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Photographs by M.J. Friedel (U.S. Geological Survey)

Sulphur Gulch watershed, Colorado

Upper - West view
Middle - Northeast view
Bottom - South View

Probable Effects of the Proposed Sulphur Gulch Reservoir on Colorado River Quantity and Quality near Grand Junction, Colorado

By M.J. Friedel

Prepared in cooperation with the
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Contents

Figures

Tables

CONVERSION FACTORS, DATUMS, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
acre-feet (acre-ft)	1,233	cubic meter (m^3)
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second per day (m^3/d)
cubic feet per second (ft^3/s)	1.983	acre-feet per day (acre-ft/d)
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
milligrams per liter (mg/L)	0.000137	tons
square mile (mi^2)	2.590	square kilometer (km^2)

Acronyms and Abbreviations

micrograms per liter (µg/L)
milligrams per liter (mg/L)
Northern Colorado Water Conservancy District (NCWCD)
Programmatic Biological Opinion (PBO)
U.S. Geological Survey (USGS)
Water year–Time period from October 1 to September 30

Probable Effects of the Proposed Sulphur Gulch Reservoir on Colorado River Quantity and Quality near Grand Junction, Colorado

By M.J. Friedel

Abstract

A 16,000 acre-foot reservoir is proposed to be located about 25 miles east of Grand Junction, Colorado, on a tributary of the Colorado River that drains the Sulphur Gulch watershed between De Beque and Cameo, Colorado. The Sulphur Gulch Reservoir, which would be filled by pumping water from the Colorado River, is intended to provide the Colorado River with at least 5,412.5 acre-feet of water during low-flow conditions to meet the East Slope's portion of the 10,825 acre-feet of water required under the December 20, 1999, Final Programmatic Biological Opinion for the Upper Colorado River. The reservoir also may provide additional water in the low-flow period and as much as 10,000 acre-feet of water to supplement peak flows when flows in the Colorado River are between 12,900 and 26,600 cubic feet per second. For this study, an annual stochastic mixing model with a daily time step and 1,500 Monte Carlo trials were used to evaluate the probable effect that reservoir operations may have on water quality in the Colorado River at the Government Highline Canal and the Grand Valley Irrigation Canal.

Simulations of the divertible flow (ambient background streamflow), after taking into account demands of downstream water rights, indicate that divertible flow will range from 621,860 acre-feet of water in the driest year to 4,822,732 acre-feet of water in the wettest year. Because of pumping limitations, pumpable flow (amount of streamflow available after considering divertible flow and subsequent pumping constraints) will be less than divertible flow. Assuming a pumping capacity of 150 cubic feet per second and year round pumping, except during reservoir release periods, the simulations indicate that there is sufficient streamflow to fill a 16,000 acre-feet reservoir 100 percent of the time. Simulated pumpable flows in the driest year are 91,669 acre-feet and 109,500 acre-feet in the wettest year. Simulations of carryover storage together with year-round pumping indicate that there is generally sufficient pumpable flow available to refill the reservoir to capacity each year following peak-flow releases of as much as 10,000 acre-feet and low-flow releases of 5,412.5 acre-feet of water.

It is assumed that at least 5,412.5 acre-feet of stored water will be released during low-flow conditions irrespective of the hydrologic condition. Simulations indicate that peak-flow release conditions (flows between 12,900 and 26,600 cubic feet per second) to allow release of 10,000 acre-feet of stored water in the spring will occur only about 50 percent of the time. Under typical (5 of 10 years) to moderately dry (3 of 10 years) hydrologic conditions, the duration of the peak-flow conditions will not allow the full 10,000 acre-feet to be released from storage to supplement peak flows. During moderate to extremely dry (2 of 10 years) hydrologic conditions, the peak-flow release conditions will not occur, and there will be no opportunity to release water from storage to supplement peak flows.

In general, the simulated daily background dissolved-solids concentrations (salinity) increase due to the reservoir releases as hydrologic conditions go from wet to dry at the Government Highline Canal. For example, the simulated median concentrations during the low-flow period range from 417 milligrams per liter (wet year) to 723 milligrams per liter (dry year), whereas the simulated median concentrations observed during the peak-flow period range from 114 milligrams per liter (wet year) to 698 milligrams per liter (dry year). Background concentration values at the Grand Valley Irrigation Canal are generally only a few percent less than those at the Government Highline Canal except during dry years.

Low-flow reservoir releases of 5,412.5 acre-feet and 10,825 acre-feet were simulated for a 30-day period in September, and low-flow releases of 5,412.5 acre-feet were simulated for a 78-day period in the months of August through October. In general, these low-flow releases resulted in changes to salinity concentrations ranging from slight decreases to slight increases in dissolved-solids concentrations over the range of hydrologic conditions simulated. Low-flow releases of 5,412.5 acre-feet of water over the 78-day period resulted in percentage increases in salinity greater than the measurement error for salinity in fewer than 10 percent of the driest years simulated. Low-flow releases of 5,412.5 acre-feet of water over the 30-day period coupled with peak-flow releases of as much as 10,000 acre-feet of water also resulted in percentage increases in salinity greater than the measurement error for dissolved-solids in fewer than 10 percent of the driest years simulated. Observed trends in stream dissolved-solids concentrations at the Grand Valley Irrigation Canal are similar to observations of simulated dissolved-solids concentrations change at the

Government Highline Canal, however, the magnitude of percent and absolute change is less except under very dry hydrologic conditions.

In addition to dissolved-solids concentration, understanding instream changes in selenium concentration following reservoir releases are of concern because selenium can be toxic to fish and other biota. In general, instream selenium concentrations are an order of magnitude greater in tributary creeks like Sulphur Gulch (1 to 25 micrograms per liter) than in the Colorado River (0.3 to 0.7 microgram per liter). Stochastic modeling indicates that random sampling may result in a 1-percent and 35-percent chance, respectively, of exceeding Colorado instream acute (18.4 micrograms per liter) and chronic (4.6 micrograms per liter) water-quality standards in Sulphur Gulch runoff. The lack of selenium in water pumped from the Colorado River to storage likely will result in diluting reservoir concentrations to respective levels ranged from 0.37 to 1.48 micrograms per liter under wet and dry hydrologic conditions. Therefore, based on the simulations and inherent assumptions, selenium concentrations in the proposed reservoir are expected to be less than the acute and chronic standards.

INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with the Northern Colorado Water Conservancy District and Denver Water, began a study in 2001 to evaluate the probable effects that development and operation of the proposed Sulphur Gulch Reservoir may have on instream quantity and quality changes in the Colorado River. The proposed 16,000 acre-ft reservoir with a 150 ft^3/s pump and discharge capacity is to be located about 25 mi east of Grand Junction, Colorado, on a tributary of the Colorado River that drains the Sulphur Gulch watershed between De Beque and Cameo, Colorado (fig. 1). The proposed Sulphur Gulch Reservoir is planned to provide the Colorado River, at a point 25 mi upstream from Grand Junction (1) at least 5,412.5 acre-ft of water during low-flow conditions to meet the East Slope's portion of the 10,825 acre-ft of water required under the December 20, 1999 Final Programmatic Biological Opinion (PBO) for the upper Colorado River (U.S. Fish and Wildlife Service, 1999), and (2) as much as 10,000 acre-ft to enhance the peak-flow when flows are in the range of 12,900 to 26,600 ft^3/s.

This report describes the stochastic modeling approach and results of simulated daily reservoir operations on instream Colorado River water quantity and quality at the Government Highline and Grand Valley Irrigation Canals, and between DeBeque and Palisade, Colorado. The use of a stochastic model that takes into account the random nature of hydrologic and water-quality variables is more suitable to provide simulated estimates of salinity change as a result of reservoir operations, because the temporal variability in daily Colorado River streamflow and salinity is large, and values for runoff and salinity from Sulphur Gulch and evaporation are uncertain. For this reason, the specific objectives in this report are to: (1) develop a stochastic mixing model that incorporates natural variability and uncertainty for evaluation of water quantity and quality (salinity and selenium) on a daily time step at locations along the entire study reach; (2) quantify the effect of simulated natural variability and uncertainty on probable changes in stream quantity and quality subject to selected operational pump and release activity; and (3) make an initial assessment of the potential for selenium concentrations at the Sulphur Gulch Reservoir.

DESCRIPTION OF STUDY AREA

The study area is in the western part of the Upper Colorado River Basin and includes the Sulphur Gulch watershed and includes a 10-mi reach of the Colorado River between De Beque and a point 15 mi upstream (east) from Grand Junction near Palisade and a 15-mi reach of concern between Palisade and Grand Junction based on the PBO (fig. 1). The Sulphur Gulch drainage area contributing runoff to the Colorado River near De Beque is about 16 mi^2, whereas the Colorado River Basin drainage area that contributes to runoff upstream from De Beque is about 7,370 mi^2. In the Colorado River Basin, physiography, climate, geology, and land use combine to affect the quantity and quality of water resources.

Physiography and Climate

The Upper Colorado River Basin near the Continental Divide contains a series of mountain ranges with elevations ranging from 5,000 to more than 14,000 ft (NAVD 88). The middle parts of the basin consist of plateaus, ranging in elevation from about 3,100 to 11,000 ft that are semiarid and deeply incised by canyons. Climate in the upper Colorado River Basin is diverse because of these physiographic features, which includes variations in elevation, latitude, and prevailing wind patterns. Because of large differences in elevation between the physiographic provinces, climate differs substantially between the eastern and western parts of the basin. Mountainous areas receive most of their precipitation as snow, whereas the lower areas have dry winters and receive most of their precipitation from intermittent summer thunderstorms. Although the mountainous headwater areas of the basin receive a large quantity of snow, most of the basin consists of semiarid or arid plains that do not contribute substantially to annual streamflow. Plateaus and high, intermontane basins typically have cold winters and hot summers (Apodaca and others, 1996).

Geology

The geology of the Upper Colorado River Basin is diverse and characterized predominantly by igneous and metamorphic rocks in the high mountains and sedimentary rocks elsewhere.

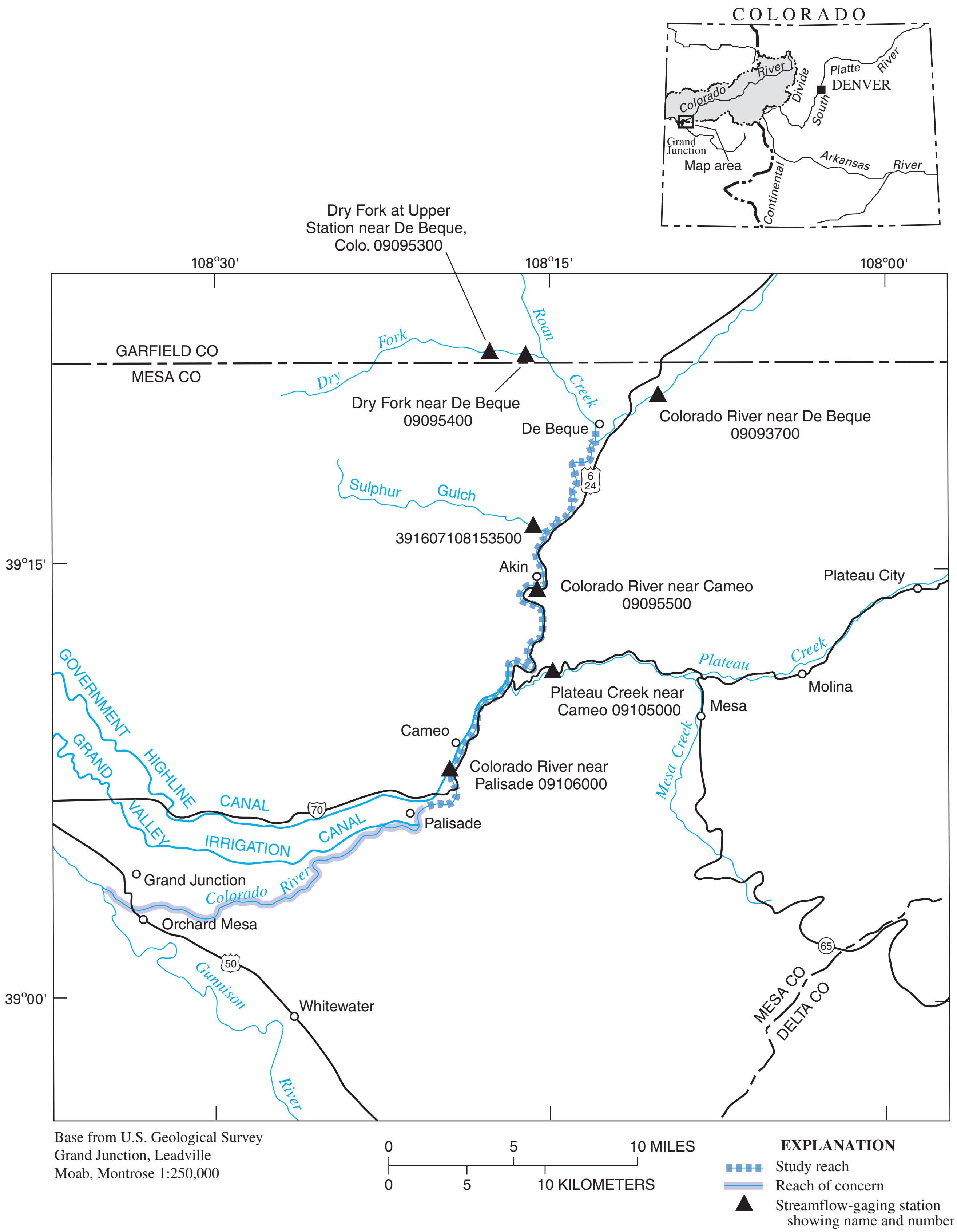

Figure 1. Location of study area between De Beque and Palisade.

Structural features, including anticlines, domes, and faults, expose large sequences of strata. Several geologic units are major natural contributors of dissolved solids to streams. For example, shale formations that contain gypsum, calcite, dolomite and sodium-rich clay are the primary contributors of dissolved solids (also called salinity). Dissolved solids such as sodium chloride, calcium bicarbonate, and calcium sulfate are transported concomitantly with ground water and surface water. About one-half of the salinity in the Colorado River is from natural sources (U.S. Department of the Interior, 1994) such as weathering of geologic deposits and thermal springs (Butler and von Guerard, 1996).

When streams come in contact with outcrops of sedimentary rocks, gypsum and calcite dissolve and salinity in the water increases. In the more arid climate at lower altitudes in the western part of the basin, precipitation commonly is in the form of thunderstorms, and runoff from thunderstorms can deliver large loads of dissolved solids to streams and, therefore, salinity can increase. In addition, evaporation in semiarid and arid regions of the basin enhance the accumulation of salts on the soil and in reservoirs that can be delivered to streams. The presence of mineral hot springs upstream from the study areas also have an effect on salinity. The springs primarily are located in carbonate rock units in the area surrounding Glenwood Springs, Colorado. The mineral hot springs contribute about 15 percent of the total salinity annually to streams in the basin (U.S. Department of the Interior, 1994). In addition to salinity, selenium is present naturally in the shale bedrock of the basin upstream from Sulphur Gulch and is also in the surface water and ground water. Because selenium can be toxic to fish and other biota, knowledge of the occurrence and distribution of selenium in the study area is also of interest.

Water Management and Use

Irrigation, reservoir operations, interbasin water transfers, and power generation are the primary human activities that may affect salinity in the Upper Colorado River Basin. In 1993, interbasin water transfers conveyed about 585,000 acre-ft of water (12 percent of the average annual streamflow in the basin) from the Upper Colorado River Basin to the South Platte, Rio Grande, and Arkansas River Basins (U.S. Department of the Interior, 1994). Interbasin water transfers generally occur near the stream headwaters, and the amount of streamflow diverted can be a substantial part of streamflow near these sources. Likewise, streamflow diversions occur through the study reach for irrigation, power generation, and other purposes. By removing water from the system, streamflow diversions decrease the dilution capacity of streams. In addition to providing drinking water, numerous basin reservoirs are used to regulate streamflow in the Colorado River. Collectively, these reservoir operations and streamflow diversions alter natural streamflow that may affect salinity and aquatic habitat of the streams.

Land Use

Rangeland and forest are the predominant land uses in the Southern Rocky Mountain physiographic province (east), whereas agricultural land use predominates in the Colorado Plateaus physiographic province (west). Agricultural activities in the basin can cause increased levels of salinity that directly affect the surface- and ground-water quality and aquatic biota (Apodaca and others, 1996). For example, irrigation return flows can increase salinity in the surface and ground waters of the study area. In addition, partly because of reuse of irrigation water and leaching of bedrock, naturally occurring trace elements such as selenium are present in water used for domestic and irrigation purposes (Apodaca and others, 1996).

DESCRIPTION OF THE MODEL

A stochastic modeling approach is used to quantify the effects that development and operation of the Sulphur Gulch Reservoir might have on daily streamflow and water-quality changes in the Colorado River. The basic approach involves development of a stochastic mixing model, stochastic model validation, and stochastic scenario modeling of reservoir operations. In the following section, the conceptualization, parameterization, and measurements used in the stochastic model development are described.

Conceptualization

The stochastic mixing model is composed of linked hydrology and water-quality submodels that incorporate random variability and uncertainty. The temporal variability and measurement uncertainty of model input is incorporated, and the distribution of probable results derived for changes in streamwater quality is determined by using the Monte Carlo method (Kalos and Whitlock, 1986). The surrogate for water quality in the stochastic mixing model is salinity, as indicated by measured instream dissolved-solids concentrations. Because salinity is considered to be conservative, the use of salinity is amenable to mixing without losing mass. Overall, the mixing model is a simplified representation of the Colorado River/Sulphur Gulch system in which daily flows are added or subtracted, and concentrations are calculated based on the conservation of mass principle.

In keeping with the conservation of mass principle, the mixing model accounts for flows and associated concentrations that are gained and lost in the Colorado River reach between the town of De Beque and the Palisade streamflow-gaging station. An overview of the study-area hydrology including cities, diversions, and location of return flow is presented in figure 2. The Palisade streamflow-gaging station is about 15 mi east of Grand Junction and is the upstream end of the so-called 15-mi reach. In the study reach, daily gains are attributed to streamflow that originates upstream from De Beque, releases

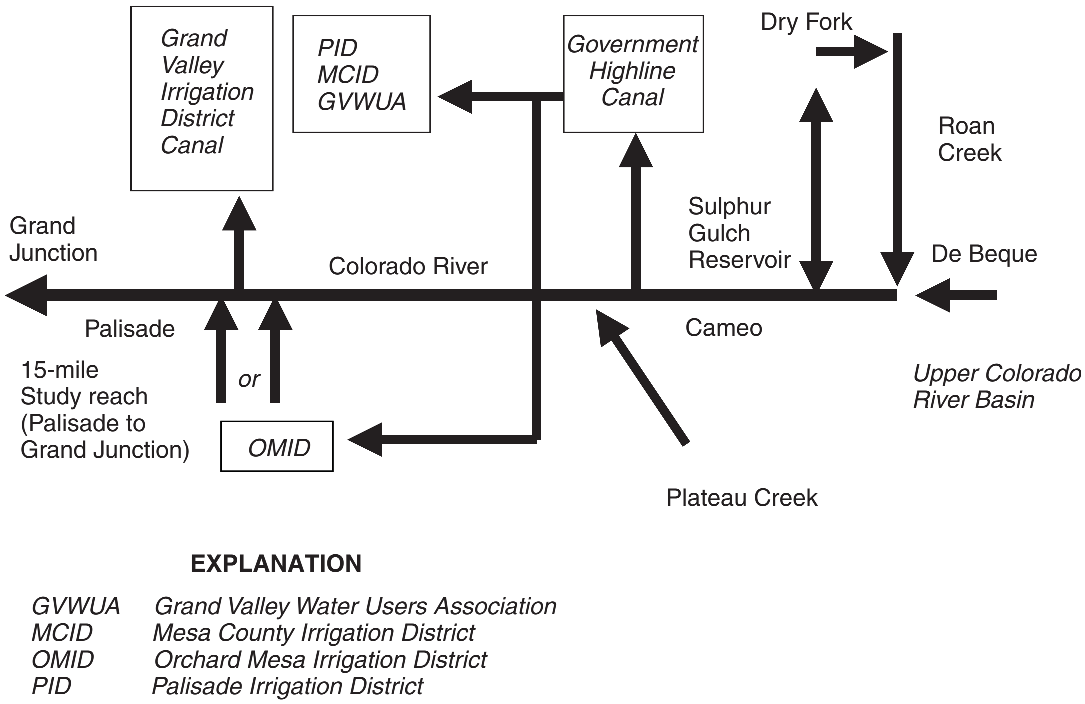

Figure 2. Primary study reach hydrologic components considered in the stochastic mixing model.

from Sulphur Gulch Reservoir, inflow from Plateau Creek, and return flow from the Orchard Mesa powerplant. The amount and quality of streamflow upstream from De Beque is a result of dissolved solids transported by runoff, ground-water inflow (baseflow), and reservoir releases. Daily streamflow losses over the study reach include diversions, reservoir pumping, and evaporation. The Government Highline and Grand Valley Canals divert Colorado River water downstream from the De Beque streamflow gaging station, but upstream from the Palisade streamflow gaging station, for use by the Grand Valley Irrigation Company, Grand Valley Water Users Association, Orchard Mesa Irrigation District, Palisade Irrigation District, and Mesa County Irrigation District. The quality of water that will be released to the Colorado River from the Sulphur Gulch Reservoir would be the result of mixing seasonally pumped Colorado River water with runoff to the reservoir and concentration of salts by reservoir evaporation.

In conceptualizing the stochastic mixing model, the following assumptions were made.

1. *No change in reservoir operations or transmountain diversions occur upstream from the city of De Beque*. It is assumed that the operations associated with reservoirs and transmountain diversions in the headwaters of the Colorado River will continue with the same (or similar) pump and release schedules. The assumption of similar operations is valid so long as the mean streamflow determined by the stochastic model does not change in time (stationarity).
2. *Streamflow record at Colorado River near Cameo adequately describes flow at the proposed Sulphur Gulch Reservoir pump and release point*. This assumption is realistic because there are no anthropogenic or perennial tributary sources of water between the proposed pump and release point and the streamflow-gaging station located about 1 mi downstream.
3. *Variability in streamflow and salinity measurements adequately reflects periods of extreme wet and dry climatic conditions*. The period of record used (1974–2001) reflects wet to dry conditions; however, future climate conditions may be different and result in extreme wet or dry (drought) conditions. As long as climatic stationarity is in effect, the minimum and maximum values of the probability distribution functions describing daily flow may be adjusted to incorporate extreme values; for example, the probability distribution function describing minimum annual (calendar year) streamflow (657,210 ft^3/s) at the gage near Cameo could be changed to the new minimum annual streamflow (604,026 ft^3/s) experienced during the 2002 drought. Because of the comparatively minor difference in minimum annual flows (about 8 percent) and similar probability of occurrence (of less than about 1-percent chance) the simulations were not repeated with the new distribution.
4. *Instantaneous routing between pump and discharge points*. Instantaneous routing assumes that there is no time delay between water sources or sinks in the study

reach between the proposed reservoir-release point 25 mi east of Grand Junction (Palisade) and De Beque. The assumption of instantaneous routing is reasonable because the daily time step used in the model is less than the time it takes a parcel of water to travel through the study reach (Don Carlson, written commun., Northern Colorado Water Conservancy District, 2002).

5. *Variability in runoff and salinity observed at the USGS streamflow-gaging station 09095300 Dry Fork at Upper Station near De Beque, Colorado, is similar to Sulphur Gulch*. The assumption that Dry Fork runoff and associated concentrations can be used as a surrogate for runoff and concentration to the Sulphur Gulch Reservoir may be reasonable because the Dry Fork watershed is located adjacent to Sulphur Gulch watershed and has similar geology and similar precipitation. Limited sampling was conducted to verify this assumption.
6. *The reservoir is completely mixed.* It is important to note that the assumption of complete mixing neglects reservoir stratification. Because seasonal stratification of the reservoir may cause increased salinity with depth, the actual nature of how and when reservoir releases are managed (from top, bottom, or mixture) may cause variability in downstream salinity that is not considered in this study.
7. *Dissolved solids (salinity) are conservative*. The assumption that dissolved solids are conservative implies that all of the sources or sinks of water within the study reach are represented. Because dissolved solids and streamflow are highly correlated (as determined by nonlinear regression), the transport of dissolved solids is assumed to be advective with no dispersion.
8. *No ground-water seepage (baseflow) to Sulphur Gulch Reservoir*. No baseflow assumes that ground-water seepage carrying dissolved solids, as evidenced by evaporative concentration along the canyon walls at the Sulphur Gulch Reservoir site, will be controlled by maintaining a reservoir level that exceeds the hydraulic head governing ground-water seepage.
9. *No evaporative concentration residue exists on reservoir canyon walls during the initial filling of the reservoir*. Whereas evaporative salts are observed on the canyon walls of Sulphur Gulch at the proposed reservoir site during spring and summer, these salts are periodically flushed following thunderstorms. For this reason, the likelihood for anomalously high initial salinity concentrations caused by dissolution of residue on the canyon walls is considered negligible.

Parameterization

Parameterization of the stochastic mixing model involves defining random variables, decision variables, and prediction variables (forecasts). Random variables do not have a fixed value at a particular point in space and time and are described in the mixing model by probability distributions that account for a range of possible values. The various daily random variables in the stochastic model include streamflow, diversions, return flows, and salinity in the Colorado River at De Beque, Cameo, and Palisade and in Plateau Creek, a tributary to the Colorado River downstream from Sulphur Gulch but near Cameo; runoff and salinity concentration in the Sulphur Gulch watershed; reservoir evaporation; reservoir surface area; and reservoir releases from Sulphur Gulch. Whereas the random variability in Colorado River streamflow and salinity at De Beque, Cameo, and Palisade reflect natural variability, the parameters used in describing streamflow and salinity at Sulphur Gulch are uncertain. The use of random variables as input to the stochastic mixing model requires identification of relevant probability distributions and related statistical summaries.

Statistical summaries of random variables are derived from records that incorporate a balanced mix of wet, dry, and average hydrologic periods to avoid model bias. The actual length of record is based on the need to minimize model time step yet provide enough measurements so that a statistically valid probability distribution can be fit for each parameter. One test used to evaluate the goodness-of-fit between measurement frequency and fitted probability distribution is the Chi-square goodness-of-fit criteria (Helsel and Hirsch, 1995). The Chi-square criteria evaluates the goodness-of-fit by breaking the distribution into areas of equal probability and comparing the data points within each area to the number of expected data points. In addition to describing variability and uncertainty using probability distributions, the correlation in time between random variables is incorporated into the mixing model by using a single lag function. In addition to fitting random variables to probability distributions, decision variables also were defined.

Decision variables are those variables that can be controlled in the stochastic mixing model. Examples of some important user-defined decision variables incorporated into the stochastic mixing model include initial reservoir storage volume, initial reservoir salinity concentration, total reservoir volume, reservoir pumping rate from the Colorado River, total amount of supplemental flow, and amount and timing of daily reservoir releases. Whereas many of these decision variables have fixed (constant) values, the infinite number of possible combinations of magnitude and timing of reservoir release is likely to affect the change in prediction variables, such as the Colorado River salinity (change or amount). Prediction variables represent distributional outcomes of model calculations based on some combination of decision and random variables. For this reason, prediction variables are summarized as either probability distribution or cumulative distribution functions.

Assumptions invoked in parameterization of the stochastic model are as follows:

1. *Fitted probability distributions accurately represent variability and (or) uncertainty associated with model*

random variables. The probability distribution assigned to a random variable represents the best-fit distribution (one of 17 possible probability distributions) as determined using the Chi-square goodness-of-fit criteria. The addition of future measurements may modify selection of the probability distribution and associated statistics.

2. *Measurement errors associated with random variables are second-order (less than 10 percent of the maximum) as compared to daily variability.*
3. *Numerical simulation using random variables captures temporal variability thereby providing a realistic assessment of the effect reservoir operations have on streamflow quantity and quality in the Colorado River.*
4. *The stability and convergence of a prediction variable is accurate to within 1 percent when using the Monte Carlo approach*. Using the bootstrap approach (Werckman and others, 2001), the minimum number of simulations required to achieve this level of stability and convergence was determined to be about 1,500.

Measurements

Measurements used in developing the stochastic mixing model were obtained from various sources including the USGS's National Water Information System (NWIS) (Kinerney, 2001); State of Colorado, Division of Water Resources HydroBase (Colorado Division of Water Resources, 2002), and Colorado State University, Orchard Mesa database (Harold Larsen; personal commun., 2002). For example, streamflow and dissolved-solids measurements were retrieved from the USGS NWIS database for the Colorado River streamflow gaging stations near De Beque (09093700), Cameo (09095500), and below the Grand Valley diversion near Palisade (09106000); Plateau Creek near Cameo (09105000); and Dry Fork near De Beque, Colorado (09095400). Daily streamflow measurements were available for a 27-year period (1974–2001), whereas values of the dissolved solids and associated instantaneous streamflow were available at an approximately monthly frequency and a fewer number of years. Because streamflow is regulated by upstream reservoirs, streamflow in the Upper Colorado River Basin system is seasonally periodic, and correlation (dependency) between annual streamflow records generally exceeds 0.70. A matrix of correlation coefficients between total annual streamflow (integrated on a daily basis) time series for the Colorado station near Cameo (09095500) is provided in table 1.

Despite the persistent seasonal periodicities, correlations between annual streamflow records for different years are less than perfect (correlation coefficient less than 1.0) due to annual variations in hydrologic conditions. Identifying the corresponding hydrologic conditions is done by using a cumulative distribution function (also called flow duration or exceedance curve) for annual flow (fig. 3). In the annual streamflow-exceedance curve, the 27-year period contains a range of hydrologic conditions that include 7 dry, 14 average, and 6 wet periods. The average hydrologic period is defined as that period where flow exceedances are in the 25 to 75 percent range, whereas the wet and dry hydrologic periods are defined as those respective annual flows that are in the 0 to 25 percent and 75 to 100 percent exceedance range.

Discrete annual cumulative streamflow values, water year, rank, exceedance value, and corresponding hydrologic conditions are summarized by calendar year for the station near Cameo (09095500) in table 2. Based on information gathered at the time of this study, the annual streamflow of 657,210 ft^3/s during 1977 was the minimum on record indicating a dry period, whereas streamflow of 2,859,690 ft^3/s during 1984 was the maximum on record indicating a wet period. The 2002 drought resulted in a slightly smaller (about 8-percent) annual minimum streamflow record of 604,026 ft^3/s compared to 1977. Selection of this streamflow record provided a wide variety and balanced number of hydrologic conditions so as to minimize any potential model bias. At time scales on the order of days or weeks, streamflow is highly variable and can be characterized by using probability distributions.

Daily Colorado River diversion records for water years 1974 to 2001 were obtained for diverters downstream from De Beque and upstream from Palisade using the Colorado State HydroBase (Colorado Division of Water Resources, 2002). Pan evaporation measurements collected at the Orchard Mesa Research Station (about 15 mi west from the study area) were obtained from Harold Larsen (Colorado State University, written commun., 2002). Because evaporation measurements were limited to the growing season, a predictive equation was fit by using nonlinear regression so that the usefulness of these data could be extended to a full year. Because of the small number of salinity and evaporation measurements, these data also were fit to predictive equations by using nonlinear regression, and the probability distributions associated with residuals (difference between measurement and prediction) were used to generate random values for use in stochastic modeling. Nonlinear regression also was used to fit functional relations for annual streamflow exceedance probability and reservoir surface area as a function of reservoir volume.

Instantaneous streamflow and salinity measurements were obtained from the USGS NWIS database for the Colorado River De Beque, Cameo, and Palisade and Plateau Creek stations, for Dry Fork and Upper Dry Fork stations near De Beque, and for a USGS National Water Quality Assessment (Spahr and others, 1996) site on the Dry Fork at Upper Station near De Beque. Hydrograph separation was performed on the Dry Fork discharge measurements using published USGS software (Rutledge, 1998). By using the computed baseflow (low-flow) hydrograph, the streamflow hydrograph was adjusted to obtain a unit runoff hydrograph that was applied to the Sulphur Gulch drainage. Two water samples also were collected from a site (391607108153500) at the mouth of the Sulphur Gulch watershed and analyzed for salinity and selenium during the spring 2002 runoff. Instantaneous streamflow and basic parameters such as dissolved oxygen, alkalinity, pH, and temperature were measured concurrently with the sample collection.

Table 1. Correlation coefficient matrix of annual streamflow between water years 1974–94 at the Cameo gaging station (09095500).

Year	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
1974	1.000																				
1975	0.728	1.000																			
1976	0.875	0.814	1.000																		
1977	0.721	0.578	0.792	1.000																	
1978	0.819	0.913	0.851	0.616	1.000																
1979	0.833	0.934	0.879	0.605	0.937	1.000															
1980	0.903	0.857	0.922	0.754	0.942	0.918	1.000														
1981	0.683	0.713	0.838	0.848	0.748	0.747	0.821	1.000													
1982	0.826	0.913	0.837	0.649	0.926	0.936	0.911	0.805	1.000												
1983	0.711	0.904	0.714	0.493	0.872	0.883	0.796	0.659	0.929	1.000											
1984	0.858	0.895	0.906	0.638	0.900	0.952	0.890	0.701	0.894	0.855	1.000										
1985	0.923	0.740	0.877	0.807	0.830	0.820	0.932	0.811	0.835	0.675	0.797	1.000									
1986	0.881	0.859	0.906	0.761	0.897	0.911	0.947	0.846	0.916	0.794	0.870	0.931	1.000								
1987	0.856	0.683	0.867	0.783	0.761	0.717	0.869	0.731	0.694	0.519	0.746	0.897	0.835	1.000							
1988	0.844	0.820	0.963	0.769	0.869	0.876	0.915	0.843	0.829	0.707	0.869	0.877	0.902	0.880	1.000						
1989	0.894	0.713	0.875	0.742	0.794	0.836	0.886	0.717	0.785	0.662	0.858	0.890	0.871	0.835	0.854	1.000					
1990	0.685	0.835	0.831	0.740	0.878	0.849	0.888	0.888	0.851	0.774	0.794	0.795	0.849	0.705	0.853	0.741	1.000				
1991	0.855	0.871	0.918	0.723	0.939	0.934	0.952	0.809	0.888	0.788	0.919	0.869	0.895	0.808	0.911	0.872	0.913	1.000			
1992	0.902	0.700	0.866	0.696	0.770	0.819	0.863	0.678	0.789	0.634	0.838	0.901	0.864	0.852	0.844	0.884	0.682	0.827	1.000		
1993	0.904	0.858	0.927	0.644	0.896	0.944	0.900	0.710	0.882	0.803	0.979	0.836	0.890	0.794	0.891	0.879	0.755	0.918	0.885	1.000	
1994	0.888	0.658	0.932	0.815	0.741	0.772	0.851	0.760	0.718	0.578	0.843	0.847	0.832	0.864	0.892	0.915	0.706	0.841	0.850	0.881	1.000

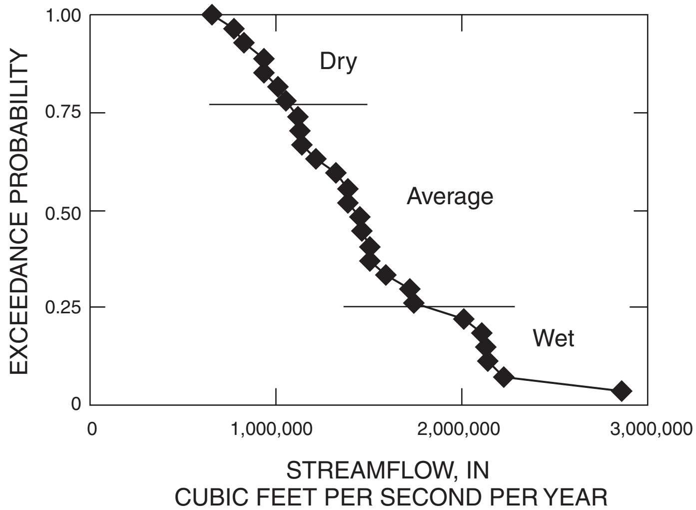

Figure 3. Annual flow exceedance at Colorado River near Cameo (09095500) for 1974–2001.

Random Variables

Most real-world problems involve elements of variability or uncertainty called random variables (Kalos and Whitlock, 1986). Random variables are those variables that do not have a fixed value at a particular point in space and time but instead are described by probability distributions that account for a range of possible values. There are two types of random variables: discrete and continuous. A discrete random variable may take on only a countable number of distinct values, such as the number of reservoir discharge days. A continuous random variable takes an infinite number of possible values. Examples of continuous random variables include measurements such as streamflow, evaporation, diversions, and salinity. Whereas a random variable has either an associated probability distribution (discrete random variable) or probability distributions (continuous random variable), all random variables (discrete and continuous) have a cumulative distribution function. The cumulative distribution function for a discrete random variable is determined by summing the probabilities, whereas the cumulative distribution function for a continuous random variable is determined by integrating the probability density function. The cumulative distribution function represents the probability that a variable will occur at or below a given value, whereas a reverse cumulative distribution function represents the probability that a variable will occur at or above a given value (exceedance probability). The cumulative and reverse cumulative distribution functions both are presented in this report by using tables of percentile so that the likelihood of selected forecast variables can be evaluated. A percentile is a number between 0 and 100 that indicates the percentage of a probability distribution that is equal to or below a value (cumulative distribution function) or equal to or above a value (reverse cumulative distribution function).

By using historical streamflow measurements, daily streamflow values were aggregated by year for the entire period of record, calendar years 1974 to 2001. This data aggregation resulted in 365 random variables, each with about 27 samples (2001 was a partial year). These daily values then were fit to one of 14 continuous probability distribution functions: Beta, Binomial, Exponential, Extreme value, Geometric, Hypergeometric, Logistic, Lognormal, Normal, Pareto, Poisson, Triangular, Uniform, and Weibull (Werckman and others, 2001). The quality of distributional fit was judged by using one of several goodness-of-fit criteria that included Chi-square, Kolmogorov-Smirnov, and Anderson-Darling (Werckman and others, 2001). Multiple goodness-of-fit criteria were used because one (or more) of these criteria yielded a best model that was judged infeasible. In general, daily streamflow measurements were best characterized using Extreme value, Logistic, Lognormal, Normal, Pareto, Triangular, Uniform, or Weibull probability distributions. The actual distribution selected to represent a daily streamflow random variable was based on the distributional fit with the highest rank.

To investigate the operational dependency between diversions and hydrologic conditions, correlation coefficients were computed between daily streamflow for the period of record (calendar year 1986 to 2001) for Colorado River near Cameo (09095500), Plateau Creek near Cameo (09105000), Colorado River near Palisade (0916000), and diversions at the Grand Valley Irrigation Canal (GVIC) and Government Highline Canal (GHC). This 15-year period of record includes three wet, nine typical, and three dry hydrologic periods. A summary of correlation coefficients between these hydrologic entities is presented in table 3.

Whereas the dependency appears high between individual streamflow-gaging stations (Cameo, Palisade, and Plateau) and between individual streamflow diversions (GVIC and GHC), correlation between streamflow and diversion records is relatively weak. The relatively weak correlation between streamflow and diversion records underscores the relative independence between diversion operations and hydrologic conditions. This high degree of independence between streamflow diversion and hydrologic condition is further illustrated by observing

Table 2. Hydrologic condition by calendar year for measurements recorded at the Cameo gaging station (09095500) during the period, 1974–2001.

Calendar year*	Colorado River flow, in cubic feet per second per year	Fitted cumulative distribution function	Hydrologic condition
1977	657,210	0.998	Dry
1981	771,050	0.950	Dry
1990	825,780	0.903	Dry
1992	932,790	0.855	Dry
1989	933,340	0.848	Dry
1994	1,007,990	0.808	Dry
1988	1,055,120	0.760	Dry
1991	1,120,040	0.713	Average
1976	1,129,780	0.665	Average
2000	1,138,310	0.596	Average
1987	1,217,210	0.618	Average
1978	1,318,060	0.570	Average
1982	1,383,040	0.523	Average
1999	1,388,260	0.438	Average
1974	1,456,050	0.475	Average
1975	1,466,270	0.428	Average
1980	1,502,020	0.380	Average
1998	1,503,770	0.388	Average
1979	1,590,280	0.333	Average
1996	1,721,920	0.316	Average
1993	1,738,760	0.285	Average
1995	2,012,770	0.250	Wet
1986	2,106,450	0.238	Wet
1985	2,125,550	0.190	Wet
1997	2,142,900	0.227	Wet
1983	2,225,390	0.143	Wet
1984	2,859,690	0.095	Wet

* Calendar year is from January 1 through December 30.

Table 3. Summary of correlation coefficients between daily streamflow and diversions along the Colorado River.

[Cameo – Cameo streamflow gage site near Cameo (1974–2001); Palisade – USGS streamflow gage site near Palisade (1990–2001); Plateau – USGS streamflow gage on Plateau Creek near Cameo (1974–2001); GHC – Government Highline Canal; includes GVWU, MCID, OMID, PID; GVIC – Grand Valley Irrigation Canal (1972–2001)]

	Cameo	Plateau	Palisade	GVIC	GHC
Cameo	1.00				
Plateau	0.77	1.00			
Palisade	0.98	0.81	1.00		
GVIC	0.44	0.27	0.29	1.00	
GHC	0.41	0.27	0.30	0.78	1.00

diversion profiles provided in figures 4 and 5. By contrast, evaluation of the diversion profiles further reveals the presence of a seasonal dependence. Because individual profiles generally are not related to hydrologic condition, the variability surrounding these seasonal diversions is modeled in this study as a set of independent random variables; therefore, individual probability distribution functions are fit to the various seasonal components between days 100 to 300. For example, three probability functions are fit and used to replicate diversion behavior for the GVIC, whereas five probability functions are fit and used to replicate diversion behavior for the GHC.

A summary of fitted probability distributions for each of the streamflow diversions is presented in table 4. Because the GHC delivers water to the Mesa County Irrigation District, Palisade Irrigation District, Mesa County Irrigation District, and Grand Valley Water Users Association, individual distributions are fit to each of their corresponding records. Whereas the random variability of Colorado River streamflow near De Beque, Cameo, and Palisade reflects documented natural variability, the quantity and quality of runoff in Sulphur Gulch are uncertain. The primary reason for runoff uncertainty is the lack of direct measurements in this ephemeral tributary. To better define uncertainty that exists in the Sulphur Gulch runoff component, hydrograph separation was performed using discharge measurements from the adjacent Dry Fork watershed and USGS software (Rutledge, 1998).

By using the computed Dry Fork baseflow hydrograph, the corresponding streamflow hydrograph was normalized by drainage area to obtain a unit runoff hydrograph for use in the Sulphur Gulch drainage. A Weibull probability distribution was fit to the corresponding derived runoff time series. Anecdotal evidence in the form of debris along the canyon walls together with the approximate cross sectional area provided information to compute an upper bound on the probability distribution that was set to 1,000 ft^3/s. For a comprehensive review of mathematical formulae describing these probability distribution func

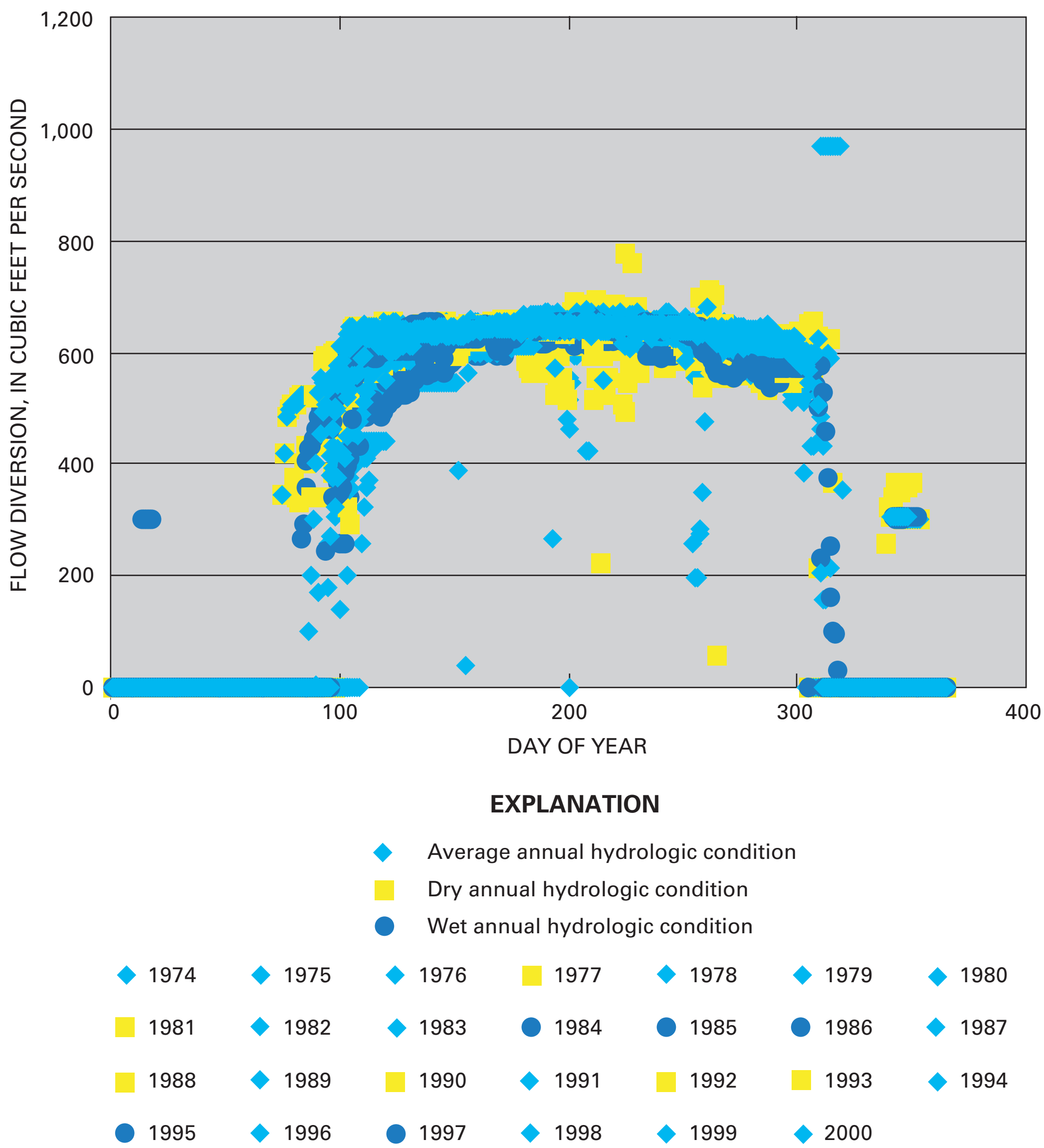

Figure 4. Historical flow diversions at the Grand Valley Irrigation Canal.

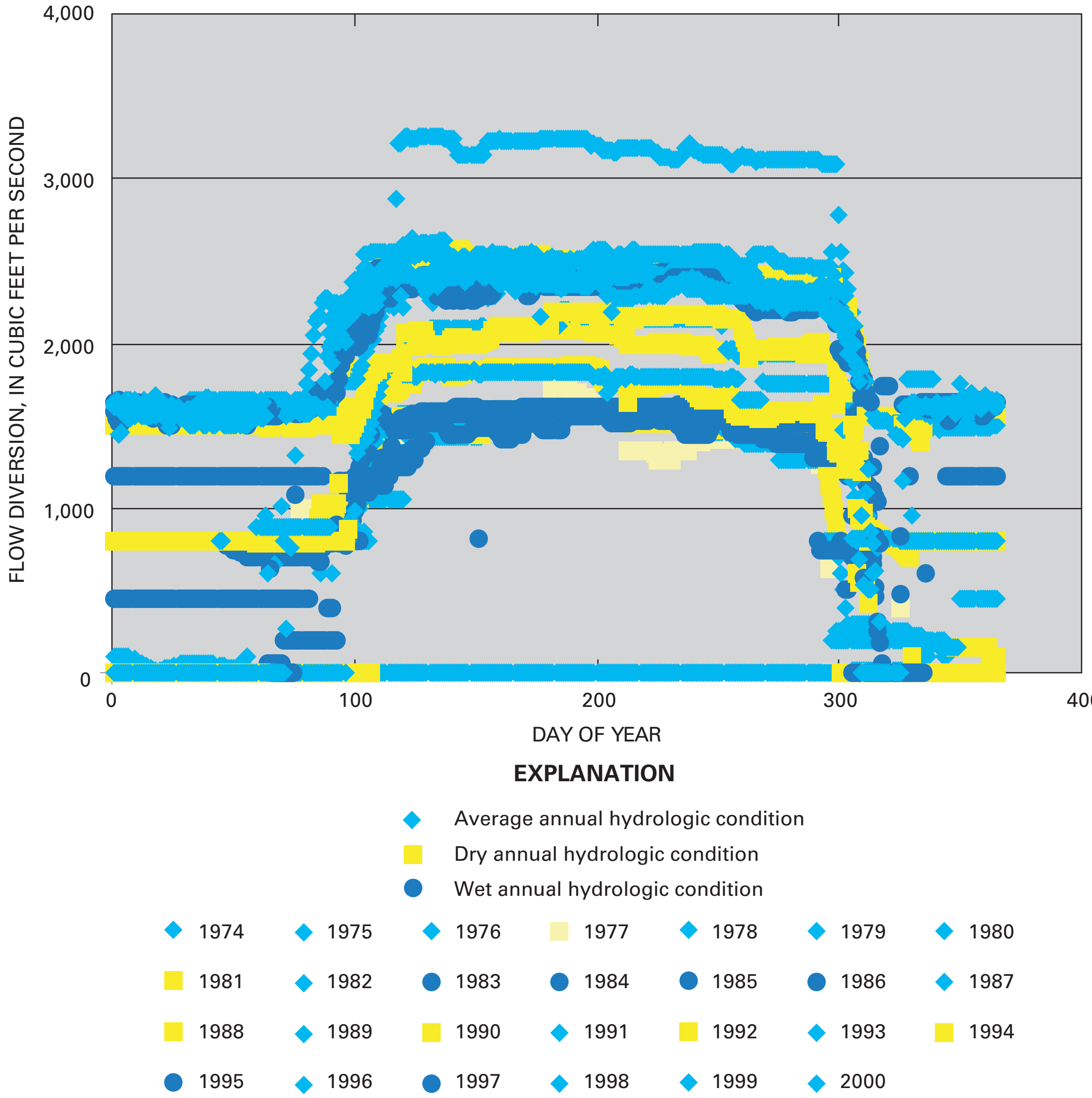

Figure 5. Historical flow diversions at the Government Highline Canal.

tions, the reader is referred to Sargent and Wainwright (1996). The runoff hydrograph for Sulphur Gulch was estimated; salinity for water samples collected from the Sulphur Gulch drainage during the spring 2002 runoff were plotted as a function of observed (estimated from two streamflow measurements made at the time of sampling) streamflow to compare with the stochastic runoff-salinity equation derived later in this report.

Table 4. Summary of fitted probability distributions to diversions.

Diversions	Fitted probability distribution		
	January–March	February–September	October–December
	0–90 days	91–321 days	322–365 days
Grand Valley Irrigation Canal	Uniform	Extreme value	Uniform
Grand Valley Water Users[1]	Lognormal	Beta	Extreme value
Mesa County[1]	None	Extreme value	None
Orchard Mesa[1]	Logistic	Extreme value	Extreme value
Palisade Irrigation District[1]	None	Triangular	None

[1] Collectively account for water diverted by the Government Highline Canal.

Autocorrelation

Two random variables are said to be independent if, and only if, the value of one variable has no influence on the other variable. When one random variable has influence on another random variable, the random variables are correlated. Random variables can be correlated temporally and (or) spatially. Examples of temporally correlated time-series variables include daily streamflow, stream diversions, and evaporation. For these random variables, observations related (correlated) through hydrologic processes (natural and anthropogenic) may persist over many days. Whereas each daily random variable could be independently sampled and used in a model calculation, neighboring daily values influence each other. For this reason, model calculations based on independently sampled daily distributions are valid only on an annual basis. To more accurately predict the hydrologic response on a daily basis, some means of identifying and incorporating temporal correlation of random variables is needed.

Autocorrelation is a mathematical technique that commonly is used to reveal the correlation between elements of time-series observations (Werckman and others, 2001). Autocorrelation also can be present when residual error terms from observations of the same variable at different times are correlated. One example of an autocorrelated random variable is daily streamflow. In this study, the calculated autocorrelation function, for the complete record of daily values of streamflow, indicates correlated (related) streamflow over a lag period of as much as about 75 days (fig. 6), whereas the autocorrelation function for annual streamflow measurements are correlated over a period of about 57 days.

By aggregating daily streamflow values over the period of record (daily record with an annual frequency), the correlation coefficient matrix was computed between daily streamflow values. As expected, streamflow correlation between adjacent days was greatest (correlation coefficient of about 0.99) with correlation between streamflow observations diminishing for measurements separated by increasing number of days (over longer periods of time). Whereas an autocorrelation function provides a characteristic (lumped) value for all time-series values at a given lag, a correlation matrix provides discrete information between individual time-series values. For example, inspection of the correlation matrix between streamflow reveals that successive daily values are variable and highly correlated with correlation coefficients between 0.883 (day 280 to 282) and 0.996 (many daily combinations). The findings based on the autocorrelation function and correlation matrix underscores the fact that daily streamflow should not be modeled as independent random variables, but rather the interdependency between daily random streamflow variables should be incorporated into the stochastic mixing model.

When defining correlation coefficients for use in the stochastic mixing model, practical limitations relating to the number of correlated variables exist, and for that reason only correlation coefficients between streamflow random variables associated with a single daily lag are introduced into the model. Implementation of correlated random variables is handled using the method described by Yastrebov and others (1996). In general, the Yastrebov method generates a sample from a multivariate random distribution using a rotation algorithm that has appropriate correlations, and then these variables are transformed so that they have the specified distributions. Other random variables that exhibited autocorrelation include streamflow diversions, evaporation, and salinity. Whereas streamflow correlation coefficients are introduced into the stochastic model using correlation coefficients associated with daily lags, stochastic nonlinear equations are developed and used to predict evaporation and salinity. Streamflow diversions, which are considered random variables, are handled on a seasonal basis (see table 4).

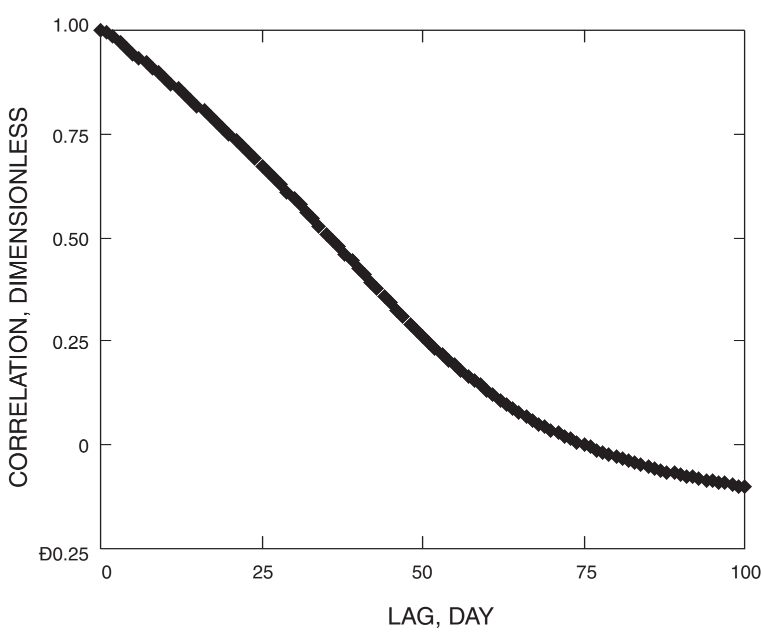

Figure 6. Autocorrelation function for streamflow at Cameo during 1974–2001.

Nonlinear Regression and Residual Analysis

In this study, a nonlinear least-squares approach (Cooley and Naff, 1982) is used to estimate best-fit parameters to predictive equations that compute reservoir surface area as a function of reservoir volume (fig. 7), probability of exceedance as a function of streamflow at Palisade (fig. 8), reservoir evaporation as function of time (fig. 9), streamflow at the Plateau Creek gage near Cameo as a function of streamflow at the Colorado River gage near Cameo (fig. 10), salinity as a function of Colorado River streamflow at Cameo and Colorado River near Palisade (figs. 11 and 13), dissolved solids (salinity) as a function of runoff salinity at Sulphur Gulch (fig. 14), and salinity (dissolved solids) as a function of streamflow at Plateau Creek near Cameo (fig. 12). The equations and fitted-parameters for these functions are summarized in table 5. Because salinity as a function of streamflow and evaporation as a function of time are stochastic, residual analysis must be performed and the results incorporated into the regression equation.

By virtue of its formulation, regression renders an otherwise stochastic process deterministic through the estimation of a single set of best-fit parameters. As described, use of these best-fit parameters in the predictive equation results in a deterministic outcome; that is, a given input always produces the same output. Whereas deterministic equations are appropriate for describing nonrandom variables, such as exceedance probabilities and reservoir surface area, these equations are inappropriate for predicting the range of behavior attributed to random variables such as streamflow, evaporation, and salinity. To convert from deterministic to stochastic equations, the process variability and (or) uncertainty are reintroduced. This variability is reintroduced into the mixing model by adding residuals to the deterministic equation following random sampling of probability distribution functions describing the set of differences between the measured and predicted values (residuals). In this study, the various residuals are fit to Logistic and Weibull probability distributions, as summarized in table 6. The Monte Carlo method used to select random residuals from these residual probability distribution functions is discussed in the next section.

Monte Carlo Method

The Monte Carlo method is an efficient technique that overcomes analytical challenges associated with devising and implementing stochastic equations through the use of a random number generator. In general, the Monte Carlo method builds up successive model scenarios (realizations) using input values that are randomly selected to reduce the likelihood for bias from probability distributions already defined. In this study, the Monte Carlo method (Sargent and Wainwright, 1996) is used to draw random values from probability distributions for each model input variable used in the calculation. For example, by incorporating residual probability distributions into the predictive equations derived through regression, repeated sampling and calculation of the associated dependent variable results in alternate realizations (equally likely simulations known as stochastic modeling). Examples of stochastic modeling for evaporation, streamflow, and salinity (dissolved solids) are shown in figures 9–14. Two realizations are shown for many model parameters to illustrate the random nature introduced through residual analysis and Monte Carlo method.

In general, the stochastic modeling reasonably replicated the random character for streamflow, evaporation, and salinity (dissolved solids) variables throughout the year. In some cases, the realizations did not appear to replicate certain extreme events. Examples of extreme events include the measured value of evaporation on day 143 that was $104{\times}10^{-2}$ in. (1.04 in.) (fig. 9), salinity (dissolved solids) of 340 mg/L at 13,100 ft^3/s (fig. 11), and 140 mg/L at 13,200 ft^3/s (fig. 11). The reason for not replicating the full range of events is attributed to limited random sampling. Statistical evaluation of random variables computed for 1,500 Monte Carlo trials better matched the range associated with extreme events than for a fewer number of trials.

Whereas stochastic simulation of dissolved-solids concentrations in runoff at Sulphur Gulch replicated the variability associated with the Dry Fork at Upper Station measurements, it is interesting and important to note that the actual dissolved-solids and streamflow measurements at Sulphur Gulch in 2002 tend to support the hydrograph separation approach used herein

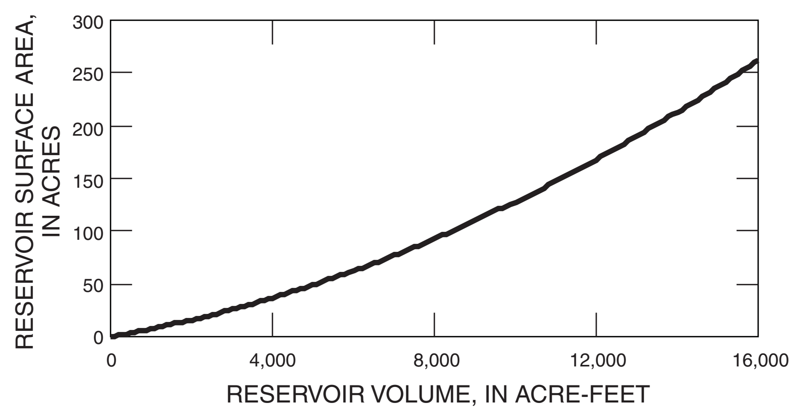

Figure 7. Comparison of reservoir volume and reservoir surface area.

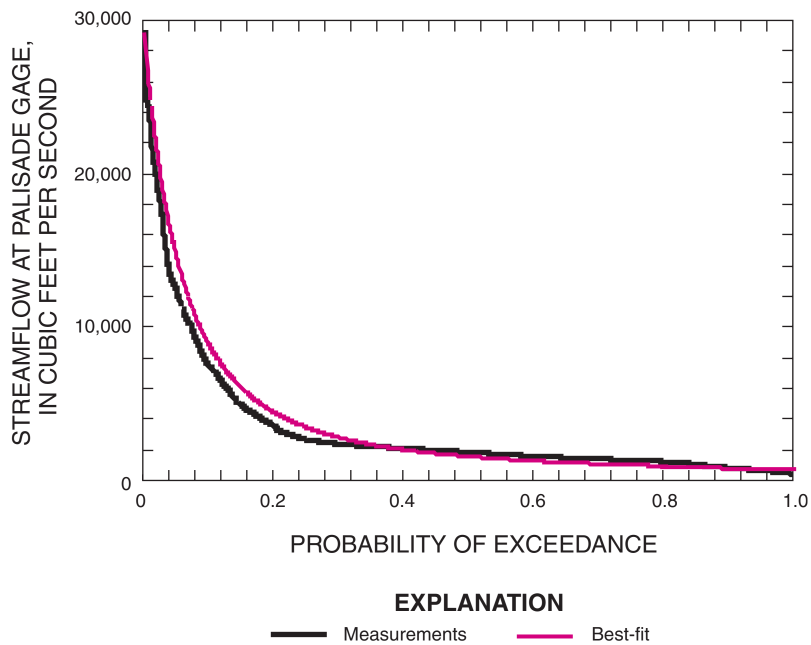

Figure 8. Comparison of best-fit curves and measurements of streamflow exceedance for Colorado River near Palisade.

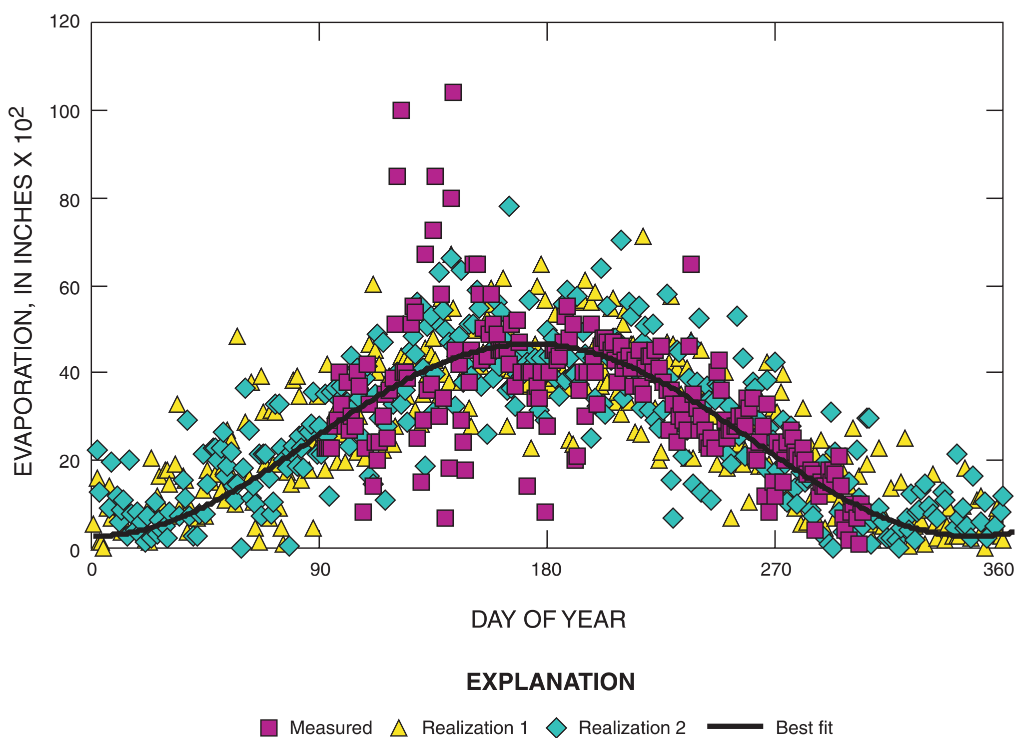

Figure 9. Stochastic simulation of reservoir evaporation at the Orchard Mesa research station near Grand Junction.

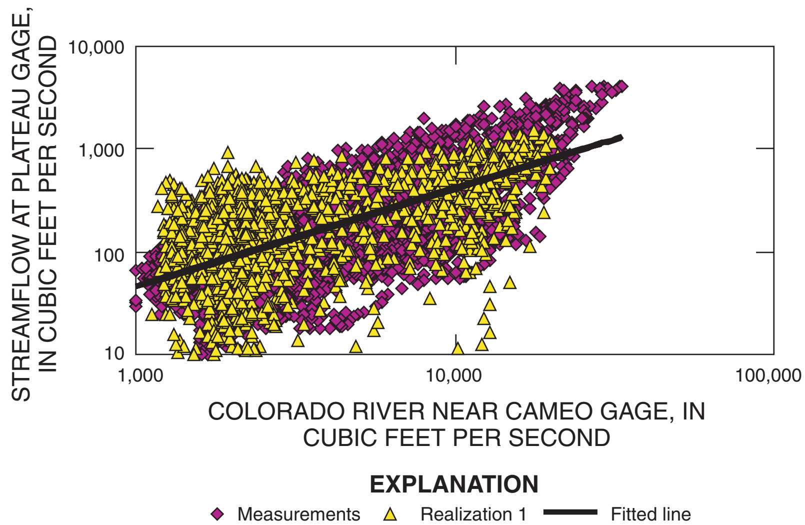

Figure 10. Stochastic simulation of streamflow at Plateau Creek (09105000) near Cameo.

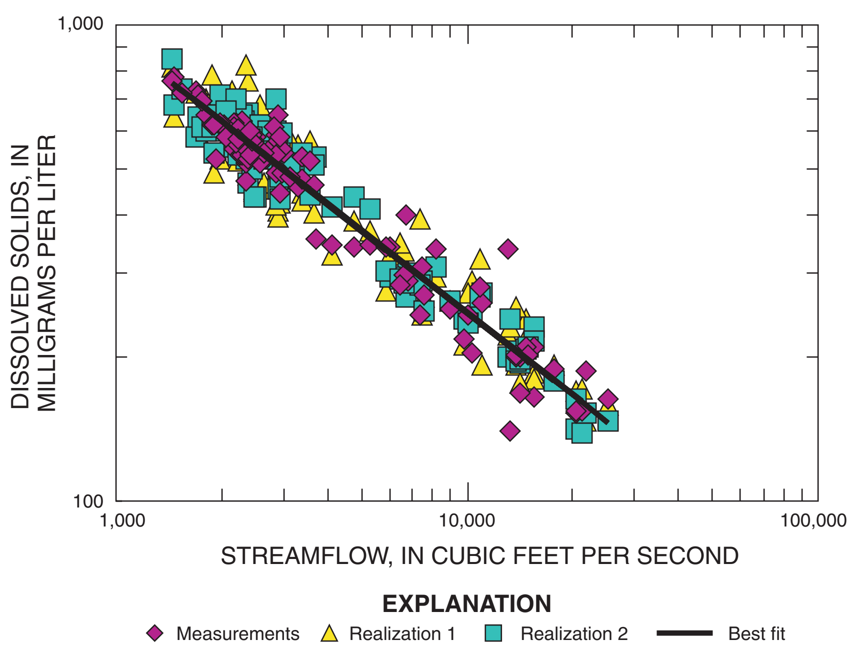

Figure 11. Stochastic simulation of dissolved-solids concentration at Colorado River (09095500) near Cameo.

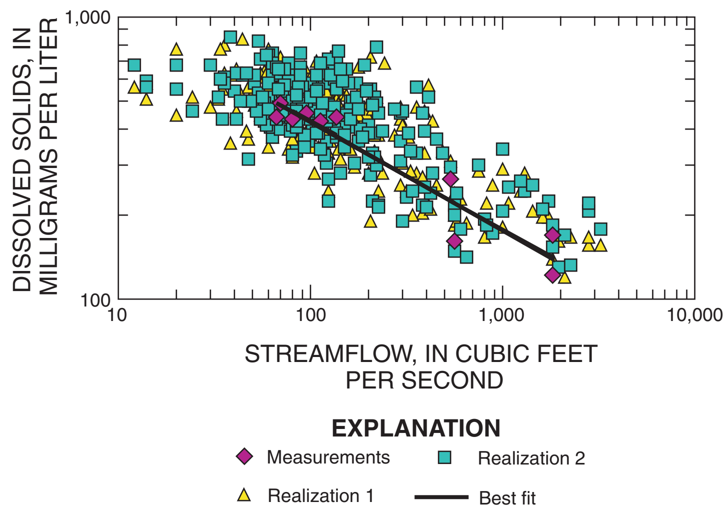

Figure 12. Stochastic simulation of dissolved-solids concentration at Plateau Creek (09105000) near Cameo.

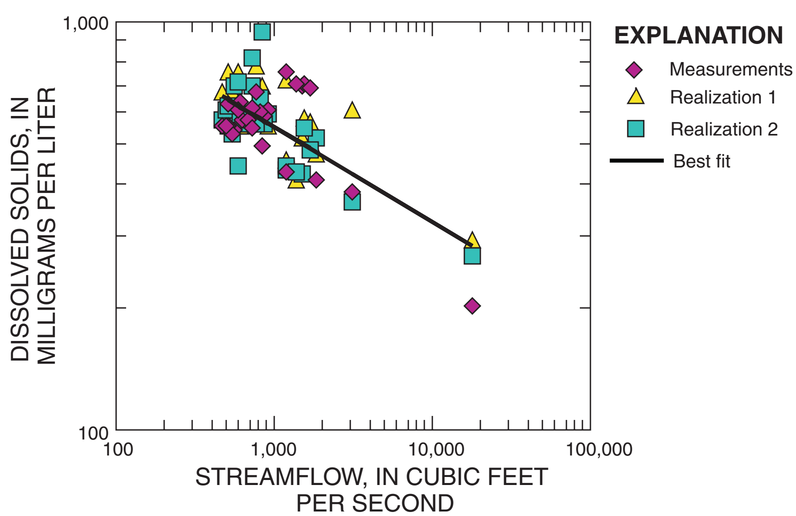

Figure 13. Stochastic simulation of dissolved-solids concentration in Colorado River near Palisade (09095500).

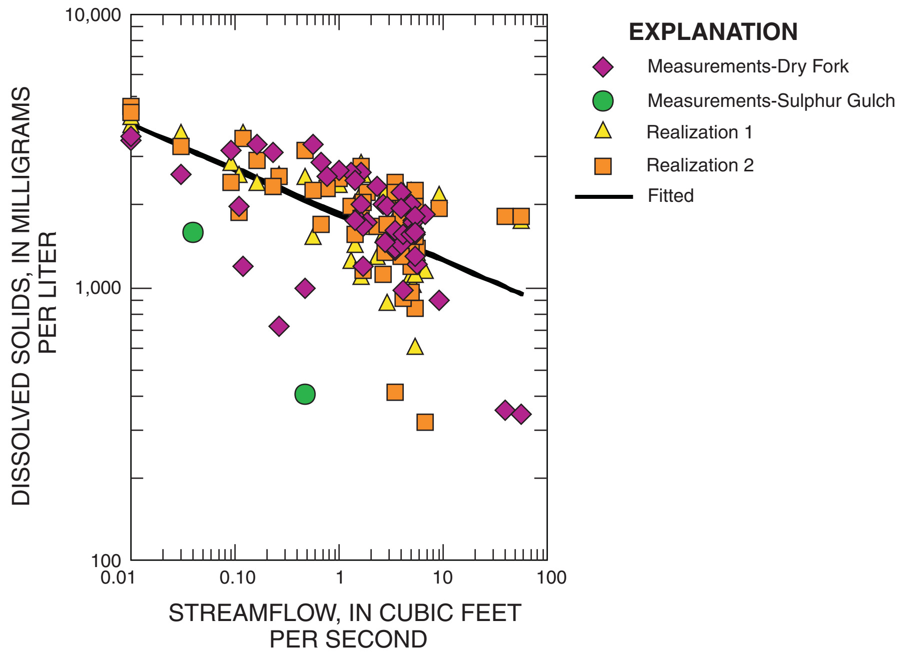

Figure 14. Stochastic simulation of dissolved-solids concentration in runoff at Dry Fork at Upper Station (09095300) near De Beque with measurements at mouth of Sulphur Gulch (391607108153500).

(fig. 14). The fact that these two Sulphur Gulch measurements appear at the margin of variability indicates that the use of this equation is nominally conservative. On the other hand, additional measurements are needed to decide whether the equation should be shifted. The stochastic equations for streamflow, evaporation, and salinity together with deterministic equations for reservoir surface area and streamflow exceedance are incorporated into the mixing model. The mixing model itself is composed of linked hydrology and water-quality submodels that are described in the following sections.

Hydrology Model

The objectives of the hydrology model are twofold: (1) compute the availability of pumpable water to the proposed reservoir, and (2) provide flows at key hydrologic points in the study reach that can be used by the water-quality model. User-defined input that is required by this model includes pump rate, beginning and ending pumping period days, Grand Valley Irrigation senior and junior water rights, and maximum allowable return flow at Orchard Mesa Irrigation District check structure.

To compute the amount of pumpable water requires six primary steps. First, the daily flow in the Colorado River and downstream demand (diversions) are generated on the basis of random sampling of corresponding probability distributions. The available daily flow then is computed by taking the difference between these random variables. Second, the cumulative distribution function for daily flow is computed to determine the streamflow exceedance. Third, quartiles associated with these daily flow exceedances are determined. Fourth, a check is conducted to see if flow exceeds diversions (total demand). If flow exceeds the total downstream demand (diversions), the demand is subtracted from the Colorado River flow. If this difference is greater than zero, then that quantity is assigned as the minimum divertible flow; otherwise, the minimum divertible flow is set to a user-defined value. Fifth, a check for peak-flow cut criteria is conducted. During the peak-flow check, if flow in the Colorado River is between 12,900 and 26,600 ft^3/s then a zero value is assigned; otherwise the minimum divertible flow value is used in the subsequent operation. In the subsequent operation, the actual divertible flow is assigned as the lesser value of the available flow or the peak-flow cut criteria. Sixth, the pumpable flow is set to the minimum value between the divertible flow and maximum pump rate. A flow chart describing the hydrologic model operations is provided (fig. 15), and a description of the Excel cell-based equations is included as Appendix 1.

Water-Quality Model

The objective of the water-quality model is to compute the dissolved-solids concentrations (salinity) at points where water enters or exits the study reach. User-defined input that is required by this model includes initial reservoir volume and concentration, total reservoir volume, seasonal release amount, seasonal release period, and peak-flow release amount. The background concentration at selected locations depends on mix

Table 5. Summary of predictive nonlinear equations and fitted-parameters.

[Evap, evaporation; SA, surface area; acre-ft, acre-foot; Q_{cdf}, daily streamflow exceedance at Palisade; percent, percent; ft^3/s, cubic feet per second; inches, in.; a,b,c, regression constants; Q_c, daily streamflow at Cameo gage; Q_p, daily streamflow at Plateau Creek; Q_{pl}, daily streamflow at Palisade gage; ft, foot; DS, dissolved solids; mg/L, milligram per liter; reservoir surface area is user dependent and can change dynamically (case 1) or remain static (case 2)]

Description	Equation	Parameters		
		a	b	c
Reservoir surface area as function of volume, SA (acres)	$SA = a * (volume)^2 + b * volume + c$	Case1: 0.00001 acre/acre-ft Case2 : 0.0 acre/acre-ft	Case 1: 0.0068 acre/acre-ft Case 2: 0.0 acre/acre-ft	Case 1: 1:0.000 acres Case 2: 260 acres
Daily flow exceedance as function of streamflow at Palisade (percent)	$\log (Q_{cdf}) = a^{-2} * \log (b/\log Q_{cdf}))$	0.4935 dimensionless	2.81 ft^3/s	None
Streamflow at Plateau Creek gage as a function streamflow at Cameo gage (ft^3/s)	$\text{Log } (Q_p) = a * \log(Q_c) + b + \text{residuals}$	0.95731	-1.21215	None
Reservoir evaporation as function of time, (ft)	$Evap = a * \cos(day * b * 3.14159/180) + c + \text{residuals}) * 0.01/12$	21.9606 in/radian	0.5174 per day	24.649 in.
Salinity (mg/L) as function of streamflow at Cameo, (ft^3/s)	$\log(DS) = a * \log(Q_c) + b + \text{residuals}$	–05741 mg/L / ft^3/s	4.924 mg/L	None
Salinity (mg/L) as function of streamflow at Plateau Creek near Cameo	$\log(DS) = a * \log(Q_p) + b + c + \text{residuals}$	-0.31664 mg/L / ft^3/s	3.43337 mg/L	0.95
Salinity (mg/L) as function of runoff at Sulphur Gulch	$\log(DS) = a * \log(Q_{sg}) + b + \text{residuals}$	-0.17 mg/L / ft^3/s	3.27 mg/L	None

Table 6. Summary of statistical parameters for streamflow, salinity, and evaporation residuals.

[ft, feet; mg/L, milligrams per liter; ft, feet; The respective terms shape and mean refer parameters used in the Weibull and Logistic probability distribution functions]

Variable residual	Probability distribution	Minimum	Maximum	Shape, or mean	Scale
Streamflow at Plateau Creek, cubic feet per second	Logistic	–484.7	511.6	13.4	83.6
Evaporation, ft	Logistic	–36.322	35.280	–0.52100	6.007000
Colorado River salinity at Cameo, mg/L	Logistic	–0.2079	0.2079	–0.00380	0.034594
Plateau Creek salinity near Cameo, mg/L	Logistic	–0.27	0.28	0.00	0.05
Colorado River salinity at Palisade, mg/L	Logistic	–155	393	6	23
Runoff salinity to Sulphur Gulch, mg/L	Weibull	–7149	1267	15	0.034594

ing of both natural and anthropogenic system concentrations just upstream from the point of interest. For example, the primary contributions to background historical (ambient) salinity over the study reach include the Colorado River basin upstream from Cameo, runoff from Sulphur Gulch, Plateau Creek, and the Orchard Mesa Irrigation District check structure. Changes to the background concentrations are directly related to reservoir releases during peak and(or) low-flow periods. Reservoir related considerations that may affect the dissolved-solids concentration of water released to the Colorado River are associated with when water is pumped into the reservoir, runoff to the reservoir, and reservoir evaporation. A general expression that describes the mixing of various water types is given by

$$C_j = \frac{\sum_{i=1}^{M} Q_{ij} C_{ij}}{\sum_{i=1}^{M} Q_{ij}}, \qquad (1)$$

where

Q is the streamflow discharge (negative values indicate losing and positive values indicate gaining),

C is the dissolved-solids concentration,

M is the total number of mixed components,

j is an index representing a location along the study reach, and

i is an index representing each type of water.

Because streamflow is required when computing concentrations with nonlinear regression equations, a direct link to the hydrology model passes streamflow values to points where computations are being conducted. A flow chart describing the stochastic water-quality model operations is provided (fig. 16), and a description of the Excel cell-based equations is included as Appendix 2.

MODEL VALIDATION

Validation of the stochastic mixing model involved three primary steps: (1) test the reliability (stability and convergence) of a representative Monte Carlo forecast, (2) compare statistics for selected forecast simulations to field measurements, and (3) evaluate the overall mass balance. In general, model validation is a subset of scenario modeling because the user is required to define one (or more) forecast(s) and enter appropriate decision variables before starting the simulation process. The following sections describe the bootstrap approach to test reliability, forecast comparisons, and availability of pumpable water.

Stability and Convergence

To test the reliability (stability and convergence) of mixing model forecasts, the so-called bootstrap approach is used (Werckman and others, 2001). In using the bootstrap approach, sample statistics (estimated mean, standard error, and confidence intervals) are computed from 200 independent (repeated) forecasts of annual streamflow at the Colorado River gage near Cameo for a fixed number of Monte Carlo trials and constant decision variables (hydrologic constants include reservoir pump, 0 ft^3/s, Grand Valley Irrigation Canal senior water right, 520 ft^3/s; Grand Valley Irrigation Canal junior water right, 120 ft^3/s; minimum flow at the Colorado River gage near Palisade, 85 ft^3/s, and maximum return flow at the Orchard Mesa Irrigation District check structure, 400 ft^3/s; whereas the water-quality constants include: initial storage = 0, initial concentration = 0, no reservoir release, maximum reservoir storage 16,000 acre-ft, and a no flag = 0 for reservoir releases). The bootstrap approach is repeated for an increasing number of Monte Carlo trials (500, 1,000, 1,500, 2,000) until the percent change in upper and lower confidence intervals is less than 1 percent.

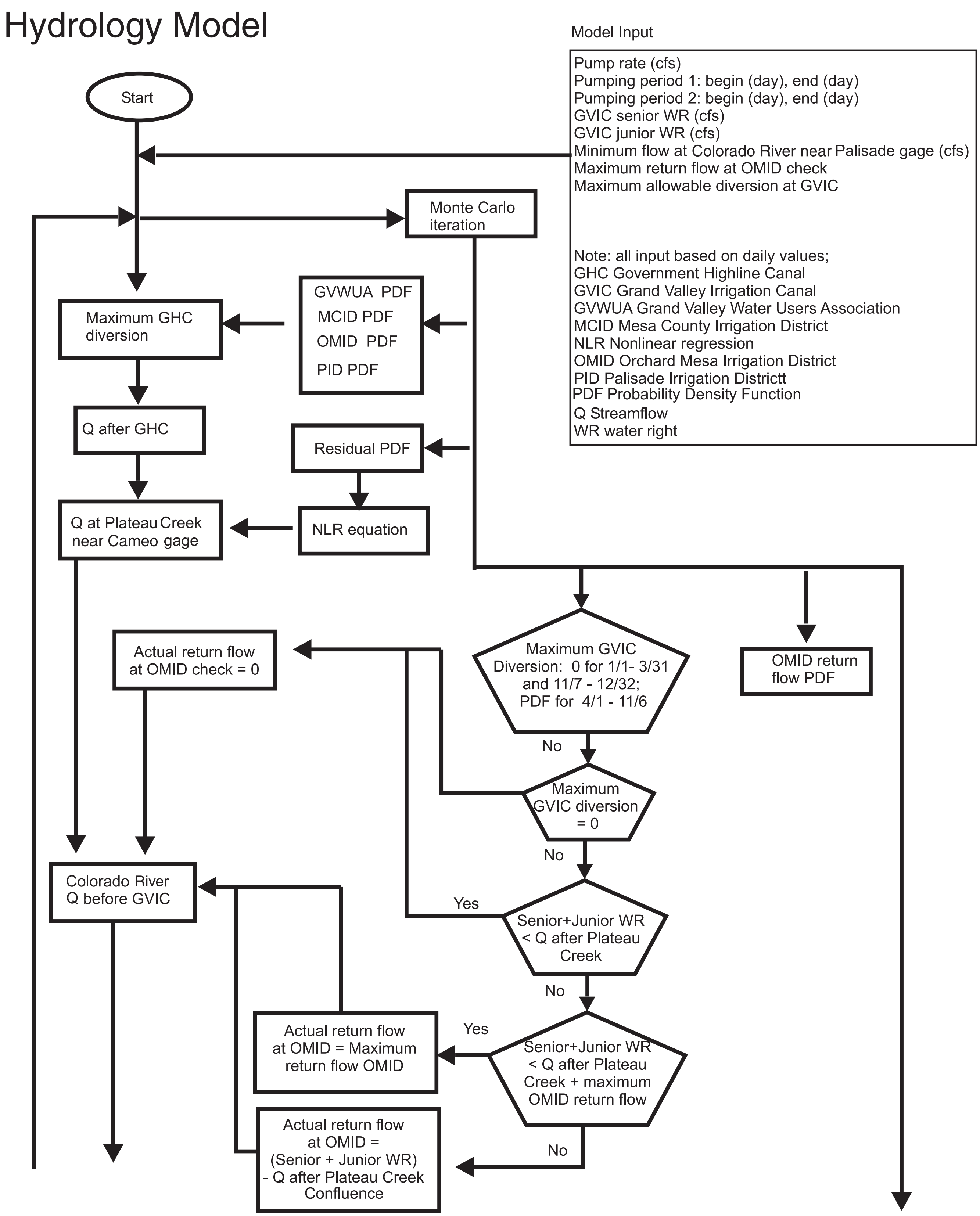

Figure 15. Flow chart of the stochastic hydrology model.

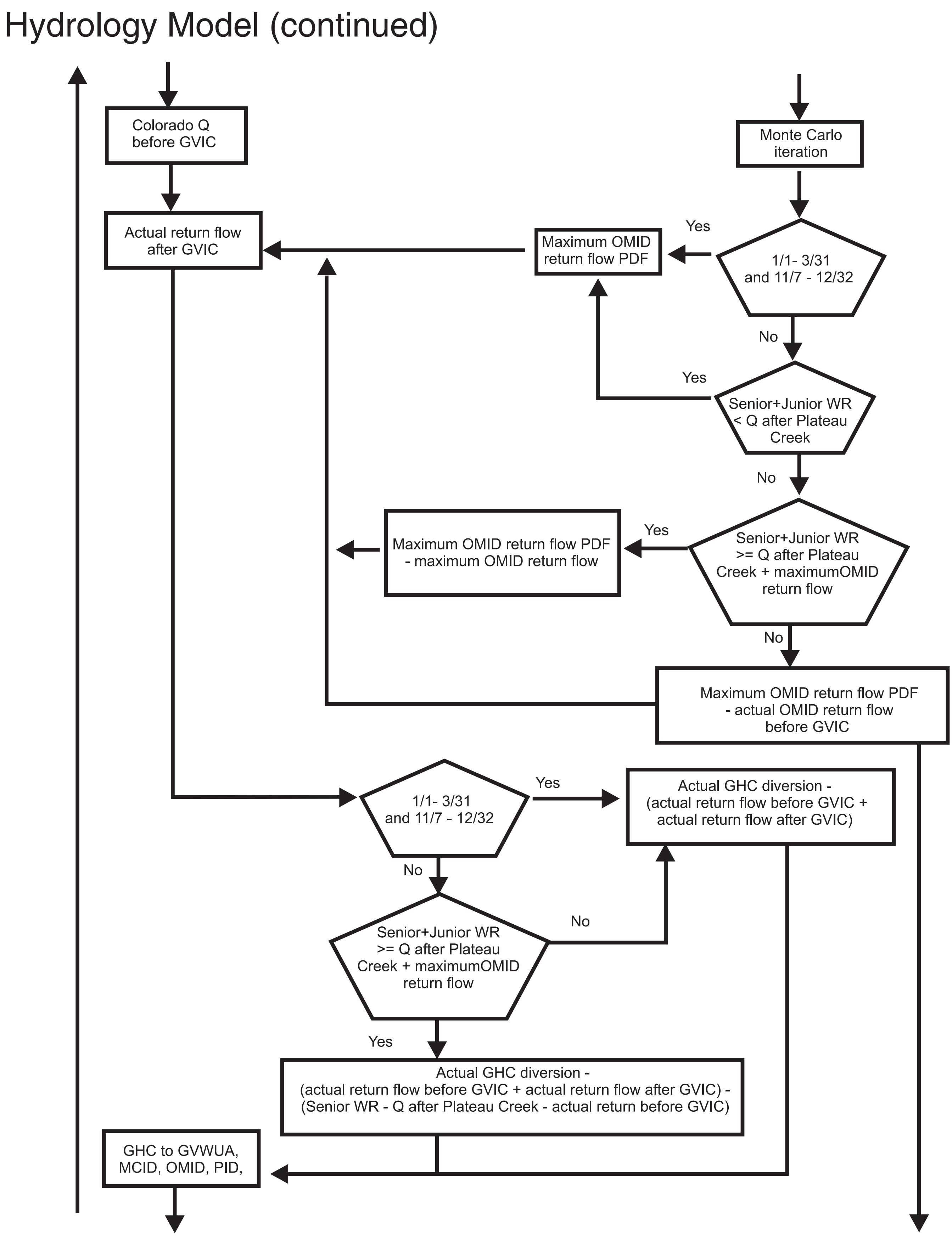

Figure 15. Flow chart of the stochastic hydrology model—Continued.

Hydrology Model (continued)

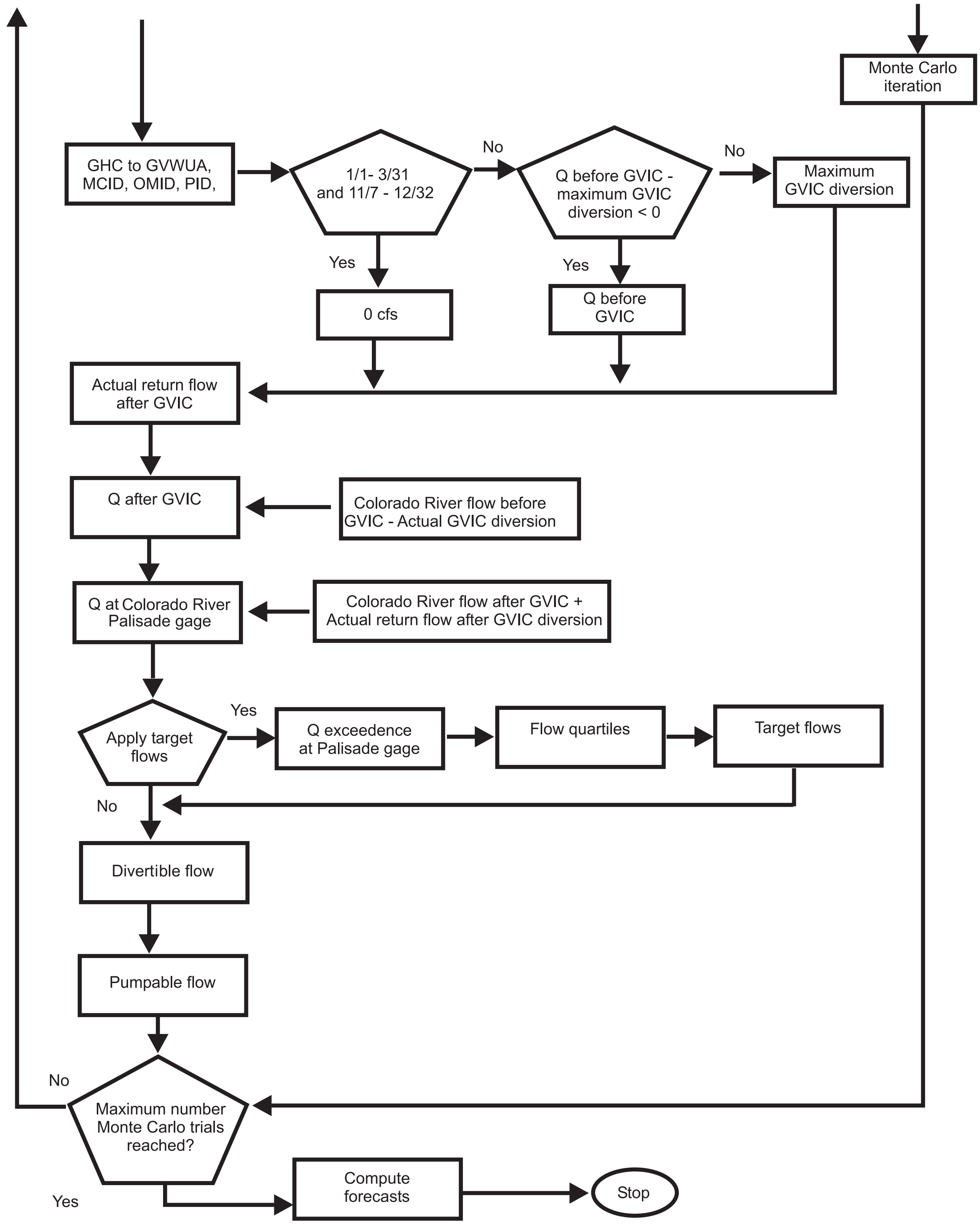

Figure 15. Flow chart of the stochastic hydrology model—Continued.

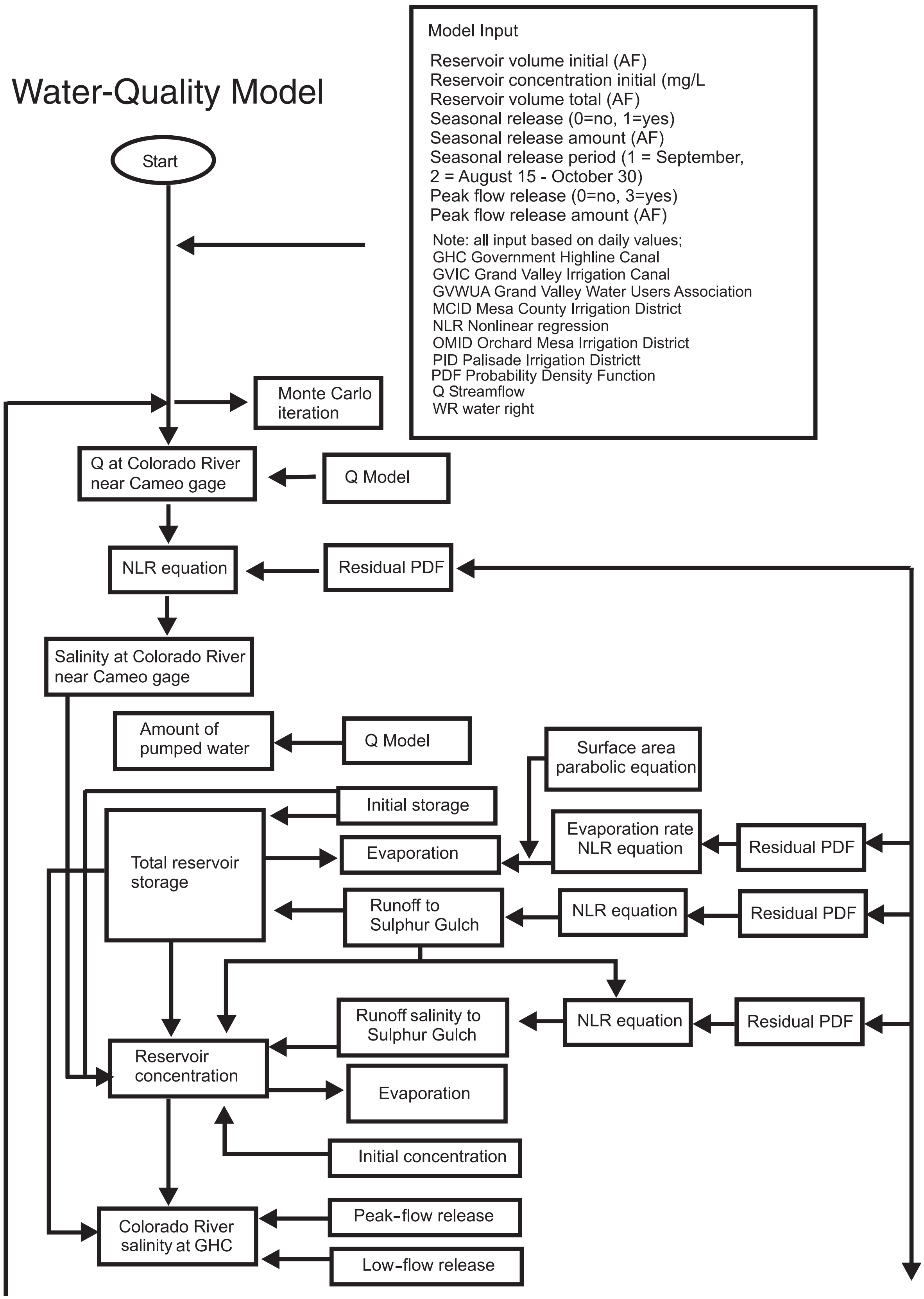

Figure 16. Flow chart of the stochastic water-quality model.

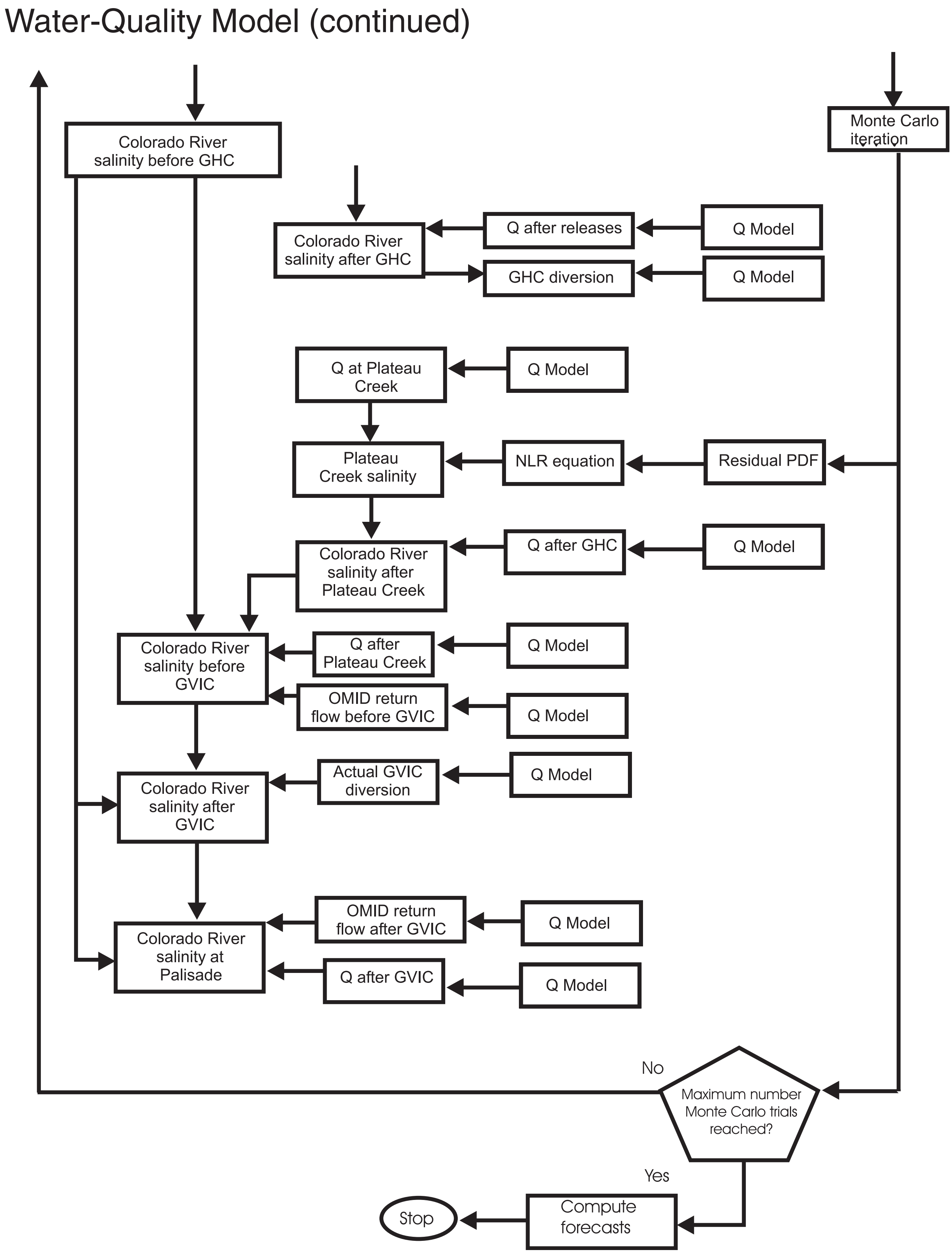

Figure 16. Flow chart of the stochastic water-quality model—Continued.

In this study, the lower and upper confidence intervals for all Monte Carlo trials agreed within 1 percent. The standard error of average simulated daily streamflow values for Colorado River near Cameo, however, continued to decrease until the total number of trials was equal to or greater than 1,500 (see fig. 17). For this reason, the use of 1,500 Monte Carlo trials is deemed sufficient to ensure convergence and stability of forecast distributions in this study. Because the daily time step is used to compute water-budget components over a calendar year, the 1,500 Monte Carlo trials is representative of 1,500 alternate calendar years and therefore hydrologic conditions.

Comparison of Simulated and Measured Forecasts

In the second phase of model validation, the objective is to evaluate the stochastic mixing model accuracy. To evaluate the accuracy of the stochastic mixing model, selected forecasts are summarized statistically and compared to selected hydrologic and water-quality data that were collected at various streamflow gaging stations along the Colorado River study reach. This validation phase uses the same decision variables previously described in the Stability and Convergence Section. The stochastic hydrology forecasts of interest include annual and daily simulations of the Colorado River streamflow near Cameo and Palisade and at Plateau Creek, a tributary to the Colorado River. A comparison of simulated and measured annual streamflow statistics is provided in table 7.

Inspection of the annual streamflow statistics indicates excellent correspondence between simulated and measured streamflow at the Colorado River near Cameo gage station. This finding underscores the validity of using correlated daily random streamflow variables in this study. Whereas the simulated and measured statistics associated with streamflow at Plateau Creek near Cameo and the Colorado River near Palisade are of the same order of magnitude, these statistical streamflow values are not as accurate as those at Cameo. One plausible reason is that the residual analysis used to convert the deterministic equations (fit using nonlinear regression) to stochastic equations is not as accurate as using correlated random variables (see fig. 10). Individual stochastic daily streamflow simulations for USGS Colorado River gage sites near Cameo, Palisade, and Plateau Creek near Cameo, however (shown in figs. 18–20), demonstrate good visual correspondence to the measured daily median values. In addition to streamflow, the mean-monthly simulated evaporation values were computed and found comparable to basin estimates published by Farnsworth and Thompson (1982). A comparison of simulated and measured daily streamflow statistics is provided in tables 8–10.

In general, good correspondence exists between measured and simulated daily streamflow statistics. Whereas the median and average statistics appear to give the best correspondence between actual and simulated values, the extreme hydrologic conditions represented by the minimum and maximum streamflow values are characterized by more uncertainty. The fact that measured and simulated streamflow statistics appear similar at the Colorado River near Cameo gage site (close to the beginning of study reach) and then at Colorado River near Palisade gage (end of study reach) indicates that the water-budget process of adding and subtracting stochastic diversions, return flow, streamflow tributary water, and evaporation works. Because the stochastic hydrologic model appears to provide adequate simulations of daily and annual streamflow throughout the study reach, the next section is used to provide information to better understand background hydrologic and water-quality conditions for selecting appropriate reservoir parameters that satisfy the PBO water-delivery requirements.

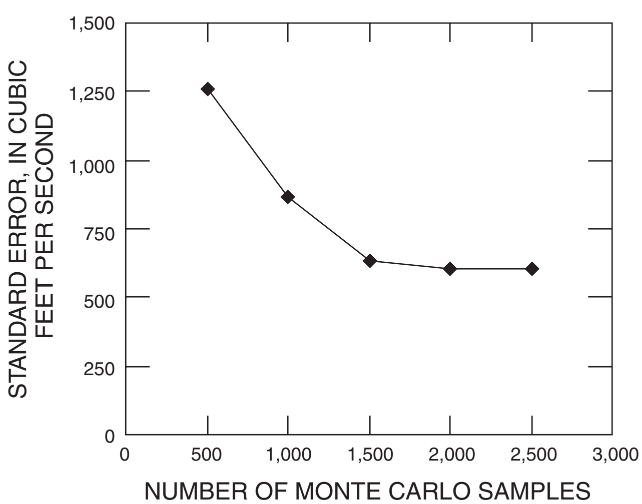

Figure 17. Mean standard error of median simulated daily streamflow values for Colorado River near Cameo as function of Monte Carlo sampling.

Table 7. Comparison of simulated and measured annual streamflow statistics.

Location	Statistic	Simulated streamflow, in cubic feet per second per year	Measured streamflow, in cubic feet per second
Colorado River near Cameo gage	Number of samples	1,500	27 (1974–2000)
	Minimum	675,355	667,813
	Maximum	2,955,395	2,862,210
	Average	1,404,100	1,445,565
	Median	1,330,210	1,388,260
	Standard deviation	390,847	394,101
	Coefficient of variation	0.278	0.273
Plateau Creek near Cameo gage	Number of samples	1,500	27 (1974–2000)
	Minimum	29,945	13,825
	Maximum	122,397	184,370
	Average	59,351	75,344
	Median	57,000	60,460
	Standard deviation	15,499	46,615
	Coefficient of variation	0.261	0.618
Colorado River near Palisade gage	Number samples	1,500	10 (1991–2000)
	Minimum	335,493	627,520
	Maximum	2,760,435	1,914,050
	Average	966,883	1,214,657
	Median	883,780	1,202,007
	Standard deviation	412,620	465,325
	Coefficient of variation	0.423	0.383

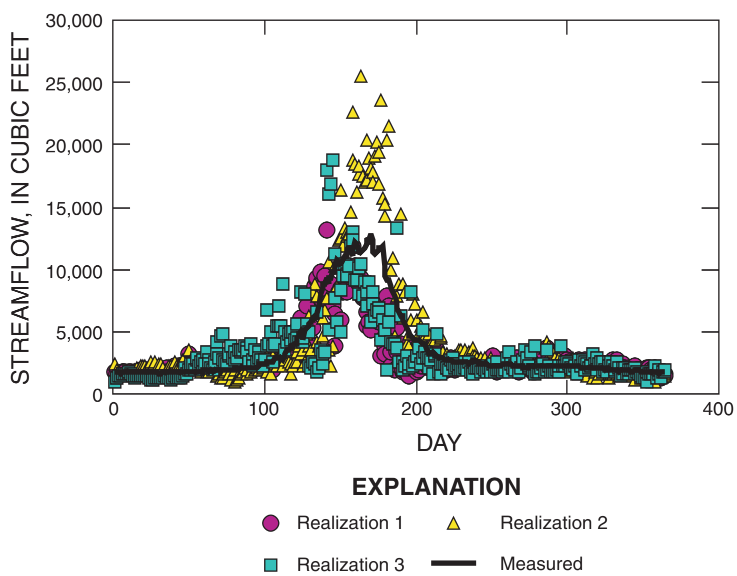

Figure 18. Stochastic simulations of daily streamflow at Colorado River gage near Cameo.

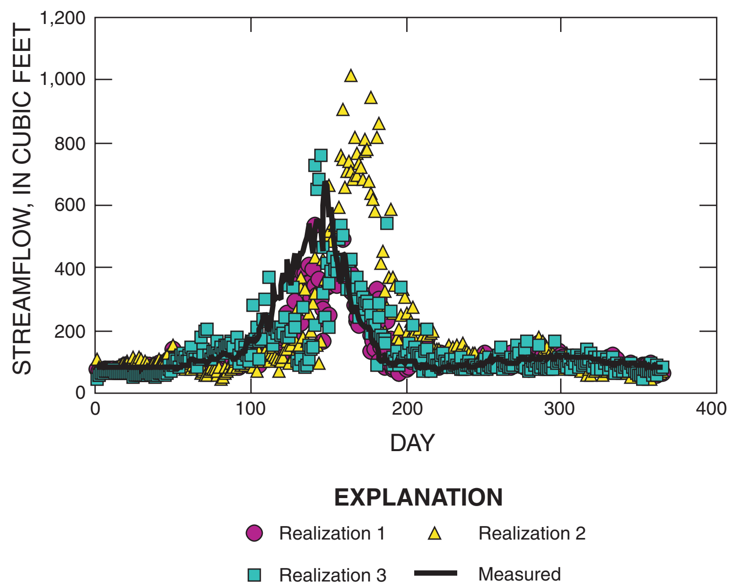

Figure 19. Stochastic simulations of daily streamflow at Plateau Creek gage near Cameo.

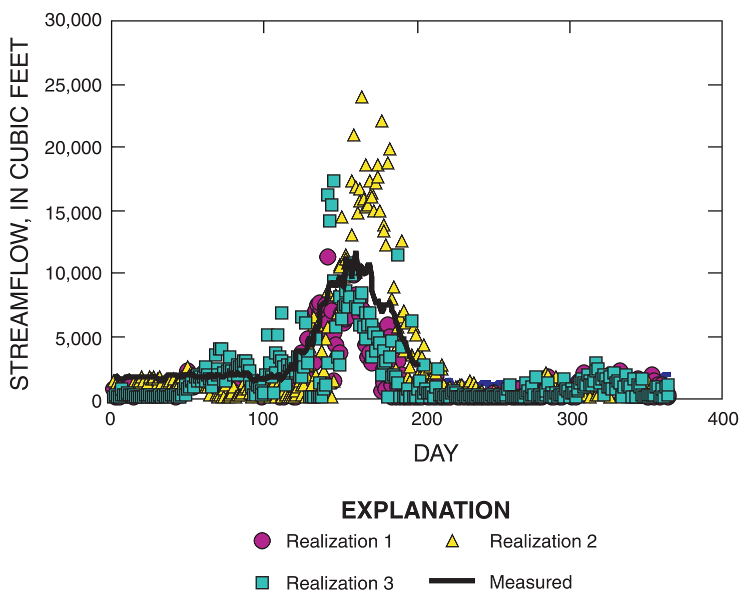

Figure 20. Stochastic simulations of daily streamflow at Colorado River gage near Palisade.

Table 8. Comparison of simulated and measured daily streamflow statistics for Colorado River near Cameo gage.

Daily (365 samples)	Minimum	Maximum	Average	Median	Standard deviation
Measured streamflow at Cameo gage (10 annual samples), in cubic feet per second					
Minimum	1,000	2,090	1,373	1,370	280
Maximum	4,540	38,000	17,399	15,400	8,037
Average	1,801	7,836	3,990	3,803	1,443
Median	1,680	3,670	2,391	2,260	517
Standard deviation	583	8,662	3,596	3,279	1,965
Simulated streamflow at Cameo gage (1,500 annual samples), in cubic feet per second					
Minimum	1,222	1,539	1,014	1,055	239
Maximum	6,912	60,823	23,607	21,228	10,247
Average	1,862	8,207	3,816	3,629	1,056
Median	1,634	3,473	2,285	2,250	276
Standard deviation	884	11,671	3,757	3,361	1,893

Table 9. Comparison of simulated and measured daily streamflow statistics for Plateau Creek near Cameo gage.

Daily (365 samples)	Minimum	Maximum	Average	Median	Standard deviation
Measured streamflow at Plateau Creek (10 annual samples), in cubic feet per second					
Minimum	8	90	53	55	21
Maximum	112	4,100	1,452	1,030	1,153
Average	38	666	213	165	146
Median	36	240	114	101	46
Standard deviation	22	982	250	161	240
Simulated streamflow at Plateau Creek (1,500 annual samples), in cubic feet per second					
Minimum	11	69	46	48	10
Maximum	291	2,332	939	851	390
Average	82	333	162	155	42
Median	73	150	101	99	12
Standard deviation	37	454	151	136	74

Table 10. Comparison of simulated and measured daily streamflow statistics for Colorado River near Palisade gage.

Daily (365 samples)	Minimum	Maximum	Average	Median	Standard deviation
Measured streamflow at Palisade (10 annual samples), in cubic feet per second					
Minimum	342	1,710	713	558	398
Maximum	7,560	29,600	17,259	13,950	7,778
Average	1,715	5,244	3,326	3,293	1,276
Median	1,330	2,680	1,907	1,900	437
Standard deviation	1,158	6,468	3,537	2,881	1,875
Simulated Streamflow at Palisade (1,500 annual samples), in cubic feet per second					
Minimum	100	589	173	142	84
Maximum	5,217	62,995	22,506	20,100	10,319
Average	882	8,748	2,663	2,469	1,090
Median	620	2,864	1,121	1,087	290
Standard deviation	739	12,414	3,744	3,303	1,933

SCENARIO MODELING

In this section, the goal is to understand the availability of, and reservoir operational effects on, Colorado River streamflow quantity and quality over the range of hydrologic conditions (variability). The operational scenarios investigated reflect various combinations of reservoir pumping and reservoir releases. The pumping scheme used in assessing water quantity involves pumping Colorado River water year-round, except during reservoir releases, beginning in winter (low-flow conditions) with various combinations of timing and magnitude of reservoir releases. The reservoir release scenarios being used to evaluate Colorado River water quantity and quality are referred to as scenario 1, 2, 3, and 4 and are described below.

Scenario 1: involves releasing 5,412.5 acre-ft of water from the reservoir over a 30-day period from September 1 through 30 (90.2 ft^3/s/d).

Scenario 2: involves releasing 5,412.5 acre-ft of water from the reservoir over a 78-day period from August 15 through October 30 (34.69 ft^3/s/d).

Scenario 3: involves releasing of 10,825 acre-ft of water from the reservoir over a 30-day period from September 1 through 30 (180.42 ft^3/s/d).

Scenario 4: involves a peak-flow release of as much as 10,000 acre-ft of water from the reservoir in addition to the low-flow releases described in scenario 1. For the peak-flow releases, it is assumed that as much as 1,000 acre-ft of water per day will be released to supplement peak-river flows between 12,900 and 26,600 ft^3/s/d.

Water Quantity

The objectives of this section are to quantify the amount of water that can be pumped, stored, and released on a daily, monthly, seasonal, and annual basis. In all of the stochastic simulations performed, the following constant variables are used: reservoir pump rate of 150 ft^3/s, reservoir storage of 16,000 acre-ft, GVIC senior water right of 520 ft^3/s, GVIC junior water right of 120 ft^3/s, minimum flow at Palisade of 85 ft^3/s, and maximum return flow at Orchard Mesa Irrigation (OMID) check structure of 400 ft^3/s. Whereas the maximum allowable diversion at GHC is 1,620 ft^3/s, the actual amount diverted is dependent on the amount that is available at Palisade after all diversions are accounted. The forecast variables being investigated include divertible flow, pumpable flow, storage by season, and storage by day.

Divertible Flow

In the first set of stochastic simulations, the ambient (background) streamflow conditions, called divertible flow, are determined by setting the pump rate equal to 0 ft^3/s. The simulated annual divertible flow (table 11) indicates the probable amount of water available at the Palisade gage. The range of likely divertible flow is given in percentiles and reflects the full range of annual hydrologic conditions; for example, the 100 percentile (dry year), 50 percentile (median year) and 0-percentile (wet year). A percentile is a number between 0 and 100 that indicates the percentage of a probability distribution

Table 11. Reverse cumulative distribution of annual divertible flows from the Colorado River near Palisade.

Percentiles[1] of annual divertible flows, in acre-feet										
Dry					Typical					Wet
100	90	80	70	60	50	40	30	20	10	0
621,860	1,013,759	1,156,681	1,259,811	1,342,550	1,425,371	1,502,462	1,587,987	1,6965,27	1,861,794	4,822,732

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

that is equal to or below a value (cumulative distribution function), or equal to or above a value (reverse cumulative distribution function). In the case where the distribution is symmetrical, the median and average year will have essentially the same value.

Inspection of the likelihood for divertible flow at Palisade indicates that in any year 100 percent of the divertible flow will be equal to or greater than 621,860 acre-ft (driest year flow) but equal to or less than 4,822,732 acre-ft (wettest year). Although there is ample supply of water available for potential reservoir storage, the rate of pumping limits the actual amount of divertible flow available for storage. The imposition of the pumping constraints on divertible flow results is what is called the pumpable flow.

Pumpable Flow

The pumpable flow is always less than the total divertible flow because of pumping constraints. The simulated pumpable flows reflecting 1,500 Monte Carlo trials (water years or hydrologic conditions) are summarized by season in table 12. Because there are no reservoir releases in these simulations, the probable amount of pumpable flow displayed represents the maximum amount of water that can be stored in the reservoir by end of the calendar year (after 365 days). Based on the results (table 12), it appears that a pump operating at 150 ft^3/s can fill an empty reservoir with at least 16,000 acre-ft of water 100 percent of the time during winter and summer, and 90 percent of the time during spring. Fall pumping alone cannot provide 16,000 acre-ft of water to fill an empty reservoir; however, even the driest hydrologic year simulated would provide about 10,000 acre-ft of water in the fall. On an annual basis, the range is 69,300 acre-ft (dry year) to 93,150 acre-ft (wet year) with a median (referred to hereinafter as typical) (50 percentile) year providing 90,900 acre-ft of pumbable flow.

To this point, the simulations of pumpable flow represent filling the reservoir on a seasonal or annual basis with no constraints other than pumping rate. Because of daily flow variability and reservoir operational constraints (timing and magnitude of pumping and releases), the amount of pumpable flow that can actually be stored will be decreased. Because of uncertainty in the amount of water that may be stored due to daily hydrologic variability and possible reservoir operation constraints, the availability of Colorado River water for initial and carryover reservoir storage at various times in the year was assessed. Toward that end, simulations are conducted and evaluated at monthly intervals over the range of natural hydrologic conditions during the initial reservoir filling in the first year, and then for subsequent years with the reservoir operational constraints applied.

Reservoir Storage

Forecasts of probable reservoir storage for year-round pumping (no reservoir operation constraints) and dates assuming an initially empty reservoir are summarized in table 13. Inspection of the simulated reservoir storage reveals that reservoir pumping beginning on January 1 can store about 9,300 acre-ft within the first month (by February 1) and about 16,000 acre-ft by the second month under any hydrologic conditions, which is enough water to meet both the peak-flow and low-flow release requirements uniformly across all hydrologic conditions (table 13).

The following simulations quantify the likely amount of water that will be stored with year-round pumping, except during reservoir release periods, and annual carryover storage under the four reservoir release scenarios previously described. The results of stochastic simulations under these model conditions are summarized by month and range of hydrologic conditions in tables 14a–d. Inspection of the storage results for scenario 1 reveals that it is possible to fill the reservoir over the range of hydrologic conditions for every month. The diminished amount of storage (about 10,500 acre-ft) on October 1 reflects the release of 5,412.5 acre-ft of reservoir water during September (low-flow period) when no pumping occurs. Pumping throughout October, however, results in refilling the reservoir almost to capacity (range of likely storage: 15,993 acre-ft during a drought year and 16,000 acre-ft during a wet year) by November 1 (table 14a). By extending the low-flow release period from 30 days (scenario 1) to 78 days (scenario 2, table

Table 12. Reverse cumulative distribution of seasonal pumpable flows from the Colorado River near Palisade (150 cubic feet per second pump rate over the year, no releases).

Season	Percentiles[1] of seasonal pumpable flows, in acre-feet										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
Winter	23,700	23,700	23,700	23,700	23,700	23,700	23,700	23,700	23,700	23,700	23,700
Spring	15,000	20,100	21,811	23,320	24,794	25,800	26,700	27,041	27,300	27,572	27,600
Summer	20,400	23,700	24,900	26,400	27,300	27,600	27,711	27,831	27,900	27,900	27,900
Fall	10,200	11,850	12,450	13,200	13,650	13,800	13,856	13,915	13,950	13,950	13,950

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 13. Reverse cumulative distributions of reservoir storage for selected dates following year-round pumping that begins on January 1 with a 150 cubic feet per second pump rate, no releases.

Date	Percentiles[1] of reservoir storage, in acre-feet										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
January 1	0	0	0	0	0	0	0	0	0	0	0
February 1	9,297	9,302	9,303	9,305	9,306	9,308	9,310	9,311	9,315	9,320	9,370
March 1	15,994	15,996	15,997	15,997	15,997	15,998	15,998	15,998	15,999	15,999	16,000
April 1	15,995	15,998	15,998	15,998	15,999	15,999	15,999	15,999	16,000	16,000	16,000
May 1	15,993	15,996	15,997	15,997	15,997	15,998	15,998	15,998	15,999	15,999	16,000
June 1	15,992	15,995	15,996	15,996	15,996	15,997	15,997	15,997	15,998	15,998	16,000
July 1	15,992	15,995	15,996	15,996	15,996	15,997	15,997	15,997	15,998	15,998	16,000
August 1	15,992	15,995	15,996	15,996	15,996	15,996	15,997	15,997	15,997	15,998	16,000
September 1	15,993	15,995	15,996	15,996	15,996	15,997	15,997	15,997	15,998	15,998	16,000
October 1	15,994	15,996	15,997	15,997	15,997	15,998	15,998	15,998	15,999	15,999	16,000
End-of-year	15,996	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 14a. Reverse cumulative distributions of probable reservoir storage following 150 cubic feet per second pumping over year (day 1–365), and low-flow releases (September 1–30): scenario 1.

Date	Percentiles[1] of reservoir storage, in acre-feet										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
January 1	15,993	15,997	15,997	15,997	15,998	15,998	15,998	15,998	15,999	16,000	16,000
February 1	15,994	15,997	15,998	15,998	15,998	15,998	15,999	15,999	15,999	16,000	16,000
March 1	15,995	15,998	15,999	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000
April 1	15,997	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000
May 1	15,996	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000
June 1	15,987	15,997	15,998	15,999	15,999	15,999	15,999	16,000	16,000	16,000	16,000
July 1	15,962	15,995	15,997	15,998	15,998	15,998	15,999	15,999	15,999	16,000	16,000
August 1	15,993	15,996	15,997	15,997	15,997	15,997	15,998	15,998	15,998	15,999	16,000
September 1	15,993	15,996	15,997	15,997	15,997	15,997	15,998	15,998	15,998	15,999	16,000
October 1	10,480	10,492	10,494	10,496	10,498	10,500	10,502	10,505	10,508	10,514	10,602
November 1	15,993	15,995	15,995	15,996	15,996	15,996	15,997	15,997	15,997	15,998	16,000
December 1	15,993	15,997	15,997	15,997	15,998	15,998	15,998	15,998	15,999	16,000	16,000

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 14b. Reverse cumulative distributions of probable reservoir storage following 150 cubic feet per second pumping over year (day 1–365), one-half PBO low-flow release amount (69.4 acre-ft per day, August 1–October 31), and no peak-flow releases: scenario 2.

Date	Percentiles[1] of reservoir storage, in acre-feet										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
January 1	15,994	15997	15,997	15,997	15,998	15,998	15,998	15,999	15,999	16,000	16,000
February 1	15,993	15,997	15,998	15,998	15,998	15,998	15,999	15,999	15,999	16,000	16,000
March 1	15,994	15,998	15,998	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000
April 1	15,996	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000
May 1	15,995	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000
June 1	15,992	15,997	15,998	15,998	15,999	15,999	16,000	16,000	16,000	16,000	16,000
July 1	15,959	15,995	15,997	15,998	15,998	15,998	15,999	15,999	15,999	16,000	16,000
August 1	15,993	15,996	15,997	15,997	15,997	15,997	15,998	15,998	15,998	15,999	16,000
September 1	14,753	14,763	14,765	14,767	14,768	14,770	14,771	14,773	14,775	14,780	14,834
October 1	12,571	12,586	12,590	12,593	12,596	12,598	12,601	12,604	12,608	12,616	12,682
November 1	10,337	10,353	10,359	10,363	10,366	10,370	10,373	10,377	10,383	10,391	10,509
December 1	15,993	15,996	15,996	15,996	15,997	15,997	15,997	15,997	15,998	15,998	16,000

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 14c. Reverse cumulative distribution of probable reservoir storage with 150 cubic feet per second pumping over year (day 1–365), all PBO low-flow releases (360 acre-ft per day, September 1–30), and no peak-flow release: scenario 3.

Date	Percentiles[1] of reservoir storage, in acre-feet										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
January 1	15,994	15,997	15,997	15,997	15,998	15,998	15,998	15,998	15,999	16,000	16,000
February 1	15,993	15,997	15,998	15,998	15,998	15,998	15,999	15,999	15,999	16,000	16,000
March 1	15,995	15,998	15,999	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000
April 1	15,995	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000
May 1	15,995	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000
June 1	15,989	15,997	15,998	15,998	15,999	15,999	15,999	16,000	16,000	16,000	16,000
July 1	15,964	15,996	15,997	15,998	15,998	15,998	15,999	15,999	15,999	16,000	16,000
August 1	15,993	15,996	15,997	15,997	15,997	15,997	15,998	15,998	15,998	15,999	16,000
September 1	15,992	15,995	15,996	15,996	15,996	15,997	15,997	15,997	15,998	15,998	16,000
October 1	5,092	5,100	5,102	5,104	5,106	5,108	5,110	5,112	5,115	5,121	5,237
November 1	13,431	13,817	13,896	13,948	13,976	14,007	14,033	14,041	14,048	14,057	14,173
December 1	15,994	15,996	15,996	15,996	15,997	15,997	15,997	15,997	15,998	15,998	16,000

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 14d. Reverse cumulative distribution of probable reservoir storage with 150 cubic feet per second pumping over year (day 1–365), one-half PBO low-flow release amount (180 acre-ft per day, September 1–30), and maximum peak-flow releases: scenario 4.

Date	Percentiles[1] of reservoir storage, in acre-feet										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
January 1	15,994	15,997	15,997	15,997	15,998	15,998	15,998	15,998	15,999	16,000	16,000
February 1	15,994	15,997	15,998	15,998	15,998	15,998	15,999	15,999	15,999	16,000	16,000
March 1	15,995	15,998	15,999	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000
April 1	15,996	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16000	16000
May 1	11,599	15,999	15,999	15,999	16,000	16,000	16,000	16,000	16,000	16,000	16,000
June 1	5,995	8,090	9,892	11,301	12,995	14,298	15,395	15,998	15,999	16,000	16,000
July 1	5,996	8,395	9,993	11,670	13,502	15,293	15,998	15,998	15,999	15,999	16,000
August 1	12,860	15,995	15,996	15,997	15,997	15,997	15,998	15,998	15,998	15,999	16,000
September 1	15,991	15,995	15,996	15,996	15,996	15,996	15,997	15,997	15,997	15,998	16,000
October 1	10,482	10,492	10,494	10,497	10,499	10,501	10,503	10,505	10,508	10,513	10,569
November 1	15,992	15,995	15,995	15,996	15,996	15,996	15,996	15,997	15,997	15,998	16,000
December 1	15,993	15,996	15,996	15,996	15,997	15,997	15,997	15,997	15,998	15,999	16,000

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

14b), the amount of stored reservoir water is diminished during the months of August through October. Despite the decrease in amount of stored reservoir water (from about 16,000 acre-ft to about 10,300 acre-ft) by November 1, the availability of Colorado River water for reservoir pumping during November provides enough water to refill the reservoir by December 1 over the range of hydrologic conditions (table 14b).

Like the first two model scenarios, pumping year-round also can provide enough water to refill the reservoir to capacity under release scenario 3 when low-flow PBO release is doubled (table 14c) or under scenario 4 when a peak-flow release is made prior to and in conjunction with the PBO low-flow release (table 14d). Decreases in stored water are fairly uniform across hydrologic conditions for the first three model scenarios, however, the fourth model scenario results in nonuniform storage across hydrologic conditions and monthly period. This finding indicates that the streamflow conditions required to permit peak-flow release (streamflow between 12,900 and 26,600 ft^3/s) are not present under all hydrologic conditions. For example, reviewing the percentiles of release days indicates that during dry water years (1 out of 10 years) the conditions for peak-flow release are not met, and in only median to wet years (5 out of 10 years) peak-flow release conditions are met so as to release part or all 10,000 acre-ft (table 15).

Water Budget

In this section, the year-round pumping scheme is applied to the four release scenarios to assess the simulated demand on pumping and the ability to release water under varying hydrologic conditions. The results of these simulations are presented in terms of water-budget components for the complete range of hydrologic conditions (table 16a–d). In terms of the system water budget, the water coming into the system includes carryover storage, reservoir pumpage, and runoff, whereas water leaving the system includes evaporation, reservoir low-flow releases, peak-flow releases, and other releases (those that spill because of overtopping the reservoir). The actual amount of water stored (water in minus water out) in the reservoir at the end of the year is used as carryover storage for the subsequent year.

In general, the runoff, evaporation, and releases due to overtopping maintain their same order of magnitude for all simulations. Differences among release scenarios are associated primarily with additional pumping to satisfy storage requirements while meeting the prescribed reservoir peak- and(or) low-flow release schedules. For example, under release scenario 4, peak-flow conditions allow release of 10,000 acre-ft from the reservoir 50 percent of the time, whereas low-flow releases of 5,412.5 acre-ft are made 100 percent of the time.

Table 15. Release history for model scenario 4: year-round pumping (day 1–365), low-flow release amount (180 acre-ft per day, September 1–30), and maximum peak-flow releases.

Hydrologic Conditions	Percentile[1]	Peak-flow Release		Low-flow Release	
		(days)	(acre-feet)	(days)	(acre-feet)
Dry	0	0	0.0	30	5,412.5
	10	0	0.0	30	5,412.5
	20	1	1,000	30	5,412.5
	30	3	3,000	30	5,412.5
	40	6	6,000	30	5,412.5
Typical	50	10	10,000	30	5,412.5
	60	10	10,000	30	5,412.5
	70	10	10,000	30	5,412.5
	80	10	10,000	30	5,412.5
	90	10	10,000	30	5,412.5
Wet	100	10	10,000	30	5,412.5

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Water Quality

In this section, the goal is to understand the probable effects that reservoir operations have on Colorado River water quality (salinity concentration). The objective is to quantify the effect that pumping and four release scenarios have on dissolved-solids concentrations at downstream diversion points: the Government Highline Canal (GHC) and the Grand Valley Irrigation District Canal (GVIC). To understand how the pumping and storage of Colorado River water and subsequent releases may affect water quality, it is useful to first review the probable background daily dissolved-solids concentration profile.

Inspection of a single stochastic realization representing Colorado River salinity concentration at the gage near Cameo reveals the temporal nature of stream salinity over the course of a single year (fig. 21). Specifically, this concentration profile represents background conditions prior to any reservoir operations and reveals daily fluctuations with maximum concentrations of about 900 mg/L in the Colorado River that occur over the winter period (day 1 to day 100) and concentrations that rapidly decline over spring period (day 100 to day 150) to about 400 mg/L, which is characterized as the rising limb of the streamflow hydrograph. The lowest concentrations of about 200 mg/L are associated with the spring peak streamflow hydrograph period (day 130 to day 170). Concentrations increase from this low salinity period during the ascending limb of the streamflow hydrograph between day 170 to 250 to about 600 mg/L.

The probable background dissolved-solids concentrations (prior to development of the Sulphur Gulch reservoir) associated with 1,500 hydrologic realizations are summarized as cumulative distribution functions for the GHC (table 17a) and GVIC (table 17b). In general, the concentrations increase from wet to dry hydrologic conditions with concentrations being much larger over the low-flow period than peak-flow period. For example, the simulated median concentration values observed at the GHC during the low-flow period range from 431 mg/L (wet year) to 722 mg/L (dry year), whereas simulated median concentrations observed at the GHC during peak-flow range from 114 mg/L (wet year) to 698 mg/L (dry year). Background concentrations at the GVIC are generally slightly less than values at the GHC except during dry years.

In the reservoir pump and release scenarios investigated, tables of probable changes (absolute and percent) between background dissolved-solids concentrations and concentrations during corresponding peak- and low-flow release periods are provided for the GHC (table 18a–d) and GVIC (table 19a–d). In general, the simulated reservoir pump and release scenarios decrease or slightly increase instream dissolved-solids concentrations, depending on the conditions. Because the maximum concentration statistic represents the worst case, the following discussions of reservoir operational effects on water quality refer to maximum changes in salinity concentrations.

It is important to note that most increases in dissolved-solids concentrations are less than ±–3 percent which is less than the precision of analytical methods for dissolved-solids analysis (Fishmon and Friedman, 1989). Low-flow releases of 5,412.5 acre-ft of water over the 78-day period (scenario 2) resulted in maximum percentage increases in dissolved-solids concentrations greater than the measurement error for salinity in fewer than 10 percent of the driest years. Low-flow releases

Table 16a. Cumulative distribution function for water-budget components during year-round pumping, low-flow release of 5412.5 acre-ft over 30 days in September, and no peak-flow release: scenario 1.

Water-budget component	Percentiles[1]										
	Wet					Typical					Dry
	100	90	80	70	60	50	40	30	20	10	0
Carryover storage, in acre-feet	16,000	16,000	15,999	15,999	15,998	15,998	15,998	15,997	15,997	15,997	15,994
Reservoir pumpage, in acre-feet	6,175	6,130	6,121	6,115	6,109	6,103	6,098	6,092	6,085	6,076	6,027
Runoff, in acre-feet	316	210	193	181	173	165	158	151	144	133	96
Reservoir Evaporation, in acre-feet	861	815	808	803	798	794	790	785	780	772	743
Reservoir release - peak-flow, in acre-feet	0	0	0	0	0	0	0	0	0	0	0
Reservoir release - low-flow, in acre-feet	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413
Reservoir release - other, in acre-feet	200	93	78	71	63	58	54	48	43	37	19

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations

Table 16b. Cumulative distribution function for water-budget components during year-round pumping, low-flow release of 5412.5 acre-ft over 78 days in August–October, and no peak-flow release: scenario 2.

Water-budget component	Percentiles[1]										
	Wet					Typical					Dry
	100	90	80	70	60	50	40	30	20	10	0
Carryover storage, in acre-feet	16,000	16,000	15,999	15,999	15,998	15,998	15,998	15,997	15,997	15,997	15,994
Reservoir pumpage, in acre-feet	6,136	6,091	6,081	6,075	6,069	6,063	6,057	6,051	6,043	6,031	5,951
Runoff, in acre-feet	302	209	195	185	175	167	160	152	144	132	94
Reservoir Evaporation, in acre-feet	812	779	772	767	762	759	754	751	745	738	707
Reservoir release - peak-flow, in acre-feet	0	0	0	0	0	0	0	0	0	0	0
Reservoir release - low-flow, in acre-feet	5,412	5,412	5,412	5,412	5,412	5,412	5,412	5,412	5,412	5,412	5,412
Reservoir release – other, in acre-feet	180	89	77	69	63	57	53	47	42	34	17

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 16c. Cumulative distribution function for water-budget components during year-round pumping, low-flow release of 10,825 acre-ft over 30 days in September, and no peak-flow release: scenario 3.

Water-budget component	Percentiles[1]										
	Wet					Typical					Dry
	100	90	80	70	60	50	40	30	20	10	0
Carryover storage, in acre-feet	16,000	15,999	15,999	15,999	15,998	15,998	15,998	15,997	15,997	15,997	15,994
Reservoir pumpage, in acre-feet	11,525	11,479	11,470	11,464	11,459	11,454	11,448	11,442	11,435	11,426	11,362
Runoff, in acre-feet	301	209	194	183	174	166	160	152	143	134	88
Reservoir Evaporation, in acre-feet	785	754	745	741	736	732	728	723	718	712	677
Reservoir release - peak-flow, in acre-feet	0	0	0	0	0	0	0	0	0	0	0
Reservoir release - low-flow, in acre-feet	10,825	10,825	10,825	10,825	10,825	10,825	10,825	10,825	10,825	10,825	10,825
Reservoir release - other, in acre-feet	182	92	80	71	65	59	54	49	44	37	13

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 16d. Cumulative distribution function for water-budget components during year-round pumping, low-flow release of 5412.5 acre-ft in September and peak-flow (spring) release: scenario 4.

Water-budget component	Percentiles[1]										
	Wet					Typical					Dry
	100	90	80	70	60	50	40	30	20	10	0
Carryover storage, in acre-feet	16,000	16,000	15,999	15,998	15,998	15,998	15,998	15,997	15,997	15,997	15,993
Reservoir pumpage, in acre-feet	16,000	16,000	16,071	16,056	16,042	16,001	12,089	9,088	7,110	6,116	6,038
Runoff, in acre-feet	322	210	194	183	174	166	158	151	142	132	85
Reservoir evaporation, in acre-feet	841	807	798	792	787	780	773	767	759	749	706
Reservoir release - peak-flow, in acre-feet	10,000	10,000	10,000	10,000	10,000	10,000	6,000	3,000	1,000	0	0
Reservoir release - low-flow, in acre-feet	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413	5,413
Reservoir release - other, in acre-feet	166	85	72	64	57	51	46	41	36	30	14

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

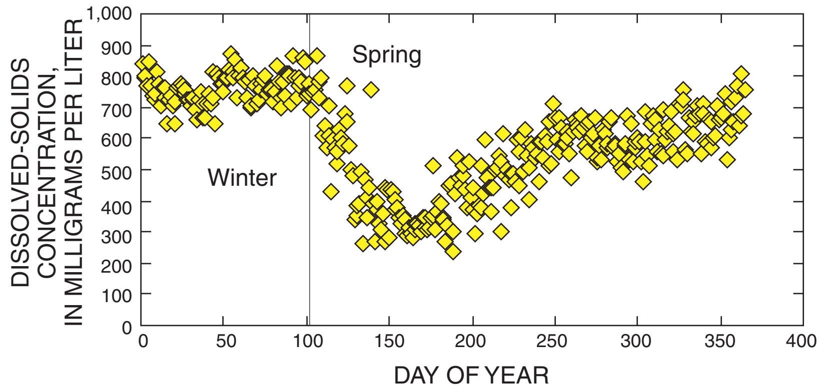

Figure 21. Stochastic simulation of dissolved-solids concentration Colorado River gage near Palisade.

Table 17a. Cumulative distribution function of simulated background instream dissolved-solids concentrations observed at the Government Highline Canal.

Statistic	Percentiles of background concentration, in milligrams per liter[1]										
	Dry	Typical									Wet
	100	90	80	70	60	50	40	30	20	10	0
Low-flow observation period (September 1–30)											
Minimum	579	467	444	429	418	403	389	372	355	332	193
Maximum	1398	960	907	874	847	826	801	777	752	723	600
Average	723	641	623	609	599	586	574	561	547	525	417
Median	722	645	627	614	604	593	581	568	554	533	431
Standard deviation	204	124	116	108	103	99	95	91	85	79	57
Peak-flow observation period (spring)											
Minimum	512	280	239	213	199	180	165	152	138	121	58
Maximum	1384	549	436	385	351	313	285	261	236	208	141
Average	681	372	317	285	262	236	217	199	183	161	110
Median	698	382	321	292	265	241	219	203	185	164	114
Standard deviation	251	86	64	53	46	40	36	32	28	23	11

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 17b. Cumulative distribution function of simulated background instream dissolved-solids concentrations observed at the Grand Valley Irrigation Canal.

Statistic	Percentiles of background concentration, in milligrams per liter[1]										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
Low-flow observation period (September 1–30)											
Minimum	590	482	461	446	434	419	406	390	371	347	219
Maximum	1290	918	870	841	819	799	778	757	734	708	598
Average	712	639	622	610	601	589	578	566	551	531	422
Median	713	643	625	613	604	594	583	570	557	537	436
Standard deviation	176	112	104	97	93	89	85	81	77	71	52
Peak-flow observation period (spring)											
Minimum	517	289	247	222	207	188	173	160	146	129	65
Maximum	1331	551	439	390	354	317	289	265	240	213	146
Average	673	377	324	291	269	242	223	205	189	167	116
Median	692	389	327	298	271	247	226	209	191	170	120
Standard deviation	234	82	62	51	45	39	34	31	27	22	11

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 18a. Cumulative distribution function of percent change in instream dissolved-solids concentration observed at the Government Highline Canal during *low-flow* period following year-round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration[1,2,3]										
	Dry	Typical									Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.7	0	–0.2	–0.3	–0.5	–0.6	–0.7	–0.9	–1.1	–1.3	–3
Maximum	7.9	3.5	3.1	2.8	2.7	2.4	2.3	2.2	2	1.8	1
Average	1.8	1.2	1.1	1	0.9	0.8	0.7	0.6	0.5	0.4	–0.3
Median	1.8	1.2	1.1	1	0.9	0.8	0.7	0.7	0.6	0.4	–0.1
Standard deviation	1.6	0.9	0.8	0.8	0.8	0.7	0.7	0.6	0.6	0.6	0.3
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0.2	–0.1	–0.2	–0.3	–0.3	–0.4	–0.4	–0.5	–0.6	–0.7	–1.7
Maximum	3.4	1.7	1.5	1.4	1.3	1.2	1.1	1.1	1	0.9	0.7
Average	0.7	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0
Median	0.7	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0
Standard deviation	0.5	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	1.3	–0.6	–1	–1.3	–1.5	–1.7	–2	–2.2	–2.5	–3	–5.5
Maximum	12.7	5.8	5.1	4.6	4.3	4	3.7	3.4	3	2.6	1.4
Average	3	1.8	1.5	1.3	1.1	1	0.8	0.5	0.3	0	–1.8
Median	3.1	1.8	1.5	1.3	1.1	1	0.8	0.6	0.4	0.1	–1.7
Standard deviation	2.6	1.7	1.5	1.5	1.4	1.3	1.3	1.2	1.1	1.1	0.8
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	–0.2	–1.4	–1.6	–1.8	–1.9	–2.1	–2.2	–2.4	–2.5	–2.8	–4.7
Maximum	3.5	1.2	0.9	0.6	0.5	0.3	0.1	0	–0.2	–0.4	–1.3
Average	0.7	–0.3	–0.5	–0.7	–0.8	–0.9	–1	–1.1	–1.3	–1.4	–2.3
Median	0.6	–0.3	–0.5	–0.7	–0.8	–0.9	–1	–1.1	–1.2	–1.4	–2.2
Standard deviation	1.1	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.3

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

Table 18b. Cumulative distribution function of percent change in instream dissolved solids concentration observed at the Government Highline Canal during *peak-flow* period following year-round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration[1,2,3]										
	Dry	Typical									Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0	0	0	0	0	0	0	0	0	0	–0.8
Maximum	0.7	0.2	0.1	0.1	0.1	0.1	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0
Median	0	0	0	0	0	0	0	0	0	0	0
Standard deviation	1.1	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.2
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0	0	0	0	0	0	0	0	0	0	–0.4
Maximum	0.8	0.2	0.1	0.1	0.1	0.1	0.1	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0
Median	0	0	0	0	0	0	0	0	0	0	0
Standard deviation	0.5	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0	0	0	0	0	0	0	0	0	0	–0.6
Maximum	0.9	0.1	0.1	0.1	0.1	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0
Median	0	0	0	0	0	0	0	0	0	0	0
Standard deviation	1.7	1.1	1	0.9	0.9	0.8	0.8	0.7	0.7	0.6	0.4
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	0	0	0	0	0	0	0	0	0	0	–2
Maximum	16.2	8.9	7.9	7.3	6.9	6.4	5.9	5.4	4.6	0	0
Average	0	0	0	0	0	0	0	0	0	0	0
Median	0.7	0.5	0.5	0.4	0.4	0.4	0.3	0.1	0.1	0	0
Standard deviation	1.4	0.9	0.9	0.8	0.8	0.7	0.7	0.7	0.6	0.4	0.2

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

Table 18c. Cumulative distribution function of absolute change in instream dissolved solids concentration observed at the Government Highline Canal during *low-flow* period following year-round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration[1,2,3]										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	4.1	0.0	–0.9	–1.3	–2.1	–2.4	–2.7	–3.3	–3.9	–4.3	–5.8
Maximum	110.4	33.6	28.1	24.5	22.9	19.8	18.4	17.1	15.0	13.0	6.0
Average	13.0	7.7	6.9	6.1	5.4	4.7	4.0	3.4	2.7	2.1	–1.3
Median	13.0	7.7	6.9	6.1	5.4	4.7	4.1	4.0	3.3	2.1	–0.4
Standard deviation	3.3	1.1	0.9	0.9	0.8	0.7	0.7	0.5	0.5	0.5	0.2
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0.2	–0.5	–0.9	–1.3	–1.3	–1.6	–1.6	–1.9	–2.1	–2.3	–3.3
Maximum	47.5	16.3	13.6	12.2	11.0	9.9	8.8	8.5	7.5	6.5	4.2
Average	0.7	3.2	3.1	2.4	2.4	2.3	1.7	1.7	1.6	1.0	0.0
Median	0.7	3.2	3.1	2.5	2.4	2.4	1.7	1.7	1.7	1.1	0.0
Standard deviation	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.1
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	1.3	–2.8	–4.4	–5.6	–6.3	–6.9	–7.8	–8.2	–8.9	–10.0	–10.6
Maximum	177.5	55.7	46.3	40.2	36.4	33.0	29.6	26.4	22.6	18.8	8.4
Average	3.0	11.5	9.3	7.9	6.6	5.9	4.6	2.8	1.6	0.0	–7.5
Median	3.1	11.6	9.4	8.0	6.6	5.9	4.6	3.4	2.2	0.5	–7.3
Standard deviation	2.6	2.1	1.7	1.6	1.4	1.3	1.2	1.1	0.9	0.9	0.5
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	–0.2	–6.5	–7.1	–7.7	–7.9	–8.5	–8.6	–8.9	–8.9	–9.3	–9.1
Maximum	48.9	11.5	8.2	5.2	4.2	2.5	0.8	0.0	–1.5	–2.9	–7.8
Average	0.7	–1.9	–3.1	–4.3	–4.8	–5.3	–5.7	–6.2	–7.1	–7.4	–9.6
Median	0.6	–1.9	–3.1	–4.3	–4.8	–5.3	–5.8	–6.2	–6.6	–7.5	–9.5
Standard deviation	1.1	0.9	0.8	0.6	0.6	0.6	0.5	0.5	0.4	0.3	0.2

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

Table 18d. Cumulative distribution function of absolute change in instream dissolved-solids concentration observed at the Government Highline Canal during *peak-flow* period following year-round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration[1,2,3]										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.5
Maximum	9.7	1.1	0.4	0.4	0.4	0.3	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	2.8	0.5	0.4	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.0
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.2
Maximum	11.1	1.1	0.4	0.4	0.4	0.3	0.3	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	1.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.3
Maximum	12.5	0.5	0.4	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	4.3	0.9	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.0
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	–0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–1.2
Maximum	224.2	48.9	34.4	28.1	24.2	20.0	16.8	14.1	10.9	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	4.9	1.9	1.6	1.2	1.1	1.0	0.7	0.2	0.2	0.0	0.0
Standard deviation	3.5	0.8	0.6	0.4	0.4	0.3	0.3	0.2	0.2	0.1	0.0

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

Table 19a. Cumulative distribution function of percent change in instream dissolved-solids concentration observed at the Grand Valley Irrigation Canal during *low-flow* period for year round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration[1,2,3]										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	51.1	1.1	0.9	0.7	0.6	0.5	0.4	0.3	0.1	0.0	0.0
Average	1.7	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	9.3	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	45.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	31.7	7.0	2.6	1.8	1.6	1.4	1.2	1.1	0.9	0.6	0.0
Average	2.4	0.9	0.7	0.5	0.4	0.3	0.2	0.2	0.1	0.0	0.0
Median	2.4	1.1	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	6.1	1.3	0.7	0.6	0.5	0.5	0.4	0.3	0.3	0.1	0.0
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	55.7	7.2	2.6	1.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Average	2.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	10.2	1.4	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

Table 19b. Cumulative distribution function of percent change in instream dissolved-solids concentration observed at the Grand Valley Irrigation Canal during *peak-flow* period for year round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration[1,2,3]										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	7.5	4.3	3.7	3.2	2.8	2.5	2.3	2.0	1.5	0.0	0.0
Average	0.5	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	1.5	0.9	0.7	0.6	0.5	0.5	0.4	0.3	0.2	0.0	0.0

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

Table 19c. Cumulative distribution function of absolute change in instream dissolved-solids concentration observed at the Grand Valley Irrigation Canal during *low-flow* period following year-round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration, mg/L[1,2,3]										
	Dry	Typical									Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	658.7	9.9	7.4	6.1	5.0	4.1	3.2	2.1	0.7	0.0	0.0
Average	12.1	1.5	0.9	0.5	0.4	0.2	0.2	0.1	0.0	0.0	0.0
Median	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	16.4	0.4	0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	580.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	4.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	12.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	408.6	64.1	22.9	14.9	13.0	11.3	9.7	8.2	6.4	4.4	0.0
Average	16.9	6.0	4.4	3.3	2.5	1.9	1.3	0.9	0.6	0.2	0.0
Median	17.0	7.0	3.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	10.7	1.5	0.8	0.6	0.5	0.4	0.3	0.3	0.2	0.1	0.0
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	719.1	66.5	22.3	8.9	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Average	17.2	1.9	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	18.0	1.6	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

Table 19d. Cumulative distribution function of percent change in instream dissolved-solids concentration observed at the Grand Valley Irrigation Canal during *peak-flow* period following year-round pumping and four release scenarios.

Statistic	Percentiles of percent change in concentration, mg/L[1,2,3]										
	Dry					Typical					Wet
	100	90	80	70	60	50	40	30	20	10	0
Release scenario 1: low-flow release (5412.5 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 2: Low-flow release (5412.5 acre-feet over 78 days in August–October), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 3: low-flow release (10,825 acre-feet over 30 days in September), no peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Release scenario 4: low-flow (5412.5 acre-feet in September) and peak-flow (spring) release											
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	99.8	23.9	16.1	12.7	10.0	8.0	6.5	5.2	3.7	0.0	0.0
Average	3.0	1.0	0.7	0.5	0.4	0.3	0.2	0.1	0.1	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard deviation	3.4	0.7	0.5	0.3	0.2	0.2	0.1	0.1	0.1	0.0	0.0

[1]The precision of analytical methods for dissolved solids analysis is ± –3-percent (Fishman and Friedman, 1989).

[2]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

[3]A negative value indicates a concentration decrease whereas a positive value indicates a concentration increase.

of 5,412.5 acre-ft of water over the 30-day period coupled with peak-flow releases of up to 10,000 acre-ft of water (scenario 4) also resulted in maximum percentage increases in dissolved-solids concentrations greater than the measurement error for dissolved-solids concentrations in fewer than 10 percent of the driest years. Scenario 3, low-flow release of 10,825 acre-ft of water in a 30-day period resulted in the greatest observed increases in maximum dissolved-solids concentrations. The difference in dissolved-solids concentrations observed in scenarios 1 and 4 after a 30-day low-flow release of 5,412.5 acre-ft of water is attributed to the additional pumping of comparatively low dissolved-solids concentration water around the hydrograph peak to refill the reservoir following peak-flow releases. In this scenario, the relatively low concentration water that is pumped following peak-flow releases mixes in the reservoir thereby reducing the reservoir concentration and instream concentrations during mixing of the low-flow releases. The effect of peak-flow releases (scenario 4) on stream dissolved-solids concentrations at the GHC is shown in table 18b. For this case, the observational changes in all statistics of dissolved-solids concentration changes during the peak-flow period at the GHC range from a 0-percent to a 16-percent increase (wet to dry). The effect of the other release scenarios during this observation period and at this location resulted in no change because there were no associated peak-flow releases. Observed trends in stream salinity at the GVIC are similar to observations of simulated dissolved-solids concentration change at the GHC, however, the magnitude of percent and absolute change is less except under very dry hydrologic conditions (table 19a–d). Even where statistically significant changes occur, the simulated changes in dissolved-solids concentration occur only under extreme hydrologic conditions.

OCCURRENCE AND DISTRIBUTION OF SELENIUM

In addition to constituents that contribute to salinity, selenium is present naturally in the shale bedrock of the Colorado River Basin, and selenium is known to occur in the surface water and ground water (Butler and von Guerard, 1996). Because selenium can be toxic to fish and other biota, the occurrence and distribution of selenium in the study area also is of interest and included in this report. The initial occurrence and distribution assessment of selenium (fig. 22) reflects plots of concentration data stored in the USGS National Water Information System. These concentration data primarily reflect limited sampling of the Colorado River at Cameo (station 09095500) from April 18, 2001 to August 21, 2001 of the Dry Fork (station 09095400) near De Beque from August 1975 to September 1983, and Dry Fork Upper Station (station 09095300) from October 1995 to September 2001. Two samples collected for this report were analyzed from sampling at the mouth of Sulphur Gulch (station 391607108153500) on March 11 and March 22, 2002.

In general, instream selenium concentrations appear to be an order of magnitude greater in tributary creeks than in the Colorado River. For example, the respective range of dissolved selenium concentrations in the Colorado River near Cameo and Dry Fork range from 0.3 to 0.7 µg/L (median concentration of 0.5 µg/L) and less than the detection limit to 25 µg/L (median concentration of 4.0 µg/L). The Dry Fork at Upper Station had the most selenium samples (37 samples) collected concurrently with instantaneous discharge; however, plotting these data for

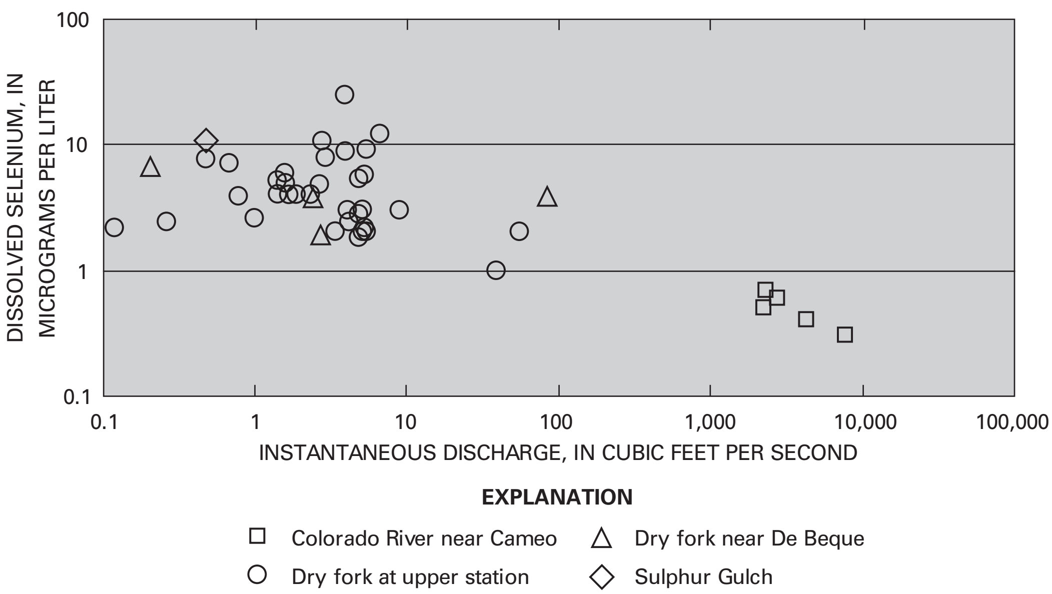

Figure 22. Dissolved selenium concentrations measured at (a) Colorado River (station 09095500) near Cameo, (b) Dry Fork (station 09095400) near De Beque, (c) Dry Fork at Upper Station (station 09095300) near De Beque, and (d) mouth of Sulphur Gulch near De Beque (station 391607108153500).

selenium concentration and streamflow (fig. 23). By contrast, a weak linear relation ($R^2 = 0.77$) was found for selenium and Colorado River streamflow near Cameo (fig. 24). The lack of measurable selenium concentrations at high streamflow in tributary creeks is attributed to a combination of dilution and geochemical effects. For these reasons, a probability density function was developed for Dry Fork (fig. 25).

Because the selenium probability distribution is lognormal, a Monte Carlo simulation of selenium occurrence was conducted to assess the likelihood for exceeding selected concentrations. For example, Monte Carlo simulation of the cumulative distribution function (table 20) indicates a 100-percent chance that random samples will contain selenium concentrations between 0 and 49.5 µg/L; however, there is only a 5-percent and 1-percent chance of exceeding a 12.06 µg/L and 19.87 µg/L concentration under similar sampling and hydrologic conditions. Given that the respective Colorado instream acute and chronic water-quality standards for selenium are 18.4 µg/L and 4.6 µg/L, respectively, there appears to be a 1-percent and 35-percent chance of exceeding these thresholds (Colorado Division of Water Resources, 2002). Even though the Colorado standards may be exceeded during certain years at Dry Fork (and therefore likely in runoff to Sulphur Gulch), the comparatively low selenium concentration in water pumped from the Colorado River will likely dilute reservoir concentrations to levels less than the standards.

To test the hypothesis that releases from Sulphur Gulch Reservoir to the Colorado River would not pose a health concern or threat to aquatic life, conservative deterministic mixing calculations were conducted for dry and wet hydrologic conditions (table 21). In these mixing calculations, the respective total annual daily runoff amounts to the proposed reservoir were estimated using the stochastic Sulphur Gulch model and determined to be about 96 acre-ft and 300 acre-ft for dry and wet hydrologic conditions; the 6,000 ft^3/s pumped represents the approximate amount required for 16,000 acre-ft storage; the respective minimum and maximum selenium concentration values representing dry and wet hydrologic conditions were determined from analyses of temporal Colorado River samples collected near Cameo. In general, the resulting reservoir concentration under either hydrologic condition is less than the acute and chronic thresholds and therefore no cause for concern, if the assumption about selenium concentrations used to develop the probability distribution function are correct.

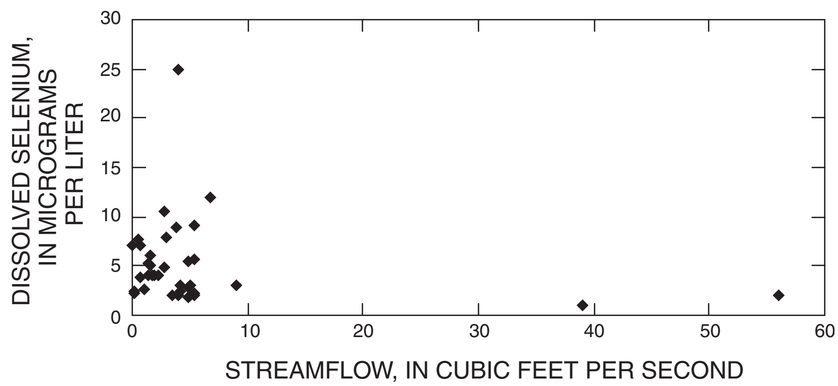

Figure 23. Selenium concentrations measured at Dry Fork at Upper Station (station 09095300) near De Beque, October 1995–September 2001.

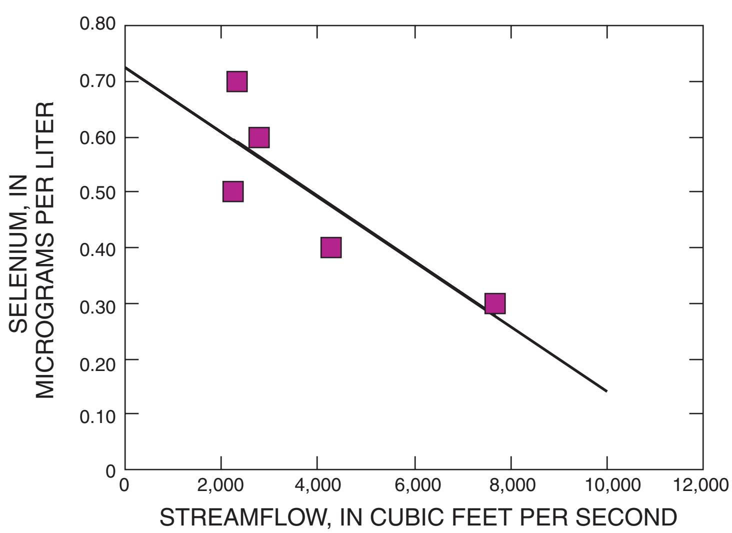

Figure 24. Selenium concentrations measured at Colorado River (09095500) near Cameo, April –August 2001.

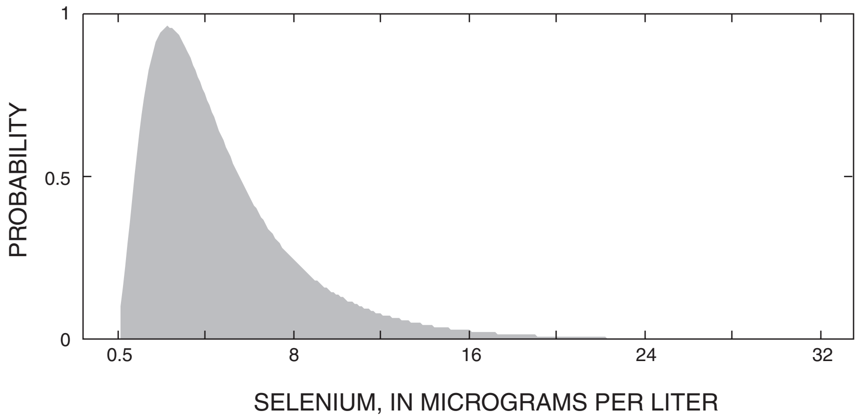

Figure 25. Probability distribution function fit to selenium concentrations measured at Dry Fork at Upper Station (station 09095300) near De Beque.

Table 20. Cumulative distribution function for instantaneous discharge and selenium concentrations measured at Dry Fork Upper Station (station 09095300) near De Beque.

Percentile[1]	Micrograms per liter	Cubic feet per second
0	0.00	51.6
10	1.73	66.6
20	2.32	71.3
30	2.90	75.4
40	3.47	79.5
50	4.05	82.9
60	4.76	87.3
70	5.81	91.8
80	7.16	98.2
90	9.51	106.1
100	49.50	150.0

[1]The 0 and 100 percentiles represent the minimum and maximum values of the probability distribution computed following 1,500 realizations.

Table 21. Summary of likely selenium concentrations for select hydrologic conditions.

[µg/L, micrograms per liter]

Hydrologic condition	Simulated Runoff to Proposed Reservoir: Flow (acre-feet)	Simulated Runoff to Proposed Reservoir: Concentration (µg/L)	Colorado River: Total pumped (acre-feet)	Colorado River: Concentration (µg/L)	Reservoir: Concentration (µg/L)
Dry	96	49.5	6,027	0.72	1.48
Wet	316	1.73	6,175	0.30	0.37

SUMMARY AND CONCLUSIONS

A new 16,000 acre-ft reservoir is proposed to be located about 25 miles east of Grand Junction, Colorado, on a tributary to the Colorado River that drains the Sulphur Gulch watershed between De Beque and Cameo, Colorado. The Sulphur Gulch Reservoir is intended to provide the Colorado River with at least 5,412.5 acre-ft of water during low-flow periods to meet the East Slope's commitment under the final Progammatic Biological Opinion, and as much as 10,000 acre-ft of water to supplement peak-flows (flows between 12,900 to 26,600 ft^3/s). A stochastic mixing model was developed and used to evaluate the probable effects of reservoir operations on stream quantity and quality subject to selected operational pump and release activity, and to make an initial assessment of the probable selenium concentrations in the Sulphur Gulch Reservoir. The study approach involves development, validation, and application of the stochastic model.

The stochastic mixing model is composed of linked hydrology and water-quality models that incorporate random variability and uncertainty. The purpose of the hydrology model is to compute the quantity of pumpable water and provide daily streamflow at key hydrologic points in the study reach that can be used by the water-quality model. The purpose of the water-quality model is to compute changes in dissolved-solids concentrations at locations where water enters or exits the study reach. The temporal variability and measurement uncertainty of model input is incorporated and distribution of probable results derived for streamwater quality determined following 1,500 Monte Carlo trials. Overall, the mixing model is a simplified representation of the Colorado River-Sulphur Gulch system in which daily flows are added or subtracted, and concentrations are calculated based on the conservation of mass principle.

In keeping with the conservation of mass principle, the mixing model accounts for flows and associated concentrations that are gained and lost over the Colorado River reach between the De Beque and Palisade streamflow-gaging stations. The use of random variables as input to the stochastic mixing model requires identification of relevant probability distributions and related statistical summaries. Because most real-world problems involve elements of variability and (or) uncertainty (called random variables), statistical summaries of daily random streamflow variables are derived from records that incorporate a balanced mix of wet, dry, and typical (median) hydrologic periods to avoid model bias. The actual length of record is based on the need to minimize model time step yet provide enough measurements so that a statistically valid probability distribution can be fit for each parameter. To predict the hydrologic response on a daily basis, daily streamflow values are aggregated over the period of record and the autocorrelated structure evaluated. Implementation of the autocorrelated structure into the model is done using a method that generates random correlated variables. Recognizing the weak correlation between streamflow and diversion records and presence of a seasonal dependence, the variability surrounding seasonal diversions is modeled as a set of independent random variables.

In this study, it is important to predict changes in dissolved-solids concentration, or salinity, as a function of streamflow, evaporation as a function of time, reservoir surface area as a function of reservoir volume, and probable exceedance as a function of daily streamflow. For this reason, a nonlinear least-squares regression approach was used to estimate best-fit parameters to predictive equations that are incorporated into the model. Because the salinity-streamflow and evaporation-time relations are stochastic, analysis of differences between the measured and predicted values was conducted and variability reintroduced into the mixing model. The variability was reintroduced into the mixing model by adding residuals to the deterministic equation following random sampling of probability distribution using the Monte Carlo technique. Whereas the random variability in Colorado River streamflow and salinity at De Beque, Cameo, and Palisade reflect natural variability, the parameters used in describing runoff and salinity at Sulphur Gulch are uncertain.

To define a runoff-salinity relation for the ephemeral Sulphur Gulch watershed, baseflow separation was performed on discharge measurements of the adjacent Dry Fork watershed. Using USGS software, the computed Dry Fork runoff hydrograph was adjusted to obtain a unit runoff hydrograph that was applied to the Sulphur Gulch drainage. Using the runoff values and dissolved-solids concentrations determined from the Dry Fork Upper Station, a stochastic equation then was developed. The two dissolved-solids concentration measurements determined from water samples collected at the Sulphur Gulch watershed support the use of the derived stochastic equation in the mixing model.

Validation of the stochastic mixing model involved testing the reliability of a representative Monte Carlo forecast, comparing statistics for selected forecast simulations to field measurements, and evaluating the overall mass balance. In this study, the lower and upper confidence intervals for all Monte Carlo trials agreed within 1-percent; however, the standard error continued to decrease until 1,500 trials. For this reason, the use of 1,500 Monte Carlo trials was deemed sufficient to ensure convergence and stability of forecast distributions.

Inspection of the streamflow statistics demonstrates excellent correspondence between simulated and measured streamflow at the Cameo gaging station. This correspondence underscores the validity of using correlated daily random streamflow variables. Correspondence between simulated and measured statistics associated with streamflow at Plateau Creek near Cameo and Colorado River near Palisade are not as good as for the Colorado River near Cameo. One reason may be that the residual analysis used to convert one or more deterministic equations to stochastic equations is not as accurate as using correlated random variables. The fact that measured and simulated streamflow statistics appear similar at the Cameo gage site (close to the beginning of study reach) and then at Palisade (end of study reach) indicates that the water-budget process of adding and subtracting stochastic diversions, return flow, and streamflow tributary water is working. This assertion is further supported qualitatively by the good visual correspondence to the daily median measured values for individual stochastic daily streamflow simulations for USGS gage sites at Colorado River near Cameo, Plateau Creek near Cameo, and Colorado River near Palisade.

In the first set of model scenarios, a stochastic simulation of background streamflow conditions, called divertible flow, was conducted. The simulated annual divertible flow at Palisade indicates that divertible flow will be greater or equal to 621,860 acre-ft in the driest year, but be less than or equal to 4,822,732 acre-ft in the wettest year.

Although there is ample water available for potential reservoir storage, the actual amount of divertible flow available for storage is constrained by the pump rate and timing. These two pumping constraints result in what is called pumpable flow. Based on results of simulated pumpable flow, it appears that a 150 ft^3/s pump can fill an empty 16,000 acre-ft reservoir nearly every year under most operating scenarios.

The reservoir storage simulations indicate that year-round pumping of Colorado River water can generally fill the 16,000 acre-ft reservoir within 2 months. Simulations of carry-over storage together with year-round pumping indicate that there is a sufficient amount of water to refill the reservoir to capacity following peak-flow releases of as much as 10,000 acre-ft and low-flow releases of 5,412.5 acre-ft of water. Whereas it is assumed that 5,412.5 acre-ft of stored water is released every year during low-flow conditions irrespective of the hydrologic condition, peak-flow release conditions (river flows between 12,900 ft^3/s and 26,600 ft^3/s) that would allow release of 10,000 acre-ft of stored water would occur only about 50 percent of the time. Under typical to moderately dry hydrologic conditions (3 of 10 years), conditions would be such that less than 10,000 acre-ft would be released from storage during the peak-flow period, and in moderate to extremely dry hydrologic conditions (2 of 10 years), no water would be released from storage during the peak-flow period.

In general, the simulated daily background dissolved-solids concentrations increase as hydrologic conditions go from wet to dry at the Government Highline Canal. The simulated reservoir pump and release scenarios decrease or slightly increase instream dissolved-solids concentrations, depending on conditions. Most observed increases in salinity are less than ±–3 percent, which is less than the precision of analytical methods for measuring dissolved solids.

Low-flow releases of 5,412.5 acre-ft of water over the 78-day period (scenario 2) resulted in maximum percentage increases in dissolved-solids concentration greater than the measurement error for dissolved-solids concentration in fewer than 10 percent of the driest years. Low-flow releases of 5,412.5 acre-ft of water over the 30-day period coupled with peak-flow releases of up to 10,000 acre-ft of water (scenario 4) also resulted in maximum percentage increases in salinity greater than the measurement error for dissolved-solids concentration in fewer than 10 percent of the driest years. Scenario 3, low-flow release of 10,825 acre-ft of water in a 30-day period resulted in the greatest observed increases in maximum dissolved-solids concentrations. Even though scenarios 1 and 4 both involved releases of 5,412.5 acre-ft over a 30-day period, the lower dissolved-solids concentrations during low flow periods observed in scenario 4 is attributed to the additional pumping of comparatively low dissolved-solids concentration water immediately following the hydrograph peak to refill the reservoir after peak-flow releases. Observed trends in stream salinity at the Grand Valley Irrigation Canal are similar to observations of simulated dissolved-solids concentration change at the Government Highline Canal; however, the magnitude of percent and absolute change is less except under very dry hydrologic conditions. Even where statistically significant changes occur, the simulated changes in dissolved-solids concentration occur only under extreme hydrologic conditions.

In addition to salinity, understanding instream changes in selenium concentration following reservoir releases are of concern because selenium can be toxic to fish and other biota. In general, instream selenium concentrations appear to be an order of magnitude greater in tributary creeks than in the Colorado River. For example, the respective range of dissolved selenium concentrations in the Colorado River near Cameo and Dry Fork near De Beque range from 0.3 to 0.7 μg/L (median concentration of 0.5 μg/L) and from less than the detection limit to 25 μg/L (median concentration of 4.0 μg/L). The Dry Fork Upper Station had the most extensive number of selenium samples (37 measurements) collected concurrently with instantaneous discharge; however, plotting these data did not reveal any relation between selenium and streamflow. By contrast, a weak linear relation ($R^2 = 0.77$) was found for selenium and Colorado River streamflow at the Cameo gage. The lack of measurable selenium at high streamflow in tributary creeks is attributed to a combination of dilution and geochemical effects. Because the selenium probability distribution is lognormal, a stochastic simulation was conducted to assess the likelihood for exceeding selected selenium thresholds. For example, stochastic simulation of the cumulative distribution function indicates a 100-percent chance that random samples will contain selenium concentrations between 0 and 49.5, μg/L; however, there is only a 5-percent and 1-percent chance of exceeding a 12.06 μg/L and 19.87 μg/L concentration under similar sampling and hydrologic conditions. Given that the respective Colorado instream acute and chronic water-quality standards for selenium are 18.4 μg/L and 4.6 μg/L, there appears to be only a 1-percent and 35-percent chance of exceeding these thresholds during random sampling. Even though the Colorado water-quality standards may be exceeded during certain years at Dry Fork (and therefore in runoff to Sulphur Gulch), the lack of selenium in water pumped from Colorado River results in diluting reservoir concentrations to respective levels between 1.48 μg/L and 0.37 μg/L under dry and wet annual hydrologic conditions, well below the acute and chronic selenium standards.

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Appendixes

Appendix 1
Hydrology Model Description

HYDROLOGY MODEL DESCRIPTION

In the Excel hydrology model (Qmodel), days 1-365 occupy rows 25-389, and the various flows occupy columns C through BT. User-defined decision variables in the hydrology spreadsheet include reservoir pump rate (cell I8), first pump day (cell I9), last pump day (cell I10), Grand Valley Irrigation Canal senior water right (cell I11), Grand Valley Irrigation Canal junior water right (cell I12), minimum acceptable flow at Palisade (cell I13), and maximum return flow at Orchard Mesa Irrigation District check structure (cell I14), maximum allowable diversion at Government Highline Canal (cell I15), target flow switch (cell I16). Whereas the target flow switch is included for use in the stochastic model, this option was not used in the present study. The following list is a description of hydrologic component by column (uppercase letter), parameter, and corresponding cell contents (square brackets). The dollar signs that appear below indicate a single cell location, whereas upper case letters are generic and represent a range of corresponding daily values that occupy rows 25-389 (analogous to an array).

ColumnVariable

A. Comments

B. *Month* [=MONTH(C)]

C. *Day*[=DAY(C)]

D. *Date* [MONTH/DAY]

E. *Colorado River flow near De Beque, CO (*cubic feet per second*)*
[Correlated daily probability distribution functions]

F. *Colorado River flow near Cameo, CO (*cubic feet per second*)*
Observed mean daily streamflow over period of record.

G. *Colorado River flow near Cameo, CO (*cubic feet per second*)*
Simulated mean daily streamflow over period of record.

H. *Colorado River Flow near Cameo, CO (*cubic feet per second*)*
[Log(Probability distribution functions)]

I.-M. Government Highline Canal diversions

I. *Grand Valley Water Users Association diversion, GVWUA DIV (*cubic feet per second*)*
[Seasonal probability distribution functions]

J. *Mesa County Irrigation District diversion, MCID DIV (*cubic feet per second*)*
[Seasonal probability distribution functions]

K. *Orchard Mesa Irrigation District diversion, OMID Div* (cubic feet per second)
[Seasonal probability distribution functions]

L. *Palisade Irrigation District diversion, PID Div* (cubic feet per second)
[Seasonal probability distribution functions]

M. *Maximum Diversion* (cubic feet per second).
[=SUM(F:I)]

N. *Actual Diversion* (cubic feet per second)
[=IF(AA>$I$13,IF(M>G,G,M),IF(M>G,G-$I$13,M-$I$13))]

O-R. *Plateau Creek streamflow* (cubic feet per second).

O. *Colorado River flow after Government Highline Canal* (cubic feet per second)
[=G-N]

P. *Plateau Creek flow variability* (cubic feet per second)
[Daily residual probability distribution function]

Q. *Plateau Creek streamflow* (cubic feet per second). Regression relation reflects the fact that Plateau Creek is a function of streamflow at Cameo.
[=10^($H$406*H+$H$407)]

R. *Colorado River flow after Plateau Creek confluence* (cubic feet per second)
[=O+Q]

S-Z. Orchard Mesa Irrigation District return flows and Grand Valley Irrigation Canal withdrawal.

S. *Maximum historical return flow* (cubic feet per second)
[Seasonal probability distribution functions]
T. *Maximum historical Grand Valley Irrigation Canal diversion* (cubic feet per second)
[Seasonal probability distribution functions]

U. *Actual return flow before Grand Valley Irrigation Canal (GVIC) diversion* (cubic feet per second). Checks to see if senior water right is satisfied. If not, then returns water (from power plant) equal to or maximum allowable return flow rate at check structure.
[=IF(T=0,0,IF($I$11+$I$12<R,0,(IF($I$11+$I$12>=
R+$I$14,IF($I$116<R+$I$14,$I$14,$I$14),$I$11+$I$12-R))))]

V. *Colorado River flow before Grand Valley Irrigation Canal* (cubic feet per second).
[=R+U]

W. *Actual return flow after Grand Valley Irrigation Canal (*cubic feet per second*).* Dependent on check structure.
[=IF(T=0,S,IF($I$11+$I$12<R,S,(IF($I$11+$I$12>=R+$I$14,IF($I$11<R+$I$14,S-$I$14,S-$I$14),S-U))))]

X. *Amount of diverted water to Palisade Irrigation District, Mesa County Irrigation District, and Grand Valley Water Users Association (*cubic feet per second*).*
[=N-(U+W)]

Y. *Actual Grand Valley Irrigation Canal diversion (*cubic feet per second*).*
[=IF(T=0,0, IF(V-T<0,V,T))]

Z. *Colorado River flow after Grand Valley Irrigation Canal withdrawals (*cubic feet per second*).*
[=V-Y]

AA. *Colorado River flow at Palisade (*cubic feet per second*).*
[=Z+W]

AB. *Daily flow exceedance values computed at Palisade (percent)*. Exceedance function fit to historical exceedance probability function computed at Palisade.
[=IF(10^(1/$H$415^2*LOG($H$416/LOG(AA)))*100<100,10^(1/$H$415^2*LOG($H$416/LOG(AA)))*100,100)]

AC. *Flow quartile computed for minimum look-up table of divertible flow.*
[=IF(AB>75,100,IF(AB>50,75,(IF(AB>25,50,25))))]

AD. *Target flow at Palisade (*cubic feet per second*).* Monthly target flow criteria are assumed to be the same for all days in that month with exceedance probabilities lumped to quartiles.
[=IF($I$16=0,0,VLOOKUP(B,minflow,HLOOKUP(AC,colindex,2,FALSE),FALSE))]

AE. *Minimum divertible flow at Palisade (*cubic feet per second*).*
[=IF(T>0,IF((AA-AD)>0,AA-AD,0),IF((AA-AD)>0,AA-AD,0))]

AF. *Divertible flow subject to peak-flow constraints (*cubic feet per second*).*
[=IF(AND(AA>12900,AA<26600),0,AE)]

AG. *Divertible flow at Palisade (*cubic feet per second*).*
[=MIN(AA,AF)]

AH. *Pumpable flow at Palisade, cubic feet per second.* Depends on user defined pump rate.
[=IF(AND(C>=$I$9,C<=$I$10),MIN(AG,$I$8),0)]

AI. *Pumpable flow at Palisade (acre-ft)*
[=MIN(AH,$I$8)*2]

AJ. *Day.*

AK. *Date.*

Rows 391 – 392 provide the respective annual quantity for flow components in cubic feet per second and acre-feet. Some of these quantities are used in the flow mass-balance table provided in rows 2-14 and columns V-AH. A summary table by season also is provided for flows at Palisade in rows 391-396 and columns X-AG. Empirical equations and their coefficients used in this model are provided beginning at row 396 between columns C and H.

Appendix 2
Water-Quality Model Description

WATER-QUALITY MODEL DESCRIPTION

The purpose of the water-quality model is to compute the change in salinity concentration at points where water enters or exits the study reach. In the Excel water-quality model (QW model), computations pertaining to days of the year (1-365) occupy rows 23-387, whereas the various flows linked to the hydrology model (Q Model) and calculations for salinity, load, and their changes with respect to hydrologic features occupy columns C through BT. The decision variables in this spreadsheet include the initial reservoir volume, acre-ft (cell D8); initial reservoir concentration, mg/L (cell D9); total reservoir volume, acre-ft (cell D10); seasonal release switch where 0 = no, 1 = yes (cell D11); total seasonal release amount, acre-ft (cell D12); seasonal release period, where 1 = daily uniform September release, and 2 = daily uniform release from August 15-October 30 (cell D13); peak-flow release switch, where 0 = no, 1 = yes (cell D14); peak-flow amount, acre-ft (cell D15). Presently, the reservoir surface area replicates a parabolic function of storage volume (characteristic of many reservoirs throughout the Western United States); however, if a constant surface area of 260 acres is required, then the constants provided in cells E416:E418 should be replaced by those constants provided in cells H416:H418. The following description of water-quality components includes spreadsheet column (uppercase letter), parameter (italics), and cell contents (square brackets).

ColumnVariable

A. *Date.*

B. *Day.*

Columns C-M involve calculations related to the Colorado River. Specifically, columns C-G pertain to initial Colorado River water-quality conditions at Cameo, and columns H-M pertain to water-quality effects after reservoir pumping.

C. *Colorado River flow at Cameo Gage* (ft^3/s).
[='Q Model'!G]

D. *Logarithm of Colorado River flow at Cameo gage* (ft^3/s). These values are linked from the Q Model page.
[=LOG(C)]

E. *Colorado River dissolved-solids concentration variability (mg/L).* These independent daily distributions were determined based on residuals analysis (difference between measured and predicted values).
[Daily probability distribution functions]

F. *Colorado River dissolved-solids concentration upstream from (before) Sulphur Gulch Reservoir pump point (mg/L)*. Stochastic determination of salinity values is based on a deterministic regression equation that adds a randomly sampled residual.
[=10^(D*$F$424+$F$425+E)]

G. *Colorado River load upstream from (before) the Sulphur Gulch pump location (tons).*
[=F*0.00137*2*C]

H. *Colorado River flow downstream from the Sulphur Gulch pump location* (ft^3/s).
[=C-P*0.5]

I. *Logarithm of Colorado River flow downstream from the Sulphur Gulch pump location* (ft^3/s).
[=LOG(H)]

J. *Colorado River salinity concentration downstream (after) Sulphur Gulch pump location (mg/L).* Stochastic determination of salinity values are based on a deterministic regression equation that adds a randomly sampled residual.
[=10^(I*$F$424+$F$425+E)]

K. *Change in Colorado River salinity concentration after pumping (percent).*
[=(J-F)/F]

L. *Colorado River salinity load after pumping (tons).*
[=J*0.00137*2*(H)]

M. *Change in Colorado River load after pumping (percent).*
[=(L-G)/G]

N-AL. Water quality pertaining to Sulphur Gulch Reservoir.
N-AL. Sulphur Gulch Reservoir.

N. *Initial reservoir storage (acre-ft).* First cell holds a decision variable: [=IF($D$8>$D$10,$D$10,$D$8)] and the rest of the cells take the difference between previous day's storage after evaporation (N) and reservoir discharge (V) [=IF(AC-(AG*2)-(AI*2)>$D$10,$D$10,AC-(AG*2)-(AI*2))]

O. *Initial reservoir salinity (mg/L)*
First cell holds user-defined initial concentration. [=$D$9]
[=AD]

P. *Colorado River flow being pumped (acre-ft).* If the total reservoir storage is greater than user-defined amount then no pumping (because could be releasing water) otherwise use amount of pumpable flow from Q Model.
[=IF(AH=1,0,IF(N>=$D$10,0,IF($D$10-N<$D$16*2,$D$10-N,IF($D$11=0,
'Q Model'!AI,IF(MAX($N$25:N)>$D$10,0,'Q Model'!AI)))))]

Q. *Salinity concentration of Colorado River being pumped (mg/L).* This concentration is the same as at Cameo.
[=J]

R. *Change in Colorado River salinity concentration (percent).*

[=(Q-F)/F]

S. *Salinity load being pumped from Colorado River (tons).*
[=Q24*0.00137*P]

T. *Natural runoff to Sulphur Gulch,* cubic feet per second. Distribution reflects runoff computed based on hydrograph separation performed on the adjacent Dry Fork watershed.
[Independent daily probability distribution functions]

U. *Runoff salinity concentration variability (mg/L)*. Variability distribution computed using residual analysis.
[Independent daily probability distribution functions]

V. *Runoff salinity concentration to Sulphur Gulch Reservoir (mg/L)*.
[=IF(S>0.005,IF(10^((S)*$F$428+$F$429)+T>0,10^((S)*$F$428+$F$429)+T,0),0)]

W. *Runoff salinity load to Sulphur Gulch Reservoir (tons).*
[=U*0.00137*2*(S)]

X. *Total reservoir storage including residual storage, runoff, and pumped water from the Colorado River (acre-ft)*.
[=N+P+(T*2)]

Y. *Reservoir salinity (mg/L)*. Concentration reflects mixing existing stored water, runoff, and pumped water.
[=(N*O+P*Q+T*2*V)/X]

Z. *Reservoir surface area (acres).* This parabolic equation was fit such that the maximum storage volume (16,000 acre-ft) has a total surface area of 260 acres.
[=((N+T)*$E$424^2 +$E$425*(N+T)+$E$426)]

AA. *Evaporative variability (10^{-2} in)*. Variability was determined by residual analysis.
[Independent daily probability distribution functions]

AB. *Reservoir evaporation (ft).*
[=IF((-21.9606*COS(B*0.5174*2*3.14159/180)+24.649+AA)*0.01/12>0,(-21.9606*COS(B*0.5174*2*3.14159/180)+24.649+AA)*0.01/12,0)]

AC. Remaining reservoir storage (acre-ft).
[=IF(W-(Y*AA)<0,0,(W-(Y*AA)))]

AD. *Remaining reservoir salinity (mg/L)*.
[=IF(X-(Z*AB)<0,0,(X-(Z*AB)))]

AE. *Concentration due to evaporative increase (percent)*.
[=IF(AD=0,0,(AD-Y)/AD)]

AF. *Ideal reservoir release (ft^{3}/s)*. The magnitude of release values (decision variables) is user defined on a daily basis.

AG. *Actual reservoir release (ft^{3}/s)*. These values are all zero if flag = 0 (D11) is used or ideal release values if a flag = 1. Also, a check is used to ensure that no releases occur until the reservoir was first filled to user-defined maximum storage.
[=IF($D$11=2,IF((AF<=X),AF,0),IF($D$11=0,0,(IF(N>AF,AF,IF(N>0,N,0))))))]

AH. *Number of seasonal reservoir release days*. If the reservoir releases water on a given day then a value of one is inserted into the cell, otherwise a value of zero is inserted into the cell.
[=IF(AG>0,1,0)]

AI. *Peak-flow release amount (ft^{3}/s)*. Supplemental flow to hydrograph peak.
[=IF($D$14=3,IF(AND(A>=$J$14,A<$K$14),($D$15*0.5)/($K$14-$J$14),0),IF($D$14=0,0,IF(AND(C>12900,C<26000), IF(SUM($AI$25:AI)<$D$15,500,0),0)))]

AJ. *Actual peak-flow release (ft^{3}/s)*. These values are all zero if flag = 0 (D11) is used or ideal release values if a flag = 1. Also, a check is used to ensure that no releases occur until the reservoir was first filled to user-defined maximum storage.
[=IF(AI<N,AI,IF(N>0,N,0))]

AK. *Number of peak-flow release days*. If the reservoir releases water on a given day then a value of one is inserted into the cell; otherwise, a value of zero is inserted into the cell.
[=IF(AJ>0,1,0)]

AL. *Colorado River flow after release (ft^{3}/s)*.
[=H+AG+AI]

AM. *Colorado River salinity concentration after releases (mg/L)*. Concentration reflects mixing existing stored reservoir and Colorado River water.
[=(H*J+AG*AD+AI*AD)/(H+AG+AI)]

AN. *Change in Colorado River salinity concentration (percent)*. Change in salinity immediately upstream and downstream from the reservoir release point.
[=(AM-J)/J]

AO. *Colorado River load (tons)*.
[=AM*0.00137*2*(AL)]

AP. *Change in Colorado River load concentration (percent)*.

[=(AO-L)/L]

AQ-AV. Government Highline Canal.

AQ. *Government Highline Canal diversion (ft^3/s)*. These cell values are computed in the Q Model page.
[='Q Model'!N]

AR. *Colorado River flow after Government Highline Canal diversion (ft^3/s)*. These cell values are computed in the Q Model page.
[='Q Model'!O]

AS. *Colorado River salinity concentrations downstream from (after) the Government Highline Canal (mg/L)*. Concentrations reflect losses to Government Highline Canal from the Colorado River.
[=IF((AL-AQ)>0,(AL*AM-AQ*AM)/(AL-AQ),0)]

AT. *Change in Colorado River salinity concentration (percent)*.
[=(AS-AM)/AM]

AU. *Colorado River load (tons)*.
[=AS*0.00137*2*(AR)]

AV. *Change in Colorado River load concentration (percent)*.
[=(AU-AO)/AO]

AW-BD. Plateau Creek.

AW. *Streamflow at Plateau Creek near Cameo gage (ft^3/s)*.
[='Q Model'!Q]

AX. *Salinity variability at Plateau Creek near Cameo gage (mg/L)*.
[Independent daily probability distribution functions]

AY. *Salinity at Plateau Creek near Cameo gage (mg/L)*.
[=
IF((10^(LOG(AW)*$F$442+$F$443)+AX)*$F$444>0,(10^(LOG(AW)*$F$442+$F$443)+AX)*$F$444,0
)]

AZ. *Colorado River salinity concentration after Plateau Creek (ft^3/s)*.
[=(AR*AS+AW*AY)/(AR+AW)]

BA. *Change in salinity concentration after Plateau Creek (mg/L)*.
[=IF(AS=0,ABS((AS-AZ)/AZ), (AZ-AS)/AS)]

BB. *Colorado River flow after Plateau Creek (ft^3/s).*
[='Q Model'!R]

BC. *Colorado River load after Plateau Creek (tons).*
[=AZ*0.00137*2*(BB)]

BD. *Change in Colorado River load after Plateau Creek (percent).*
[=IF(AU=0,1,(BC-AU)/AU)]

BE-BP. Grand Valley Irrigation Canal and Orchard Mesa Irrigation return flow.

BE. *Orchard Mesa Irrigation return flow upstream from Grand Valley Irrigation Canal (ft^3/s).* [='Q Model'!U]

BF. *Colorado River flow upstream from Grand Valley Irrigation Canal (ft^3/s).*
[='Q Model'!V]

BG. *Colorado River salinity concentration after Grand Valley Irrigation Canal return flow (mg/L).*
[=(BE*AM+BB*AZ)/(BE+BB)]

BH. *Change in Colorado River salinity after Grand Valley Irrigation Canal return flow* (percent).
[=(BG-AZ)/AZ]

BI. *Colorado River load before Grand Valley Irrigation Canal return flow (tons).*
[=BG*0.00137*2*(BF)]

BJ. *Actual Grand Valley Irrigation Canal diversion (ft^3/s).*
[='Q Model'!Y]

BK. *Colorado River flow after Grand Valley Irrigation Canal diversion (ft^3/s).*
[='Q Model'!Z]

BL. *Colorado River salinity concentration after Grand Valley Irrigation Canal diversion (mg/L).*
[=IF((BF-BJ)=0,0,(BF*BG-BJ*AM)/(BF-BJ))]

BM. *Change in Colorado River salinity concentration after Grand Valley Irrigation Canal diversion (percent).*
[=IF(BL=0,-1,(BL-BG)/BL)]

BN. *Colorado River load after Grand Valley Irrigation Canal diversion (tons).*
[=BL*0.00137*2*(BK)]

BO. *Change in Colorado River load after Grand Valley Irrigation Canal diversion (percent).*

[=(BN-BI)/BI]

BP. *Orchard Mesa Irrigation return flow downstream from Grand Valley Irrigation Canal (ft^3/s).*
[='Q Model'!W]

BQ-BU. Flow and salinity components at Palisade gage (beginning of 15-mile reach).

BQ. *Colorado River flow at Palisade (ft^3/s).*
[='Q Model'!AA]

BR. *Colorado River salinity concentration at Palisade (mg/L).*
[=(BK*BL+BP*AM)/(BP+BK)]

BS. *Change in Colorado River salinity concentration at Palisade (percent).*
[=IF(BL = 0,1,(BR-BL)/BL)]

BT. *Colorado River load at Palisade (tons).*
[=BR*0.00137*2*(BP+BK)]

BU. *Change in Colorado River load at Palisade (tons).*
[=IF(BN=0,1,(BT-BN)/BN)]

BV-BX. Summary of flow and salinity changes over study reach (Cameo to Palisade).

BV. *Change in Colorado River flow over study reach* (ft^3/s)
[(BQ-C)/C]

BW. *Change in Colorado River salinity concentration over study reach (mg/L).*
[=(BR-F)/F]

BX. *Change in Colorado River load over study reach (tons).*
[=(BT-G)/G]

BY. *Day.*

BZ. *Date*.

Rows 390–394 provide seasonal quantities for the respective water-quality components. Basic statistics for the various quantities are provided directly below the daily values computations and can be found in rows 396-400. Some of these quantities are used in the load mass-balance table provided in cells AG2:AL13. A summary table by season also is provided for flows at Palisade in rows 391-396 and columns X-AG. Empirical equations and their coefficients used in this model are provided beginning at row 396 between columns C and H.