32	MBEGMT	I8	blank, +	First month for reading monthly data input. Default = 1
5	33-40	MENDYR	I8	+	Last year for reading monthly data input.
6	41-48	MENDMT	I8	blank, +	Last month for reading monthly data input. Default = 12
7	49-56	DBEGYR	I8	+	First year for reading daily data input.
8	57-64	DBEGMT	I8	blank, +	First month for reading daily data input. Default = 1
9	65-72	DENDYR	I8	+	Last year for reading daily data input.
10	73-80	DENDMT	I8	blank, +	Last month for reading daily data input. Default = 12

Time Range for the Reading Data from the Input File

The input file containing the monthly and daily flows can potentially cover a large period of record, of which the user may wish to only operate on a subset. Using the *RANGES* record, the user can specify what temporal range the dissagregation method will apply towards. For instance, the user may have a monthly data covering a period of record from 1900 through 1999. Complementing the monthly data the user might have daily flows covering a few decades centered around a drought occurring in the 1950's. The user would be able to isolate the input data occurring in the worst year of the drought, say 1952, by selecting the appropriate starting and ending dates in fields 3 through 10 of the *RANGES* record.

If the disaggregation method selected does not require either monthly or daily input data, the corresponding fields on the *RANGES* record may be left blank. If the number of months for the daily input data is shorter than the selected period of record of the monthly input data, the daily data is repeated until the number of months in the monthly period of record is reached.

Records For Muskingum Parameter Optimization

JOBMSK Record − Muskingum Parameter Optimization Job

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	JOBMSK	Record identifier
					Calibration Option
2	9-16		I8	blank, 0	Both direct and optimization options are applied.
				1	Direct option is applied for parameter calibration.
				2	Optimization option is applied.
				3	Simulation only to compute objective function.
					Optimization Objective Function
3	17-24	FUNC	I8	blank, 0, 1	Objective function option 1 (Z_1) is applied.
				2	Objective function option 2 (Z_2) is applied.
				3	Objective function option 3 (Z_3) is applied.
				4	Objective function option 4 (Z_4) is applied.
				5	Objective function option 5 (Z_4) is applied.
					Number and Names of Control Points
2	9-16	NGAGES	I8	+	Number of inflow(s) and outflow cpts in input file.
				blank, 0	Default = 2 for one inflow and one outflow gage.
3	17	GNAMES(I) I=1,NGAGES	2x,A6	AN	Names assigned to the inflow and outflow control points used in the calibration.

There must be at least one inflow and only one outflow known series in the input file. The values for *GNAMES(I)* are optional. If they are not used, *DAY* proceeds with the optimization using the following defaults names:

GNAMES(1:*NGAGES*) = “INFLOW_01”, “INFLOW_02”,…. , *INFLOW_N-1*, “OUTFLOW”

KLOWER Record − Lower Constraints for Muskingum *K* in the Optimization

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	KLOWER	Record identifier
2	9	KMIN(I) I=1,NGAGES	F8.3	0,+	Lower limit of the value of *K*. The units are time steps. Default = 0.0

KUPPER Record − Upper Constraints for Muskingum *K* in the Optimization

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	KUPPER	Record identifier
2	9	KMAX(I) I=1,NGAGES	F8.3	+	Upper limit of the value of *K*. The units are time steps.

XLOWER Record − Lower Constraints for Muskingum *X* in the Optimization

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	XLOWER	Record identifier
2	9	XMIN(I) I=1,NGAGES	F8.3	0,+	Lower limit of the value of *X*. The units are time steps. Default = 0.0

XUPPER Record − Upper Constraints for Muskingum *X* in the Optimization

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	XUPPER	Record identifier
2	9	XMAX(I) I=1,NGAGES	F8.3	+	Upper limit of the value of *X*. The units are time steps. Default = 0.5

The records for specifying the lower and upper bounds for *K*, *X* and α are optional. If they are omitted, the optimization proceeds with default constraints:

$$0.0 \le K \le 10.0 \qquad 0.0 \le X \le 0.5 \qquad 0.0 \le \alpha \le 1.0$$

RANGES Record − Time and Flow Range of the Input Hydrograph Data

field	columns	variable	format	value	description
1	1-8	CD	A6,2x	RANGES	Record identifier
					<u>*Temporal Range*</u>
2	9-16	BEGYR	I8	+	First year for reading input hydrographs.
3	17-24	BEGMT	I8	blank, +	First month reading input hydrographs. Default = 1
4	25-32	ENDYR	I8	+	Last year for reading input hydrographs.
5	33-40	ENDMT	I8	blank, +	Last month reading input hydrographs. Default = 12
					<u>*Flow Range*</u>
6	41-48	QMIN(I)	F8.0	0,blank,+	Lower limit on upstream flows. Default = 0.0
7	49-56	QMAX(I) I=1,NGAGES	F8.0	0,blank,+	Upper limit on upstream flows. Default = no upper limit on flows.

<u>**Explanation of the Temporal and Flow Ranges**</u>

The input file of flow hydrographs can contain a large period of record. The entire period of record can be considered for calibrating the Muskingum parameters through optimization and by the traditional regression analysis. Alternatively, a subset of the period of record, down to a single month, can be selected for the calibration. A flow regime itself can also be selected using *SIDE* and *THRESHOLD*. If the flow range variables are left blank, the default is to consider all of the time steps in the specified temporal range. If the variables are initialized for a range of flows, only those time steps in the temporal range where the gaged flow at the upstream location falls on the selected *SIDE* of the *THRESHOLD* will be considered in the calibration. All sequential time steps specified by the temporal range will be used to generate routing data. However, the calibration algorithms will count only those time steps which also conform to the flow range when seeking the fit for Muskingum parameters. If the temporal range and flow range do not result in selection of at least two positive valued time steps of gaged flow at the upstream location, the calibration will not proceed.

For example, the user may have a period of record from 1950 through 1959 for a major river. The flow regime in the period of record might range from a drought characterized by many years with an average daily flow rate of under 1,000 cfs to a drought breaking flood when average daily flow rates in excess of 50,000 cfs are recorded for several weeks. The *RANGES* record could be used to isolate the month(s) of the record for the flood event. The flow range could be set so that only time steps with flows above 1,000 cfs at the upstream gage are considered. All time steps would be used to compute the calibration data. However, only the time steps corresponding to the flood event when the gaged inflow exceeds 1,000 cfs will be used to compute the calibration fit.

The optimization of Muskingum parameters with *DAY* allows for multiple upstream gages. In this case, a value of *THRESHOLD* can be selected for each upstream gage. If the value is left blank or set to zero for any of the multiple upstream gages, the default is to assume all flow values. For example, the flood flow routing parameters of one of the upstream gages may be of interest in a case where there are three upstream gages. The user will select *SIDE* equal to 1 and then specify the flood threshold value for the upstream gage of interest. The thresholds at the remaining two gages are left blank or set to zero. The optimization will now proceed to find the best Muskingum parameter set that corresponds to time steps of flood flow conditions at the particular upstream gage. The Muskingum parameters at the other two upstream gages are also optimized for the respective flow regimes experienced during the isolated time steps.

APPENDIX D
INSTRUCTIONS FOR PREPARING *SALT* INPUT RECORDS

The *WRAP-SALT* salinity input file has the filename extension SIN. A set of *JC*, *CO*, *CP*, *CC*, and *ED* records begin with a *JC* record and end with an *ED* record. *S* records follow after the *ED* record. Comment records beginning with asterisks ** as the first two characters are not read by the program and may be included anyplace in the data file. The *JC*, *CP*, and *ED* records are required. The others are optional. There is always one *JC* record and one *ED* record and one or more *CP* records. Any number of optional *CO*, *CC*, and *S* records may be used.

The *JC* record is the first record read. A set of optional *CO* records normally follows immediately behind the *JC* record but actually may be placed anywhere between the *JC* and *ED* records. A *CP* record is required for each control point for which data are provided in the salinity input file. There must be at least one *CP* record. The *SIM/SIMD* input file may include additional control points that are not included in the salt input file. The input data associated with a salinity input file *CP* record may be repeated for any number of other control points included in the *SIM/SIMD* input file. The *CC* records must follow immediately behind their associated *CP* record. The *S* records are grouped together after the *ED* record.

SALT Input Records

Record Identifier	Type of Information	Page Number
JC	Job Control	220
CO	Control Points Included in Output File	223
CP	Control Point Salt Data Specifications	223
CC	Water Quality Constituent Concentrations	225
ED	End of CO/CP/CC Record Data	226
S	Salt Concentrations or Loads	227

JC Record – Job Control

field	columns	variable	format	value	description
1	1-2	CD	A2	JC	Record identifier
2	3-8	YRST	I6	+	First year of simulation
3	9-12	NYRS	I4	+	Number of years in simulation
4	13-16	NC	I4	+	Number of water quality constituents
				blank,0	Default = 1
5	17-20	MCP	I4	+	Maximum number of *CP* records in *SALT* input file
				blank,0	Default = 10
6	21-24	MAXUPCP	I4	+	Maximum number of upstream control points
				blank, 0	Default = 30
					Beginning-of-Simulation Storage Volume
7	28	BEGSTO	I4	blank,0,1	*SIM* beginning reservoir storage BRS file is read subject to being overridden by *CP* record field 8.
				2	Entered in *CP* record field 8 or otherwise is zero.
				3	Estimated from *SIM* OUT file variables subject to being overridden by *CP* record field 8.
					Beginning Reservoir Concentration (BRC) File
8	32	BEGCON	I4	blank,0,1	BRC file is not created.
				2	Ending storage concentration written to BRC file.
				3	Beginning storage concentration read from BRC file.
				4	BRC file is both written and read.
					Sequencing of Salt Input Data on S Records
9	36	GROUP	I4	blank,0,1	Grouped by control point with sets of annual records.
				2	Grouped by year with a set of records for each year.
					Options for Repeating Salt Data
10	40	REPEAT	I4	blank,0,1	Data are repeated at control points located upstream.
				2	Data are repeated for downstream control points.
				3	Data are not repeated.
					Control Points Included in SALT Output File
11	44	CPOUT	I4	blank,0,1	Output includes only control points on *CO* records.
				2	Output includes all cpts with *CP* records in *SALT* input file plus those cpts listed on *CO* records.
				3	Output includes all control points.
					Information Written to SALT Message File
12	48	MF	I4	blank,0,1	Warning messages and summary are in message file.
				2	Only summary table is written to the message file.
				3	Detailed results are also written to message file.
				4	Reservoir lagged load-balance results to SMS file.
				5	Control point listing is written to message file.
				6	None of the above are included in message file.
				–1	Only warning messages are written to message file.

JC Record – Job Control (Continued)

					Adjustments for Negative Inflow Volume and Load
13	52	NEGINF	I4	blank,0,1	No adjustments are made to negative inflows.
				2	Adjustments based on beginning-of-period storage.
				3	Negative inflow volumes and loads are set to zero.
					Concentration Conversion Factor
14	53-60	CF	F8.0	blank,0	default = 735.48 for concentration conversion factor
				+	conversion factor: concentration = CF (load/volume)

Explanation of JC Record Fields

Fields 2 and 3: The *SALT* simulation period-of-analysis is defined by a starting year and length in years. The *SALT* period-of-analysis must be contained within the *SIM* period-of-analysis but may be shorter.

Field 4: The simulation may be repeated for up to 15 salt constituents in a single execution.

Field 5: MCP sets the dimension limit for the maximum number of control points to be included in the salt input file. The number of *CP* records in the salt input file can not exceed MCP and also may be less than the number of *CP* records included in the *SIM* input file.

Field 6: MAXUPCP is the maximum number of tributaries that flow into any confluence. Each control point may have up to MAXUPCP control points located immediately upstream.

Field 7: The reservoir storage at each control point at the beginning of the simulation may be read from either a BRS file created by *SIM* or *CP* records. Alternatively, beginning storages may be computed, subject to the computed values being overridden by *CP* record field 8. Option 3 initial storages computed from *SIM* simulation results may be in error because downstream reservoir releases that are not included in the *SIM* output file variables may sometimes be pertinent. Reading a BRS file (option 1) is recommended.

Field 8: Options 2, 3, and 4 result in creation of a beginning reservoir concentration file with the filename extension BRC. The concentration of reservoir storage at the beginning of the simulation for each salt constituent may be provided either by *CC* records or read from a BRC file. Program *SALT* may be executed iteratively until reservoir storage concentrations are the same at the beginning and end of the simulation. End-of-simulation concentrations written to the BRC file are read as beginning concentrations.

Field 9: With option 1 for sequencing the *S* records, all annual records for a particular control point are grouped together. A set of all annual *S* records for a control point follows the complete set for the preceding control point. Option 2 entails placing the *S* records for all control points together as a group for a given year. A set of all *S* records for a given year follows the set of all S records for the preceding year.

Field 10: The number of control points in the *SIM* simulation may greatly exceed the number of *SALT CP* records in the salinity input SIN file. The salt data in the SIN input file for a particular control point may be repeated for any number of other control points located either upstream or downstream.

Field 11: Options are provided to specify which control points to include in the *SALT* output *SAL* file and the control point volume/load budgets in the SMS file. The *SIM* output file should include all control points. The *SIM* simulation and *SALT* salinity tracking computations may include many control points that are not included in the *SALT* input *SIN* file. Any of the control points included in the salinity computations may be included in the *SALT* output file.

Field 12: Options are provided to control whether warning messages, total volume and load summary table, control point volume/load budgets, and reservoir lag results are written to the message file. A listing of control points showing spatial connectivity and assignment of salt input data may also be created. These options do not affect the trace and error messages always written to the message file. However, most warning messages are activated only if field 12 is blank, 0, 1, or -1. The volume and load summary table is included with options 1, 2, 3, and 4.

Field 13: Negative inflows may result from the computation of the salt loads flowing into a control point. Option 1 carries the negative load forward in the computations without adjustment. Option 2 limits the adjustment of negative inflow loads to not exceed the load in reservoir storage at the beginning of the month. The negative load inflow is changed to zero or as close to zero as the storage load allows, but the load balance is maintained by a corresponding change in end-of-month storage load. Options 1 and 2 are recommended since load balances are maintained. Option 3 is not recommended since it has the effect of creating additional load.

Field 14: The conversion factor CF is f_C in Equation 5.1. concentration = CF(load/volume)

CO Record – Control Points Included in *SALT* Output File

field	columns	variable	format	value	description
1	1-2	CD	A2	CO	Record identifier
2	3-8	NCPOUT	I6	+	Number of control points listed on this record
3	9-88	CPOID(J) J=1,10	2x,A6	AN	Control point identifiers

A set of one or more optional *CO* records may be inserted anyplace after the *JC* record but before the *ED* record. Any number of control points may be listed on any number of *CO* records with up to ten control points per *CO* record. Data for these control points will be included in the *SALT* output file (filename root.SAL) and in the control point volume/load table in the message file (filename root.SMS). *JC* record field 11 is used along with *CO* records in specifying the selection of which control points to include in the results written to the output files.

CP Record – Control Point Salt Data Specifications

field	columns	variable	format	value	description
1	1-2	CD	A2	CP	Record identifier
2	3-8	CPSALT(I)	A6	AN	Control point identifier
					Water Quality Data Options
3	16	TSC(I)	I8	blank,0,1	Time series are entered on *S* records.
				2	Constant concentrations/loads follow on *CC* records.
				3	Concentrations and loads are zero.
				4	Control point is not included in the salt simulation.
4	24	ISALT(I)	I8	blank,0,1	Concentrations of incremental naturalized flows.
				2	Data are incremental loads.
				3	Data are total loads at an upstream boundary.
				4	Concentrations of total regulated flows at boundary.
					Parameters for Concentration of Reservoir Outflows
5	32	TM(I)	I8	blank,0,1	Adopt mean storage concentration during month.
				2	Adopt storage concentration at beginning of month.
6	33-40	LAG1(I)	I8	blank,0	Lag features are not activated. Default is no lag.
				+	Maximum lag in months. Optionally lag if LAG2=–1
7	41-48	LAG2(I)	F8.0	blank,0	Default multiplier used in computing lag is 1.0
				+	Retention multiplier factor used in computing lag.
				–1	Flow retention option for computing lag is not used. Reservoir lag LAG = LAG1(I)
					Beginning-of-Simulation Storage Volume
8	49-56	VBS(CP)	F8.0	blank,0	Beginning storage volume is specified elsewhere.
				+	Beginning-of-simulation reservoir storage volume.

Explanation of CP Record Fields

A *CP* record is provided for all control points for which salinity data are specified. A non-zero entry in any of the fields 3 through 8 means the CP record is needed. Program *SALT* repeats the salinity data for other control points that are not included in the SIN file set of C*P* records.

Field 2: An error check routine checks that the control point identifier on the *SALT CP* record matches an identifier on a *SIM CP* record. The control point identifiers on the *S* records are checked against the identifiers on the *SALT CP* records.

Field 3: Fields 3 and 4 define the meaning and computational role of the salinity input data entered on the *S* and *CC* records. Concentrations or loads of local incremental naturalized flows at a control point may be entered on *S* or *CC* records or set at zero. Control points located upstream of upper boundary control points defined by ISALT(CP) in field 4 are omitted from the salinity simulation.

Field 4: The salt data entered on *S* or *CC* records are defined as being either concentrations or loads for either local incremental naturalized flows or the total stream flow at an upstream boundary. Upstream naturalized flow boundaries occur at the actual most upstream control point on each stream branch. A regulated flow boundary on a stream branch may be set as the most upstream control point that is included in the salt tracking simulation.

Field 5: Concentrations of diversions, releases, and regulated flow leaving a reservoir control point in the current month are set equal to the concentration of reservoir storage in the current or a preceding month as defined by fields 5, 6, and 7. The concentration may be the mean storage concentration during the month (field 5 option 1) or the storage concentration at the beginning of the month (field 5 option 2). The default mean concentration option is recommended.

Field 6: The reservoir outflow (diversion, release, regulated flow) concentration is set equal to storage concentration for the month set by the lag defined in fields 6 and 7. LAG1 is applied differently in the two alternative lag options. With the recommended option activated by a non-zero LAG1 in field 6 and blank field 7 or positive number for LAG2, the lag is computed each month based on retention time with LAG1 being an optional upper limit on the lag. With a negative number for LAG2 in field 7, the LAG1 in field 6 is a fixed constant lag.

Field 7: With a positive number entered for LAG2 or a blank field 7 (default LAG2=1.0), LAG2 is the multiplier factor in Equation 5.32. A negative number entered in field 7 switches to the alternative option in which the lag is set equal to LAG1 from field 6 for all months.

Field 8: *JC* record field 7 option 1 specifies that the beginning-of-simulation storage is entered in *CP* record field 8. VBS(CP) in *CP* field 8 also replaces the storage that may have been set by BEGSTO options 2 and 3 activated by *JC* record field 7. VBS(CP) applies only to this control point, whereas all other *CP* record entries may be repeated for other control points as specified by REPEAT in *JC* record field 10.

CC Record – Water Quality Constituent Concentrations at Control Point

field	columns	variable	format	value	description
1	1-2	CD	A2	JD	Record identifier
2	3-8		6X		Not read.
3	9-16	CS(I,IC)	F8.0	+	Constant naturalized flow concentration or load corresponding to TSC(I) = 2 in *CP* field 3.
4	17-24	CBS(I,IC)	F8.0	+ blank	Beginning-of-simulation storage concentration. Concentration is zero or provided by BRC file.
5	25-32	CRF(I,IC)	F8.0	+ –1.0	Concentration of return flows. Return flow concentration is determined by *SALT*.
6	33-40	CCI(I,IC)	F8.0	+ –1.0	Concentration of other *CI* record constant inflows. CI record concentration is determined within *SALT*.
					Concentration Limits
7	41-48	MINOC (I, IC)	F8.0	+ blank	Minimum concentration limit for return flows, CI record inflows, and losses/credits. Default = 0.0
8	49-56	MAXOC (I,IC)	F8.0	+ blank	Maximum concentration limit for return flows, CI record inflows, losses/credits. Default = 999,000,000
9	57-64	MINSC(CP,IC)	F8.0	+	Minimum storage concentration limit. Default = 0.0
10	65-72	MAXROC (I,IC)	F8.0	+	Maximum limit on reservoir outflow concentration. Default = 999,000,000
					Multiplier Factor for Loads of Losses/Credits
11	73-80	CLF(I,IC)	F8.0	+	Multiplier for loads of channel losses. Default = 1.0

An optional set of *CC* records follows directly behind a *CP* record. A *CC* record is provided for each salt constituent. *CP* record field 2 defines the control point location for the *CC* record data. The index I means the data may be repeated for any number of control points. The index IC refers to salinity constituent.

Explanation of CC Record Fields

Field 3: Concentrations or loads of incremental naturalized flows or regulated flows may be a constant entered in *CC* field 3 or a time series provided on *S* records. *CP* fields 3 and 4 define the meaning and computational use of the salinity input data entered on the *S* and *CC* records.

Field 4: The beginning-of-simulation reservoir storage concentration may either be entered in *CC* record field 4 or optionally read from a BRC file if activated by *JC* record field 7.

Field 5: A constant concentration for return flows returning at this control point may be input in *CC* field 5. If –1.0 is entered in *CC* field 5, the return flow concentration is computed by *SALT* as the upstream outflow concentration constrained by the limits in *CC* fields 7 and 8.

Field 6: A concentration for constant inflows from *SIM CI* records reflecting return flows from groundwater or flows from other sources is specified in *CC* record field 6 in the same manner as the return flow concentrations in field 5. A –1.0 in *CC* field 6 activates an option by which the concentration of outflows from control points located immediately upstream are adopted for the *CI* record constant inflows. This adopted concentration is adjusted as necessary to not violate the minimum and maximum concentration limits specified in *CC* record fields 7 and 8.

Fields 7 and 8: Options in fields 5 and 6 activate application of the limits of fields 7 and 8 to return flows and *SIM CI* record inflows. These limits are also applied to channel losses and loss credits. Return flows and *CI* record inflows are assigned the concentration of the outflows at the one or more (tributaries) control points located immediately upstream. The concentration of each channel loss/credit is the outflow concentration at a single control point. These upstream outflow concentrations are constrained to fall within the limits specified in *CC* fields 7 and 8. If the computed outflow concentration is less than the *CC* field 7 *MINOC(I,IC)* or greater than the field 8 *MAXOC(I,IC)*, it is set equal to the limit prior to applying it to assign the concentration to return flows, *CI* record constant inflows, and/or channel losses and loss credits.

Field 9: In performing reservoir load balance computations, the concentration of the water in storage at the end of the month is not allowed to drop below the minimum limit specified in *CC* record field 9. This has the effect of controlling the maximum concentration of the water released or withdrawn from the reservoir. The field 9 lower limit on storage concentration constrains the maximum load that can be removed from the reservoir that month and thus the outflow concentration.

Field 10: A maximum concentration of the outflow from a reservoir may be specified in field 10. If the computed reservoir outflow load results in a concentration exceeding this maximum outflow concentration limit, the outflow load is adjusted accordingly. Thus, to maintain the reservoir load balance, the load remaining in storage increases correspondingly.

Field 11: The salt loads of channel losses and channel loss credits are computed by applying the upstream outflow concentration constrained by the limits of *CC* fields 7 and 8 to the volumes of channel losses and loss credits read from the *SIM* simulation results output file. Thus, loads of channel losses are directly connected to volumes of channel losses. The loads thus computed are multiplied by the factor *CLF* entered in *CC* field 11. With a default CLF of 1.0, loads are loss to channel losses in direct proportion to volumes. With a *CLF* less than 1.0, channel losses result in a lesser loss of load than volume. With a *CLF* greater than 1.0, channel losses result in a greater proportion of the salinity load being loss than the loss in water volume.

ED Record – End of Data (End of *CO*/*CP/CC* Records)

field	columns	variable	format	value	description
1	1-2	CD	A2	ED	Record identifier

The *ED* record signals the end of the *CO*/*CP/CC* records. *S* records follow behind the *ED* record. The *CO*, *CP*, and *CC* records are read at the beginning of model execution, and *S* records are read later in the *SALT* simulation loops. An *ED* record is the last record in the *SALT* input SIN file if it contains no *S* records.

S Record (S1, S2, ... , S9, SA, SB, ...) – Salt Concentrations or Loads

field	columns	variable	format	value	description
1	1-2	CD	A2	S_	Record identifier (second character is optional)
2	3-8	ID	A6	AN	Control point identifier
3	9-16	YR	4x,I4	+	Year
4	17-24	SM(1)	F8.0	+	Mean concentration or load during month 1
5	25-32	SM(2)	F8.0	+	Mean concentration or load during month 2
6	33-40	SM(3)	F8.0	+	Mean concentration or load during month 3
7	41-48	SM(4)	F8.0	+	Mean concentration or load during month 4
8	49-56	SM(5)	F8.0	+	Mean concentration or load during month 5
9	57-64	SM(6)	F8.0	+	Mean concentration or load during month 6
10	65-72	SM(7)	F8.0	+	Mean concentration or load during month 7
11	73-80	SM(8)	F8.0	+	Mean concentration or load during month 8
12	81-88	SM(9)	F8.0	+	Mean concentration or load during month 9
13	89-96	SM10)	F8.0	+	Mean concentration or load during month 10
14	97-104	SM(11)	F8.0	+	Mean concentration or load during month 11
15	105-112	SM(12)	F8.0	+	Mean concentration or load during month 12

S records follow behind the *ED* record.

The switch variable *TSC* in *CP* record field 3 specifies whether or not *S* records are read for a particular control point. The salt data are defined by the variable *ISALT* in *CP* record field 4. *GROUP* in *JC* record field 10 indicates whether the *S* records are sequenced by grouping all control point records together for a particular year or by grouping all annual records together for a particular control point.

Each water quality constituent may be assigned a different two-character record identifier such as *S1*, *S2*, *S3*, ... , *S9* or *SA*, *SB*, *SC*. The first character of the CD must be *S* but the optional second character is arbitrary. Data may be read for up to 15 different water quality constituents. The data are grouped by constituent, with the set of all *S* records (*S2* records) for the second salt constituent following behind the set of all *S* records (*S1* records) for the first salt constituent. The set of all *S3* records follow after the set of all *S2* records.

The salt data entered on *S* or *CC* records may be either concentrations or loads for either local incremental naturalized flows or the total regulated flows at an assigned upstream boundary. A boundary has other control points located upstream that are not included in the salinity tracking computations. The concentrations or loads may be for local incremental naturalized flows at any control point, which in the case of the most upstream control point on any stream branch are also the total naturalized flows. Upstream boundaries may also be defined at the most upstream control point on a stream branch that is included in the salt tracking simulation even though other *SIM* control points are located upstream. In this case, the concentration or load on the *S* records are for the regulated flow leaving the control point.

APPENDIX E
INSTRUCTIONS FOR PREPARING *TABLES* INPUT RECORDS

Instructions for applying program *TABLES* provided in Chapter 4 of the *Users Manual* are supplemented as follows to cover conditional reliability modeling, sub-monthly time step, flood control, and salinity modeling features of the expanded WRAP. The *TABLES* input record types included in Appendix H are listed in the following table. *TABLES* input records are entered in a file with the filename extension TIN. These input records provide specifications for creating tables and data listings that organize the simulation results read by *TABLES* from *SIM*, *SIMD*, and *SALT* output files.

TABLES Input Records Described in Appendix E

Record Identifier	Type of Information	Data File	Page Number
	Conditional Reliability Modeling		230
5CRM	Conditional Reliability Modeling	CRM	231
5CR1	Develop FF or SFF Relationship	OUT	232
5CR2	Develop Incremental Probability Array	-	235
5COR	Correlation Coefficients	OUT	237
	The type 6 records listed below and corresponding type 2 records may be applied with a CRM file for conditional reliability analyses as well as with a SUB and OUT file.		
	Sub-Monthly Time Steps with Non-CRM or CRM Applications		
6REL	Water Supply Diversion or Hydropower Reliability	SUB	239
6FRE	Flow or Storage Frequency Relationships	SUB	240
6FRQ	Frequency for Specified Flow or Storage	SUB	240
6RES	Reservoir Storage and Drawdown Frequency	SUB	241
Page 242	Time Series Records	SUB	243
	Flood Control Operations		242
7FFA	Flood Frequency Analysis	FFA	244
	Salinity Simulation		245
8SAL	Time Series Tables of *SALT* Results	SAL	245
8FRE	Frequency Relationships	SAL	246
8FRQ	Frequency Relationships	SAL	247
8SUM	Control Point Summary	SAL	248
8REL	Diversion Reliability Summary	SAL	248
8CON	Maximum Concentration Limits	SAL	248

Conditional Reliability Modeling

A conditional reliability *CR* record entered in a *SIM* or *SIMD* input file activates the CRM mode of modeling. As indicated in Table 12 of the basic *Users Manual*, eight numbers are recorded in the 5th record of the *SIM* output file, with the last two being CR1, CR2, and CR4 from the *CR* record. *SIM/SIMD* simulation results are written to a file with the filename root.CRM. A *5CRM* or *5CRM2* record entered in a *TABLES* input file causes the *SIM/SIMD* CRM output file (filename root.CRM) to be opened in preparation for activating the conditional reliability modeling (CRM) features of *TABLES*.

The *5CRM*, *5CR1*, *5CR2*, and *5COR* records are the only *TABLES* input records that are used solely for CRM. The other *TABLES* input records and associated tables are applicable for either CRM or conventional non-CRM simulations. The *5CR1* and *5CR2* records activate the routines for assigning probabilities to simulation sequences in reliability and frequency analyses. Without these records, the relative frequency option is adopted by default. With the relative frequency option, the computations associated with the *2REL*, *2FRE*, *2FRQ*, and *2RES* records are the same with either a CRM or conventional modeling application. With the probability array option activated by a set of *5CR1* and *5CR2* records, an array of probabilities associated with the simulation sequences is provided to the *2REL*, *2FRE*, *2FRQ*, and *2RES* record routines.

The sole purpose of a set of *5CR1* records is to develop a flow-frequency (FF) or storage-flow-frequency (SFF) relationship from the results of a conventional long-term *SIM/SIMD* simulation. The purpose of a set of *5CR2* records is to develop an incremental probability (IP) array using the FF or SFF relationship previously created by *5CR1* records. The incremental probability array created with a *5CR2* record is used by the *2REL*, *2FRE*, *2FRQ*, and *2RES* record routines. A set of *5CR1* and *5CR2* records include a main *5CR1* record and main *5CR2* record along with supplemental *5CR1* and *5CR2* records listing pertinent control points, reservoirs, and initial storage. The parameters on the main *5CR1* and *5CR2* records refer to a series of intermediate computational steps in the procedure that produces the FF or SFF relationship (*5CR1* record) and the final incremental probability array (*5CR2* record).

The final product of a set of *5CR1* and *5CR2* records is an IP array assigning probabilities to each hydrologic sequence of the CRM that is used as input to the reliability and frequency analysis routines activated by *2REL*, *2FRE*, *2FRQ*, and *2RES* records. The probability array remains in computer memory for use by any number of subsequent *2REL*, *2FRE*, *2FRQ*, and *2RES* records. If more than one *5CR2* record set is included in a *TABLES* input file, the IP array created by the last *5CR2* record set read will be in effect for those *2REL*, *2FRE*, *2FRQ*, and *2RES* records read after it. A *5CR2* record set applies to all records located after the *5CR2* records in the *TABLES* input file but before any subsequent set of *5CR2* records.

The main output file from two different executions of *SIM/SIMD* are read (filenames root.OUT and root.CRM). The *5CR1* record develops a FF or SFF relationship from the results of a conventional long-term *SIM* simulation read from an OUT file. The *5CR2* record develops an incremental probability (IP) array by combining the FF or SFF array with storage and flow data from the CRM output file of a CRM application of *SIM/SIMD*.

5CRM Record – Conditional Reliability Modeling

field	columns	variable	format	value	description
1	1-4	CD	A4	5CRM	record identifier
2	5-8	CRHEAD	I4	blank,0,+ −1	CRM headings are inserted at top of each table. CRM headings are not written.

A *5CRM* or *5CR2* record results in opening a *SIM* CRM output file. Since a *5CR2* record also opens the *SIM* CRM output file, the *5CRM* record is actually only required to open the CRM output file for the relative frequency option in which a *5CR2* record is not used. If preceded in the TIN file by a 5CRM or 5CR2 record, the time series, frequency, and reliability records cited earlier in this Appendix use the *SIM* or *SIMD* simulation results from a CRM file for their analyses.

By default, four lines of information from the CR record and 2CR2 record are written on the cover page and at the top of the tables produced by the 2REL, 2FRE, 2FRQ, and 2RES records. A −1 entered for the parameter CRHEAD in 5CRM record field 2 prevents the CRM headings from being printed. The only reason to deactivate the heading is to reduce the size of the tables. Multiple 5CRM records may be used to turn the headings on and off for different tables.

5CR1 Record – Conditional Reliability Record to Develop a FF or SFF Relationship

field	columns	variable	format	value	description
1	1-4	CD	A4	5CR1	record identifier
					Control Points or Reservoirs for Flow and Storage
2	5-8	NFLOW	I4	+	number of control points for naturalized flow
				blank,0	flow at all control points is summed
3	9-12	NSTOR	I4	+	number of control points or reservoirs for storage
				blank,0	storage at all control points is summed
				-1	storage at all reservoirs is summed
					Annual or Monthly Cycle Options
4	13-16	TCR2	I4	+	starting month activates annual cycle option
				blank,0	monthly or non-annual option adopted by default
					Months Used to Sum Flows
5	17-20	FM	I4	+	number of months for naturalized flow volume
				blank,0	default is simulation length CR1 from CR record.
					Option for Assigning Exceedence Frequencies
6	24	DIST	I4	blank,0,1	log-normal distribution
				2	Weibull formula
					Regression Options for Storage-Flow Function
7	27-28	FIT	I4	blank,0	FF relationship developed without storage regression.
				1, -1	Exponential regression for storage-flow function.
				2, -2	Combined function used for storage-flow function.
				3, -3	Linear regression used for storage-flow function.
				4, -4	Power function used for storage-flow function.
					Note: -1, -2, -3, or -4 activates fields 9, 10, 11.
8	32	INTZERO	I4	blank,0	Intercept is not forced to zero
				1	y-intercept (flow) is set at zero.
					Coefficients for $Q = a\,e^{b/S}$ *or* $Q = a + bS^{c}$
9	33-40	A	F8.0	+	coefficient a
10	41-48	B	F8.0	+	coefficient b
11	49-56	C	F8.0	+	coefficient c
					Storage Interval
12	57-64	LOWLIM	F8.0	blank,0	No lower limit, or option is not used.
				+	Lower storage limit defining flow sequences used.
13	65-72	UPLIM	F8.0		No upper limit, or option is not used.
				+	Upper storage limit defining flow sequences used.
					Options for Writing Results to SFF and TAB Files
14	76	FILE1	I4	blank,0	Nothing is written to the SFF and TAB files.
				1	The probability array is written to the SFF file.
				2	Regression and correlation statistics to TAB file.
				3	Both probability array and statistics are written.
					Root of SIM OUT File
15	77-96	FILESIM	A20	blank	Root of OUT file is root entered for *TABLES* log-in.
				AN	Root of OUT file.

Explanation of Fields of the Main 5CR1 Record

Field 2: If field 2 is blank, there is no listing of control point identifiers, and the naturalized flow at all control points included in the *SIM/SIMD* output file is summed. Otherwise, the naturalized flow used for the FF or SFF relationship is the total flows at the NFLOW control points listed on a supplemental *5CR1* record. FLOW is entered in field 2 of the supplemental *5CR1* record. The number of control point identifiers read from the supplemental *5CR1* record is specified by field 2 of the initial *5CR1* record and cannot exceed 15.

Field 3: If field 3 is blank, there is no listing of control point or reservoir identifiers, and the storage from all control point output records included in the *SIM/SIMD* output file is summed. A –1 results in use of all reservoir records in the *SIM/SIMD* output file. Otherwise, the reservoir storage is the total of the reservoir storage at the NSTOR control points or reservoirs listed on a supplemental *5CR1* record. STCP or STRE is entered in field 2 of the supplemental *5CR1* record. The number of identifiers read from the supplemental *5CR1* record is specified by field 3 of the initial *5CR1* record and cannot exceed 15.

Field 4: Entering a starting month ranging from 1 to 12 activates the annual cycle option. The monthly cycle option is activated by default by a blank field 4. The same information is provided by CR2 on the *CR* record. However, field 4 specifies the option used to develop the SFF array from the results of a long-term non-CRM *SIM/SIMD* simulation.

Field 5: The storage and flow are summed over the first FM months of each simulation sequence. If field 4 is blank, the default is to sum the storage and flow for the entire simulation period CR1, which is set by *CR* record field 2 and included in the 5th record of the main WRAP-SIM output file.

Field 6: The two alternative options for assigning exceedance probabilities to R (Eq. 2.2) in developing the SFF relationship or to flow volume in developing the FF relationship are based on the log-normal probability distribution (Eq. 2.12) and Weibull formula (Eq. 2.13).

Field 7: The following regression equations may be used to relate flow Q to storage S for a SFF relationship.

Exponential (Eq. 2.3) $Q = a \times e^{b/S}$
Combined (Eq. 2.6): $Q = a + bS^{c}$
Linear (Eq. 2.5): $Q = a + b\,S$
Power (Eq. 2.4): $Q = b\,S^{c}$

A blank field indicates that a FF relationship is being developed without considering storage. Developing a SFF relationship requires selection of a regression method. With options 1, 2, 3, and 4, regression analysis are performed within *TABLES* to determine the coefficients a, b, and c. With options -1, -2, -3, and -4, the coefficients are read from fields 9, 10, and 11 rather than activating the regression analysis computations.

Field 8: The coefficient a representing the y-intercept (flow for zero storage) in Eqs. 2.5 and 2.6 may be set equal to zero.

Fields 9, 10, and 11: These fields are used to enter values for the regression coefficients if option –1, -2, -3, or -4 is selected for the variable FIT in field 7.

Fields 12, and 13: Lower and upper limits define a range of reservoir storage from which the corresponding naturalized flow sequences are adopted for use in developing the FF or SFF relationship.

Field 14: The SFF or FF relationship information is stored in active computer memory but may also be written as an array to a SFF file (root.SFF) to be read by a *5CR2* record in subsequent executions of *TABLES*. Regression and correlation statistics may be written to the main *TABLES* output file (root.TAB).

5CR1 Record – FF or SFF Control Points and SFF Reservoirs (2nd and 3rd *2CP1* records)

field	columns	variable	format	value	description
1	1-4	CD	A4	5CR1	record identifier
2	5-8	CD2	A4	FLOW STCP SRES	control points for naturalized flows to be summed control points for reservoir storage to be summed reservoirs for storage to be summed
3-17	9-128	CPF(I) or CPS(I)	15(2x,A6)	AN	control point or reservoir identifiers for summing flow (I = 1,NFLOW) or storage (I = 1,NSTOR)

Up to 15 control point or reservoir identifiers are listed in fields 3-17 of the two supplemental *5CR1* records as specified by fields 2 and 3 of the main *5CR1* record. The two supplemental *5CR1* records follow behind the main *5CR1* record.

If NFLOW in field 2 of the first *5CR1* record is non-zero, a *5CR1FLOW* record is required to list the control points at which naturalized flows are summed for use in developing a SFF relationship.

If NSTOR in field 3 of the first *5CR1* record is non-zero, either a *5CR1STCP* or *5CR1SRES* record is required to list the control points or reservoirs at which storage is summed.

If NFLOW or NSTOR in fields 2 and 3 of the initial *5CR1* record are blank or -1, the corresponding supplemental record is not entered.

5CR2 Record – Control Points and Reservoirs (2nd, 3rd, and 4th *2CP2* records)

field	columns	variable	format	value	description
1	1-4	CD	A4	2SFF	record identifier
2	5-8	CD2	A4	FLOW STCP SRES INIT	control points for naturalized flows to be summed control points for reservoir storage to be summed reservoirs for storage to be summed initial storage volumes for storage control points
3-17	9-128	CPS(I) CPF(I)	15(2x,A6)	AN	control point or reservoir identifiers for summing flow (I = 1,NFLOW) or storage (I = 1,NSTOR)
3-17	9-128	IS(I)	15(F8.0)	+	initial storage volumes for CD2=INIT (I=1,NSTOR)

Supplemental *5CR2* records are included in the input file only as specified by fields 2, 3, and 4 of the initial *5CR2* record. Up to 15 control point or reservoir identifiers are listed in fields 3-17 of the two supplemental *5CR2* records as specified by fields 2 and 3 of the main *5CR2* record. Initial reservoir storage volumes are entered on a third *5CR2* record if specified by field 4 of the main *5CR2* record. The three supplemental *5CR2* records follow behind the main *5CR2* record.

If NFLOW in field 2 of the main *5CR2* record is non-zero, a *5CR2FLOW* record is required to list the control points at which naturalized flows are summed for use in developing a SFF relationship.

If NSTOR in field 3 of the main *5CR2* record is not zero or -1, either a *5CR2STCP* or *5CR2SRES* record is required to list the control points or reservoirs at which storage is summed.

If READINI in field 4 of the main *5CR2* record is non-zero, a *5CR2INIT* record is required for the starting storage volumes for each of the control points or reservoirs listed on the *5CR2STCP* or *5CR2SRES* record.

5CR2 Record – Conditional Reliability Record to Build the Incremental Probability Array

field	columns	variable	format	value	description
1	1-4	CD	A4	5CR2	record identifier
					Control Points or Reservoirs for Flow and Storage
2	5-8	NFLOW	I4	+	number of control points for naturalized flow
				blank,0	flow at all control points is summed
3	9-12	NSTOR	I4	+	number of control points or reservoirs for storage
				blank,0	storage at all control points is summed
				-1	storage at all reservoirs is summed
					Starting Reservoir Storage Condition
4	13-16	READINI	I4	blank,0	Initial storages read from 2CP2INIT record.
				+	Initial storages read from BES file.
					Months Used to Sum Flows
5	17-20	FM	I4	+	number of months for naturalized flow volume
				blank,0	default is simulation length CR1 from CR record.
					Regression Options for Storage-Flow Function
6	24	FIT	I4	blank,0	FF relationship is developed with storage regression.
				1	Exponential (Eq. 2.3) coefficients from 5CR1 record.
				2	Combined (Eq. 2.6) coefficients from 5CR1 record.
				-1	Exponential (Eq. 2.3) coefficients fields 10, 11, 12.
				-2	Combined (Eq. 2.6) coefficients from fields 10,11,12.
					FF or SFF Relationship
7	28	FILE1	I4	blank,0,1	SFF or FF is created with preceding 5CR1 record.
				2	SFF or FF relationship is read from SFF file.
					Option to Write Probability Array to SFF File
8	32	FILE2	I4	blank,0	Nothing is written to the SFF file.
				1	The probability array is written to the SFF file.
					Multiplier Factor
9	40	MFACTOR	F8.0	+	Multiplier factor for storages on 2CP2INIT record
				blank,0	default=1.0
					Coefficients for $Q = a e^{b/S}$ *or* $Q = a + bS^{c}$
10	41-48	A	F8.0	+	coefficient a
11	49-56	B	F8.0	+	coefficient b
12	57-64	C	F8.0	+	coefficient c

Explanation of Fields of the Main 5CR2 Record

Field 2: If field 2 is blank, there is no listing of control point identifiers, and the naturalized flow at all control points included in the *SIM/SIMD* output file is summed. Otherwise, the flow used to build the incremental probability (IP) array is the total of the naturalized flows at the NFLOW control points listed on a supplemental *5CR2* record. FLOW is entered in field 2 of the supplemental *5CR2* record. The number of control point identifiers read from the supplemental *5CR2* record is specified by field 2 of the initial *5CR2* record and cannot exceed 15.

Field 3: If field 3 is blank, there is no listing of control point or reservoir identifiers, and the storage from all control point output records included in the *SIM/SIMD* output file is summed. A –1 results in use of all reservoir records in the *SIM/SIMD* output file. Otherwise, the reservoir storage used to build the probability array is the total of the reservoir storage at the NSTOR control points or reservoirs listed on a supplemental *5CR2* record. STCP or STRE is entered in field 2 of the supplemental *5CR2* record. The number of identifiers read from the supplemental *5CR2* record is specified by field 3 of the initial *5CR2* record and cannot exceed 15.

Field 4: If field 4 is blank, the starting reservoir storage volumes used in developing the probability array are provided on a *5CR2INIT* record. A positive integer entered in field 4 activates the option of reading the starting storages from a BES file created by *SIM/SIMD*.

Field 5: The storage and flow are summed over the first FM months of each simulation sequence. If field 4 is blank, the default is to sum the storage and flow for the entire simulation period CR1, which is set by *CR* record field 2 and included in the 5th record of the main *WRAP-SIM* output file.

Field 6: Field 6 is blank if a flow-frequency (FF) relationship is used to construct the incremental probability (IP) array without considering storage. The following regression equations may be used to relate flow Q to storage S if a storage-flow-frequency (SFF) relationship is used to construct the IP array. A positive 1 or 2 in field 6 indicates that Eq. 2.3 or Eq. 2.4 is used with coefficients determined by the previous *5CR1* record. Negative integers -1 or -2 in field 6 activate the option of reading coefficients from fields 10, 11, and 12. If the coefficient b is 1.0, the linear equation is used. The power equation is specified by a value for b other than 1 with a coefficient c of zero. The combined equation has a non-unity b and non-zero c.

Exponential (Eq. 2.3) $Q = a \times e^{b/S}$

Combined (Eq. 2.6): $Q = a + bS^{c}$

Linear (Eq. 2.5): $Q = a + b\,S$

Power (Eq. 2.4): $Q = b\,S^{c}$

Field 7: The default is to use the SFF array developed by the previous *5CR1* record that is in active computer memory. The second option is to read a SFF array from a previously created SFF file.

Field 8: The incremental probability array is stored in active computer memory for use by *2REL*, *2FRE*, *2FRQ* and *2PER* record routines. The probability array may also be written to a SFF file if the model-user wants to see the numbers.

Field 9: All starting storage volumes are multiplied by the factor entered in field 9 with a default of 1.0. MFACTOR serves the same function as *CR4* on the CR record.

Fields 10, 11, and 12: These fields are used to enter values for the regression coefficients so specified by the variable FIT in field 6.

5COR Record – Correlation Coefficients

field	columns	variable	format	value	description
1	1-4	CD	A4	5COR	record identifier
					Control Points or Reservoirs for Flow and Storage
2	5-8	NFLOW	I4	+	number of control points for naturalized flow
				blank,0	flow at all control points is summed
3	9-12	NSTOR	I4	+	number of control points or reservoirs for storage
				blank,0	storage at all control points is summed
				-1	storage at all reservoirs is summed
					Annual or Monthly Cycle Options
4	13-16	TCR2	I4	+	starting month activates annual cycle option
				blank,0	monthly or non-annual option adopted by default
					Months Used to Sum Flows
5	17-20	FM	I4	+	number of months for naturalized flow volume
				blank,0	default is simulation length CR1 from CR record.
					Root of Conventional Simulation SIM file
6	21-40	FILESIM	A20	AN	Root of conventional simulation *SIM* file (root.OUT)

Field 2: If field 2 is blank, there is no listing of control point identifiers, and the naturalized flow at all control points included in the *SIM/SIMD* output file is summed. Otherwise, the naturalized flow used to build correlation coefficients is the total of the flows at the NFLOW control points listed on a supplemental *5COR* record. FLOW is entered in field 2 of the supplemental *5COR* record. The number of control point identifiers read from the supplemental *5COR* record is specified by field 2 of the initial *5COR* record and cannot exceed 15.

Field 3: If field 3 is blank, there is no listing of control point or reservoir identifiers, and the storage from all control point output records included in the *SIM/SIMD* output file is summed. A –1 results in use of all reservoir records in the *SIM/SIMD* output file. Otherwise, the reservoir storage used to compute correlation coefficients is the total of the reservoir storage at the NSTOR control points or reservoirs listed on a supplemental *5COR* record. STCP or STRE is entered in field 2 of the supplemental *5COR* record. The number of identifiers read from the supplemental *5COR* record is specified by field 3 of the initial *5COR* record and cannot exceed 15.

Field 4: Entering a starting month ranging from 1 to 12 activates the annual cycle option. The monthly cycle option is activated by default by a blank field 4. The same information is provided by CR2 on the *CR* record. However, field 4 specifies the option used to develop correlation coefficients from the results of a long-term non-CRM *SIM/SIMD* simulation.

Field 5: The storage and flow are summed over the first FM months of each simulation sequence. If field 5 is blank, the default is to sum the storage and flow for the entire simulation period CR1, which is set by *CR* record field 2 and included in the 5th record of the main WRAP-SIM output file.

Field 6: The correlation coefficients are developed from the results of a single conventional *SIM/SIMD* simulation read from a *SIM/SIMD* output file with the filename root.OUT. This option is useful when modeling multiple scenarios that share the same long term simulation results. If left blank, the OUT file will have the same root as specified when running TABLES.

5COR Record – Correlation Coefficients (2nd and 3rd *5COR* records)

field	columns	variable	format	value	Description
1	1-4	CD	A4	5COR	record identifier
2	5-8	CD2	A4	FLOW STCP SRES	control points for naturalized flows to be summed control points for reservoir storage to be summed reservoirs for storage to be summed
3-17	9-128	CPF(I) or CPS(I)	15(2x,A6)	AN	control point or reservoir identifiers for summing flow (I = 1,NFLOW) or storage (I = 1,NSTOR)

Up to 15 control point or reservoir identifiers are listed in fields 3-17 of the two supplemental *5COR* records as specified by fields 2 and 3 of the main *5COR* record. The two supplemental *5COR* records follow behind the main *5COR* record.

If NFLOW in field 2 of the first *5COR* record is non-zero, a *5CORFLOW* record is required to list the control points at which naturalized flows are summed for use in developing correlation coefficients.

If NSTOR in field 3 of the first *5COR* record is non-zero, either a *5CORSTCP* or *5CORSRES* record is required to list the control points or reservoirs at which storage is summed.

If NFLOW or NSTOR in fields 2 and 3 of the initial *5COR* record are blank or -1, the corresponding supplemental record is not entered.

Sub-Monthly Time-Step Reliability and Frequency Tables

The 2FRE, 2FRQ, 2REL (with 2RET), and 2RES records used with monthly simulation results are described in Chapter 4 of the *Users Manual.* The corresponding sub-monthly 6FRE, 6FRQ, 6REL (with 6RET), and 6RES records are described here. Either the type 2 monthly or type 6 sub-monthly records may be combined a *SIMD* CRM output file to perform conditional reliability modeling (CRM) analyses. These records are used with a CRM output file if and only if preceded by a 5CRM or 5CR2 record. Otherwise, the type 6 reliability and frequency records read long-term sub-monthly simulation results from a *SIMD* SUB output file and the type 2 records record a *SIM* or *SIMD* OUT file. The reliability and frequency analysis computations are basically the same regardless. The format of the resulting reliability and frequency tables is the same with CRM versus non-CRM and/or monthly versus sub-monthly time steps. The CRM and sub-monthly time step features affect the size and organization of the *SIM* or *SIMD* simulation results dataset read from *TABLES* from the SUB, OUT, or CRM file. The frequency and reliability analyses computations are performed within *TABLES*.

The fields of the 6FRE, 6FRQ, 6REL (with accompanying 6RET not shown), and 6RES records are identical to the corresponding type 2 records described in the *Users Manual*.

6REL Record – Water Supply Diversion or Hydroelectric Energy Reliability Summary

field	columns	variable	format	Value	Description
1	1-4	CD	A4	6REL	Record identifier
2	8	TFLAG	I4	0, blank	Optional feature is not used.
				1,+	Diversion summary table is added at the end of the reliability table. A 6RET record must follow.
3	12	RFLAG	I4	0,blank	N = number of months with non-zero targets
				1,+	N = NYRS*MONTHS for $R_P = (n/N)*100\%$
4	16	ID	I4	0	Table includes selected control points.
				1	Table includes selected water rights.
				2	Table includes selected hydropower reservoirs.
				3	Table includes selected water right groups.
5	20	MONTH	I4	0,blank	All months are included in the computations.
				+	The month for which the analysis is performed.
6	24	NUM	I4	0	Include all control points (ID=0), water rights (ID=1), or reservoirs (ID=2) in table.
				+	Number of water rights, reservoirs, water right groups, or control points to follow (1 to 80; 8 per record)
				–	NUM identifiers from previous record are repeated.
7-14	25-88 25-88 25-152	IDEN IDEN8 IDEN16	8(2x,A6) 8A8 8A16	AN	Identifiers of control points (ID=0), water rights (ID=1), reservoirs (ID=2), or water right groups (ID=3) to include in table (IDEN(ID,I),I=1,NUM)
				Blank	If NUM is zero or negative.

6FRE Record – Flow-Frequency or Storage-Frequency Relationships

field	columns	variable	format	Value	Description
1	1-4	CD	A4	6FRE	Record identifier
2	5-8	ID	I4	1	Naturalized flows
				2	Regulated flows
				3	Unappropriated flows
				4	Reservoir storage associated with a control point
				–4	Reservoir storage with only totals included in table
				5	Reservoir storage associated with a water right
				–5	Reservoir storage with only totals included in table
				6	Instream flow shortage for an *IF* record right
3	9-12	MONTH	I4	0,blank	All months are included in the computations.
				+	The month for which the analysis is performed.
4	16	NUM	I4	0	Include all control points or water rights in table
				+	Number of control points or rights to follow (80 maximum, eight per record)
				–	NUM identifiers from previous record are repeated.
5-12	17-80	IDCP IDEN16	8(2x,A6) 8A16	AN	Identifiers of control points (ID=1-4) or rights (ID=5,6) to include in table. IDEN(ID,I), I = 1,NUM
				Blank	If NUM is zero or negative

6FRQ Record – Frequency for Specified Flow or Storage

field	columns	variable	format	Value	Description
1	1-4	CD	A4	6FRQ	Record identifier
2	5-8	ID	I4	1	Naturalized flows
				2	Regulated flows
				3	Unappropriated flows
				4	Reservoir storage associated with a control point
				5	Reservoir storage associated with a water right
				6	Instream flow shortage for an *IF* record right
3	12	MONTH	I4	0,blank	All months are included in the computations.
				+	The month for which the analysis is performed.
4	16	NM	I4	+	Number of flows or storages entered for *TABLES* to determine frequencies (NM may range from 1 to 7)
5	17-24 17-32	IDEN IDEN16	2x,A6 A16	AN	Identifier of control point (ID=1-4) or water right (ID=5,6)
6-12	25-80 33-88	QF(I) I=1,NM	7F8.0	+	Streamflows (ID=1,2,3), storage (ID=4,5), or instream flow shortage (ID=6) for which to compute frequency

6RES Records – Reservoir Storage Tables

First 6RES Record

field	Columns	variable	format	Value	Description
1	1-4	CD	A4	6RES	Record identifier
2	8	TABLE	I4	0	All three tables are created.
				1	Storage contents as a percentage of capacity table.
				2	Storage draw-down duration table is created.
				3	Storage reliability table is created.
				4	Both draw-down and reliability tables are created.
3	11-12	MONTH	I4	0,blank	All months are included in the computations.
				+	The month for which the analysis is performed.
4	15-16	NUM	I4	+	Number of reservoir identifiers in following fields.
5-24	17-176	IDEN(res) res=1,20	20(2x,A6)	AN	Reservoir identifiers

Second 6RES Record – Total Storage Capacity (required)

field	columns	variable	format	Value	Description
1	1-4	CD	A4	6RES	Record identifier
2-4	5-16		12X		Blank or comments (not read by *TABLES*)
5-24	17-176	C1(res) res=1,20	20F8.0	+	Total storage capacity in each reservoir (C_1).

Third 6RES Record – Inactive Storage Capacity (optional)

field	columns	variable	format	Value	Description
1	1-4	CD	A4	6RES	Record identifier
2-3	5-16		12X		Blank or comments (not read by *TABLES*)
5-24	17-176	C2(res) res=1,20	20F8.0	+	Inactive storage capacity in each reservoir or bottom of the storage zone being considered (C_2).

The third 6RES record is generally optional, with all C_2 defaulting to zero. However, the third record is required even if the C_2 are zero if followed by another set of 6RES records.

The detailed explanations of the type 2 monthly versions of these records found in the *Users Manual* are also applicable to the type 6 sub-monthly time step versions.

Sub-Monthly Time-Step Time Series

As discussed in Chapter 4 of the *Users Manual*, the time series input records build tables in the same optional formats, with the only difference being the selection of variable from the list below to be tabulated. The items in parenthesis indicate whether the variable is associated with a control point, water right, and/or reservoir. The monthly (type 2) and sub-month (type 6) versions of the time series records obtain simulation results from OUT and SUB files, respectively. The type 2 or type 6 time series records will also access and tabulate data from a CRM file is so specified by a preceding 5CRM or 5CR2 record.

6NAT Record – Naturalized Streamflow (control points)
6REG Record – Regulated Streamflow (control points)
6UNA Record – Unappropriated Streamflow (control points)
6CLO Record – Channel Loss (control points)
6CLC Record – Channel Loss Credits (control points)
6RFR Record – Return Flow Entering at this Control Point (control points)
6URR Record – Regulated Flow at this Control Point from Upstream Reservoir Releases (control points)
6STO Record – Reservoir Storage (control points, water rights, reservoirs)
6EVA Record – Reservoir Evaporation-Precipitation Volume (control points, water rights, reservoirs)
6DEP Record – Streamflow Depletion (control points, water rights)
6TAR Record – Diversion Target (control points, water rights)
6SHT Record – Diversion Shortage (control points, water rights)
6DIV Record – Diversion (control points, water rights)
6RFL Record – Return Flow (water rights)
6ASF Record – Available Streamflow (water rights)
6ROR Record – Releases from Other Reservoirs (water rights)
6IFT Record – Instream Flow Target (instream flow rights)
6IFS Record – Instream Flow Shortage (instream flow rights)
6HPS Record – Hydropower Shortage (+) or Secondary Energy (-) (reservoir/hydropower)
6HPE Record – Energy Generated (reservoir/hydropower)
6RID Record – Inflows to Reservoir from Streamflow Depletions (reservoir/hydropower)
6RIR Record – Inflows to Reservoir from Releases from Other Reservoirs (reservoir/hydropower)
6RAH Record – Releases Accessible to Hydropower (reservoir/hydropower)
6RNA Record – Releases Not Accessible to Hydropower (reservoir/hydropower)
6EPD Record – Evaporation-Precipitation Depths (reservoir/hydropower)

Time Series Records – All Record Types Listed on Preceding Page

field	columns	variable	format	value	Description
1	1-4	CD	A4	page 112	Record identifier from the list on preceding page.
2	8	TA	I4	Blank,0	Do not develop annual row/monthly column table.
				1	Develop table with annual rows and monthly columns. (Not allowed with 6SUB record submonthly interval.)
3	12	PT	I4	Blank,0	Do not activate either HEC-DSS or text file option.
				1	Develop columns of monthly data in text file.
				2	Develop columns of annual totals or means in text file.
				3	Develop columns of 12 monthly means in text file.
				4	Develop HEC-DSS monthly time series records.
				5	Develop HEC-DSS annual time series records.
4	16	NEW	I4	0	Write columns; next record starts a new table.
				1	Add more columns to existing table or start first table.
5	20	ID	I4	0	Develop tables for default ID or for control points.
				1	Develop tables for water rights.
				2	Develop tables for reservoirs.
				3	Develop tables for water right groups.
6	24	NUM	I4	0	Tables for all control points (ID=0), rights (ID=1), or reservoirs (ID=2). NUM cannot be zero if ID=3.
				−	Develop tables for the NUM control points, water rights, or reservoirs listed on the previous record.
				+	Number of control points, water rights, reservoirs, or water right groups to follow (up to 80, eight per record)
7-14	25-88 25-88 25-152	IDEN IDEN8 IDEN16	8(2x,A6) 8A8 8A16	AN	Identifiers of control points (ID=0), water rights (ID=1), reservoirs (ID=2), water right groups (ID=3) to include in the table. IDEN(ID,I), I=1,NUM
				blank	If NUM is zero or negative.

TABLES time series records activate routines that read *SIM* or *SIMD* simulation results from a OUT, CRM, or SUB file and write the data in the format specified by fields 2 and 3. The tabulation formats include:

1. a text file with filename extension TAB that organizes the data into tables with annual rows and monthly columns
2. a text file with filename extension TAB with each time series variable tabulated as one column of a table
3. a binary file with filename extension DSS with each time series variable stored as a HEC-DSS record

All three formats are applicable for data from an *SIM/SIMD* OUT file. The second and third formats are applicable to data from a *SIMD SUB* file. The second and third formats are applicable for data from a CRM file.

Flood Frequency Analysis

7FFA Record – Flood Frequency Analysis

field	columns	variable	Format	value	description
1	1-4	CD	A4	2FFA	Record identifier
2	5-8	ID	I4	1	Naturalized flows
				2	Regulated flows
				3	Reservoir storage
3	9-12	TAB	I4	blank,0,1	Create annual frequency table using log-Pearson III.
				2	Tabulate annual peaks with Weibull probabilities.
				3	Both of the above.
3	13-16	SKEW	I4	blank,0,1	Compute skew coefficients with Eq. 4.8.
				2	Directly apply the following skew coefficients.
				3	Use Eq.4.8 and Eqs. 4.9-4.14 with following G_R.
4-	17-112	G(I), I=1,12	12F8.0	F8.0	Skew coefficients.

The 7FFA record activates a routine which applies the log-Pearson probability distribution to the annual series of maximum naturalized flow, regulated flow, or reservoir storage read from a FFA file created by *SIMD* to develop an annual frequency. An option also creates a table assigning an exceedance frequency computed with the Weibull formula to each peak annual flow or storage volume.

Salinity Simulation

The *8SAL*, *8FRE*, *8FRQ*, and *8REL* records activate *TABLES* routines that read the SAL file containing the *SALT* simulation results. The *8SAL* record and resulting table have the same format as the *2NAT*, *2REG*, *2STO*, and other time series tables described in the basic *Users Manual*. Explanations provided for the time series records in the *Users Manual* are valid for the *8SAL* record as well. Likewise, the *8FRE* and *8FRQ* records are salinity counterparts of the *2FRE* and *2FRQ* records described in the *Users Manual*. The *8REL* record table extends the *2REL* record table to include reliabilities with and without considering salinity constraints.

8SAL Record – Time Series Tables for SALT Simulation Results

field	columns	variable	Format	value	description
1	1-4	CD	A4	8SAL	Record identifier
2	8	TA	I4	blank, 0	Do not develop annual row/monthly column table.
				1	Develop table with annual rows and monthly columns.
3	12	PT	I4	blank, 0	Do not activate either HEC-DSS or text file option.
				1	Develop columns of monthly data in text file.
				2	Develop columns of annual totals or means in text file.
				3	Develop columns of 12 monthly means in text file.
				4	Develop HEC-DSS monthly time series records.
				5	Develop HEC-DSS annual time series records.
4	16	MORE	I4	0	Write columns; next record starts a new table
				1	Add more columns to existing table or start first table.
5	20	ID	I4	1	Inflow volumes.
				2	Inflow loads.
				3	Inflow concentrations.
				4	Storage volumes.
				5	Storage loads.
				6	Storage concentrations.
				7	Outflow volumes.
				8	Outflow loads.
				9	Outflow concentrations.
6	24	SC	I4	blank,0,1	Tables are for first or only water quality constituent.
				2, 3, ... , 15	Selection of constituent for which to build tables.
7	28	NUM	I4	0	Develop tables for all control points in SAL file.
				−	Develop tables for the NUM cpts on previous record.
				+	Number of cpts to follow (up to 80, eight per record).
8-15	29-92	IDCP(I) I=1,NUM	8(2x,A6)	AN	Control point identifiers.
				blank	Not used if NUM in field 7 is zero or negative.

8FRE Record –Volume, Load, or Concentration Frequency Relationships

field	columns	variable	format	value	description
1	1-4	CD	A4	8FRE	Record identifier
2	5-8	ID	I4	1	Inflow volumes.
				2	Inflow loads.
				3	Inflow concentrations.
				4	Storage volumes.
				5	Storage loads.
				6	Storage concentrations.
				7	Outflow volumes.
				8	Outflow loads.
				9	Outflow concentrations.
3	9-12	SC	I4	blank, 0, 1	Tables are for first or only water quality constituent.
				2, 3, ... , 15	Selection of constituent for which to build table.
4	13-16	CC	I4	blank, 0, 1	All months are counted for concentrations.
				−1, 2	Months with zero volume are not counted.
5	20	NUM	I4	0	Develop tables for all control points in SAL file.
				−	Develop tables for the NUM cpts on previous record.
				+	Number of cpts to follow (up to 80, eight per record).
6-13	17-80	IDCP(I) I=1,NUM	8(2x,A6)	AN	Control point identifiers.
				blank	Not used if NUM in field 5 is zero or negative.

The *8FRE* and *8FRQ* records are salinity versions of the *2FRE* and *2FRQ* records. The following fields in the *8FRE* and *8FRQ* records deal specifically with salinity.

Field 2: Frequency tables are developed for volumes, salt loads, and concentrations of control point inflows (ID=1,2,3), storage (ID=4,5,6), or outflows (ID=7,8,9). Inflows volumes (ID=1) and loads (ID=2) are the total of all inflows to a control point and the concentrations (ID=3) are means. Outflow volumes (ID=7) and loads (ID=8) are summations of regulated flows, diversions, and other releases for hydropower and instream flow requirements. The concentrations of regulated flows, diversions, and other releases are the same and are equal to the outflow concentration (ID=9).

Field 3: Salt constituent *SC* = 1, 2, 3, ... , 15. Each individual *8FRE* or *8FRQ* record is for one specific salinity constituent defined in field 3. Constituent 1 is the first constituent in the SAL file and may be the only constituent. An entry of 2 refers to the second constituent in the SAL file.

Field 4: The concentration count *CC* switch in field 4 is pertinent only for concentrations (ID = 3, 6, or 9). In performing the frequency analysis computations for concentrations, the concentration in a month is set equal to zero if the volume is zero. With the default *CC* (blank field 4), all months are included in the total number of months (MONTHS = 12×NYRS) used in the concentration frequency, mean, and standard deviation computations. With a −1 or 2 for CC, months with zero or negative volume are not counted in the total number of months.

8FRQ Record – Frequency for Specified Volume, Load, or Concentration

field	columns	variable	format	value	description
1	1-4	CD	A4	2FRQ	Record identifier
2	8	ID	I4	1	Inflow volumes.
				2	Inflow loads.
				3	Inflow concentrations.
				4	Storage volumes.
				5	Storage loads.
				6	Storage concentrations.
				7	Outflow volumes.
				8	Outflow loads.
				9	Outflow concentrations.
3	9-12	SC	I4	0,blank	Tables are for first or only water quality constituent.
				+	Selection of constituent for which to build table.
4	13-16	CC	I4	blank, 0, 1	All months are counted for concentrations.
				−1, 2	Months with zero volume are not counted.
5	20	NM	I4	+	Number of quantities entered for which to determine frequencies. NM may range from 1 to 7.
6	21-28	IDCP(1)	2x,A6	AN	Identifier of control point.
7-13	29-84	QF(I) I=1,NM	7F8.0	+	Inflow, storage, or outflow volumes (ID=1,4,7), loads (ID=2,5,8), or concentrations (ID=3,6,9) for which to compute frequencies.

2FRE and 8FRE records build frequency tables using the same procedures to compute the mean, standard deviation and exceedance frequencies for equaling or exceeding specified amounts, regardless of the particular variable represented by the data amounts. Amounts are determined corresponding to set exceedance frequencies of 100%, 99%, 98%, 95%, 90%, 75%, 60%, 50%, 40%, 25%, 10%, and 0%. 2FRQ and 8FRQ records determine amounts corresponding to user-specified exceedance frequencies. With either 2FRE, 8FRE, 2FRQ, or 8FRQ records, exceedance frequencies are defined based on the concept counting the relative frequency of amounts being equaled or exceeded.

$$\text{exceedance frequency} = \text{relative frequency} = \frac{n}{N}(100\%)$$

where n is the number of months that a specified amount is equaled or exceeded in the simulation and N is the total number of months considered.

8SUM Record – Control Point Summary

field	columns	variable	format	value	description
1	1-4	CD	A4	2SUM	Record identifier
2	12	SC	I4	0,blank +	Table is for first or only water quality constituent. Selection of constituent for which to build table.

8REL Record – Water Supply Diversion Reliability Summary

field	columns	variable	format	value	description
1	1-4	CD	A4	2REL	Record identifier
2	12	NUMC	I4	blank,0,1 +	Default = one water quality constituent considered. Number of constituents to be considered.
3	16	RFLAG	I4	0,blank 1,+	N = number of months with non-zero targets N = NYRS×MONTHS for $R_P = (n/N)\times100\%$
5	24	NUM	I4	0 − +	Develop tables for all control points in SAL file. Develop tables for the NUM cpts on previous record. Number of cpts to follow (up to 80, eight per record).
5	25-32	CONC	F8.0	+	Maximum allowable concentration limit (NUMC=1).
6-13	33-96	IDCP(I) I=1,NUM	8(2x,A6)	AN blank	Control point identifiers. Not used if NUM in field 5 is zero or negative.

8CON Record – Maximum Allowable Concentration Limits

field	columns	variable	format	value	description
1	1-4	CD	A4	8CON	Record identifier
2	5-8		4x		Field is not read.
3	8	CONC(I) I=1,NUMC	F8.0	+	Maximum allowable concentration limits.

The *8CON* record is used if and only if more than one water quality constituent is being used to constrain reliabilities, as indicated by NUMC in the preceding 8REL record being 2 or greater. If only one constituent is considered, the maximum allowable concentration is entered in *8REL* record field 5. If two or more constituents are considered, the maximum allowable concentrations for all constituents are provided on the *8CON* record.