Prepared in cooperation with the U.S. Department of the Interior Bureau of Reclamation and Bureau of Land Management

Spatially Referenced Statistical Assessment of Dissolved-Solids Load Sources and Transport in Streams of the Upper Colorado River Basin

Scientific Investigations Report 2009-5007

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph to the northwest showing Gunnison Butte and agricultural land along Green River near Green River, Utah. Photograph by Steven J. Gerner, September 2004.

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
tons per year (tons/yr)	0.9072	metric tons per year (metric tons/ yr)
inch per year (in./yr)	25.4	millimeter per year (mm/yr)
	Mass	
ton	0.9072	metric ton
	Yield	
tons per square mile ($tons/mi^2$)	350	kilograms per square kilometer (kg/km^2)

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88);

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Abbreviations and Acronyms Used in the Text

(Clarification or additional information given in parentheses)

Assign_hydseq	Assign Hydrologic Sequence computer program
BOR	U.S. Bureau of Reclamation
DEM	Digital Elevation Model
GIS	geographic information system
GUG	geologic unit group
HUC	Hydrologic Unit Code
KB	King and Beikman
LOADEST	Load Estimator computer program
mKB	modified King and Beikman
NED	National Elevation Dataset (USGS)
NHD	National Hydrography Dataset (USGS)
NSRS	National Spatial Reference System
NWIS	National Water Information System (USGS)
PRISM	Precipitation-elevation Regressions on Independent Slopes Model (Oregon State University)
RSME	root mean square error
SPARROW	Spatially Referenced Regressions on Watershed attributes (USGS)
STATSGO	State Soil Geographic Data Base
UCRB	Upper Colorado River Basin
U.S.	United States
USGS	U.S. Geological Survey

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Abstract

The Upper Colorado River Basin (UCRB) discharges more than 6 million tons of dissolved solids annually, about 40 to 45 percent of which are attributed to agricultural activities. The U.S. Department of the Interior estimates economic damages related to salinity in excess of $330 million annually in the Colorado River Basin. Salinity in the UCRB, as measured by dissolved-solids load and concentration, has been studied extensively during the past century. Over this period, a solid conceptual understanding of the sources and transport mechanisms of dissolved solids in the basin has been developed. This conceptual understanding was incorporated into the U.S. Geological Survey Spatially Referenced Regressions on Watershed Attributes (SPARROW) surface-water quality model to examine statistically the dissolved-solids supply and transport within the UCRB. Geologic and agricultural sources of dissolved solids in the UCRB were defined and represented in the model. On the basis of climatic and hydrologic conditions along with data availability, water year 1991 was selected for examination with SPARROW.

Dissolved-solids loads for 218 monitoring sites were used to calibrate a dissolved-solids SPARROW model for the UCRB. The calibrated model generally captures the transport mechanisms that deliver dissolved solids to streams of the UCRB as evidenced by R^2 and yield R^2 values of 0.98 and 0.71, respectively. Model prediction error is approximated at 51 percent. Model results indicate that of the seven geologic source groups, the high-yield sedimentary Mesozoic rocks have the largest yield of dissolved solids, about 41.9 tons per square mile (tons/mi^2). Irrigated sedimentary-clastic Mesozoic lands have an estimated yield of 1,180 tons/mi^2, and irrigated sedimentary-clastic Tertiary lands have an estimated yield of 662 tons/mi^2. Coefficients estimated for the seven landscape transport characteristics seem to agree well with the conceptual understanding of the role they play in the delivery of dissolved solids to streams in the UCRB.

Predictions of dissolved-solids loads were generated for more than 10,000 stream reaches of the stream network defined in the UCRB. From these estimates, the downstream accumulation of dissolved solids, including natural and agricultural components, were examined in selected rivers. Contributions from each of the 11 dissolved-solids sources were also examined at select locations in the Grand, Green, and San Juan Divisions of the UCRB. At the downstream boundary of the UCRB, the Colorado River at Lees Ferry, Arizona, monitoring site, the dissolved-solids contribution of irrigated agricultural lands and natural sources were about 45 and 57 percent, respectively. Finally, model predictions, including the contributions of natural and agricultural sources for selected locations in the UCRB, were compared with results from two previous studies.

Introduction

The economic effects of increased salinity in the Colorado River have prompted a number of water-quality related legislative actions. In particular, the Colorado Salinity Control Act and its amendments provide the means and authority for Federal agencies to implement or assist local entities with projects that mitigate the discharge of dissolved solids to the Colorado River. Salinity in streams of the Upper Colorado River Basin (UCRB), as measured by dissolved-solids concentration and load varies substantially. Geologic and land cover characteristics, land-use practices, and precipitation are some of the sources and controlling mechanisms in the production and delivery of dissolved solids to rivers and streams. Management and(or) mitigation of salinity in UCRB streams requires an improved understanding of the spatial distribution of salinity sources, load accumulation, and transport mechanisms.

Streamflow, dissolved-solids concentration, and specific conductance have been measured regularly at more than 200 U.S. Geological Survey (USGS) stream-monitoring sites in the UCRB (fig. 1). River streamflow and chemistry are controlled by the geology, land cover, land use, and precipitation characteristics of the drainage basin. Coupling measurements of discharge, dissolved-solids concentration, and(or) specific conductance at stream-monitoring sites with geology, land cover, land use, climate, and other physical geospatial data within a spatially referenced statistical model can provide a tool for assessing the sources and transport of dissolved solids throughout the UCRB.

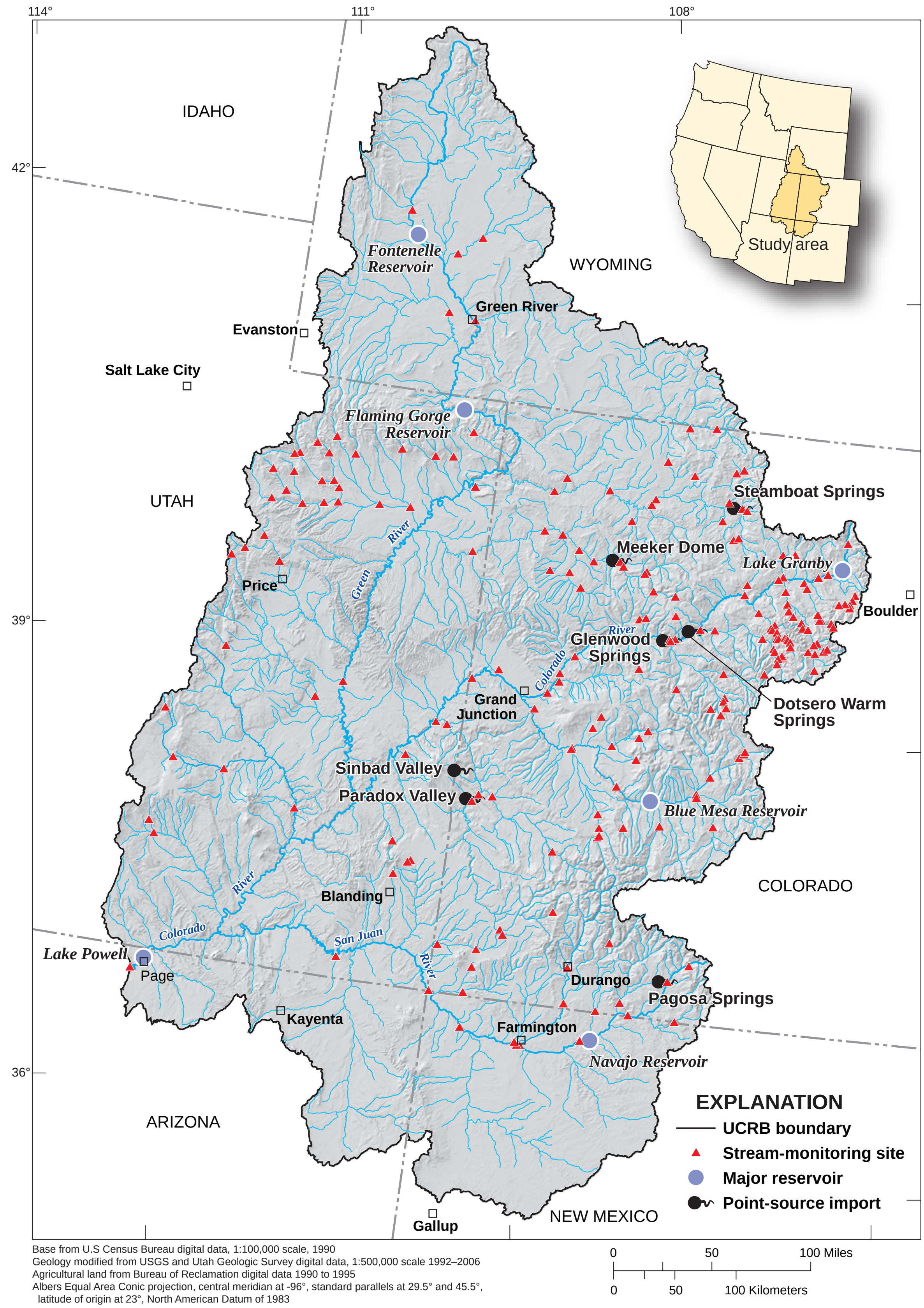

Figure 1. Study area and stream-monitoring sites in the Upper Colorado River Basin (UCRB).

The USGS Spatially Referenced Regressions on Watershed Attributes (SPARROW) surface-water quality model relates measured chemical constituent transport at monitoring stations to upland catchment attributes including contributing upstream reaches (Smith and others, 1997). A large scale, dissolved-solids SPARROW model has been developed for the southwestern United States (U.S.), encompassing the Upper and Lower Colorado and Rio Grande River Basins along with the Great Basin and portions of southern California (Anning and others, 2007). Using similar methods, the USGS, in cooperation with the U.S. Department of the Interior Bureau of Reclamation (BOR) and the U.S. Department of the Interior Bureau of Land Management (BLM), developed a dissolved-solids SPARROW model of the UCRB to assess the sources and transport mechanisms of dissolved-solids loads in streams throughout the basin.

Purpose and Scope

This report documents the methods and data used to develop a dissolved-solids SPARROW model for the UCRB for water year 1991. Model calibration data that includes annual dissolved-solids load estimates from 218 USGS water-quality monitoring sites, are from the 1991 water year, and all catchment attributes were computed from geospatial data representative of conditions during this same time period. Results from this model, including estimates of dissolved-solids load for all defined stream reaches with incremental catchments ranging from less than 1 mi^2 to a maximum of 78 mi^2 within the UCRB, are presented. A discussion of model-generated coefficients specific to their role in producing and transporting dissolved solids to streams in the UCRB is also presented. The applicability of these results to other periods is discussed, and the limitations and uncertainties associated with the model results and interpretation are outlined.

Description of Study Area

The Colorado River Basin, which drains portions of seven states, is the largest river basin in the southwestern U.S.. The UCRB, for this study, is defined as the drainage basin upstream of USGS streamflow-gaging station 09380000, Colorado River at Lees Ferry, Arizona. The UCRB has a contributing drainage area of about 108,000 mi^2 and includes parts of Wyoming, Colorado, Utah, New Mexico, and Arizona (fig. 1). The UCRB drains a large portion of the Rocky Mountains west of the continental divide, from the Wind River Mountains in Wyoming, south to the San Juan Mountains in Colorado. Major river drainages of the UCRB include the Colorado, Green, and San Juan Rivers. The landscapes of the UCRB are varied and consist of high alpine, arid badlands, and slickrock canyonlands. The annual precipitation ranges from about 40 in., mostly as snow, near the continental divide to less than 10 in. on the Colorado Plateau (PRISM Group, Oregon State University, 2007). The Great Divide Basin is a closed basin in southwestern Wyoming, adjacent to the Green River drainage, which is formed from a bifurcation of the continental divide. This portion of the UCRB does not contribute runoff to the remainder of the basin and has been excluded from the study area.

The main stem of the Colorado River and many river systems in the UCRB have perennial streamflow; however, many tributary streams, particularly in low elevation reaches, have intermittent or ephemeral streamflow as a result of climate, hydrogeology, stream regulation, and(or) water diversions. Water development has substantially altered streamflow in the Colorado River drainage. Streamflow in the UCRB is controlled at numerous locations by reservoirs. Many of the larger reservoirs in the Colorado River system alter the seasonal patterns of flow by storing water from snowmelt runoff, a substantial component of the total annual flow, and then releasing it at lower magnitude discharges for longer durations during the remainder of the year. Transbasin diversions of water from the UCRB to the Missouri River Basin (Denver area), the Great Basin (Utah Wasatch Front), Rio Grande Basin (New Mexico), and others account for nearly 5 percent of the virgin streamflow of the UCRB, which is more than 730,000 acre-ft/yr (Liebermann and others, 1989) (table 1). Most waters diverted through these transbasin diversions generally contain a small dissolved-solids load, less than 1 percent of the load at Lees Ferry, Arizona, (Iorns and other, 1965; Anning and others, 2007), because the diversions are in the headwater reaches where there are minimal sources of dissolved solids. While these diversions do not remove a large amount of dissolved solids from the UCRB, diverting these waters leads to an increase of dissolved-solids concentrations during baseflow periods.

Previous Studies

The occurrence and distribution of dissolved solids in surface and ground water of the UCRB has been extensively studied and characterized with a number of significant investigations completed in the 1970s and 1980s. The first comprehensive evaluation of dissolved solids in the basin was made by Iorns and others (1965) who developed many of the dissolved-solids load estimates currently used in models and management plans. Increasing dissolved-solids concentrations in the Lower Colorado River Basin and their associated adverse economic impact led to the enactment of the Colorado River Basin Salinity Control Act in 1974 and the establishment of water-quality criteria for salinity in the Colorado River system (Colorado River Basin Salinity Control Forum, 2005). This in turn, spurred many studies of dissolved solids in the UCRB (U.S. Department of the Interior, 2003). For example, BOR investigated the feasibility of implementing salinity-control measures in agricultural areas such as the Grand Valley of Colorado (U.S. Bureau of Reclamation, 1978) and assessed specific point sources such as Glenwood Springs (Eisenhauer, 1983). Regional studies completed in the 1970s

Table 1. Transbasin diversions that, on average, export more than 2,000 acre-feet of water per year from the Upper Colorado River Basin.
[CO, Colorado; UT, Utah; WY, Wyoming; NA, not available]

Conveyance name	State of origin	Stream origin	Mean annual export (acre-feet per year) [1]	Water year 1991 total export (acre-feet)
Azotea Tunnel	CO	Navajo River	106,600	119,000
H.D. Roberts Tunnel	CO	Blue River	67,720	[2] 66,000
Moffat Water Tunnel	CO	Fraser River	59,720	[2] 64,900
Homestake Tunnel	CO	Eagle River	34,310	[2] 638
C.H. Boustead Tunnel	CO	Frying Pan River	41,470	[2] 61,100
Busk-Ivanhoe Tunnel	CO	Frying Pan River	5,850	[2] 5,660
Twin Lakes Tunnel	CO	Roaring Fork River	42,330	[2] 42,980
A.P. Gumlick Tunnel	CO	Williams Fork	NA	[2] 3,870
Wurtz Ditch	CO	Eagle River	2,910	[2] 2,260
Alva B. Adams Tunnel	CO	Grand Lake, Colorado River	247,200	[2] 199,000
Grand River Ditch	CO	Colorado River	17,540	[2] 18,400
Hoosier Pass Tunnel	CO	Blue River	8,000	[2] 12,400
Strawberry Tunnel	UT	Strawberry River	67,820	[3] 88,900
Duchesne Tunnel	UT	Duchesne River	18,180	[3] 21,100
Fairview Tunnel	UT	Huntington Creek	2,340	3,460
Ephraim Tunnel	UT	Cottonwood Creek	4,350	2,750
Spring City Tunnel	UT	Cottonwood Creek	2,210	2,150
Cheyenne Diversion	WY	Little Snake River	7,050	[4] 17,600

[1] From Lieberman and others, 1989.

[2] From Colorado Division of Water Rights, 2006.

[3] From Central Utah Water Conservancy District (written commun. Aug. 17, 2006).

[4] From State of Wyoming Engineer (written commun. Nov. 3, 2006).

and 1980s characterized dissolved solids in many subbasins of the UCRB such as the Dirty Devil (Mundorf, 1979) and San Rafael (Lindskov, 1986) River Basins. An evaluation of the ground-water contributions to salinity of the UCRB was completed by Warner and others (1985). Liebermann and others (1989) characterized the occurrence and trends of streamflow and dissolved solids in the UCRB. More recently, the results of implementing salinity-control projects, such as those in the Grand Valley (Champion and others, 2004), have been studied as well as trends in dissolved-solids concentrations in surface waters of the UCRB (Vaill and Butler, 1999). Finally, the regional study of dissolved solids in surface water of the southwestern U.S. by Anning and others (2007), which included a dissolved-solids SPARROW model, provided a framework for this finer scale SPARROW modeling effort specific to the UCRB.

Conceptual Model of Dissolved Solids in the UCRB

The SPARROW surface-water quality model uses a mass-balanced approach to examine the transport of instream constituent mass, or flux, on the basis of a nonlinear weighted least squares regression technique. Flux is modeled by simplifying the constituent transport process into diffuse, or nonpoint, source variables, and landscape and aquatic transport characteristics that act upon individual source variables. The first step in developing a dissolved-solids SPARROW model for the UCRB was to refine the conceptual understanding of how dissolved solids are generated, transported, and evolve within the UCRB and incorporate this into the framework of the SPARROW model. Previous studies have identified the significant sources, transport mechanisms, and geochemistry of dissolved solids in the UCRB. The general conceptual model of the sources and transport of dissolved solids within the UCRB is shown in figure 2.

Sources of Dissolved Solids

Major sources of dissolved solids in the UCRB are generally categorized as either natural or agricultural. Iorns and others (1965) found municipal sources to be negligible. Bedrock geology, particularly sedimentary rock, is the largest natural source of dissolved solids to streams in the UCRB (Iorns and others, 1965; Liebermann and others, 1989; U.S. Department of the Interior, 2003; Anning and others, 2007). Dissolved solids are produced from various bedrock lithologies through the

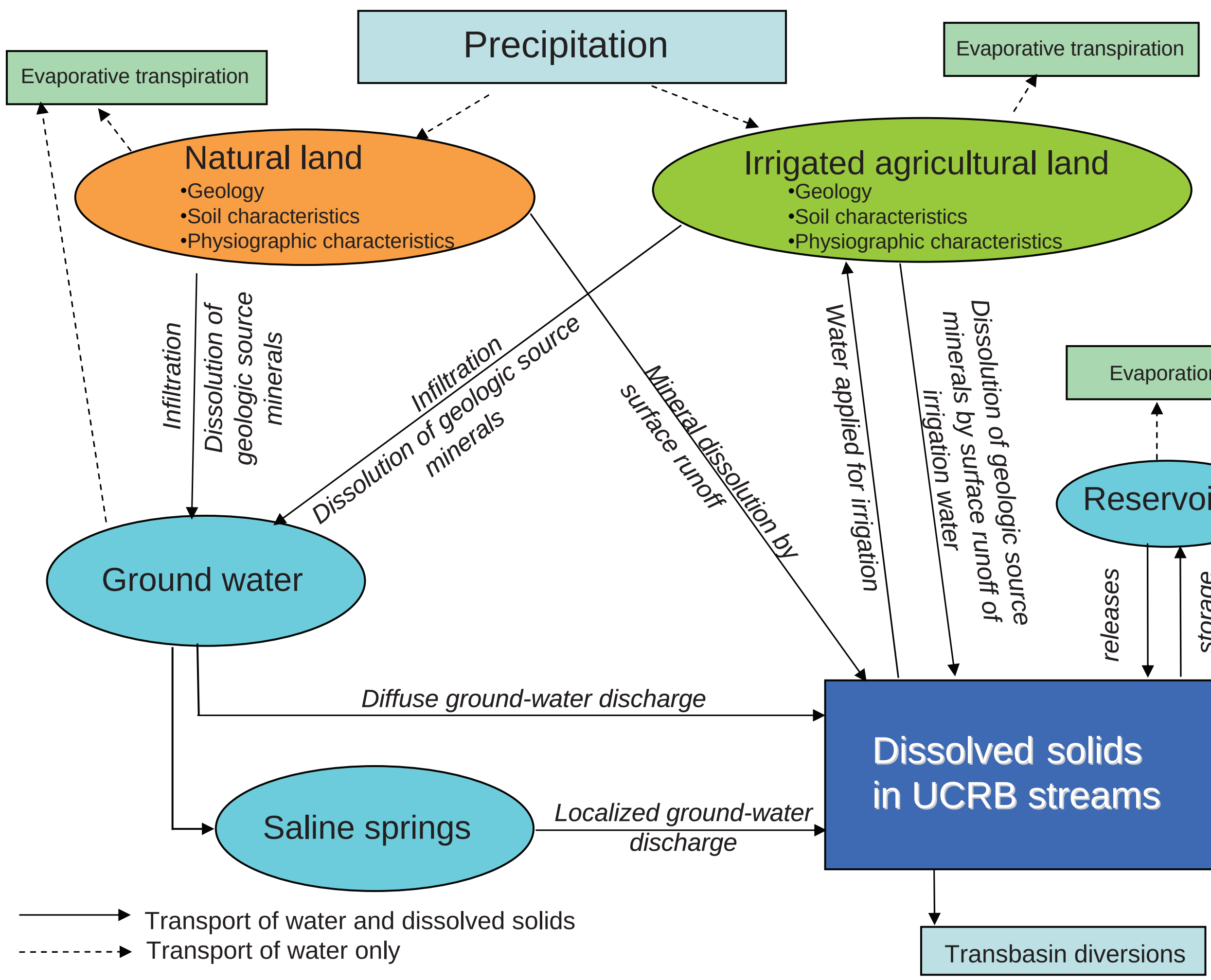

Figure 2. Conceptual model illustrating the processes by which the dissolved-solids loads are generated and transported to streams in the Upper Colorado River Basin (UCRB).

process of dissolution of mineral salts by both surface runoff and ground-water flow. Saline springs, large point sources of ground-water discharge, are natural sources of dissolved solids. Dissolved solids discharged from the seven largest springs in the UCRB—Dotsero, Glenwood, Meeker Dome, Paradox Valley, Steamboat, Pagosa, and Sinbad Valley—have been estimated at 800,000 tons/yr (U.S. Department of the Interior, 2003). Irrigation of agricultural lands, particularly those derived from sedimentary rocks, is the major anthropogenic source of dissolved solids in the UCRB, accounting for about 40 percent of the dissolved-solids load (Iorns and others, 1965; Liebermann and others, 1989; U.S. Department of the Interior, 2003). Application of irrigation water to arid lands alters the natural rate at which solids are dissolved and transported to streams.

Landscape Transport of Dissolved Solids

The major land-to-water transport mechanism associated with natural sources of dissolved solids is precipitation. Chemical weathering of geologic materials high in dissolvable minerals, either as surface runoff or ground-water flow, is highly correlated with precipitation. Evaporative transpiration in the context of the SPARROW framework, is another mechanism that can enhance the transport of dissolved solids to streams. Evaporative transpiration is the process of transferring water to the atmosphere through evaporation of water and transpiration from plants. Vegetation consumes water containing dissolved solids from within the soil zone and transpires pure water leaving behind the dissolved minerals. Over time, these minerals are concentrated within the upper portion of the soil, a zone that is readily accessible for dissolution through precipitation and surface runoff. Evaporation on bare soils also removes pure water and precipitates evaporite minerals on the soil surface, which are immediately available for dissolution through precipitation and surface runoff. Other mechanisms that allow for the transport of dissolved solids from landscape sources to streams in the UCRB are generally not very well defined or understood particularly because they modify the effects of precipitation. For example, an equal amount of rainfall transports dissolved solids differently in steep terrain than in flat terrain, and in vegetated soils compared with bare soils. Physical parameters associated with the landscape, such as basin slope, soil characteristics, or land cover, conceptually can play a role in either enhancing or impeding the transport of dissolved solids to streams.

Instream Evolution of Dissolved Solids

In general, dissolved solids in surface waters of the UCRB are geochemically conservative. Thus, it can be assumed that under steady streamflow conditions, the dissolved-solids load will remain constant and will not change under the natural temperature range or as a result of geochemical reactions with other natural constituents contained within the water, open-water evaporation, or reactions with streambed materials. Applying these assumptions to the SPARROW framework essentially eliminates the consideration of changes in the dissolved-solids load within the streams in the UCRB.

While dissolved-solids loads in the streams in the UCRB conceptually do not change, reservoirs, specifically their management and the process of evaporation of their water, can affect the fate of dissolved solids within the aquatic environment. Increased storage of water, and therefore, increased dissolved-solids load within a reservoir leads to a smaller load at the outflow than the sum of reservoir inflows. A decrease in reservoir storage, either from outflows exceeding inflows or from evaporation, conceptually increases the dissolved-solids load at the outflow relative to the sum of reservoir inflows.

SPARROW Model Description

The SPARROW surface-water quality model relates instream constituent mass, or flux, at monitoring sites in a basin to upstream catchment attributes using a nonlinear regression technique that can be described as a hybrid statistical and process-based approach (Schwarz and others, 2006). Through a defined interconnected stream reach network, a SPARROW model is able to take advantage of the spatial referencing of catchment attributes and monitoring data. The connectivity of the network allows for routing of flux through the basin and thus, is capable of providing estimates of flux at all defined reaches using a mass-balance approach.

The interconnected stream reach network defines the surface streamflow paths for the basin of interest and spatially connects the sources and landscape characteristics to the monitoring sites (Schwarz and others, 2006). The network is comprised of uniquely numbered reaches that are connected to one another by upstream and downstream nodes, termed the “from-node” and “to-node,” respectively. All nodes are uniquely numbered and can take the form of both from- and to-nodes within the network. For example, the to-node for a reach becomes the from-node in the next downstream reach. The confluence of two or more reaches is represented by a shared to-node. Using this infrastructure, a hydrologic sequence of flow in the downstream direction can be defined. It is this sequence that the model, as shown in equation 1, is applied.

By combining the stream reach network with digital elevation models (DEMs), catchments can be defined for each unique stream reach. These catchments represent the contributing drainage area, or incremental drainage area, for each individual reach as defined by the from- and to-nodes. The total drainage area for any location within the network can be obtained by summing all incremental drainage areas upstream of the location of interest. Using geographic information system (GIS) tools, geospatial data to be evaluated in the SPARROW model as sources, landscape transport variables, or aquatic transport variables can be computed for each defined catchment of the stream reach network.

The SPARROW modeling framework classifies catchment attributes into three terms: diffuse or nonpoint sources, landscape transport, and aquatic transport. Diffuse-source terms represent the sources of a chemical constituent that are distributed throughout the basin, such as mineral salts in a specific shale unit. Environmental processes that affect the release and transport of the constituent mass from the sources to the streams are represented by the landscape transport characteristics to which the landscape transport function is applied, such as the precipitation. Likewise, instream decay or attenuation processes of the constituent of interest as it is transported within streams and(or) reservoirs are represented by the aquatic transport characteristics to which the aquatic transport function is applied. It is the sources and process-related characteristics that coefficients are estimated for during model calibration. The mathematical representation of the SPARROW model is given by the equation (Schwarz and others, 2006):

$$L_i = \underbrace{\left(\sum_{j \in J(i)} L'_j \right) \delta_i A(\mathbf{Z}_i^{\mathrm{S}}, \mathbf{Z}_i^{\mathrm{R}}; \boldsymbol{\theta}_{\mathrm{S}}, \boldsymbol{\theta}_{\mathrm{R}})}_{\text{Load component of upstream reaches}} + \underbrace{\left(\sum_{n=1}^{N_s} S_{n,i} \alpha_n D_n(\mathbf{Z}_i^{\mathrm{D}}; \boldsymbol{\theta}_{\mathrm{D}}) \right) A'(\mathbf{Z}_i^{\mathrm{S}}, \mathbf{Z}_i^{\mathrm{R}}; \boldsymbol{\theta}_{\mathrm{S}}, \boldsymbol{\theta}_{\mathrm{R}})}_{\text{Load component of the incremental reach}} \quad (1)$$

where

- L_i is the load leaving reach i, in units of mass/time,
- L'_j is the load that leaves upstream reaches and is delivered to reach i, in units of mass/time,
- δ_i is the fraction of upstream flux delivered to the incremental reach, dimensionless,
- $A(\cdot)$ is the aquatic transport function,
- $\mathbf{Z}^{\mathrm{S}}$ is the vector of stream characteristics associated with aquatic transport,
- $\mathbf{Z}^{\mathrm{R}}$ is the vector of reservoir characteristics associated with aquatic transport,
- $\boldsymbol{\theta}_{\mathrm{S}}$ are the estimated coefficient vectors of stream characteristics associated with aquatic transport,
- $\boldsymbol{\theta}_{\mathrm{R}}$ are the estimated coefficient vectors of reservoir characteristics associated with aquatic transport,
- S_n is source n, in units of mass, area or other property,
- α_n is the estimated source coefficient for source n,
- $D_n(\cdot)$ is the landscape transport function,
- $\mathbf{Z}_i^{\mathrm{D}}$ are the vector environmental characteristics associated with landscape transport,
- $\boldsymbol{\theta}_{\mathrm{D}}$ are the estimated coefficient vectors of environmental characteristics associated with landscape transport, and
- $A'(\cdot)$ is the aquatic transport function as applied to the incremental reach.

The load leaving a given reach, L_i, is comprised of an upstream component and the incremental reach component (equation 1). The upstream component is a summation of the calculated incremental loads from upstream reaches, with attenuation functions for aquatic transport of mass applied, $A(\mathbf{Z}_i^{\mathrm{S}}, \mathbf{Z}_i^{\mathrm{R}}, \boldsymbol{\theta}_{\mathrm{S}}, \boldsymbol{\theta}_{\mathrm{R}})$, which is then multiplied by the fraction of upstream flux delivered value, δ_i, of the given reach.

The load of the incremental reach is computed by applying the estimated source coefficients to the sources contained within the incremental reach, applying the specified landscape transport function for each source, which includes the landscape transport characteristics of the incremental reach and their estimated coefficients, and finally, applying the specified attenuation function, which includes the aquatic transport characteristics of the incremental reach and their estimated coefficients. Water diversions, which conceptually remove constituent mass from the system, can be accounted for in the stream network by defining the fraction of upstream flow delivered, which is assumed equal to the fraction of upstream flux delivered, δ_i, to the next downstream reach. In most cases, the amount of constituent mass that is diverted is unknown, but an estimate of the fraction of water that is diverted is likely more readily available. The total load leaving a given reach, L_i, is the sum of the upstream and incremental load components.

This nonlinear model structure with additive sources and multiplicative transport terms is conceptually consistent with the mechanisms that explain contaminant supply and transport (Richard Alexander, U.S. Geological Survey, oral commun., October 25, 2006). Of particular importance to modeling flux through a stream network, is that this nonlinear approach preserves mass balance. For a more detailed and technical discussion on the SPARROW surface-water quality model, see Schwarz and others (2006).

The calibration routine for a SPARROW model utilizes the spatial referencing and connectivity of the stream network. The network infrastructure to which all stream reaches are linked allows for unique calibration reaches specific to each monitoring site. The size and composition of calibration reaches, in terms of upstream catchment attributes, are determined by the location of monitoring sites within the stream network. Each monitoring site represents a unique calibration reach that is bound upstream by either headwater reaches, a combination of headwater reaches and upstream monitoring site(s), or solely by upstream monitoring site(s). A schematic representation of a calibration reach comprised of a series of individual catchments is shown in figure 3. This compartmentalizing of independent calibration reaches facilitates a mass-balanced calibration. By following this approach throughout the calibration process, the model separates the amount of flux delivered between monitoring sites (the difference of measured flux between the calibration reach bounds) and relates it to the attributes of the catchment defined by the reach. By using the unique calibration reaches, mass remains balanced and independence between observations is preserved.

Through the calibration process, source-specific coefficients, α_n, are determined for each significant diffuse source, S_n. The landscape transport function, $D_n(\mathbf{Z}_i^{\mathrm{D}}; \boldsymbol{\theta}_{\mathrm{D}})$, is applied to each of these sources. Landscape transport is a source-specific function of a vector of delivery characteristics, $\mathbf{Z}_i^{\mathrm{D}}$, and an associated vector of estimated coefficients, $\boldsymbol{\theta}_{\mathrm{D}}$ (Schwarz and others, 2006), determined during model calibration. As a decay or attenuation function, aquatic transport, $A(\mathbf{Z}_i^{\mathrm{S}}, \mathbf{Z}_i^{\mathrm{R}}, \boldsymbol{\theta}_{\mathrm{S}}, \boldsymbol{\theta}_{\mathrm{R}})$, accounts for mass changes over time spent in the stream or reservoir environment. $A'(\mathbf{Z}_i^{\mathrm{S}}, \mathbf{Z}_i^{\mathrm{R}}, \boldsymbol{\theta}_{\mathrm{S}}, \boldsymbol{\theta}_{\mathrm{R}})$ represents the aquatic transport function describing decay or attenuation of the incremental reach load, which differs slightly from $A(\mathbf{Z}_i^{\mathrm{S}}, \mathbf{Z}_i^{\mathrm{R}}, \boldsymbol{\theta}_{\mathrm{S}}, \boldsymbol{\theta}_{\mathrm{R}})$ because flux associated with incremental reaches receives the square root of the reaches instream decay because it is assumed to be delivered at the midpoint of the reach and thus, experiences only half the travel time of the reach (Schwarz and others, 2006). Contained within the aquatic

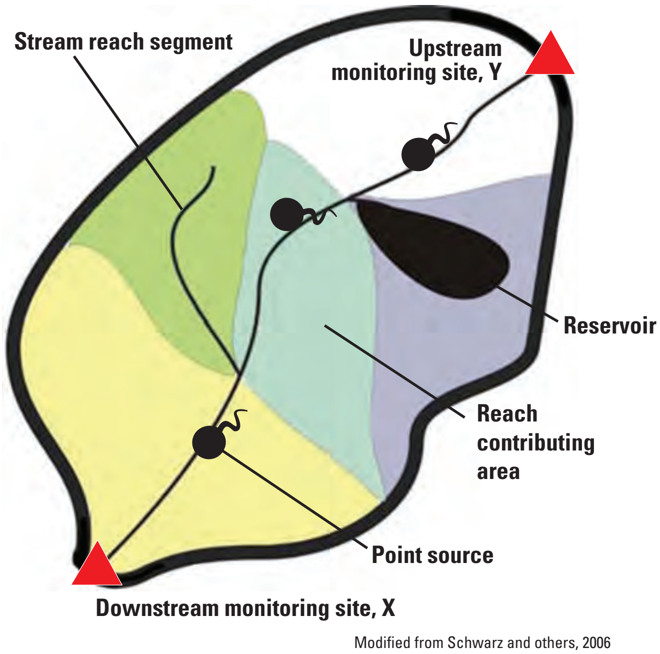

Figure 3. Schematic representation of a calibration reach made up by a series of incremental reaches, defined by colors, and bound by an upstream monitoring site and headwater reaches.

transport function are stream and reservoir characteristics, denoted by the vectors $\mathbf{Z}_i^S$ and, $\mathbf{Z}_i^R$ respectively, and estimated vectors of coefficients $\boldsymbol{\theta}_S$ and $\boldsymbol{\theta}_R$. During calibration, coefficients are estimated for each diffuse source, landscape transport characteristic, and aquatic transport characteristic. For this reason, these coefficients represent an average condition of the role each term and characteristic play throughout the basin of interest, assuming an unbiased distribution of the monitoring sites used in model calibration.

UCRB Dissolved-Solids SPARROW Model

The first application of the SPARROW modeling framework to the transport of dissolved solids was done with median annual dissolved-solids loads for the period 1974–2003 in the southwestern U.S., which includes the Upper and Lower Colorado and Rio Grande River Basins along with the Great Basin and portions of southern California (Anning and others, 2007). The conceptual sources and transport mechanisms of dissolved solids in the southwestern U.S. parallel those of the UCRB. The southwestern U.S. effort provided a regional understanding for a 30-year period of how dissolved solids are produced and transported. By adopting similar methods to those of Anning and others (2007), this investigation of the UCRB was able to examine dissolved-solids transport at a finer scale, in terms of the stream reach network and geospatial data used, within a smaller basin. Different from Anning and others (2007), and further described below, a single water year was selected in an effort to provide resource managers with time-specific, dissolved-solids conditions in streams of the UCRB.

The conservative behavior of dissolved solids in streams of the UCRB was verified in Anning and others (2007) in that the only aquatic transport characteristics dealing with the removal of loads were associated with decreases in streamflow: changes in reach discharge and percent Quaternary basin fill. While an aquatic transport function was applied to these characteristics, it was not used to account for geochemical constituent decay or attenuation processes. The geology of the UCRB indicates little Quaternary fill and minimal streamflow-losing reaches. In general, most decreases in downstream streamflow for the 1991 UCRB stations are related to reservoirs and to large diversions, such as the Government Highline Canal and Grand Valley water diversion structures near Grand Junction, Colorado. Large diversions and flow decreases associated with reservoir storage were accounted for using the fraction of upstream flux delivered, δ_i, reach characteristic.

In considering the temporal resolution selected for this modeling effort of a single water year, together with the quantity of flux being modeled versus the influence of processes that could affect dissolved solids in the aquatic environment, the assumption that any dissolved solids that enter streams in the UCRB are transported through the system, unless diverted or stored in reservoirs, is justified. Conceptually, this conservative behavior suggests that there are no attenuation or decay processes associated with dissolved-solids loads in UCRB streams or reservoirs that need to be accounted for. For these reasons, along with available data, aquatic transport processes were assumed minimal enough to discount and were not considered in this modeling effort. Hence, the aquatic transport terms of the SPARROW modeling framework were not considered for the UCRB. Eliminating the aquatic transport terms from equation 1 and specifying it to represent dissolved-solids sources and transport in the UCRB generates the equation:

$$L_i = \underbrace{\left(\sum_{j \in J(i)} L'_j \right)\delta_i}_{\text{Load component of upstream reaches}} + \underbrace{\left(\sum_{n=1}^{N_s} S_{n,i}\alpha_n D_n(\mathbf{Z}_i^{\mathrm{D}}; \boldsymbol{\theta}_{\mathrm{D}}) \right)}_{\text{Load component of the incremental reach}} \quad (2)$$

where

L_i is the dissolved-solids load leaving reach i, in units of mass/time,

L'_j is the dissolved-solids load that leaves upstream reaches and is delivered to reach *i*, in units of mass/time,

δ_i is the fraction of upstream flux delivered to incremental reach, dimensionless,

S_n is the dissolved-solids source *n*, in units of mass, area or other property,

α_n is the estimated source coefficient for dissolved-solids source n,

$D_n(\cdot)$ is the landscape transport function,

$\mathbf{Z}_i^D$ are the vector environmental characteristics associated with landscape transport of dissolved solids, and

$\boldsymbol{\theta}_D$ are the estimated coefficient vectors of environmental characteristics associated with landscape transport of dissolved solids.

Selection of Water Year 1991

The SPARROW surface-water quality model allows for a mass-balanced examination of the spatial and statistical relation that exist between measured flux, and flux sources and transport characteristics for large basins. Conventionally, the SPARROW model has been applied to study the transport of constituent mass using monitoring data from longer periods of record, often 10 or more years, adjusted for desired conditions such as a target year. This approach has been used for a number of reasons, including the desire to understand time-averaged conditions of contaminant transport, or simply because of data availability. The southwestern U.S. dissolved-solids SPARROW model (Anning and others, 2007) was calibrated on median annual loads computed for monitoring sites with periods of record generally greater than 10 years that occurred within a defined 30-year period (1974–2003). Using these criteria, the median statistic was assumed temporally representative of recent years (Anning and others, 2007).

Dissolved solids have been studied extensively in the UCRB over the past 40 years. These efforts have provided resource managers with a conceptual understanding of the sources and major landscape transport mechanisms associated with dissolved solids. Anning and others (2007) described the general time-averaged conditions of dissolved-solids transport for the entire southwestern U.S., which included the UCRB. For this investigation of dissolved solids in the UCRB, a single water year, 1991, was chosen.

Modeling a single year has a number of advantages. A principal goal of this investigation was to provide resource managers with a statistical assessment of dissolved-solids transport in the UCRB for use in water and salinity management decisions. An analysis of dissolved-solids transport in the UCRB for water year 1991 provides a temporal reference point to which conditions in the basin for other periods can be readily compared. Utilizing the annual dissolved-solids load at water-quality-monitoring sites for a single year reduces the influence of multi-year climatic variability inherent in models that contain data from multiple years. Estimated coefficients for source variables and landscape transport characteristics are specific to the conditions experienced in the basin for that year rather than average conditions over a longer period.

Dissolved-solids monitoring data consisting of dissolved-solids concentrations and specific-conductance measurements were available annually at more than 195 USGS streamflow-gaging stations with periods of record of 10 or more years during the period of 1984 through 1991 (fig. 4; Anning and others, 2007). Much less data are available in the UCRB for other periods. For these 8 years, annual streamflow and precipitation were compared with long-term averages to select a year that was similar to normal climatic and hydrologic conditions.

Thirty-year average precipitation estimates for the UCRB for the period 1974–2003 were computed at a 4-km resolution from annual precipitation estimates obtained from the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) Group (PRISM Group, Oregon State University, 2007). Precipitation estimates for the years 1984–1991, the period with maximum dissolved-solids data available, were compared with the 30-year average precipitation, and water years 1987, 1988, and 1991 appeared to be most similar to the 30-year average. The spatial distribution of the deviation of the annual precipitation from the average precipitation for these years was further examined graphically (fig. 5) and numerically (fig. 6). Total annual streamflow for water years 1984–1991 were compared with mean annual streamflow for selected streamflow-gaging stations in the UCRB with periods of record of 10 or more years. This analysis indicated that streamflows in water years 1987 and 1991 were nearest to average conditions in the UCRB for the periods of record of the streamflow-gaging stations.

The final decision to model water year 1991, after analyzing the meteorologic and hydrologic data for 1984–1991, the period with maximum dissolved-solids data available, was influenced by the availability of geospatial datasets. Many landscape transport characteristics to be tested as predictors of dissolved-solids loads in the UCRB were computed from geospatial data that is time dependent. The UCRB has experienced a large population growth over the past quarter century,

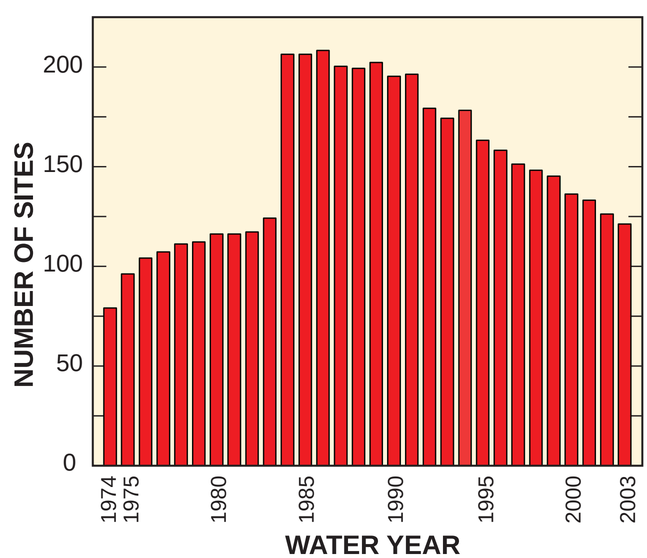

Figure 4. Number of USGS streamflow-gaging stations with dissolved-solids monitoring data in the Upper Colorado River Basin (UCRB) for the period 1974 through 2003.

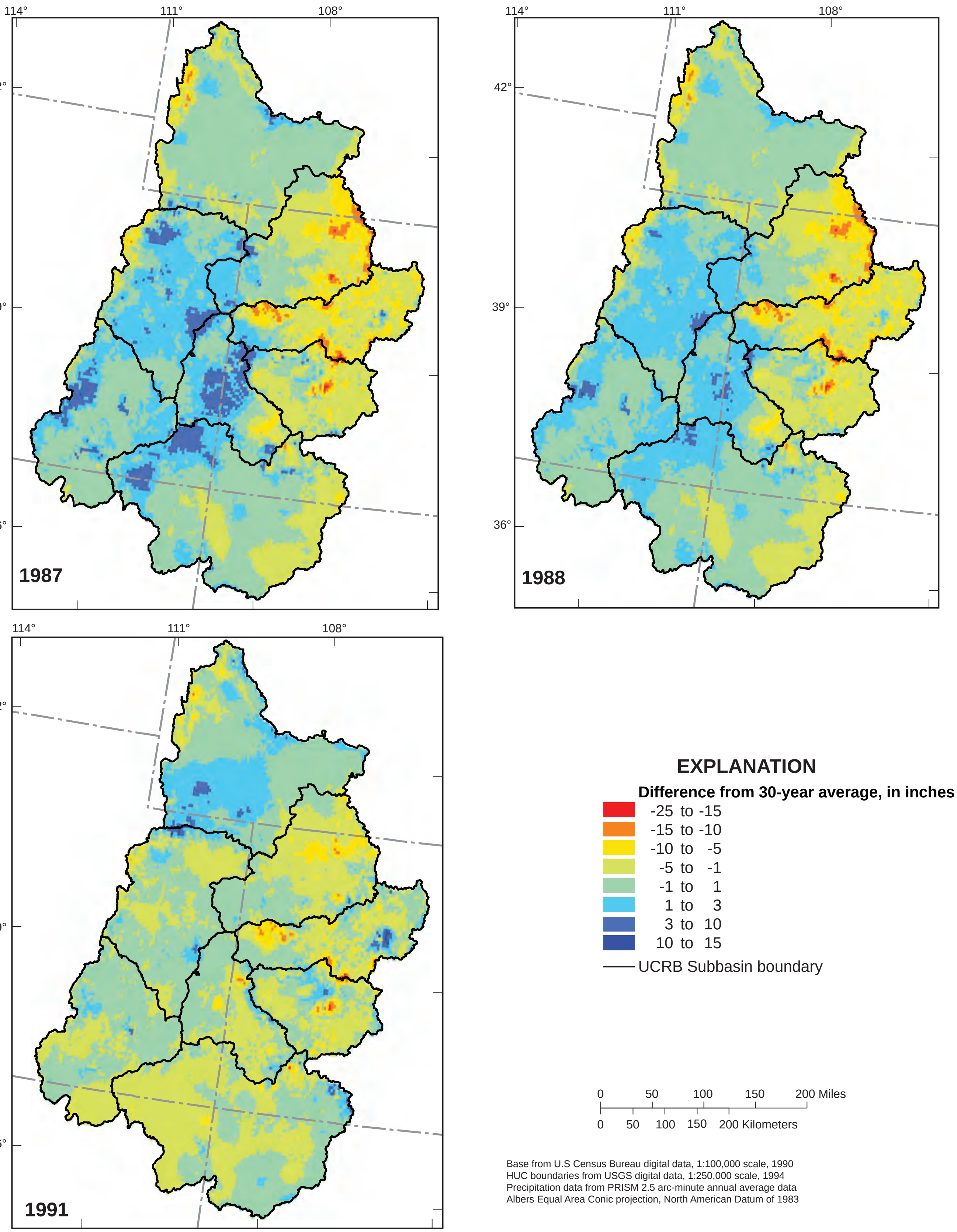

Figure 5. Annual deviation of precipitation from the 30-year average in the Upper Colorado River Basin (UCRB) for water years 1987, 1988, and 1991.

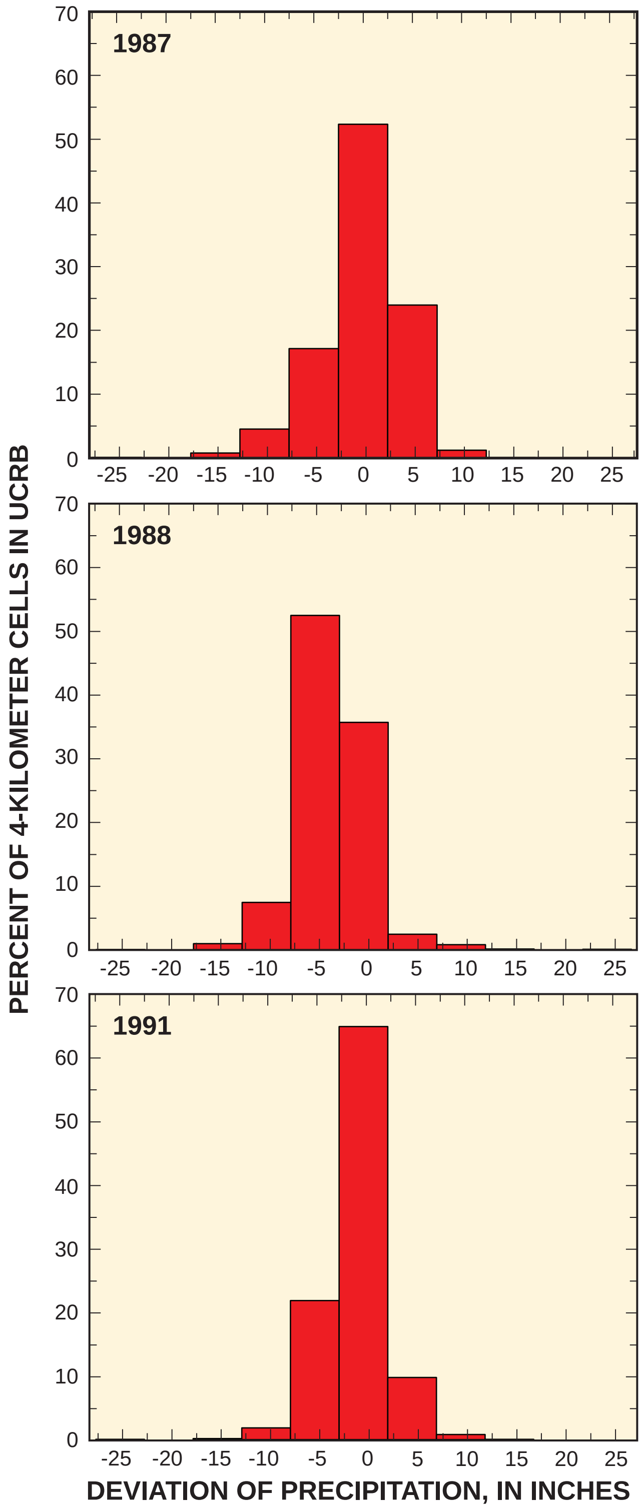

Figure 6. Annual deviation of precipitation for 4-kilometer cells in the Upper Colorado River Basin (UCRB) for water years 1987, 1988, and 1991.

which has had an effect on land use. Most available geospatial datasets are from the 1990s, and it was determined to be most beneficial to select water year 1991, which was hydrologically near normal, but also closer in time to the geospatial data available.

Dataset Development

A comprehensive dataset for the UCRB was assembled for input into the SPARROW model. These data consisted of a high resolution stream reach network, annual dissolved-solids load data from monitoring sites, and a variety of geospatial data related to the conceptual sources and landscape transport mechanisms. Generally, most data were readily available from their developing institutions or agencies; however, some unique datasets, as described below, were constructed or modified from readily available datasets to meet the needs of this modeling effort.

SPARROW is a predictive statistical model, and fundamental to predictive statistical modeling is the testing of a number of independent parameters for significance in predicting the dependent variable—for this study, annual dissolved-solids load. Thirty-seven parameters were tested as either sources or landscape transport characteristics. Table 2 contains the unique parameters tested and their associated dataset(s). References for the datasets used are contained in table 3. Tested sources and landscape transport characteristics that were found to be significant predictors of annual dissolved-solids loads in the streams of the UCRB, and therefore, remained in the final calibrated model, are described in more detail below.

Stream Reach Network and Associated Catchments

The SPARROW model requires a hydrologically connected representation of a stream network through which loads are transported from an upstream reach to the next reach downstream (Schwarz and others, 2006; Moore and others, 2004). Each stream reach or segment within this synthetic stream network has an associated local drainage area or catchment. The synthetic stream reach network and associated catchments created for the UCRB SPARROW model were assembled using a DEM and a vector-based representation of the major streams in the UCRB. The data were processed using ArcInfo Workstation Grid methods (Environmental Systems Research Institute, 1999). Processing steps are outlined below.

A DEM is a representation of topographic elevation that uses a grid of square cells each with an associated value that is the average elevation of the area covered by the cell. The DEM used for development of the UCRB SPARROW catchments was the 1/3 arc-second National Elevation Dataset (NED; U.S. Geological Survey, 2002). A single grid cell in the 1/3 arc-second NED has a spatial resolution of approximately

10 m and occupies 100 m^2. The vector-based stream data used in processing was the 1:100,000-scale National Hydrography Dataset (NHD; U.S. Geological Survey, 1999). The NHD is a dataset that interconnects and uniquely identifies representations of the stream segments that make up the nation's surface-water drainage system (U.S. Geological Survey, 1999). The hydrologic network and catchments were developed in discrete parts on the basis of 8-digit Hydrologic Unit Code (HUC) subbasins (Seaber and others, 1987) that contribute flow within the UCRB. These parts were later merged together to create a single dataset for the entire study area.

The source DEM was first passed through a function that exaggerated the height or created walls at each subbasin boundary. The height was exaggerated everywhere except at the outlet, or pour-point, of the subbasin. Building a walled DEM ensured that flow would remain within the boundary and would exit the subbasin at a single pour-point during subsequent processing. The walled DEM was passed through a surface reconditioning algorithm known as Agree (Hellweger, 1997). This created a new DEM into which stream segments derived from the NHD were deeply incised. The Agree method ensured that the stream network derived from the DEM would more accurately represent the flow paths mapped by the NHD. The NHD stream segments used during the Agree process were selected on the basis of NHD attributes and in a way that man-made structures and flow diversions such as pipelines and canals were removed before incision into the DEM.

The final phase of DEM processing created three derivatives of the Agree DEM that were used to create the final stream network and associated reach catchments. The three datasets, in the order that they were produced, are a DEM with depressions filled, a dataset defining the flow direction for each grid cell, and a flow accumulation grid in which each cell receives a value equal to the total number of cells that drain into it (Jenson and Dominque, 1988).

Stream lines were delineated from the elevation derivatives by a grid modeling process that located and connected consecutive grid cells where the flow accumulation was above a predetermined threshold limit. Cells above this limit were assigned a value of one and remaining cells were assigned values of "no data." The cells with values equal to one were then merged into distinct stream reaches by applying a link code that changed values where two stream reaches formed a confluence. The individual catchments for each stream reach were defined using the linked stream reach cells in conjunction with the flow direction grid to define the spatial extent of the cells that flowed through each unique stream segment (Maidment, 2002).

Table 2. Sources and landscape transport characteristics and associated datasets used in the SPARROW model.

[USGS NWIS, U.S. Geological Survey National Water Information System; BOR, U.S. Bureau of Reclamation; EPA STORET, Environmental Protection Agency Storage and Retrieval database; DLG, Digital Line Graph; NED, National Elevation Dataset; NHD, National Hydrography Dataset; PRISM, Parameter-Elevation Regressions on Independent Slopes Model; NLCDe, Enhanced National Land Cover Dataset; STATSGO, State Soil Geographic Database]

Tested model parameters	Datasets used
Dissolved-solids sources	
Point-source imports, in tons	USGS NWIS, BOR sources of salt loading, EPA STORET
Crystalline and volcanic rocks, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming
High-yield sedimentary Cenozoic rocks, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming
Low-yield sedimentary Cenozoic rocks, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming
High-yield sedimentary Mesozoic rocks, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming
Low-yield sedimentary Mesozoic rocks, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming
High-yield sedimentary Paleozoic and Precambrian rocks, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming
Low-yield sedimentary Paleozoic and Precambrian rocks, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming
Irrigated sedimentary-clastic Tertiary lands, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming. BOR irrigated lands data
Irrigated sedimentary-clastic Mesozoic lands, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming. BOR irrigated lands data
Irrigated lands of other lithologies, in square miles	Geologic map of United States, 1:500,000-scale digital geologic maps of Arizona, Colorado, New Mexico, Utah, and Wyoming. BOR irrigated lands data

Table 2. Sources and landscape transport characteristics and associated datasets used in the SPARROW model.—Continued

Tested model parameters	Datasets used
Landscape transport characteristics	
Drainage density, dimensionless	1:24,000-scale NHD
Density of all roads, dimensionless	1:100,000 DLG Roads
Density of improved roads, dimensionless	1:100,000 DLG Roads
Density of unimproved roads, dimensionless	1:100,000 DLG Roads
Catchment maximum elevation, in feet	30-meter NED
Catchment minimum elevation, in feet	30-meter NED
Catchment relief	30-meter NED
Reach slope, dimensionless	30-meter NED
Total 1991 precipitation, in inches	PRISM
Total 1991 evapotranspiration, in inches	30-minute total evapotranspiration estimates for water year 1991 (Wilmott and Matsurra, 2001)
1991 total precipitation, total evapotranspiration ratio, dimensionless	PRISM and 30-minute total evapotranspiration estimates for water year 1991 (Wilmott and Matsurra, 2001)
Total 1991 precipitation, catchment maximum elevation ratio, dimensionless	PRISM and 30-meter NED
Total 1991 precipitation, catchment minimum elevation ratio, dimensionless	PRISM and 30-meter NED
Available water capacity, in inches per hour	STATSGO
Clay content, in percent by weight	STATSGO
Organic matter content, in percent by weight	STATSGO
Permeability, in inches per hour	STATSGO
Mean cumulative thickness of soil, in inches	STATSGO
Mean hydrologic soil characteristic code, dimensionless	STATSGO
Percentage of area covered by forest	NLCDe 1992
Percentage of area covered by urban	NLCDe 1992
Percentage of area covered by agriculture	NLCDe 1992
Percentage of area covered by rangeland	NLCDe 1992
Percentage of area covered by barren land	NLCDe 1992
Percentage of area covered by water area	NLCDe 1992
Percentage of area covered by wetland	NLCDe 1992

Table 3. Data sources used to compute sources and landscape transport characteristics.

Dataset name	Source description
30-meter National Elevation Dataset (NED)	U.S. Geological Survey, 1999, National Elevation Dataset: U.S. Geological Survey Fact Sheet 148-99, accessed September 22, 2006, at *http://erg.usgs.gov/isb/pubs/factsheets/fs14899.html*
Enhanced National Land Cover Data 1992 (NLCDe 1992)	Nakagaki, N., Price, C.V., Falcone, J.A., Hitt, K.J., and Ruddy, B.C., 2005, Enhanced National Land Cover Data 1992, version 1.0: U.S. Geological Survey, accessed September 22, 2006, at *http://water.usgs.gov/GIS/metadata/usgswrd/XML/nlcde92.xml*
Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate mapping system	Daly, C., Nielson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, no. 2, p. 140–158, accessed July 31, 2006, at *http://prism.oregonstate.edu/products*
Geologic Map of United States	King, P.B., and Beikman, H.M., 1974, Geologic map of the United States: U.S. Geological Survey Professional Paper 901, 40 p., 2 pl., accessed August 15, 2006, at *http://pubs.usgs.gov/dds/dds11/kb.html*
1:500,000-scale digital geologic map of Arizona	Hirschberg, D.M., and Pitts, G.S., 2000, Digital geologic map of Arizona: A digital database derived from the 1983 printing of the Wilson, Moore, and Cooper 1:500,000-scale Map, version 1.0: U.S. Geological Survey Open-File Report 00-409, accessed June 21, 2006, at *http://geopubs.wr.usgs.gov/open-file/of00-409/*
1:500,000-scale digital geologic map of Colorado	Green, G.N., 1992, The digital geologic map of Colorado in Arc/Info format: U.S. Geological Survey Open-File Report 92-507, accessed June 21, 2006 at *http://pubs.usgs.gov/of/1992/ofr-92-0507/*
1:500,000-scale digital geologic map of New Mexico	Green, G.N., and Jones, G.E., 1997, The digital geologic map of New Mexico in Arc/Info format, version 1.0: U.S. Geological Survey Open-File Report 97-0052, accessed June 21, 2006 at *http://pubs.usgs.gov/of/1997/ofr-97-0052/*
1:500,000-scale digital geologic map of Utah	Ludington, S., Moring, B.C., Miller, R.J., Stone, P.A., Bookstrom, A.A., Bedford, D.R., Evans, J.G., Haxel, G.A., Nutt, C.J., Flyn, K.S., and Hopkins, M.J., 2006, Preliminary integrated geologic map databases for the United States. Western States: California, Nevada, Arizona, Washington, Oregon, Idaho, and Utah, version 1.0: U.S. Geological Survey Open-File Report 2005-1305, accessed June 21, 2006 at *http://pubs.usgs.gov/of/2005/1305/*
1:500,000-scale digital geologic map of Wyoming	Green, G.N., and Drouillard, P.H., 1994, The digital geologic map of Wyoming in Arc/Info format: U.S. Geological Survey Open-File Report 94-0425, accessed June 21, 2006 at *http://pubs.usgs.gov/of/1994/ofr-94-0425/*
1:250,000-scale State Soil Geographic Database (STATSGO) soil characteristics	Wolock, D.M., 1997, STATSGO soil characteristics for the conterminous United States: U.S. Geological Survey Open-File Report 656, accessed October 10, 2006 at *http://water.usgs.gov/GIS/metadata/usgswrd/XML/ussoils.xml*
1:24,000-scale National Hydrography dataset	U.S. Geological Survey, 1999, The National Hydrography Dataset, U.S. Geological Survey Fact Sheet 109-99, accessed September 21, 2006 at *http://erg.usgs.gov/isb/pubs/factsheets/fs10699.html*
U.S. Bureau of Reclamation irrigated lands data	David Eckhart, Bureau of Reclamation Remote Sensing and Geographic Information Group, 1990–1995, Potentially irrigated lands in Colorado, New Mexico, Utah, and Wyoming, unpublished data

Table 3. Data sources used to compute sources and landscape transport characteristics.—Continued

Dataset name	Source description
U.S. Bureau of Reclamation quantified sources of salt loading	U.S. Department of the Interior, 2003, Quality of water—Colorado River Basin, progress report no. 21: U.S. Department of the Interior, 90 p., accessed October 19, 2004, at *http://usbr.gov/uc/progact/salinity/pdfs/PR21Final08042004.pdf*
1:100,000-scale Digital Line Graph transportation data	U.S. Geological Survey, 1996, US GeoData Digital Line Graphs: U.S. Geological Survey Fact Sheet 078-96, accessed September 29, 2006 at *http://erg.usgs.gov/isb/pubs/factsheets/fs07896t.pdf*
30-minute resolution evapotranspiration estimates for the conterminous United States	Willmott, C.J., and Matsuura K., 2001, Terrestrial water budget data archive: monthly time series (1950–1999), version 1.02, accessed September 20, 2007, at *http://climate.geog.udel.edu/~climate/html_pages/README.wb_ts2.html*
Environmental Protection Agency Storage and Retrieval (STORET) database	U.S. Environmental Protection Agency, 2008, U.S. Environmental Protection Agency STOrage and RETrieval (STORET) database, accessed January 15, 2008, at *http://www.epa.gov/storet/*
U.S. Geological Survey National Water Information System (NWIS)	U.S. Geological Survey, 2006, NWISWeb data for the nation, accessed August 13, 2006, at *http://water.usgs.gov/nwis*

The linked stream cells were merged to a single dataset and converted to a vector-based synthetic stream network in which flow direction and location approximated real-world conditions. The network was edited to ensure proper flow direction where necessary. The catchment grids for each sub-basin were merged together to form a single dataset for the UCRB. The merged catchment grid was converted to a vector dataset, inspected for accuracy, and edited where necessary. Each stream segment and associated catchment was assigned a unique identification code for use by the SPARROW model. The final step in preparing the interconnected stream reach network for use in SPARROW is the definition of the downstream order of the reaches, or hydrologic sequence, that allows SPARROW to accumulate flux in the downstream direction. The Assign Hydrologic Sequence (Assign_hydseq) computer program (Richard Alexander, U.S. Geological Survey, written commun., 2003) was used to determine the hydrologic sequence and total drainage area for each reach from reach characteristics defined in the interconnected network. The network consisted of 10,813 unique stream reaches that ranged in size from less than 1 mi^2 to a maximum of 78 mi^2. The average incremental drainage area for the network was 10 mi^2.

Removal of Flux by Water Diversion and Reservoir Storage

Extensive water development for municipal, industrial, and agricultural uses has occurred in the UCRB over the past century and a half. This development has affected the natural routing of water in the streams of the basin. Aquatically transported contaminant mass, such as dissolved solids, is affected in a similar manner. Water diversions, which remove water along with dissolved materials, are abundant and can be found on most rivers and streams in the UCRB. For example, the Grand Valley in western Colorado diverts a substantial amount of Colorado River water through the Government Highline Canal and Grand Valley diversion structures, approximately 620,000 acre-ft in 1991. There are also a number of large transbasin diversions that divert water to the Arkansas, Rio Grande, and North Platte River Basins, and the Great Basin. Table 1 is a list of transbasin diversions that divert on average 2,000 acre-ft or more of water per year out of the UCRB (Liebermann and others, 1989). The assembled stream reach network described above did represent transbasin diversions and therefore, an effort was made to account for losses of flux, often using flow as a surrogate, caused by large transbasin diversions.

The fraction of upstream flux delivered to an incremental reach, δ_i, (equation 1) of the SPARROW model allows for losses in constituent mass from water diversions. Term δ_i is unitless and, assuming that contaminants are removed proportionally to the amount of water removed, is often computed from quantified or estimated streamflow data. For this study, an effort was made to account for the large transbasin diversions, those contained in table 1, along with the large water diversions such as those in Grand Valley, Colorado mentioned above. The term δ_i was computed for most of the transbasin diversions using reported diversion flows and river streamflows. Most river streamflows were obtained from nearby downstream USGS streamflow-gaging stations; however, estimates were required for a few transbasin diversions lacking nearby gaging stations. The fraction of upstream flux for affected incremental catchments was computed by dividing the river streamflow by the total nondiverted streamflow, often obtained by summing the available downstream gaged source streamflow and the diverted amount. Diversion records for the Government Highline Canal and Grand Valley Diversion were obtained from the State of Colorado (Judy Sappington, Colorado Division of Water Resources, written commun., December 11, 2007). Because these diversions are associated with multiple uses and a substantial amount of flow is returned to the Colorado River, the fraction of upstream flux for the two affected incremental catchments was computed using the diversion records and the difference in annual streamflow at USGS streamflow-gaging stations 09095500, Colorado River near Cameo, Colorado, and 09106150, Colorado River below Grand Valley Diversion near Palisade, Colorado.

While the assumption that dissolved solids act conservatively within the streams and reservoirs of the UCRB over the period of a single water year is warranted, the management of reservoirs over this same temporal scale can affect the mass of dissolved solids transported throughout the basin. Conceptually, reservoirs with increases in storage over a given time period are a mechanism that removes flux from a basin, albeit temporarily. For this reason, δ_i values were computed for reaches immediately downstream of the 18 reservoirs shown in table 4 with net increases in storage for water year 1991. These values were computed by dividing the total annual streamflow released from a given reservoir by the sum of the total annual streamflow released and net increase in storage.

Dissolved-Solid Loads at Water-Quality Monitoring Sites

The dependent variable of the UCRB dissolved-solids SPARROW model consisted of water year 1991 dissolved-solids loads computed at 218 water-quality monitoring sites (appendix 1). Data from 192 of these sites were available from Anning and others (2007) and data from 26 sites were determined using the Load Estimator (LOADEST) computer program of Runkel and others (2004) adapted for use with S-Plus (Insightful Corporation, 2005) statistical software (Dave Lorenz, U.S. Geological Survey, written commun., 2005), based on the methods of Runkel and others (2004) from data obtained from the USGS National Water Information System (NWIS).

Source Variables

Dissolved-solids sources in the UCRB are generally categorized as either natural or agricultural. The major natural sources include geologic units high in dissolvable minerals and saline springs. The largest agricultural dissolved-solids source is attributed to irrigation of agricultural lands. Methods used for representing these sources within the SPARROW model are described below.

Geology

The largest source of naturally generated dissolved solids in streams in the southwestern U.S., including the UCRB, is derived from the rocks underlying stream basins, particularly those high in dissolvable minerals. In the southwestern dissolved-solids SPARROW model (Anning and others, 2007), statistically significant source coefficients were associated with nine groupings of rock types derived from the King and Beikman (1974) 1:2,500,000-scale bedrock geology map of the U.S. For the UCRB model, the geology was best represented at a scale compatible with the selected NHD stream reach network. The 1:2,500,000 scale of the King and Beikman (1974) map lacks the desired detail when compared with the catchments of the modified NHD stream network (fig. 7A). However, the number of geologic units (34) from the map for the UCRB is desirable for model-required simplification. Available state geologic maps at scales of 1:500,000, while lacking consistency of unit names and continuity across state lines, represent a similar resolution to the NHD stream network (fig. 7B). With more than 270 defined geologic units for the UCRB, the five state geologic maps do not lend themselves easily to the simplification methods of grouping rock types for this modeling effort. In an effort to exploit the benefits the two available geologic map scales present to our modeling methodologies, a geologic map was developed that combines the resolution of the state geologic maps with the 34 defined units from King and Beikman (1974) for the UCRB (fig. 7C). The boundaries of the state geologic units were analyzed for assignment of King and Beikman (KB) unit names, as described below.

To determine the boundaries of the modified King and Beikman (mKB) geologic units, a digital KB map was overlaid with digital state geology maps within a GIS, and a system intersect tool was used to compute the percentage of each KB unit associated with a state unit. This relation was then used to determine the KB unit that is most closely associated (areally) with the state geologic unit. Very few of the KB units corresponded on a 1:1 basis with state geologic units, primarily because of scale differences between the KB and state geologic maps. Consequently, the KB unit associated with each state geologic unit was determined using a stepwise method that considered the lithologies of the KB and state geologic units as well as the geologic unit groups (GUGs) that the KB and state geologic units fit into. The method involves the following steps, which were completed in order until a KB

Table 4. Reservoirs in the Upper Colorado River Basin with capacities greater than 25,000 acre-feet not associated with transbasin diversion projects that were examined for storage changes during water year 1991.

[BOR, U.S. Bureau of Reclamation; DBW, Denver Board of Water; RMP, Rocky Mountain Power; NA, none associated; USGS, U.S Geological Survey; EPA, U.S. Environmental Protection Agency; mg/L, milligrams per liter; NA, not applicable]

Reservoir	Authority	Associated stream	Maximum capacity of storage volume (acre-feet)	Reservoir storage volume, Oct. 1, 1990 (acre-feet)	Reservoir storage volume, Sept. 30, 1991 (acre-feet)	1991 reservoir storage volume change (acre-feet)	Dissolved-solids concentration, from nearest available location (mg/L)	Calculated fraction of upstream flux delivered to incremental reach (δ_i), dimensionless	Apparent import of dissolved solids, in tons, associated with storage volume decrease	Source of dissolved-solids concentration and (or) specific conductance data
Lake Powell	BOR	Colorado River	28,820,000	15,720,450	14,699,143	–1,020,000	521	NA	723,000	USGS; Colorado River at Lees Ferry, Arizona
Flaming Gorge Reservoir	BOR	Green River	4,002,700	3,081,486	3,390,465	309,000	NA	0.74	0	NA
Navajo Reservoir	BOR	San Juan River	1,986,200	1,363,928	1,586,397	222,000	NA	0.70	0	NA
[1]Strawberry Reservoir	BOR	Strawberry River	1,127,200	475,188	486,740	11,600	NA	0.12	0	NA
Blue Mesa Reservoir	BOR	Gunnison River	940,700	617,241	700,364	83,100	NA	0.89	0	NA
Fontenelle Reservoir	BOR	Green River	405,160	278,673	325,076	46,400	NA	0.95	0	NA
McPhee Reservoir	BOR	Dolores River	381,000	239,400	305,828	66,428	NA	0.75	0	NA
Starvation Reservoir	BOR	Strawberry River, [2]Duchesne River	189,000	72,267	98,468	26,200	NA	0.79	0	NA
Vallecito Reservoir	BOR	Los Pinos River	139,200	80,107	74,579	–5,530	[3] 52	NA	391	[4]USGS; Los Pinos River above Vallecito Reservoir
Morrow Point Reservoir	BOR	Gunnison River	121,300	115,016	111,520	–3,500	116	NA	552	USGS; Gunnison River below Gunnison Tunnel
Taylor Park Reservoir	BOR	Taylor River	119,970	80,194	85,495	5,300	NA	0.96	0	NA
Ruedi Reservoir	BOR	Frying Pan River	119,000	92,302	90,810	–1,490	131	NA	265	USGS; Frying Pan River near Ruedi, Colorado
Scofield Reservoir	BOR	Price River	111,300	7,410	9,318	1,910	NA	0.97	0	NA
Williams Fork Reservoir	DBW	Williams Fork River	109,000	79,968	82,107	2,140	NA	0.98	0	NA
Joes Valley Reservoir	BOR	Seely Creek	71,860	25,238	34,263	9,020	NA	0.73	0	NA
Big Sandy Reservoir	BOR	Big Sandy River	54,400	12,084	15,492	3,410	NA	0.96	0	NA
Moon Lake	BOR	Lake Fork River	50,700	9,236	11,918	2,680	NA	0.96	0	NA
Lemon Reservoir	BOR	Florida River	48,600	17,303	26,291	8,990	NA	0.80	0	NA
Steinaker Reservoir	BOR	[2]Ashley Creek	40,350	2,025	17,591	15,600	NA	0.78	0	NA
Vega Reservoir	BOR	Plateau Creek	40,300	2,207	8,758	6,550	NA	0.33	0	NA
Meeks Cabin Reservoir	BOR	Blacks Fork River	38,720	1,926	12,718	10,800	NA	0.77	0	NA
Electric Lake	RMP	Huntington Creek	35,500	22,221	20,413	–1,810	[3] 126	NA	310	EPA (2008)
Red Fleet Reservoir	BOR	Big Brush Creek	33,000	14,404	20,212	5,810	NA	0.78	0	NA
Crystal Reservoir	BOR	Gunnison River	30,700	16,827	16,151	-676	116	NA	107	USGS; Gunnison River below Gunnison Tunnel

[1] Also associated with transbasin diversion project.

[2] Reservoir is offstream of indicated stream.

[3] Estimated from specific-conductance measurements.

[4] Data from 1996–2002.

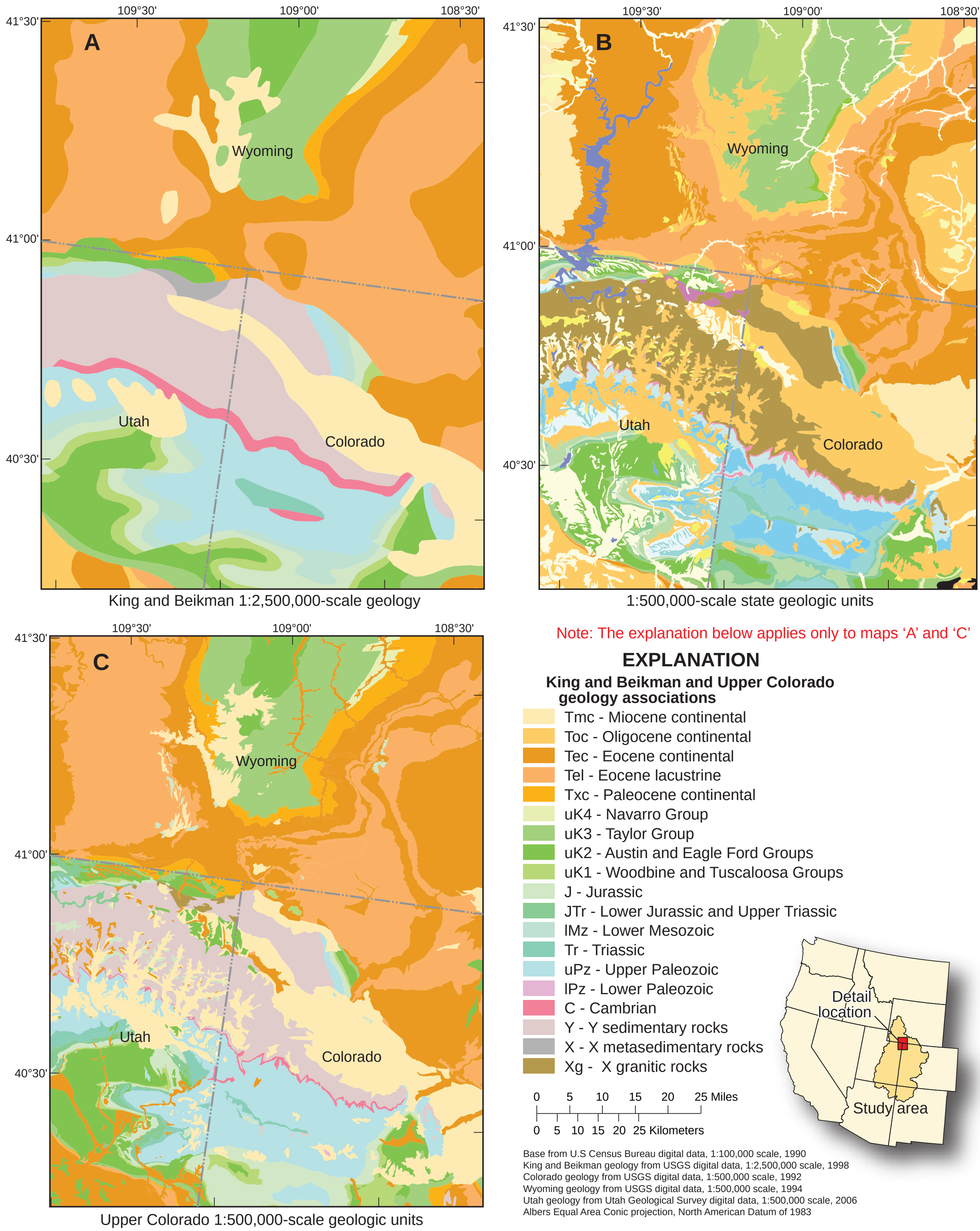

Figure 7. Representation of geologic units of differing scales for a select location in the Upper Colorado River Basin (UCRB).

unit was associated with the state geologic unit being considered:

1. If the lithology of a state geologic unit was similar to the lithology of the KB unit with the largest corresponding area to the state geologic unit (the dominant KB unit), and both were contained in the same GUG, then those two units were associated. This situation occurred in 79 percent of the UCRB.

2. Where the state geologic unit indicated a surficial cover such as alluvium, colluvium, landslide deposits, or water, the associated KB unit was assumed to be the bedrock unit underlying the surficial cover with the largest corresponding area. The corresponding KB unit may or may not be in the same GUG as the state geologic unit. This situation occurred in 6 percent of the UCRB.

3. If the lithology of a state geologic unit was not similar to the lithology of the dominant KB unit, and the KB unit with the second largest area or another KB unit in a different GUG did correspond with the state geologic unit but did not consist of a larger area than the dominant KB unit, then the state unit was associated with the dominant KB unit. This situation occurred in 5 percent of the UCRB.

4. If the lithology of a state geologic unit was not similar to the lithology of the dominant KB unit, but the KB unit with the second largest area in a different GUG did correspond with the state geologic unit and also exceeded 40 percent of the total area, then those two units were associated. This situation occurred in 1 percent of the UCRB.

5. If the lithology of a state geologic unit was not similar to the lithology of the dominant KB unit, but was similar to the KB unit with the second largest corresponding area within the same GUG, then those two units were associated. This situation occurred in 1 percent of the UCRB.

6. If the lithology of a state geologic unit was not similar to the lithology of the dominant KB unit, but was similar to the KB unit with the second largest corresponding area in a different GUG, and the cumulative area of all the KB units within that GUG exceeded the area of the dominant KB unit, then those two units were associated. This situation occurred in 1 percent of the UCRB.

7. If the lithology of a state geologic unit was not similar to the lithology of the dominant KB unit and no other KB unit corresponded with the state geologic unit (no percentage was assigned to the corresponding unit), then the assigned KB unit was the dominant unit. This situation occurred in 8 percent of the UCRB.

The 70 geologic units in the southwestern U.S. from the King and Beikman (1974) 1:2,500,000-scale bedrock geology map were aggregated into nine rock type groups in the southwestern U.S. SPARROW model (Anning and others, 2007). The groupings of Anning and others (2007) were first based on lithology: crystalline (plutonic and metamorphic) rocks, mafic volcanic rocks, felsic volcanic rocks, eugeosynclinal rocks, and sedimentary rocks. Sedimentary rocks were further broken down by age: Cenozoic, Mesozoic, and Paleozoic and Precambrian; and by dissolved-solids yield: low, medium, or high. The determination of dissolved-solids yield classes for the sedimentary rocks was done by individually testing each geologic unit with a calibrated preliminary dissolved-solids SPARROW model. Anning and others (2007) individually transferred each unit to the corresponding sedimentary age high-yield group, ran the preliminary model, and examined model output. Geologic units were reassigned to the high-yield group if, as a result of the transfer, (1) the source coefficient for the low-yield group decreased, and the source coefficient for the high-yield group increased, (2) the probability value of the source coefficients remained about the same or decreased, and (3) the R^2 of the model remained about the same or increased (Anning and others, 2007). This grouping scheme simplified the model input data, yet resulted in coefficients that made distinctions between significant geologic dissolved-solids sources.

This study used a methodology of grouping geologic units similar to that used by Anning and others (2007). Seven geologic source groups were defined for the UCRB (table 5), six of which were associated with sedimentary rocks of three different ages. The three ages of sedimentary rocks were divided into high- and low-yield groups. To determine which sedimentary geologic units from each age group belonged in respective high- and low-yield classifications, a preliminary SPARROW model was calibrated with the point-source imports, irrigated agricultural lands and four geologic source groups—crystalline and volcanic rocks, and three age-related sedimentary rock groups.

Using the defined source groups and statistically significant landscape transport characteristics from this model, sedimentary geologic units from each group were tested individually as a unique source through iterative model recalibration. After testing each unit individually, the unit from each age group with the lowest probability (*p*-value) that the estimated coefficient is equal to zero as a unique source group became the initial member of the respective age-related, high-yield group. Beginning first with the sedimentary Cenozoic rocks, units were individually added to the high-yield group in a stepwise fashion by the lowest *p*-value, and the model was recalibrated. The unit remained in the high-yield group if (1) the *p*-value of the high-yield group decreased and both low- and high-yield source coefficients changed, and (2) the *p*-value remained the same or slightly increased but the low-yield source coefficient decreased and the high-yield source coefficient increased. Once the high-yield groups were set, each unit of the low-yield groups was added back into the high-yield groups and examined again for meeting the above criteria. Following calibration of the final model, with all sig-

Table 5. King and Beikman (1974) geologic units and names and geologic units from state geology maps for the Upper Colorado River Basin.

[mi^2, square miles]

King and Beikman (1974) geologic units	Area (square miles)	Name (King and Beikman, 1974) [1]	Geologic units from state geology maps (Green and Drouillard, 1994; Green and Jones, 1997; Green, 1992; Hirschberg and Pitts, 2000; Ludington and others, 2006) assigned to King and Beikman (1974) units. [1]
Crystalline and volcanic rocks—9,680 mi^2 total area			
Ti	610	Tertiary intrusive rocks	Ti, TKdi, Tmi, Tui
Tpv	1,200	Pliocene volcanic rocks	Tbb, Tbbi, Tmv, Tpb
ITv	1,460	Lower Tertiary volcanic rocks	Te, Tpl, Tv
ITf	1,190	Lower Tertiary felsic volcanic rocks	Taf, Tbr, Tbrt, Tial, Tiql
Kg_3	110	Latest Cretaceous granitic rocks	TKi
Cg	7.98	Cambrian granitic rocks	_am
Yg_1	838	Older Y granitic rocks	Xgy, Xqd, Xsv, Yg, Yxg
Xg	36	X granitic rocks	PCm
Xm	3,480	X orthogneiss and paragneiss	Jmw, KJdw, Qd, Qdo, _s, Xb, Xfh, Xg, Xlc, Xm, Xq, Yam, @cc, @ch
Wg	345	W granitic rocks	Wg, Wgd, Ws
Wgn	377	W orthogneiss and paragneiss	Ksb, shear, Tgc, Ugn, Ugn +, Wgn, WVg, WVsv, !W
X	30.5	X metasedimentary rocks	Xdl
High-yield sedimentary Cenozoic rocks—12,300 mi^2 total area			
Tel	7,950	Eocene lacustrine	T_2, Tg, Tgl, Tglm, Tglu, Tgp, Tgt, Tgw, Tgwt, Twn,
Txc	4,340	Paleocene continental	Kmw, T_1, Tc, Tf, Tfu, Tgv, TK, Tmu, Tn, Toa
Low-yield sedimentary Cenozoic rocks—25,700 mi^2 total area			
Q	8.82	Quaternary	KJ, Tdb, Tep, TKp
Tpc	98.1	Pliocene continental	Tov, Tvm
Tmc	2,710	Miocene continental	Mz, QTg, T4, T5, Tbi, Tbp, Tm, Tt
Toc	129	Oligocene continental	Toe, Twru
Tec	22,800	Eocene continental	Qa, Ql, Qs, QT, QTa, Qu, T_3, Tb, Tbs, Tglw, Tgrw, Th, Tp, Tsj, Tu, Tw, Twa, Twc, Twd, Twg, Twlc, Twm, Two
High-yield sedimentary Mesozoic rocks—14,000 mi^2 total area			
uK_3	9,450	Taylor Group	K_3, Kal, Kbl, Kch, Ke, Kh, Ki, Kle, Kls, Kmf, Kmgs, Kmp, Kmv, Kmvu, Kp, Kpcl, Kpl, Kr, Ks, Ksc, Kw, Qi, Tbf
TR	4,570	Triassic	J@gc, Tr1, Tr2, TRc, TRcs, TRm, @d, @kc, @m, @wc
Low-yield sedimentary Mesozoic rocks—36,200 mi^2 total area			
uK_1	4,600	Woodbine and Tuscaloosa Groups	J, Jmc, K_1, Kd, Kdb, Kfd, Kjde, KJdm, Kmfm, Ku, Pzr, Tos
uK_2	10,500	Austin and Eagle Ford Groups	K_2, Kav, Kba, Kc, Kcc, Km, Kmj, Kml, Kmm, Kms, Kmu, Kmvl, Kn, Kph, Kss, MzPz, Qao, Qgo, Td, Tii, TKe, TKec
uK_4	1,950	Navarro Group	Kfl, Kkf, Kl, Kpc, Tka
IK, IK_1	305	Lower Cretaceous	Ka, Kbb, Kbr, Kf, Kft, KJg
J	11,800	Jurassic	J_1, J_2, Jm, Jmce, Jme, Jmj, Jms, Jmse, Jmwe, Jsr, J@g, J@mc, J@mg, KJdj, KJds, O, Qe, Qls, @Pcp, @Pcs, @Pr
JTR	6,730	Lower Jurassic and Upper Triassic	JTRgc, Jg, @, @rp
IMz	400	Lower Mesozoic	Jsg, Jst, J@n, J@nd, Kg, KJs, Kmt, @ad, @cd

Table 5. King and Beikman (1974) geologic units and names and geologic units from state geology maps for the Upper Colorado River Basin.—Continued

King and Beikman (1974) geologic units	Area (square miles)	Name (King and Beikman, 1974) [1]	Geologic units from state geology maps (Green and Drouillard, 1994; Green and Jones, 1997; Green, 1992; Hirschberg and Pitts, 2000; Ludington and others, 2006) assigned to King and Beikman (1974) units. [1]
High-yield sedimentary Paleozoic and Precambrian rocks—4,210 mi² total area			
uPz	3,660	Upper Paleozoic	IP, M_ml, M_1, M_2, M_3, Mm, P&m, P&w, P&wm, P^2, Pc, PIP, PM, Pp, &b, &e, &ee, &h, &m, &mb, &mr, &rh, @c, @Pdc, @Pjs, @Ps
IPz	553	Lower Paleozoic	M_, MD, MD_, MDO, O_, Qb
Low-yield sedimentary Paleozoic and Precambrian rocks—5,940 mi² total area			
C	29.7	Cambrian	C_1, _l
P	2,480	Permian	P_1, Pct, @Pmc
P_2a	82.4	Lower part of Leonardian Series	Pdc
Y	3,350	Y sedimentary rocks	C_2, PCs, Qg, Wr, Yu, YXu

[1] See References Cited for the complete reference of these citations.

nificant source groups and landscape transport characteristics, this process was repeated again, starting with four geologic source groups to verify the grouping.

Irrigated Agricultural Lands

Past investigations have estimated the contribution of dissolved solids from agricultural activities in the UCRB to be about 40 percent of the dissolved-solids load at the Lees Ferry, Arizona gage (Iorns and others, 1965; U.S. Department of Interior, 2003). Dissolved solids are derived from agricultural lands in the UCRB as a result of the application of irrigation water, soil disturbance, and to a lesser degree, the application of soluble fertilizers. In general, unconsolidated aquifers in agricultural regions are artificially recharged by irrigation water. The deeper the percolation of water into these aquifers, the greater the amount of available minerals for dissolution and potential transport to streams. The mineralogic characteristics of the soils, together with the quantity of water applied, determine the amount of dissolved solids that can be produced by specific irrigated lands. For arid lands with minimal organic soil horizons, the soil mineralogy is most similar to the mineralogy of the bedrock geology from which they were generated.

In an attempt to evaluate how irrigated lands throughout the UCRB differ as dissolved-solids sources, and assuming that the mineralogy of the soils for these irrigated lands are associated with the local bedrock geology they overlay, irrigated lands were classified into six distinct lithologies on the basis of bedrock geology they overlay from the modified geology map described previously. There are about 2,700 mi² of irrigated lands in the UCRB, as determined from BOR's "Potentially irrigated lands in Colorado, New Mexico, Utah, and Wyoming" dataset (David Eckhart, U.S. Bureau of Reclamation, written commun., September 28, 2006). Because of the small amount of irrigated lands compared with the total drainage area of the UCRB, along with the disproportionate amount of irrigated lands distributed between the six lithologic classifications, three irrigated agricultural lands source groups were defined for input into the SPARROW model: (1) irrigated sedimentary-clastic Tertiary lands, (2) irrigated sedimentary-clastic Mesozoic lands, and (3) irrigated lands of other lithologies (fig. 8). Table 6 contains the groups of irrigated lands defined as sources of dissolved solids in streams in the UCRB. Whereas it is well documented that different irrigation water delivery practices, such as flood or sprinkler irrigation, have a noticeable effect on the production and delivery of dissolved solids from agricultural lands to streams, this modeling effort was unable to distinguish between different irrigation practices because of a lack of uniform irrigation practice data across the states within the UCRB. This lack of irrigation practice data may result in over prediction of dissolved-solids loads in areas that are predominately irrigated by sprinkler systems.

Point Sources of Dissolved Solids

Springs

Saline springs represent the largest natural point sources of dissolved solids to streams in the UCRB. It is estimated that the seven springs listed in table 7 annually discharge as much as 800,000 tons of dissolved solids (U.S. Department of the Interior, 2003). To represent these point sources in the SPARROW model, an estimate of the water year 1991 dissolved-solids load was assigned to the stream reach(s) or catchment(s) associated with each spring discharge point(s). In general, there are sparse dissolved-solids load monitoring data available for springs in the UCRB other than the annual loading estimates provided by BOR (U.S. Department of the Interior, 2003). Fortunately, four of the seven major springs discharge directly to streams with monitoring sites located upstream and downstream of the spring orifice(s). Data from these

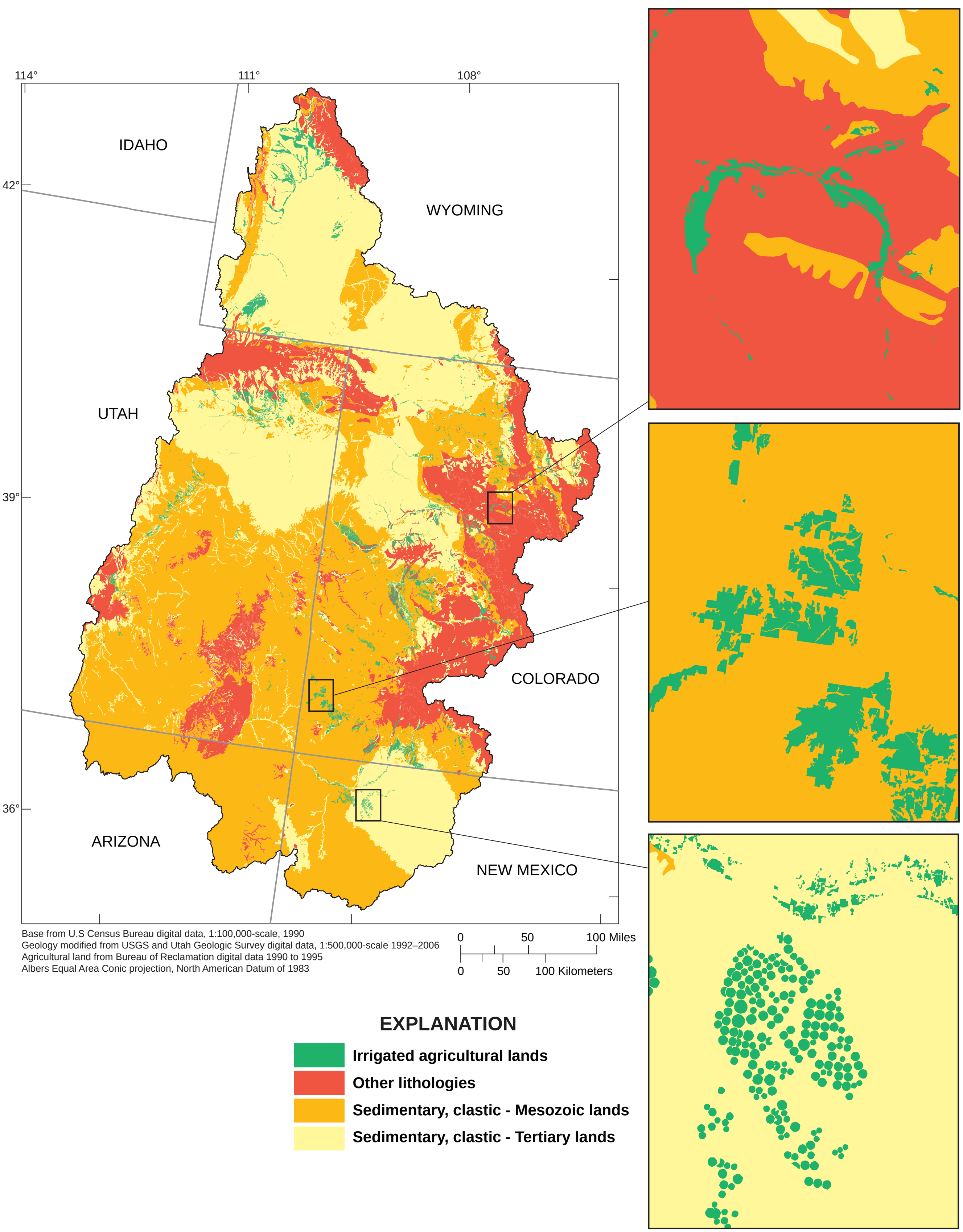

Figure 8. Irrigated agricultural lands in the Upper Colorado River Basin (UCRB) and associated lithologic classification group.

Table 6. Dissolved-solids source groups of Upper Colorado River Basin irrigated agricultural lands by lithologic classification.

Source group	Total area of source group (square miles)	Lithologic classifications included in source group	Total area of irrigated lands by lithologic classification (square miles)
Irrigated sedimentary-clastic Tertiary lands	1,380	Sedimentary, clastic—Tertiary (continental)	1,380
Irrigated sedimentary-clastic Mesozoic lands	900	Sedimentary, clastic—Mesozoic	900
Irrigated lands of other lithologies	420	Igneous and Metamorphic lithologies	72.2
		Sedimentary carbonate (marine)	27.8
		Sedimentary mixed (continental and marine)	320
		Sedimentary basin fill (continental)	0.03

monitoring sites allowed for an indirect means to estimate the water year 1991 dissolved-solids load for Glenwood Springs, Dotsero Springs, Meeker Dome, and Paradox Valley (table 7). The computed upstream-downstream differences indicate that for water year 1991, the BOR estimates were between 24 and 39 percent high. For the three springs without indirect monitoring data—Steamboat Springs, Pagosa Springs, and Sinbad Valley—the average percentage difference, 32 percent, between the BOR estimates and the indirect monitoring data was applied to the BOR estimates shown in table 7.

Reservoirs

A net storage decrease in a reservoir during a water year indicates that more water was removed from it than flowed into it. The removal of water occurs through a combination of outflows exceeding inflows and evaporation. Both of these processes lead to an increase in dissolved solids downstream of the reservoir. The total annual releases exceeding total annual inflows, assuming that the quantity of constituent mass and flow is proportional, would increase the dissolved-solids load immediately downstream of the reservoir. Excess releases from one water year introduces dissolved solids downstream that were not generated or transported from upstream in that given water year. The evaporation process removes pure water, causing dissolved-solid concentrations in the reservoir to increase, which would then increase concentrations and thus, loads immediately downstream as well.

Twenty-four reservoirs with normal capacities of 25,000 acre-ft or more in the UCRB not associated with transbasin diversions were examined for changes in net storage in an effort to account for changes in dissolved-solids loads downstream. Of those 24 reservoirs, 6 were found to have a net decrease in storage, suggesting an increase in dissolved-solids loads downstream for the 1991 water year (table 4). For these reservoirs, an estimated apparent load was computed using nearest available dissolved-solids concentration data and the computed reservoir net storage decreases. These load increases were treated as point sources of flux and were assigned to the stream reach, or catchment, immediately downstream of the reservoir. Table 4 shows the reservoirs with net storage decreases for water year 1991 and the data used to estimate the apparent import of dissolved solids. The process of evaporation and its role in increasing dissolved-solids loads is not directly accounted for using the method described above. For most of the six reservoirs with net storage decreases, evaporation is a small consideration. However, evaporation on Lake Powell, the largest reservoir in the UCRB, is large. Unfortunately, evaporation data were not readily available, and the method used to determine the apparent dissolved-solids load only considered the net storage decrease and dissolved-solids concentrations, which introduces uncertainty in the estimates. The point-source load for Lake Powell was computed using the median dissolved-solids concentration at USGS streamflow-gaging station 09380000, Colorado River at Lees Ferry, Arizona, immediately downstream of the reservoir. As mentioned above, excess releases in a given water year introduce dissolved solids from a different time period; however, to balance the model using the best available data, it was important to include a parameter to represent the reservoir management practices of 1991. The apparent dissolved-solids load of Lake Powell was removed from the results presented for locations below Lake Powell. The apparent dissolved-solids loads for the other five reservoirs were minor enough not to be removed from the results presented.

The apparent dissolved-solids loads for the six reservoirs were grouped with the dissolved-solids loads of the saline springs to define the point-source imports source group. There is uncertainty related to the estimated point source dissolved-solids loads of the saline springs and reservoirs in the UCRB. Fortunately, by treating these increases in dissolved solids as point sources within the SPARROW modeling framework, the model has flexibility in assigning the coefficient. Assuming an accurate representation of all other sources and their specified landscape transport functions, the SPARROW calibration routine will adjust the estimates of the point sources by assigning a representative coefficient. For example, if on average, the point-source load estimates were too high, the point-source coefficient would be expected to be less than one. Conversely, if the point source load estimates were too low, the point-

Table 7. Estimated water year 1991 dissolved-solids load for selected springs in the Upper Colorado River Basin.

[NA, not available]

Saline spring point source	Estimated annual dissolved-solids load (U.S. Department of the Interior, 2003) (tons)	Estimated water year 1991 dissolved-solids load computed from indirect monitoring data (tons)	Percent difference of estimated dissolved-solids load for 1991 and estimated annual dissolved-solids load (percent)	Estimated dissolved-solids load for water year 1991 computed from average percent difference (tons)
Dotsero Springs	182,600	138,000	24	NA
Glenwood Springs	335,000	205,000	39	NA
Meeker Dome	57,000	37,100	35	NA
Paradox Valley	205,000	148,000	28	NA
Steamboat Springs	8,500	NA	NA	5,770
Pagosa Springs	7,300	NA	NA	4,950
Sinbad Valley	6,500	NA	NA	4,400

source coefficient would be expected to be greater than one. For obvious conceptual reasons, point sources are not specified any landscape transport function. The distribution of the 11 defined sources of dissolved solids in the UCRB is shown in figure 9.

Landscape Transport Characteristics

Twenty-six landscape transport characteristics were computed for statistical evaluation as significant predictors of dissolved-solids loads for streams in the UCRB during the calibration process (table 2). Conceptually, climatic characteristics such as precipitation and evaporative transpiration, play a large role in the delivery of dissolved solids from sources to streams. Physical drainage basin characteristics, along with land cover and soil characteristics, are other potential significant landscape transport characteristics. All landscape transport characteristics examined were computed for each catchment from readily available geospatial datasets (table 3) using GIS tools.

Within the SPARROW modeling framework, landscape transport is a source-specific function, which means that landscape transport characteristics are applied to specified sources. This application should adhere to the conceptual understanding of how dissolved solids are transported to streams in the UCRB. Point sources of dissolved solids are not affected by landscape transport mechanisms and therefore, no landscape transport was specified for the point-source imports dissolved-solids source. The transport of dissolved solids from irrigated agricultural lands is related to irrigation practices, specifically the quantity of water applied. Comprehensive data on the application of water to agricultural lands throughout the UCRB are not readily available. Growing seasons and climate vary in different agricultural locations within the UCRB. Conceptually, climate and growing season, and the amount of irrigation water needed, are dependent on elevation. Therefore, in an effort to capture a distinguishing characteristic related to the amount of water used for irrigating crops in different locations within the basin, catchment minimum and maximum elevation were considered individually as landscape transport characteristics for the irrigated agricultural lands sources. The remaining 24 landscape transport characteristics were specified for the seven geologic sources and statistically tested during model calibration.

Calibration of UCRB Dissolved-Solids SPARROW Model

Dissolved-solids loads for water year 1991 at 218 monitoring sites were used to calibrate the UCRB dissolved-solids SPARROW model. This dataset equated to 218 unique calibration reaches that were examined for the defined dissolved solids sources and their specified landscape transport characteristics. Eleven sources of dissolved solids were tested during model calibration: seven geologic groups, three irrigated agricultural lands groups, and the point-source imports. Appendix 2 shows how the 11 source groups were represented within each of the 218 calibration reaches. In accordance with the conceptual understanding that these are sources of dissolved solids, coefficients for the source terms were constrained to be positive.

Landscape transport functions were specified for all sources except the point source imports. Coefficients for the landscape transport characteristics were not constrained and were allowed to be either positive or negative. After individually testing the landscape transport characteristics catchment minimum and maximum elevation specified for irrigated agricultural lands, the t-test statistic for catchment minimum elevation indicated it to be a better predictor. Numerous combinations of the remaining landscape transport characteristics, each specified to the seven geologic source groups, were explored. Model diagnostics indicated that six of these characteristics, as applied to the landscape transport function specified for the geologic source groups, were significant,

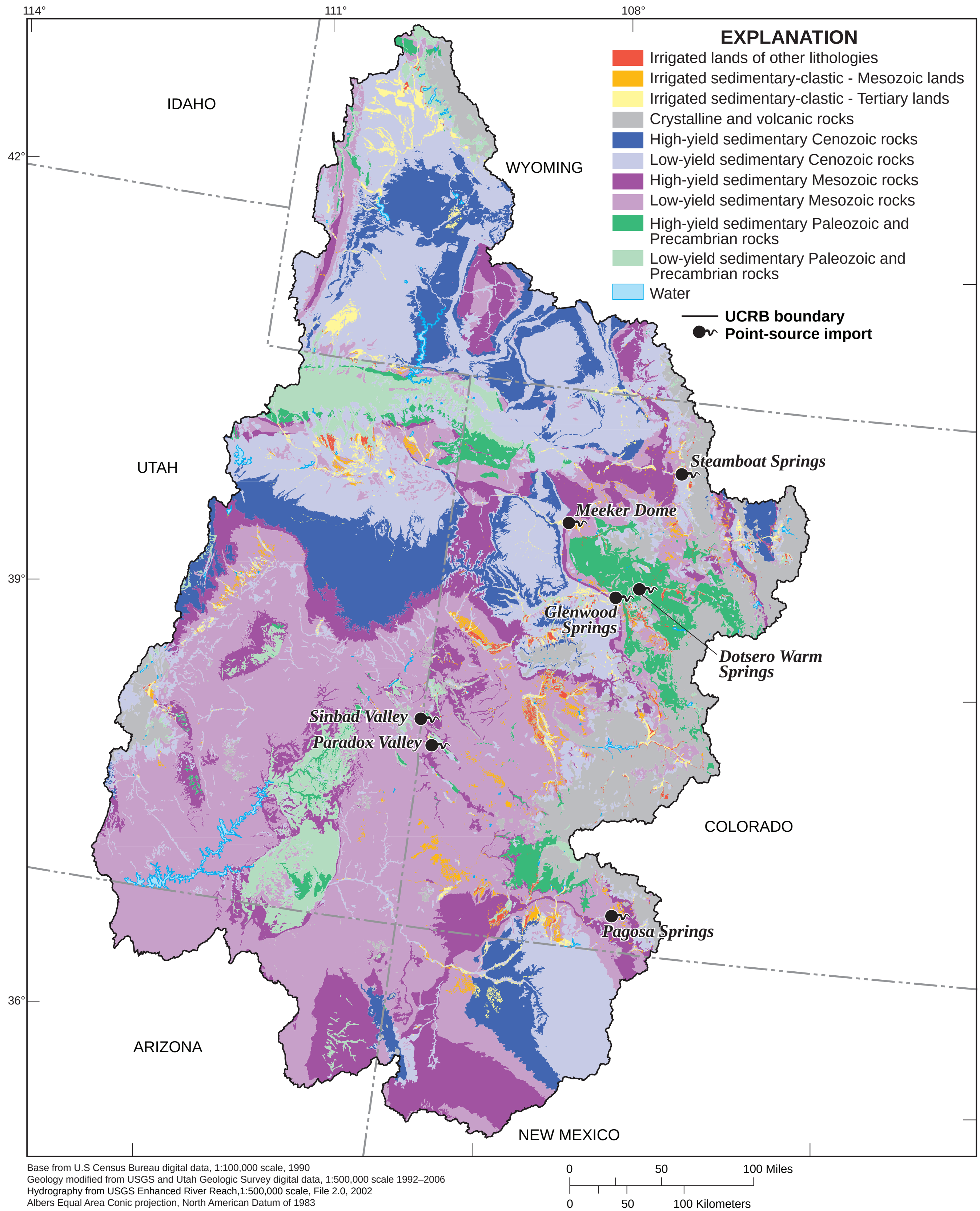

Figure 9. Map of the 11 defined sources of dissolved solids in the Upper Colorado River Basin (UCRB) that were input to the SPARROW model.

with probabilities of the coefficient being zero much less than 0.001 for all but one (table 8). Of these six characteristics, two were climate related—total precipitation and total evaporative transpiration; two were soil characteristics—mean cumulative thickness of soil and mean hydrologic soil characteristic code; one was related to land cover—fraction of catchment area covered by forest; and one was a combination of a climatic metric with a physical characteristic—the ratio of total precipitation to maximum elevation.

In general, statistical evaluation metrics indicate a good fit of the nonlinear least squares model to the observed data. Figure 10 shows the relation between observed loads and model predicted loads for the 218 sites. Residuals appear uniformly scattered about the correlation line, which suggests unbiased predictions throughout the range in observed dissolved-solids loads. The R^2 value of 0.98 and the yield R^2 value of 0.71 suggest that the model generally represents the sources and transport of dissolved solids to streams in the UCRB. For spatially referenced regression models, such as SPARROW, there is a high correlation between drainage area and flux. For such models, the yield R^2 metric is a better representation of the variance explained by the model fit because the area-flux correlation is removed (Schwarz and others, 2006). Yield R^2 is computed with the equation:

$$R^2_{\text{Yield}} = 1 - \frac{\sum_{i=1}^{N} \varepsilon_i^2}{\sum_{i=1}^{N}\left[\left(y_i - \bar{y}\right) - \left(d_i - \bar{d}\right)\right]^2} \tag{3}$$

Where

R^2_{Yield} is the yield R^2,

ε are the model residuals,

y is variance in observations, and

d is the drainage areas of basins or catchments.

The spatial distribution of standardized residuals (fig. 11) does not show any obvious patterns that would indicate location related bias in the model. Root mean square error (RMSE) for the calibrated model was 0.51, from which a prediction error of about 51 percent can be approximated. This compares favorably with the RMSE of the southwestern U.S. dissolved-solids SPARROW model of 0.71, which equates with a prediction error of approximately 71 percent (Anning and others, 2007).

Following the initial nonlinear least squares calibration procedure, a 200 iteration resampled bootstrap analysis was done. Resampled bootstrapping is a technique that estimates unbiased coefficients, which then can be used to assess the validity of the nonlinear least squares estimates that are generated from a finite sample size. Nonlinear least squares coefficient estimates and their standard errors are valid only asymptotically (Schwarz and others, 2006). Assumptions that sample sizes are large enough that coefficient estimates are unbiased with standard normal distributions are inherent in the nonlinear least squares technique. The resampled bootstrapping technique generates coefficient estimates that are obtained from a large artificial sample population developed from the distribution implied by the available sample data (Schwarz and others, 2006). The concept is that if the finite sample population meets the assumptions associated with large sample sizes, sufficient resampling will generate mean coefficient estimates that are similar to those of the nonlinear least squares calibration. A sufficient sample size that agrees with the assumptions associated with the nonlinear least squares technique is validated if coefficient estimates generated from the nonlinear least squares calibration and the resampled bootstrap analysis are agreeable.

Model Results

The results of the nonlinear least squares calibration and resampled bootstrap analysis are shown in table 8. As shown, the mean coefficients determined from the resampled bootstrap analysis are very similar to the nonlinear least square coefficients except for the irrigated lands of other lithologies parameter. The *p*-value is an estimate of the probability that parameter coefficients are equal to zero, or statistically insignificant in describing the dependent variable. In most predictive statistical modeling, parameters with high *p*-values are usually disregarded as being non-explanatory. This approach of eliminating model parameters was followed when testing landscape transport characteristics; however, for conceptual reasons, all tested sources were left in the model regardless of the *p*-value. As shown in table 8, the irrigated lands of other lithologies source group had *p*-values of 0.96 and 0.305, and

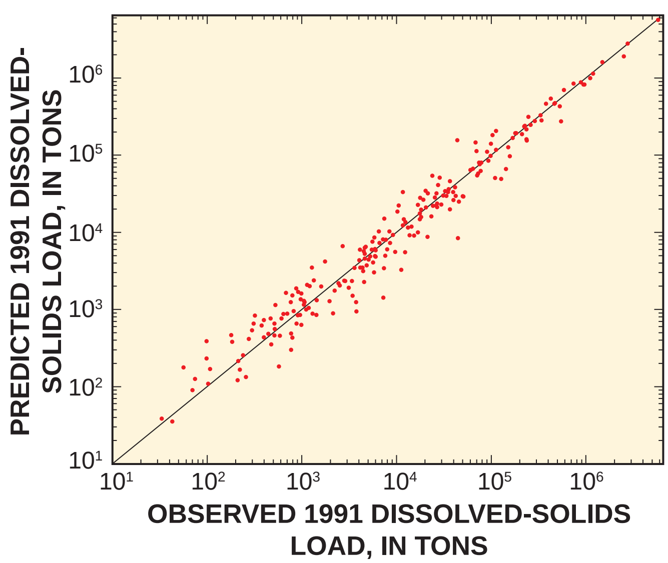

Figure 10. Relation between predicted and observed dissolved-solids loads for 218 monitoring sites in the Upper Colorado River Basin (UCRB) used to calibrate the UCRB dissolved-solids SPARROW model.

Table 8. Results of nonlinear least squares calibration and resampled bootstrap analysis for 1991 Upper Colorado River Basin dissolved-solids SPARROW model.

[D, dimensionless; tons/mi², tons per square mile; <, less than; yr/, years per; yr, year; in., inch; ft, feet; mi², square miles]

Model parameters	Coefficient units	Nonlinear least squares calibration			Resampled bootstrap analysis				
		Coefficient	Standard error	*p*-value	Lower bound 90-percent confidence interval	Mean coefficient	Upper bound 90-percent confidence interval	Standard error	*p*-value
Dissolved-solids sources									
Point-source imports	D	0.94	0.56	0.09	0.67	0.81	1.10	1.41	0.015
Crystalline and volcanic rocks	ton/mi²	4.47	1.27	<0.001	0.99	4.17	6.08	1.52	0.015
Sedimentary rocks									
High-yield Cenozoic	ton/mi²	36.2	11.4	0.002	15.0	35.3	57.0	14.9	0.02
Low-yield Cenozoic	ton/mi²	16.9	4.76	<0.001	5.94	16.0	25.5	6.04	0.005
High-yield Mesozoic	ton/mi²	41.9	12.4	<0.001	18.14	43.4	66.0	14.6	0.005
Low-yield Mesozoic	ton/mi²	2.65	1.41	0.06	–2.09	2.01	4.55	2.46	0.1
High-yield Paleozoic and Precambrian	ton/mi²	25.6	6.96	<0.001	6.93	23.7	35.4	9.33	0.01
Low-yield Paleozoic and Precambrian	ton/mi²	1.26	0.55	0.02	–0.13	1.05	1.88	0.93	0.045
Irrigated lands of other lithologies	ton/mi²	22.8	473	0.96	–1,520	–295	45.6	558	0.305
Irrigated sedimentary-clastic Mesozoic lands	ton/mi²	1,180	281	<0.001	636	1,200	1,680	343	0.005
Irrigated sedimentary-clastic Tertiary lands	ton/mi²	662	254	0.01	273	779	1,320	349	0.01
Landscape transport characteristics									
Minimum catchment elevation	1/ft	–0.0006	0.0002	0.002	–0.0009	–0.0005	–0.0002	0.0007	0.005
Mean catchment total precipitation	yr/in.	0.16	0.02	<0.001	0.12	0.17	0.23	0.03	0
Mean catchment total precipitation, maximum catchment elevation ratio	yr	–171	29.9	<0.001	–247	–178	–115	38.9	0
Mean catchment total evapotranspiration	yr/in.	0.11	0.03	<0.001	0.05	0.11	0.17	0.03	0
Mean catchment cumulative thickness of soil	1/in.	–0.05	0.01	<0.001	–0.08	–0.05	–0.03	0.02	0
Mean catchment hydrologic soil characteristic code	D	–1.6	0.26	<0.001	–2.54	–1.68	–1.19	0.43	0
Fraction of catchment area covered by forest	D	–0.76	0.34	0.03	–1.39	–0.77	–0.15	0.37	0.025

R^2	[1]Yield R^2	Mean square error	Root mean square error	Number of observations
.98	.71	.26	.51	218

[1] Indicates variance of model after removing correlation between drainage area and flux.

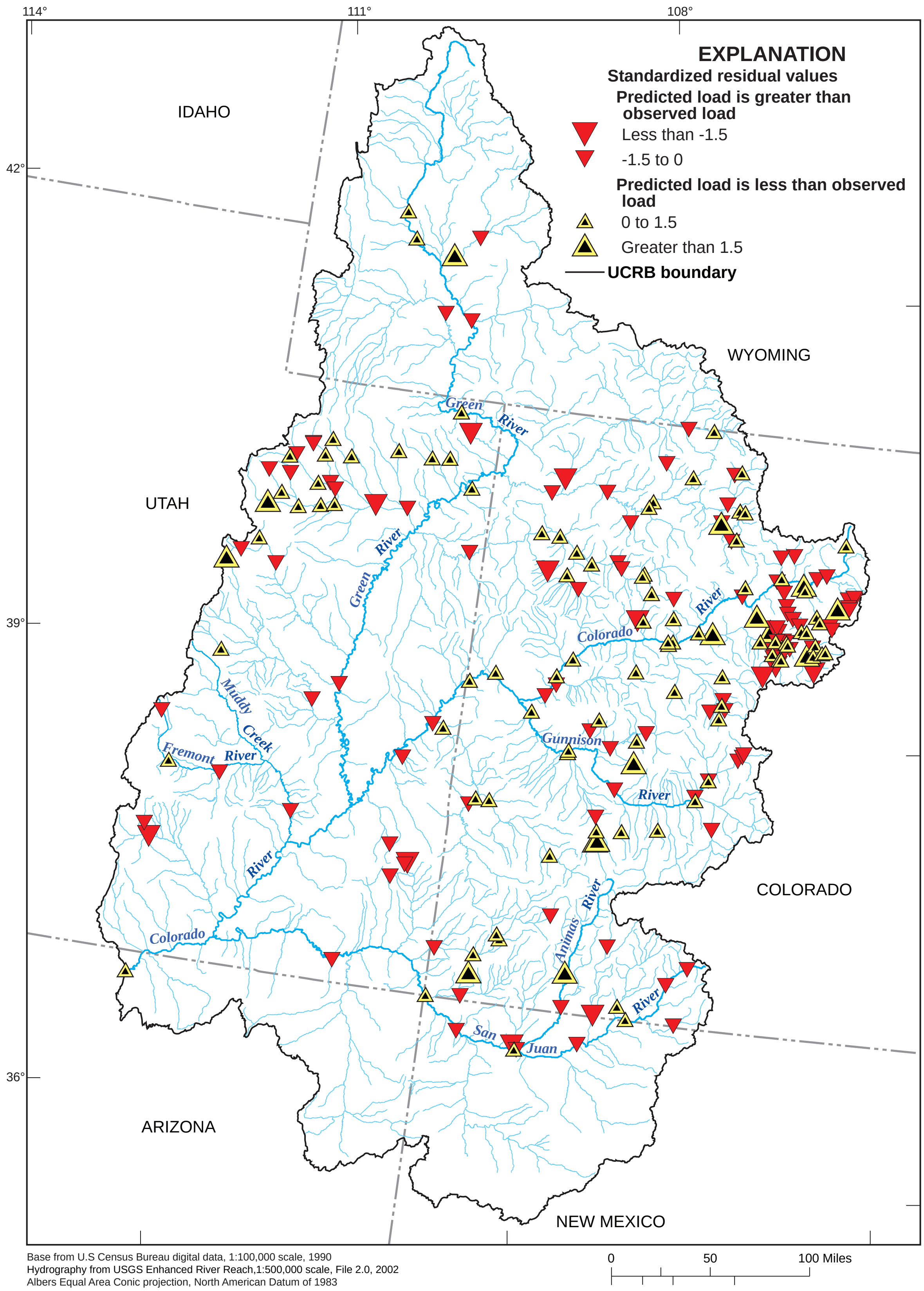

Figure 11. Standardized residual values for 218 monitoring sites in the Upper Colorado River Basin (UCRB) used to calibrate the UCRB dissolved-solids SPARROW model.

accordingly, the nonlinear least squares coefficient differed greatly from the mean coefficient of the bootstrap analysis. While this suggests that irrigated lands of other lithologies do little to explain dissolved-solids loads in streams of the UCRB, for the purposes of this modeling effort, and possibly at the expense of increasing model uncertainty, it was important that all sources, including irrigated lands, be represented.

UCRB Dissolved-Solids SPARROW Model Coefficients

Dissolved-solids source and landscape transport characteristic coefficients, as determined from the nonlinear least squares calibration, provide insight into the role to which each defined source, or source group, and landscape transport characteristic play in dissolved-solids loading to streams in the UCRB. Source coefficients approximate the average delivery of the source to the streams. As shown in table 8, the coefficients of the geologic and irrigated lands source groups represent estimated yields, in tons/mi^2, to streams in the UCRB. The dimensionless coefficient estimated for the point source imports was 0.94. While statistical metrics indicate some uncertainty in this estimate, as evidenced by a standard error of 0.56 and a *p*-value of 0.09, the coefficient near one suggests that the estimated loads for the saline springs and six reservoirs with net storage decreases for water year 1991 are generally accurate and certainly not statistically different from one.

The high-yield sedimentary rock groups possess the highest delivery rates of the seven rock groups. The high-yield sedimentary Mesozoic rocks have the largest coefficient, and thus, the highest yield of dissolved solids, which is 41.9 tons/mi^2. However, the high-yield sedimentary Cenozoic rocks have a very similar yield, and when the standard errors associated with the coefficients are considered, the yields of the groups are statistically equivalent. As would be expected, the low-yield sedimentary rock groups, except for the low-yield sedimentary Cenozoic rocks, have small yields and(or) high *p*-values, greater than 0.01, that suggest there is a high probability that they are not all that different from zero and likely contribute very little dissolved solids to streams in the UCRB.

Estimated coefficients for the irrigated lands source groups indicate large dissolved-solids yields associated with irrigated agriculture. Other studies have estimated that irrigated lands make up roughly 40 percent of the dissolved-solids load at USGS streamflow-gaging station 09380000, Colorado River at Lees Ferry, Arizona (Iorns and others, 1965; U.S. Department of the Interior, 2003). Irrigated lands, as computed for 1991 (David Eckhart, Bureau of Reclamation Remote Sensing and Geographic Information Group, written commun., September 28, 2006), occupy less than 3 percent, or about 2,700 mi^2, of the UCRB. Irrigated sedimentary-clastic Mesozoic lands have an approximate yield of 1,180 tons/mi^2, nearly twice that of irrigated sedimentary-clastic Tertiary lands. Figure 8 shows locations of these irrigated lands in the UCRB. The high yields predicted by the SPARROW model for these two irrigated lands groups tend to agree with the conceptual model of dissolved solids in the UCRB. The coefficient associated with the irrigated lands of other lithologies source group was quite small compared with the other irrigated lands groups. This coefficient has a large standard error and the largest *p*-value of any source group, which suggests irrigated lands of other lithologies are likely not significant sources of dissolved solids to streams in the UCRB.

Coefficients associated with the landscape transport characteristics do not lend themselves as easily to interpretation as the source coefficients. Recall from equations 1 and 2 that the landscape transport characteristics are applied to the landscape transport function, which is then multiplied by the source terms. The transport function, as applied to the sources, is exponential. Landscape transport is source-specific, and as specified in this model, single characteristics are applied to numerous sources. For example, the seven geologic source groups have six landscape transport characteristics applied, and minimum catchment elevation is specified for the three irrigated lands source groups. The estimated coefficients for the landscape transport characteristics, which are shown to be the reciprocals of the units of the specific landscape transport characteristics in table 8, can be interpreted as follows: 100 times the coefficient of a specific landscape transport characteristic equates to the percentage change in the delivered source(s) it is applied to from one unit change in the landscape transport characteristic (Greg Schwarz, U.S. Geological Survey, written commun., November 16, 2007). For example, the coefficient for mean catchment total precipitation is 0.16 yr/in. Multiplying this coefficient by 100 equates to a 16-percent change in the sources it is applied to, which are the seven geologic source groups. If within a given catchment, the total precipitation increased by 1 in/yr, a 16-percent increase in the predicted dissolved-solids load associated with each of the seven source groups would be expected to occur.

A more simplified, albeit qualitative, means to interpret the coefficients associated with the landscape transport characteristics is to examine the conceptual meaning of the sign predicted for their coefficients. Mean catchment total precipitation was assigned a positive coefficient. An increase in precipitation on the seven geologic source groups increases the availability of water to dissolve minerals from rock. Similarly, the estimated coefficient for mean catchment total evaporative transpiration was positive. Evaporative transpiration concentrates minerals within the upper portion of the soil horizon. The positive coefficient suggests that increased evaporative transpiration augments the amount of dissolved solids transported from source rocks to streams in the UCRB.

Coefficient estimates for the remaining landscape transport characteristics were negative. Recall that landscape transport is applied as an exponential function to the specified sources. Larger values of a landscape transport characteristic multiplied by a negative coefficient that is less than one, such as –1.5, will generate a smaller yield; and larger values of a landscape transport characteristic when multiplied by a negative landscape transport characteristic coefficient greater than one, such as –0.5, will generate a larger yield. The negative coefficient assigned to the ratio of mean catchment total precipitation to maximum catchment elevation suggests that for identical source rocks, under similar precipitation conditions, catchments at higher elevations would produce more dissolved solids. Prior to incorporating this ratio into the model, which adjusts the effect of precipitation on rock sources as a function of elevation (David Anning, U.S. Geological Survey, written commun., June 2, 2008), predicted dissolved-solids loads, when compared with monitoring data, were generally too large at the downstream reaches of the larger rivers. This parameter appears to represent a variety of characteristics, such as slope, and stream density, that conceptually enhance transport of dissolved solids. However, these characteristics when represented in the model alone, either do not appear to be significant landscape transport characteristics or have a tendency to enhance transport at lower elevations, in a similar manner as at higher elevations. In general, higher elevations are more likely to have steeper slopes and shorter transport paths, and thus, rock sources at higher elevations should produce more dissolved solids than at lower elevations.

The soil related characteristics, cumulative thickness of soil and mean hydrologic soil characteristic code, were each negative. There are four hydrologic soil characteristic codes as defined in the State Soil Geographic Data Base (STATSGO) (Wolock, 1997) (table 9). From the 1:250,000-scale map of soil characteristics, a mean value was computed for each catchment. The negative coefficients assigned to both soil landscape transport characteristics, a –0.05 for cumulative soil thickness and a –1.60 for mean hydrologic soil characteristic code, suggest that in general, the presence of soils inhibits the amount of dissolved solids delivered to streams. In regards to the cumulative thickness characteristic, there are a variety of plausible interpretations of the negative coefficient such as thinner soils indicate less weathered rock and thus more available solids, thicker weathered soils impede access to unweathered rocks, and thicker soils may act as a reservoir for long-term storage of solids. As shown in table 9, the highest hydrologic soil characteristic code, 4, is associated with low infiltration rates and a high water table. The lowest characteristic code, 1, describes deep soils with high infiltration rates. Conceptually and according to the model results, catchments with lower hydrologic soil characteristic code values enhance the transport of dissolved solids compared with catchments with higher values. The –0.76 coefficient assigned to the fraction of catchment area covered by forest characteristic, which, unless the entire catchment is forested, are less than one, indicates that less forest increases dissolved solids.

The coefficient of the minimum catchment elevation characteristic specified for the irrigated lands source groups was estimated to be –0.0006. This value indicates that an increase in elevation for those lands leads to less dissolved solids generated from irrigated lands. Conceptually, higher elevations have a shorter growing season, which shortens the time that water can be applied. Also, precipitation increases and temperature decreases with elevation, which decreases the amount of irrigation water needed. If application of irrigation water is the transport mechanism leading to increased dissolved solids, this negative coefficient is in agreement.

Table 9. State Soil Geographic Data Base (STATSGO) soil characteristic code descriptions.

[1]Hydrologic soil characteristic code	Hydrologic soil characteristic description
1	High infiltration, deep soils, well drained to excessively drained sands and gravels.
2	Moderate infiltration rates, deep and moderately deep, moderately well and well drained soils with moderately coarse textures.
3	Slow infiltration rates, soils with layers impeding downward movement of water, or soils with moderately fine or fine textures.
4	Very slow infiltration rates, soils are clayey, have a high water table, or are shallow to an impervious layer.

[1] From Wolock (1997).

Prediction of Dissolved-Solid Loads

Following the nonlinear least squares calibration and validation of the inherent least squares assumptions by the resampled bootstrap analysis, a parametric bootstrap analysis was performed to generate unbiased predictions of dissolved-solids loads for all reaches of the stream reach network. If the coefficient estimates of the nonlinear least squares calibration are asymptotically normally distributed, the technique of parametric bootstrapping can be used to remove bias in model predictions. Parametric bootstrapping iteratively generates random coefficient estimates from a multivariate normal distribution with the mean and covariance equal to those of the nonlinear least squares coefficient estimates. For each set of artificial coefficient estimates, predictions are made at all sites, and residuals are computed at observation sites. The set of iterative bootstrap predictions is used to estimate the distribution of the model component of the model predictions, and the set of iterative bootstrap residuals at observation sites is used to estimate the distribution of the estimated mean re-transformation factor for model residuals. These distributions can be used to unbias the predictions on the basis of nonlinear least squares coefficient estimates and to determine the standard error and confidence interval of each prediction (Schwarz and others, 2006). Because the predictions of dissolved-solids loads for the reaches of the stream network were generated using a parametric bootstrapping technique in which strict mass balance is lost, it is possible that the sum of the dissolved-solids load attributed to each of the individual sources for a given location in the UCRB may not exactly equal the predicted dissolved-solids load.

The 1991 dissolved-solids load predictions for streams in the UCRB are presented in this report as predicted dissolved-solids loads and adjusted predicted dissolved-solids loads. The predicted dissolved-solids loads are those generated from the parametric bootstrap analysis described above. These predictions provide a statistically unbiased assessment of dissolved-solids load sources and transport in streams of the UCRB, which is important for basin-wide questions related to dissolved solids. As would be expected, the predicted dissolved-solids loads do not always match those from stream-monitoring sites, and resource managers are often interested in predictions at specific locations in the UCRB. In an effort to provide the most accurate predictions of dissolved-solids loads throughout the basin, a second set of predictions was generated—adjusted predicted dissolved-solids loads. The residuals between the predicted and observed loads were computed at all monitoring sites and applied to the incremental dissolved-solids loads for each catchment of the associated calibration reach upstream to the next monitoring site(s) or headwater(s). The total incremental dissolved-solids load, along with the incremental dissolved-solids load attributed to each of the 11 sources, were adjusted in this manner. These incremental loads were then accumulated using the interconnected stream reach network, with proper consideration to the fraction of upstream flux-delivered values assigned to each catchment. These results are presented as the adjusted predicted dissolved-solids loads. At most locations, the adjusted predicted dissolved-solids loads more favorably match the loads of the monitoring sites. However, at some locations, large differences still exist.

Dissolved-Solids Loads in Selected Rivers of the UCRB

Predicted and adjusted predicted dissolved-solids loads for the reaches of the stream reach network were generated using the UCRB dissolved solids SPARROW model. Using the interconnected stream reach network representing streams in the UCRB, the downstream accumulation of dissolved solids in some of the major rivers were examined. Along with the predicted and adjusted predicted dissolved-solids load, the adjusted predicted natural and agricultural load components were plotted as well. The natural component includes dissolved solids associated with the point-source imports and seven geologic source groups. The agricultural load component is made up of the dissolved-solids loads from the three irrigated lands source groups. The locations of major river confluences, monitoring sites, reservoirs, saline springs, and other pertinent information along the river courses are noted. From these plots, dissolved-solids load increases that are associated with inflows from other rivers are visible. Decreases in dissolved-solids load, such as those related to the Government Highline Canal and Grand Valley diversions on the Colorado River and Navajo Reservoir on the San Juan River, are evident as well.

These cumulative plots are useful in assessing how well the model is capturing dissolved-solids load sources and transport in the major streams of the UCRB. The plots also allow for an examination of how the natural and agricultural components of dissolved-solids loads in the UCRB accumulate along the courses of the major rivers. As discussed below, there are many locations along these selected rivers where the predicted and adjusted predicted dissolved-solids loads do not agree with the loads associated with monitoring sites. In most cases, the differences between the predicted and observed values are well within the approximated prediction error of the model, which is 51 percent. The standard errors associated with the estimated coefficients also need to be considered when evaluating differences in the predicted and observed dissolved-solids loads.

Colorado River

Generally, the adjusted predicted cumulative dissolved-solids load for the Colorado River (fig. 12) agrees with monitoring data at most locations upstream of the Gunnison River. Large differences between monitoring data and the predicted and adjusted predicted loads along the Colorado River are noticed downstream from the Gunnison and Dolores Rivers, and at Lees Ferry, Arizona. At these locations, the model appears to be under-predicting the dissolved-solids load. Some of the diverted water from the two major diversions of the Grand Valley is known to return to the Colorado River below monitoring site 09106150, Colorado River below Grand Valley Diversion near Palisade, Colorado. The dissolved-solids load associated with this water could not be represented in the model because of a lack of data. As discussed below, the adjusted predicted dissolved-solids load for the Gunnison River at monitoring site 09152500, Gunnison River near Grand Junction, Colorado, was about 252,000 tons, or 23 percent, less than the monitored load of 1,080,000 tons. At the Lees Ferry, Arizona, monitoring site, the adjusted predicted dissolved-solids load was 463,000 tons, or 8 percent, less than the monitored load. As previously mentioned, the apparent dissolved-solids load associated with Lake Powell, contained in the point source imports source, was removed from the presented results and accordingly from the monitored data as well.

As shown in the cumulative dissolved-solids load plot for the Colorado River, for the first 250 mi along the mainstem, the natural component accounts for nearly the entire dissolved-solids load. At the confluence with the Gunnison River, the natural and agricultural components become about 50 percent each. This nearly even distribution of the two dissolved-solids load components continues until the confluence with the Green River when the natural load becomes dominant at about 55 percent. This 55 percent natural and 45 percent agricultural distribution continues to the bottom of the UCRB, represented by the Lees Ferry, Arizona, monitoring site.

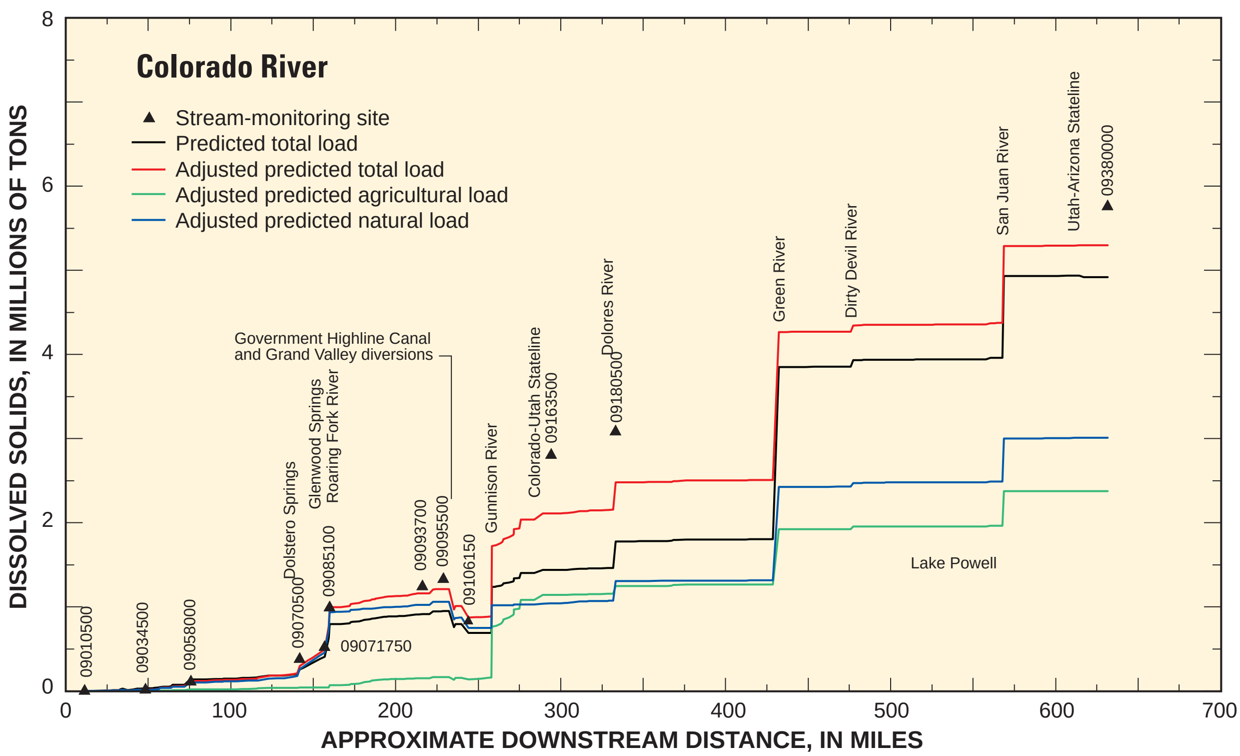

Figure 12. Predicted downstream accumulation of dissolved solids for the Colorado River, from the Upper Colorado River Basin (UCRB) SPARROW model of dissolved-solids transport, for 1991.

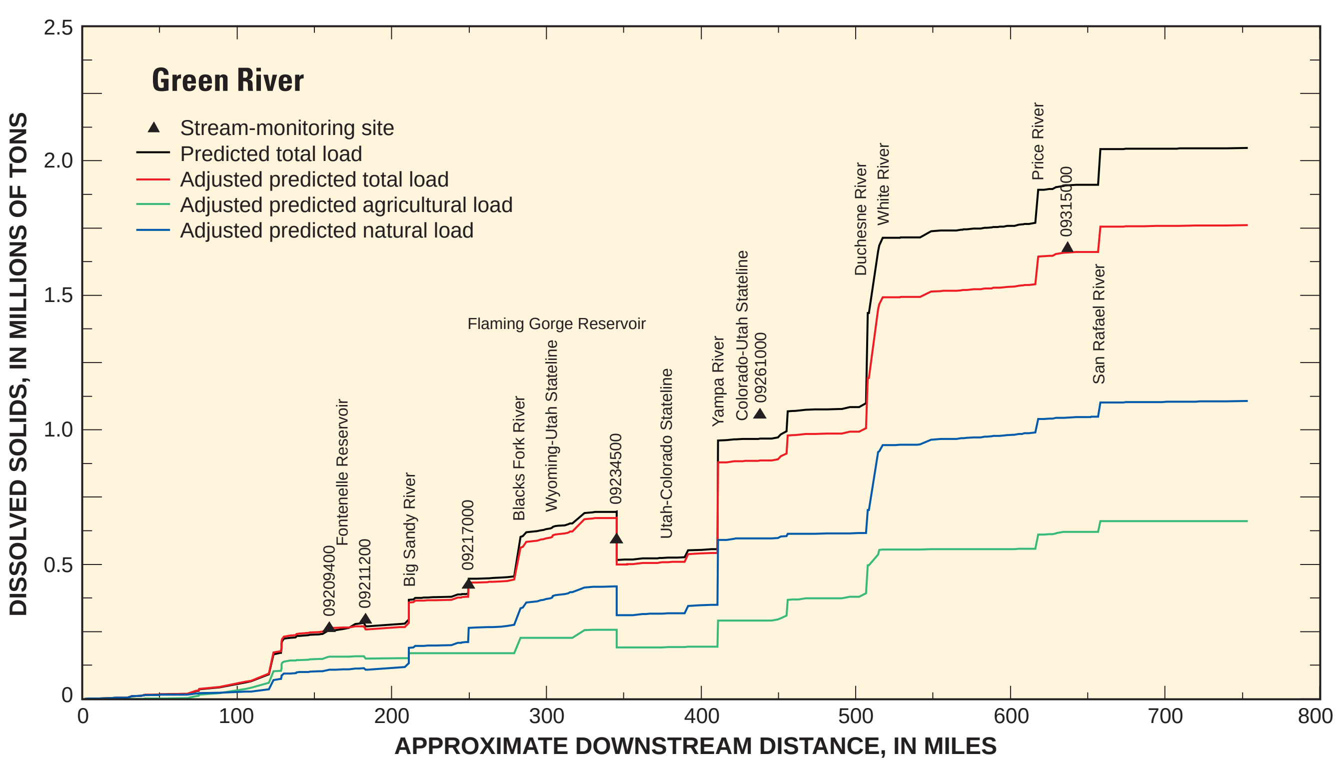

Figure 13. Predicted downstream accumulation of dissolved solids for the Green River, from the Upper Colorado River Basin (UCRB) SPARROW model of dissolved-solids transport, for 1991.

Green River

Predicted and adjusted predicted dissolved-solids loads for the Green River generally agree favorably with monitored loads (fig. 13). The largest differences between the predicted and adjusted predicted loads occur at the two most downstream monitoring sites. At monitoring site 09261000, Green River near Jensen, Utah, the adjusted predicted total load of 886,000 tons is about 170,000 tons, or 16 percent, less than the monitored load of 1,056,000 tons. The predicted load is 8 percent less than the monitored load. At the 09315000, Green River at Green River, Utah, monitoring site, the adjusted predicted load is 16,900 tons, or 1 percent greater than the monitored load whereas the predicted load is 14 percent greater. These results suggest that the model is accurately representing the sources and transport of dissolved solids throughout the Green River drainage basin.

From the adjusted predicted total dissolved-solids load for the entire Green River Basin, the natural component is about 63 percent, and the agricultural component is about 37 percent. The natural component becomes dominant at the confluence with the Big Sandy River and continues through the course of the Green River. The largest increases in the natural load occur at the confluences of the Yampa and White Rivers with the Green River. The Duchesne River appears to be related to the largest increase of agricultural-related dissolved solids. The decrease in dissolved solids associated with the net storage increase for Flaming Gorge Reservoir is evident in figure 13 at downstream mile 345.

San Juan River

The cumulative predicted and adjusted predicted dissolved-solids loads for the San Juan River (fig. 14) at most locations are substantially greater than dissolved-solids loads measured at monitoring sites. Below Navajo Reservoir at monitoring site 09355500, San Juan River near Archuleta, New Mexico, the predicted and adjusted predicted dissolved-solids loads are 121,000 and 64,000 tons greater than the monitored load of 116,000 tons. The adjusted predicted dissolved-solids load is on average 35 percent higher than the monitored load at the three most downstream monitoring sites on the San Juan River. Below the confluence of the Animas River, the adjusted predicted agricultural load steadily increases, and McElmo Creek contributes about 115,000 tons of agricultural-related dissolved solids. It is difficult to determine a reason for the overprediction throughout the San Juan River. However, the large difference found below Navajo Reservoir together with some irrigated lands that appear to be associated with sprinkler irrigation, may provide some explanation.

The decrease in dissolved solids associated with the net storage increase for Navajo Reservoir is evident in figure 14 at downstream mile 100. As can be seen, the predicted and adjusted predicted dissolved-solids loads at this location are greater than the load at the San Juan River near Archuleta, New Mexico, monitoring site by about 51,000 and 11,000 tons. It appears that either the dissolved-solids load is being overpredicted between monitoring site 09346400, San Juan River near Carracas, Colorado, and the Archuleta site, or

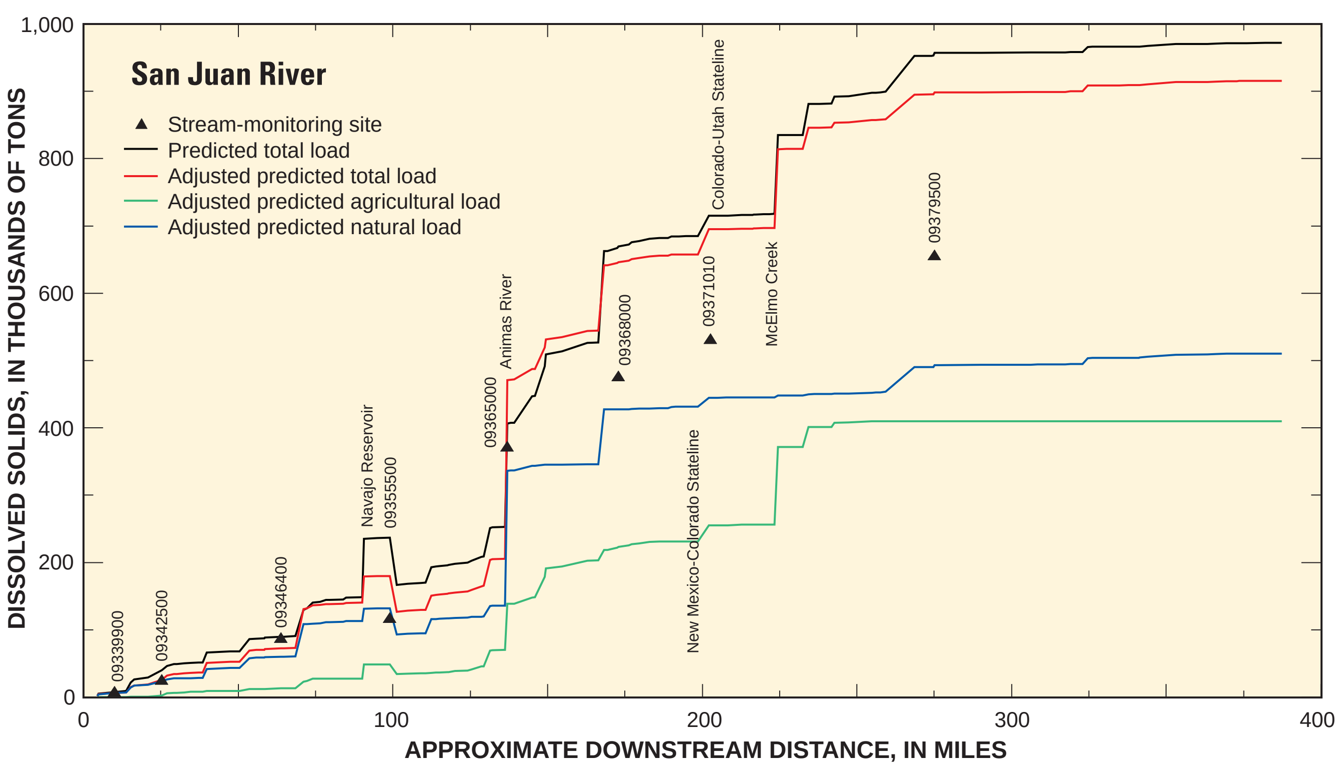

Figure 14. Predicted downstream accumulation of dissolved solids for the San Juan River, from the Upper Colorado River Basin (UCRB) SPARROW model of dissolved-solids transport, for 1991.

the determined fraction of upstream flux-delivered value for Navajo Reservoir was too large and did not remove enough of the predicted dissolved solids.

Irrigation practices, such as flood or sprinkler irrigation, were not differentiated between the irrigated lands source groups. Flood irrigation is a less efficient method of irrigating crops and generally causes increased dissolved-solids loading to streams when compared with sprinkler irrigation. Below the confluence of the San Juan and Animas Rivers, there are approximately 35 mi^2 of irrigated sedimentary-clastic Mesozoic lands (fig. 15). A map of these irrigated lands indicates that many of the fields are circular in shape, which is consistent with fields irrigated with center pivot sprinkler systems. The adjusted predicted dissolved-solids load associated with these fields is about 49,000 tons. There also are 42 mi^2 of irrigated sedimentary-clastic Tertiary lands upstream, which also are the same circular shape common to center pivot sprinklers. These lands, which have a yield roughly 56 percent of the irrigated sedimentary-clastic Mesozoic lands, are associated with an adjusted predicted dissolved-solids load of about 33,300 tons. The loads attributed to these sprinkler irrigated lands are likely to be much less than predicted by this model because of the efficiencies of sprinkler irrigation.

Gunnison River

The model predicted that the cumulative dissolved-solids load in the Gunnison River (fig. 16) is dominated by agricultural activities in the North Fork Gunnison and Uncompahgre Rivers, which are predicted to contribute a total of about 438,000 tons. The dissolved-solids loads for monitoring sites on the Gunnison River generally agree well with predicted loads upstream of the North Fork Gunnison River and the adjusted predicted dissolved-solids loads at downstream monitoring sites 09144250, Gunnison River at Delta, Colorado, and 09152500, Gunnison River near Grand Junction, Colorado, are 179,000 and 252,000 tons, respectively, less than the monitored loads. The adjusted predicted load for the most downstream monitoring site on the Uncompahgre River, 09149500, Uncompahgre River at Delta, Colorado, is 310,000 tons, about 26,000 tons more than the predicted load. These results suggest that the large differences between monitored loads and predicted loads at the two most downstream monitoring sites on the Gunnison River are likely due to an under prediction of the dissolved-solids load associated with the North Fork Gunnison River. No monitoring data were available for the North Fork Gunnison River for water year 1991.

Dolores River

The Dolores River traverses Paradox Valley, which was formed by a collapsed salt dome (U.S. Department of the Interior, 2003). Prior to 1996, when the Paradox Valley project to intercept saline ground water for deep re-injection commenced (Chafin, 2002), brine waters naturally discharged to the Dolores River as it passed through the valley. Monitoring data from sites located on the upstream and downstream boundaries of the valley were used to estimate a load of 148,000 tons of dissolved solids for water year 1991 (table 7). As previously described, this load was treated as a point-source import. The cumulative dissolved-solids load plot (fig. 17) shows substantial increases associated with Paradox Valley and the San Miguel River, which enters the Dolores River less than 10 mi downstream of Paradox Valley. The adjusted predicted dissolved-solids load for the San Miguel was 116,000 tons, of which 71,300 tons were associated with agriculture. From the cumulative dissolved-solids load plot, it appears that the model is accurately representing dissolved-solids loads in the Dolores River.

Distribution of Dissolved-Solids Loads by Source at Selected Locations in the UCRB

Aside from the predicted and adjusted predicted dissolved-solids load for each reach in the stream reach network, the contribution of the total load by each of the 11 defined sources is also available. Resource managers of the UCRB concerned with dissolved solids are often interested in the apportioning of the total load by source at specific locations in the basin. Plots showing the percentage of the adjusted predicted dissolved-solids load attributed to each of the 11 sources of dissolved solids examined with the SPARROW model are shown for selected locations in each of the three divisions of the UCRB, as defined by Iorns and others (1965) (figs. 18 through 20).

Grand Division

The contribution of dissolved solids by each of the 11 defined sources is shown in figure 18 for selected streams in the Grand Division. The most downstream location, which is just above the confluence with the Green River, indicates that irrigated sedimentary-clastic Mesozoic lands are the most dominant source of dissolved solids in the Grand Division, contributing 40 percent. Irrigated sedimentary-clastic Tertiary lands contribute about 10 percent of the dissolved-solids load. The agricultural areas along the Colorado River, specifically Grand Valley, the Gunnison River, and the Uncompahgre River, are dominated by sedimentary rocks of Mesozoic age. The impact these lands have on dissolved-solids loading is evident in the distribution of loading sources below the confluence of the Gunnison and Colorado Rivers. Upstream of this confluence at monitoring site 09093700, Colorado River near DeBeque, Colorado, 40 percent of the load is associated with the saline springs, represented by the point-source imports, and high-yield sedimentary Paleozoic and Precambrian rocks account for 26 percent. Saline springs contribute 18 percent of the dissolved-solids load for the Grand Division. Of the 18 percent, about 11 percent are discharged from Dotsero and Glenwood Springs. Saline ground-water discharge associated with Paradox and Sinbad Valleys is the dominant load source for the Dolores River, representing 43 percent of its total load.

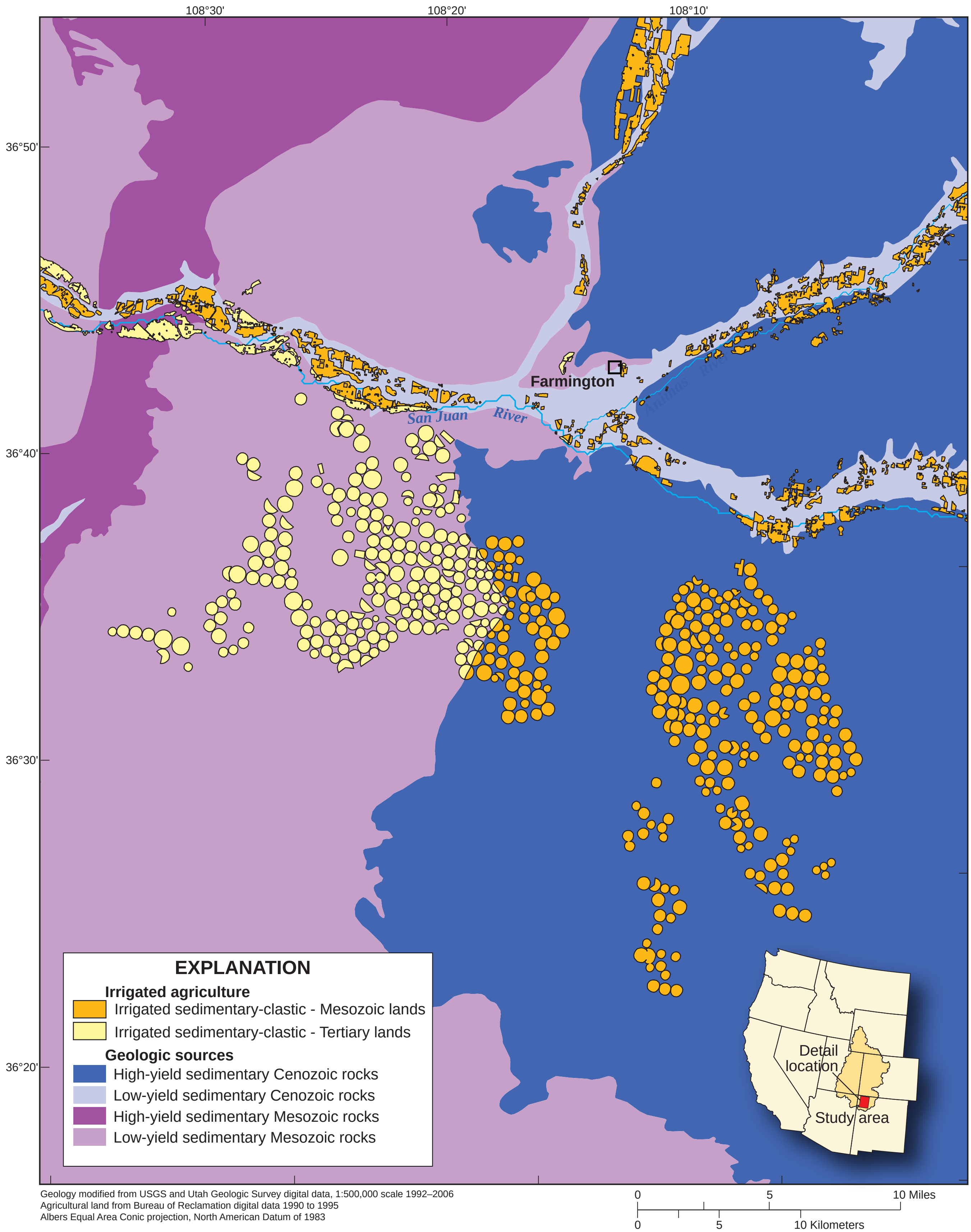

Figure 15. Irrigated lands along the San Juan River near Farmington, New Mexico, that appear to be related to center pivot sprinklers.

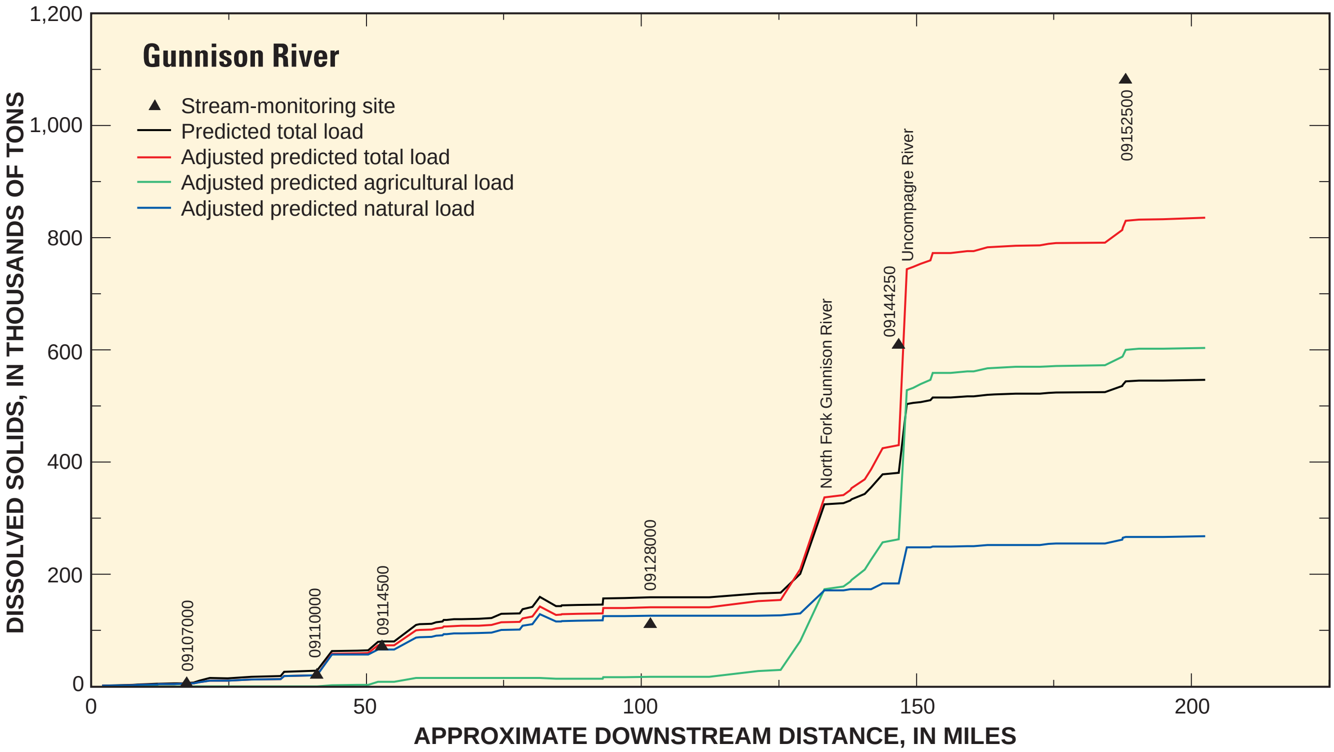

Figure 16. Predicted downstream accumulation of dissolved solids for the Gunnison River, from the UCRB SPARROW model of dissolved-solids transport, for 1991.

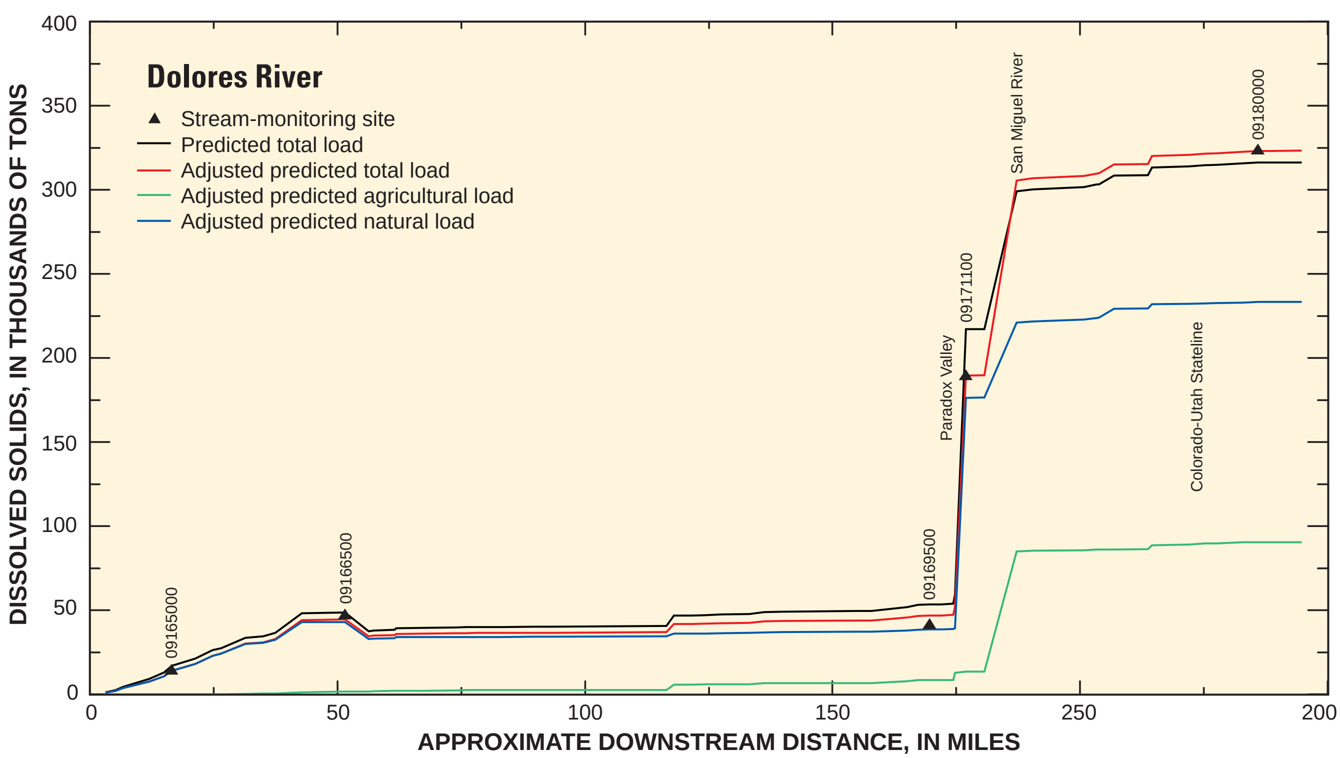

Figure 17. Predicted downstream accumulation of dissolved solids for the Dolores River, from the Upper Colorado River Basin (UCRB) SPARROW model of dissolved-solids transport, for 1991.

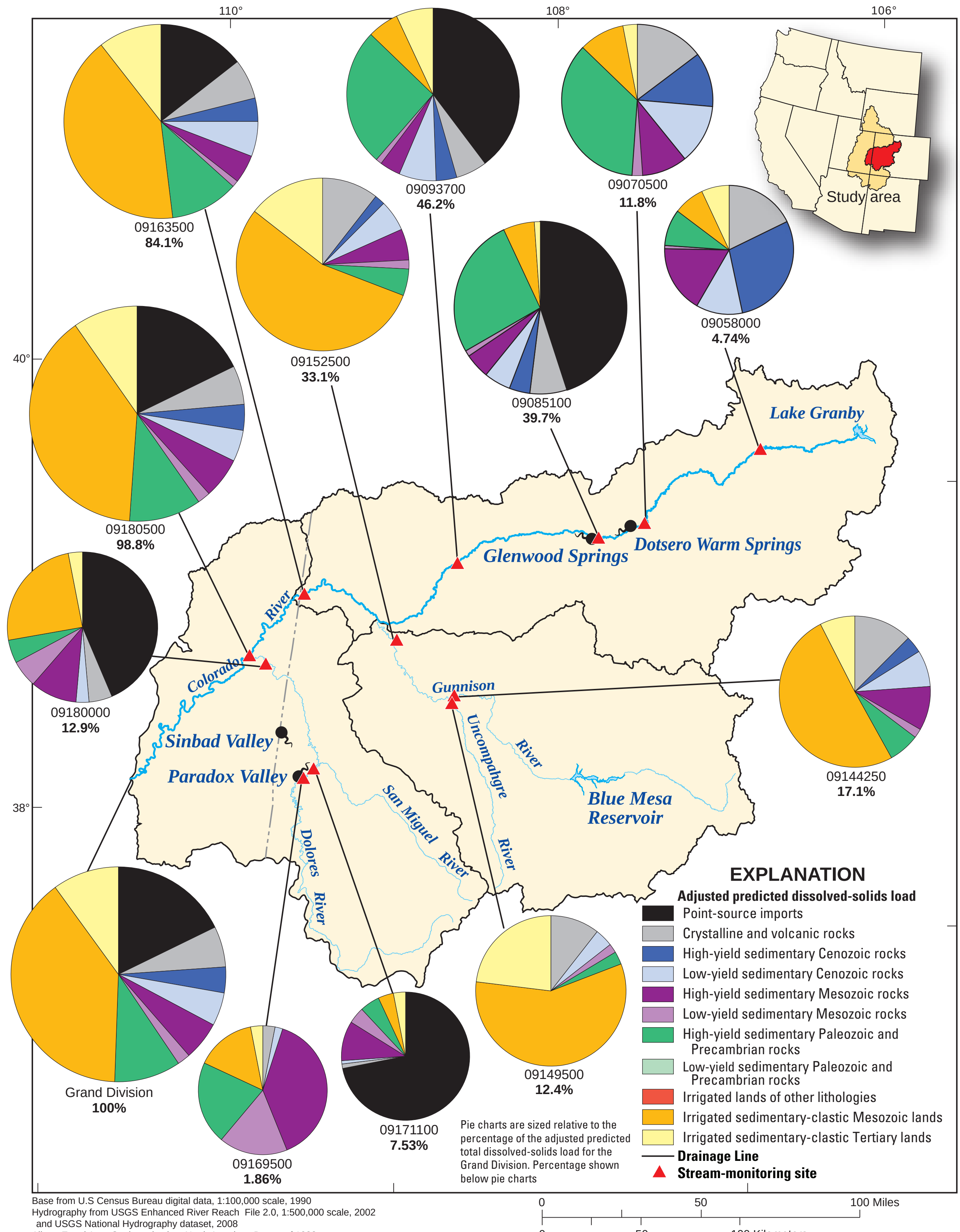

Figure 18. Distribution of dissolved-solids loads by source for selected streams in the Grand Division, from the Upper Colorado River Basin (UCRB) SPARROW model of dissolved-solids transport, for 1991.

Green Division

Thirty-seven percent of the dissolved-solids load for the Green Division, defined as the Green River drainage basin upstream of the confluence with the Colorado River, is associated with irrigated agricultural lands (fig. 19). Different from the Grand Division, irrigated sedimentary-clastic Tertiary lands are the largest contributing agricultural source at 22 percent, and irrigated sedimentary-clastic Mesozoic lands make up the remaining 15 percent. Dissolved-solids loads from the Yampa and White Rivers provide most of the load in the Green Division associated with natural geological sources. Low-yield sedimentary Cenozoic rocks are the most dominant source in the Yampa River, and high-yield sedimentary Paleozoic and Precambrian rocks are the most dominant source in the White River.

San Juan Division

The San Juan Division, which terminates at monitoring site 09380000, Colorado River at Lees Ferry, Arizona, is comprised of the San Juan River and the Colorado River below the confluence with the Green River (fig. 20). Below the confluence, the dissolved-solids load in the Colorado River is apportioned as 30 percent irrigated sedimentary-clastic Mesozoic lands, 15 percent irrigated sedimentary-clastic Tertiary lands, 12 percent point-source imports, and 47 percent associated with the seven geologic source groups. This distribution of load between the 11 sources is nearly identical for the Lees Ferry, Arizona, monitoring site. The load at Lees Ferry, Arizona, is comprised of about 45 percent irrigated agriculture and 57 percent natural sources, which does not include the apparent reservoir point-source load for Lake Powell.

Comparison of Dissolved-Solids Load Predictions with other Studies at Selected Locations in the UCRB

Iorns and others (1965) determined the probable amounts of dissolved solids, computed from the annual average of 1914–1957 and adjusted to 1957 watershed development conditions, from natural sources and from human activities (Iorns and others, 1965), or agricultural sources, for selected stream locations in the three divisions of the UCRB. The locations in the UCRB presented in Iorns and others (1965) by Division are contained in tables 10–12. For each of these locations, where available, dissolved-solids loads from Iorns and others (1965), and the 1991 UCRB model, are presented along with the contributions associated with natural and agricultural sources for the two periods. Associated irrigated acres for each location and period along with associated streamflows provide further information when comparing the two load components. Table 13 contains measured precipitation at locations within the UCRB presented in Iorns and others (1965) for the two periods. Because dissolved-solids loads in streams are variable from year to year, the precipitation, streamflow, and watershed conditions, specifically the amount of irrigated acres, should provide perspective when comparing the dissolved-solids loads for the two periods. The period of 1914–1957 predates the large-scale reservoir projects of the UCRB, such as Fontenelle and Flaming Gorge Reservoirs on the Green River, Navajo Reservoir on the San Juan River, and Lake Powell on the Colorado River, which as discussed earlier, affect the transport of dissolved solids through the basin.

For the selected locations in the Grand Division, the dissolved-solids loads for 1991 are generally less than those for the period 1914–1957 (table 10). Precipitation at the locations presented in Iorns and others (1965) indicates that 1991 was less than the average for the period 1914–1957. Similarly, the annual average streamflows for the period 1914–1957 are larger than the annual total for 1991 at all but one of the locations. The total load at Colorado River below Grand Valley Divide, near Palisade, Colorado, in 1991 is affected by the Government Highline Canal and Grand Valley diversions; however, the percentage of load apportioned between natural and agricultural sources is representative of the flows upstream of the diversions because of the manner in which the SPARROW model treats diversions. In general, the 1991 results attribute more of the dissolved-solids loads for the Grand Division above the Gunnison River to natural sources than those of Iorns and others (1965).

Table 11 contains the stream locations presented in Iorns and others (1965) for the Green Division, along with corresponding dissolved solids and streamflow information for the two periods. Dissolved-solids loads were greater for the 1914–1957 period at all but one location, and the average streamflows for 1914–1957 were greater than 1991 at all locations. Precipitation differences between the 1914–1957 period and 1991 in the Green Division ranged from –2.64 in. to +4.45 in. at the selected locations. For all locations of the Green Division examined by Iorns and others (1965), with the exception of the White River near Watson, Utah, and the San Rafael River near Castle Dale, Utah, the amount of irrigated acres increased in 1991, on average by about 50 percent. Interestingly, when compared with Iorns and others (1965), the predicted contribution of dissolved solids attributed to agriculture for 1991 for locations on the Green River remained about the same, aside from the most upstream location, Green River near La Barge, Wyoming, which increased from 38 to 60 percent. The amount of irrigated acres at the most downstream location represented in table 11, Green River at Green River, Utah, increased by more than 35 percent by 1991, and the contribution of dissolved solids associated with irrigated agriculture was predicted to be between 37 and 42 percent, roughly equal to the 39 percent from Iorns and others (1965). Improved irrigation delivery practices, such as sprinklers, along with water development projects, likely play a role in balancing the irrigated agricultural contribution.

Dissolved-solids data for selected locations in the San Juan Division for the 1914–1957 period (Iorns and others) and 1991 are contained in table 12. The number of irrigated acres in the San Juan Division, as measured at locations contained

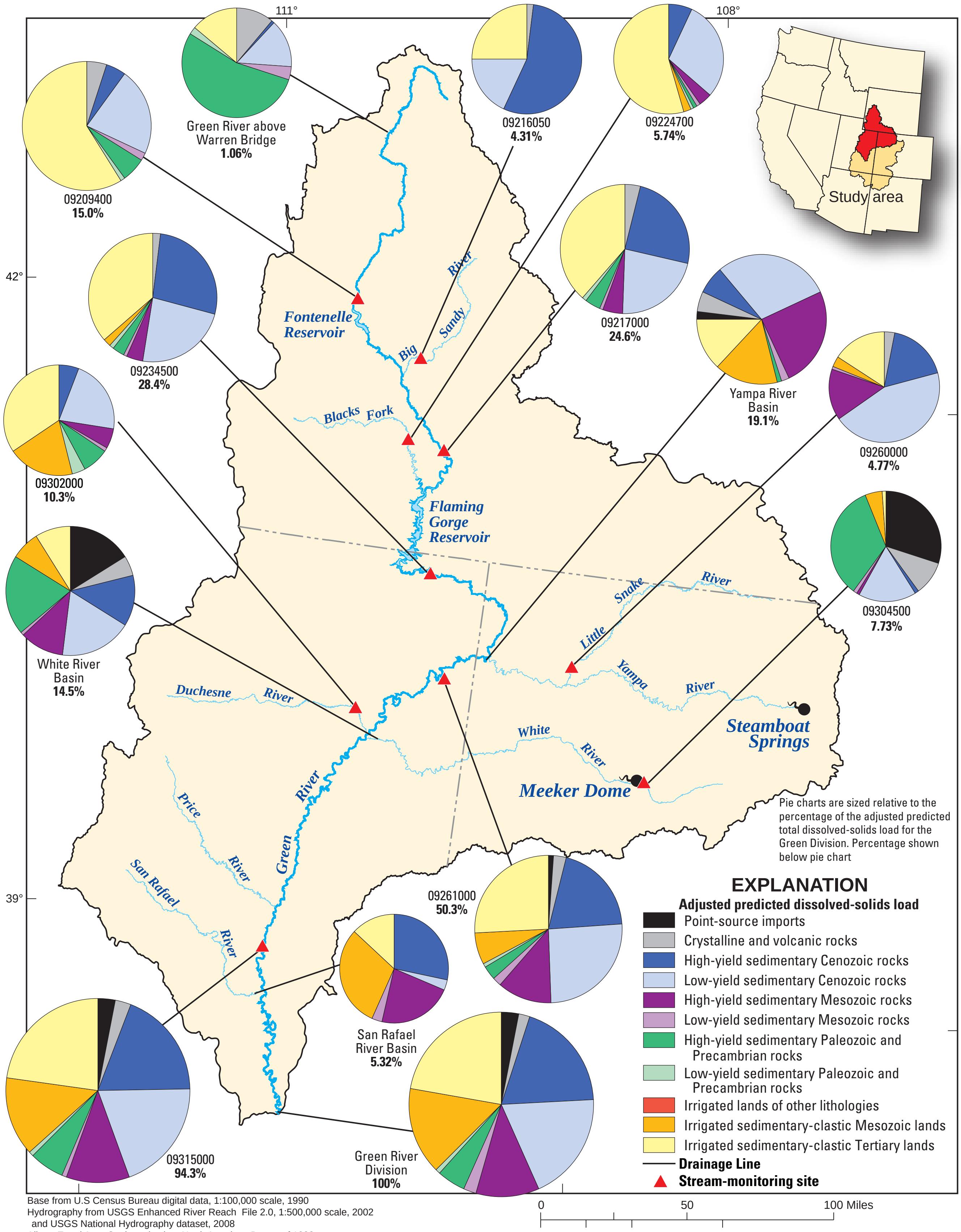

Figure 19. Distribution of dissolved-solids loads by source for selected streams in the Green Division, from the Upper Colorado River Basin (UCRB) SPARROW model of dissolved-solids transport, for 1991.

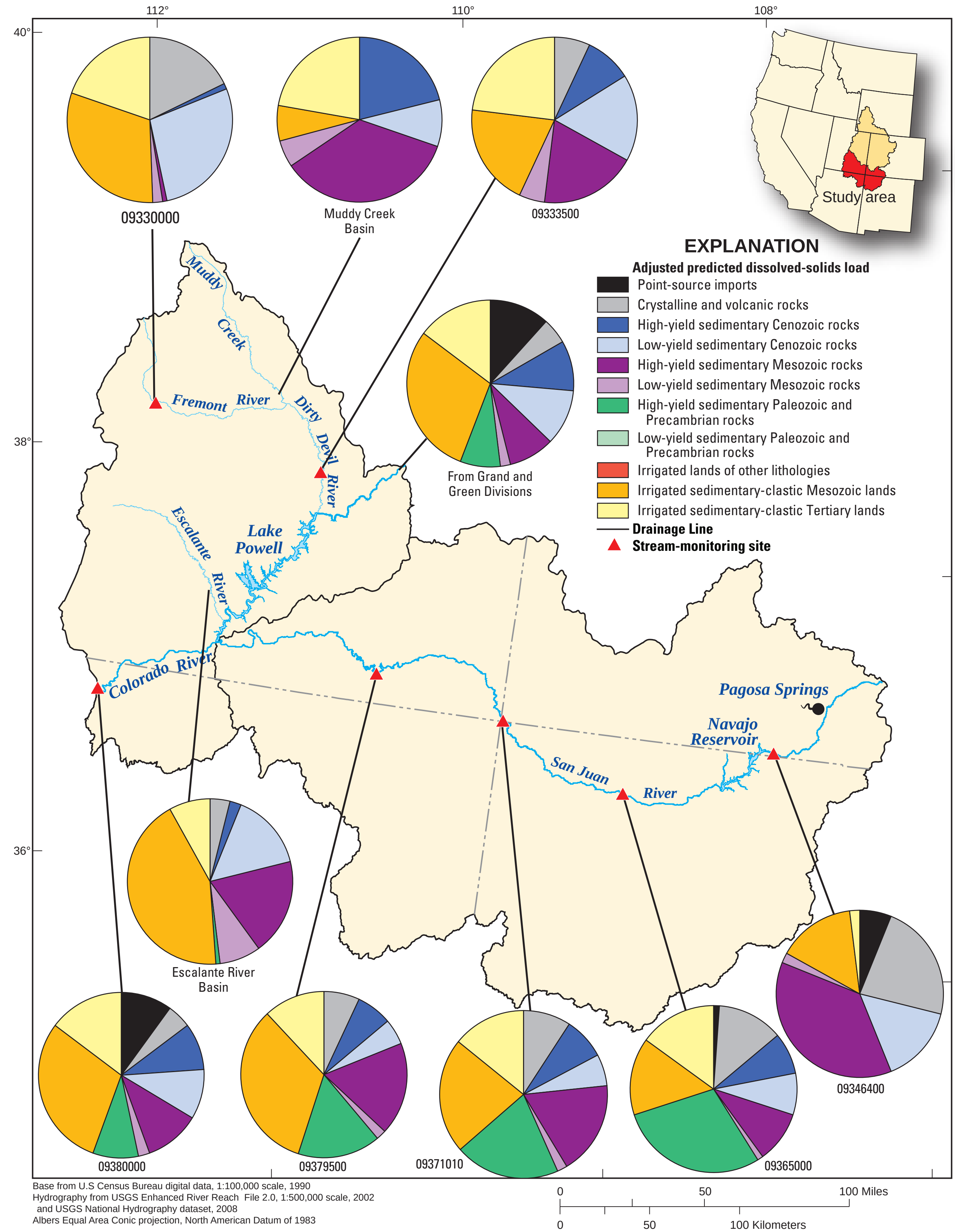

Figure 20. Distribution of dissolved-solids loads by source for selected streams in the San Juan Division, from the Upper Colorado River Basin (UCRB) SPARROW model of dissolved-solids transport, for 1991.

Table 10. Dissolved-solids loads and contributions from natural and agricultural sources for the 1914–1957 period adjusted for 1957 and 1991 for the Grand Division above the Gunnison River, Colorado.

[An explanation of adjusted predicted and predicted 1991 dissolved-solids loads can be found on page 31. Sum of 1991 natural and agricultural dissolved-solids percent may not always equal 100. CO, Colorado]

Location	Drainage area (square miles)	[2]Acres irrigated, 1957	Acres irrigated, 1991	Annual streamflow		Dissolved-solids load					
								Natural		[1]Agricultural	
				[3]Average 1914–1957 (acre-feet)	1991 total (acre-feet)	[3]Average 1914–1957 total (tons)	Monitored 1991 total (tons)	[4]Average 1914–1957 (percent)	Adjusted predicted [predicted] 1991 (percent)	[4]Average 1914–1957 (percent)	Adjusted predicted [predicted] 1991 (percent)
Colorado River at Hot Sulphur Springs, CO	825	15,700	15,400	176,800	118,000	18,300	13,400	62	91 [90]	38	9 [10]
[5]Colorado River near Glenwood Springs, CO	4,556	83,700	83,500	1,738,000	1,990,000	639,200	519,000	81	93 [92]	19	8 [9]
Roaring Fork at Glenwood Springs, CO	1,451	31,400	34,200	980,200	741,000	299,900	267,000	69	90 [92]	31	12 [11]
Colorado River near Cameo, CO	8,050	163,400	172,000	2,998,000	2,170,000	1,578,000	1,330,000	76	88 [88]	24	14 [13]
Plateau Creek near Cameo, CO	592	29,100	31,300	170,200	71,400	66,100	36,600	43	50 [52]	57	60 [62]
[6]Colorado River below Grand Valley Divide, near Palisade, CO	8,753	192,500	205,000	3,168,200	1,550,000	1,644,100	828,000	76	86 [86]	24	16 [16]

[1] Man-caused in Iorns and others (1965).

[2] From Iorns and others (1965).

[3] Average adjusted for 1957 watershed development conditions from Iorns and others (1965).

[4] Computed from Iorns and others (1965).

[5] Colorado River above Glenwood Springs in Iorns and others (1965).

[6] Colorado River Basin above Gunnison River in Iorns and others (1965).

Table 11. Dissolved-solids loads and contributions from natural and agricultural sources for the 1914–1957 period adjusted for 1957 and 1991 for the Green Division of the Upper Colorado River Basin.

[An explanation of adjusted predicted and predicted 1991 dissolved-solids loads can be found on page 31. Sum of 1991 natural and agricultural dissolved-solids percent may not always equal 100. CO, Colorado; UT, Utah; WY, Wyoming; NA, data not available]

				Annual streamflow		Dissolved-solids load					
								Natural		[1]Agricultural	
Location	Contribution drainage area (square miles)	[2]Acres irrigated 1957	Acres irrigated, 1991	[3]Average 1914–1957 (acre-feet)	1991 total (acre-feet)	[3]Average 1914–1957 total (tons)	Monitored 1991 total (tons)	[4]Average 1914–1957 (percent)	Adjusted predicted [predicted] 1991 (percent)	[4]Average 1914–1957 (percent)	Adjusted predicted [predicted] 1991 (percent)
Green River near La Barge, WY	3,910	NA	242,000	NA	1,003,418	NA	263,000	NA	41 [41]	NA	59 [60]
Green River near Fontenelle, WY	[2]3,970	131,600	NA	1,166,000	NA	294,000	NA	62	NA	38	NA
Green River near Green River, WY	9,740	151,600	269,000	1,295,000	973,736	504,000	424,000	63	61 [63]	37	39 [37]
Green River near Greendale, UT	15,390	255,400	397,000	1,645,000	895,547	847,400	593,000	63	62 [62]	37	38 [38]
[5]Green River Basin above Yampa River	16,850	258,400	399,000	NA	NA	967,100	543,000	67	64 [64]	33	36 [36]
[6]Yampa River near Maybell, CO	3,410	51,300	69,300	1,152,000	872,380	218,800	251,000	86	68 [68]	14	33 [33]
[7]Little Snake River near Lily, CO	3,730	20,400	32,200	450,600	237,968	120,500	76,500	75	81 [81]	25	19 [19]
[5]Yampa River Basin	[2]8,000	73,700	106,000	NA	NA	405,800	336,000	85	72 [74]	15	28 [26]
Duchesne River near Randlett, UT	4,250	135,700	145,000	555,700	86,152	460,200	125,000	29	47 [29]	71	55 [74]
White River near Watson, UT	4,020	29,900	25,400	553,500	418,236	330,600	254,000	50	85 [85]	50	16 [15]
[5]Green River at Ouray, UT	31,540	530,100	714,000	4,508,000	NA	2,407,000	1,010,000	61	61 [62]	39	39 [39]
Green River at Green River, UT	40,890	550,600	757,000	4,558,000	2,432,529	2,652,000	1,670,000	61	63 [59]	39	37 [42]
[5]San Rafael River near Castle Dale, UT	[2]927	36,000	27,900	96,350	NA	171,300	83,600	33	55 [48]	77	45 [52]

[1] Man-caused in Iorns and others (1965).

[2] From Iorns and others (1965).

[3] Average adjusted for 1957 watershed development conditions from Iorns and others (1965).

[4] Computed from Iorns and others (1965).

[5] No gage at location in 1991; used adjusted predicted load.

[6] Yampa River at bridge on county road near Maybell, CO; in Iorns and others (1965).

[7] Little Snake River at bridge on State Highway 318, near Lily, CO; in Iorns and others (1965).

Table 12. Dissolved-solids loads and contributions from natural and agricultural sources for the 1914–1957 period adjusted for 1957 and 1991 for the San Juan Division of the Upper Colorado River Basin.

[An explanation of adjusted predicted and predicted 1991 dissolved-solids loads can be found on page 31. Sum of 1991 natural and agricultural dissolved-solids percent may not always equal 100. CO, Colorado; NM, New Mexico; UT, Utah; WY, Wyoming; NA, data not available]

				Annual streamflow		Dissolved-solids load					
								Natural		[1]Agricultural	
Location	Contribution drainage area (square miles)	[2]Acres irrigated 1957	Acres irrigated, 1991	[3]Average 1914–1957 (acre-feet)	1991 total (acre-feet)	[3]Average 1914–1957 total (tons)	Monitored 1991 total (tons)	[4]Average 1914–1957 (percent)	Adjusted predicted [predicted] (percent)	[4]Average 1914–1957 (percent)	Adjusted predicted [predicted] 1991 (percent)
San Juan River near Carracas, CO	1,230	NA	15,800	NA	464,000	NA	86,200	NA	82 [84]	NA	18 [17]
San Juan River near Arboles, CO	[2]1,340	13,300	NA	NA	NA	77,000	NA	83	NA	17	NA
San Juan River near Archuleta, NM	3,260	NA	73,100	NA	519,000	NA	116,000	NA	73 [66]	NA	27 [34]
San Juan River near Blanco, NM	[2]3,560	61,600	NA	1,100,000	NA	187,000	NA	79	NA	21	NA
San Juan River near Bluff, UT	23,000	206,400	307,000	2,028,000	1,080,000	997,000	655,000	71	55 [51]	29	46 [49]
[5]San Juan River Basin	[2]24,900	206,400	307,000	NA	NA	1,073,000	915,000	73	56 [52]	27	45 [49]
Dirty Devil River above Poison Spring Wash, near Hanksville, UT	4,160	NA	29,000	NA	41,000	NA	67,700	NA	58 [59]	NA	43 [42]
Dirty Devil River near Hite, UT	[2]4,360	23,300	NA	[6]73,890	NA	197,600	NA	72	NA	28	NA
[5]Escalante River at mouth, near Escalante, UT	[2]2,010	7,000	3,800	[7]61,720	NA	25,200	16,200	68	51 [53]	32	49 [48]
Colorado River at Lees Ferry, AZ	108,000	1,410,000	1,727,026	12,710,000	[8]7,080,000	8,642,000	[8]5,760,000	60	[8]57 [59]	40	[8]45 [43]

[1] Man-caused in Iorns and others (1965).

[2] From Iorns and others (1965).

[3]Average adjusted for 1957 watershed development conditions from Iorns and others (1965).

[4] Computed from Iorns and others (1965).

[5] No gage at location in 1991; used adjusted predicted load.

[6] Average 1949–1957.

[7] Average 1951–1955.

[8] 1991 apparent reservoir point-source load and storage decrease-related streamflow for Lake Powell removed.

Table 13. Water year 1991 total precipitation and average annual total precipitation for 1914–1957 at index stations in the Grand, Green and San Juan Divisions of the Upper Colorado River Basin.

[AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah; WY, Wyoming; NA, data not available]

	[1]1991 total precipitation (inches)	[2]Average annual total precipitation, 1914–1957 (inches)
Grand Division		
Spicer, CO	14.1	13.02
Estes Park, CO	13.33	17.55
Fraser, CO	NA	18.82
Idaho Springs, CO	NA	15.12
Dillon, CO	13.1	18.29
Leadville, CO	10.4	19.47
Shosone, CO	22.23	17.78
Collbran, CO	14.33	15.24
Grand Junction, CO	8.89	8.86
Cedaredge, CO	12.79	11.94
Paonia, CO	12.82	15.47
Montrose, CO	9.53	9.62
Gunnison, CO	NA	10.79
Pitkin, CO	NA	16.4
Ames, CO	NA	25.57
Rico, CO	30.72	26.35
Moab, UT	6.57	9.32
Green Division		
Lander, WY	14.52	13.84
Encampment, WY	12.06	13.78
Border, WY	16.71	12.98
Evanston, WY	14.43	12.09
Green River, WY	10.94	8.34
Bedford, WY	24.34	19.89
Hayden, CO	17.97	16.08
Steamboat Springs, CO	23.22	24.19
Meeker, CO	16.22	16.55
Vernal, UT	7.8	8.46
Elkhorn Ashley, UT	NA	13.73
Duchesne, UT	9.21	9.45
Snake Creek, UT	21.06	23.09
Spanish Fork, UT	19.13	17.54
Moroni, UT	7.94	10.58
Green River, UT	7.24	6.22
San Juan Division		
Silverton, CO	28.12	23.52
Hermit, CO	15.85	16.19
Ignacio, CO	13.63	15.4
Fort Lewis, CO	15.69	18.56
Aztec Ruins, NM	9.54	9.56
Regina, NM	NA	16.3
Crownpoint, NM	NA	10.57
Blanding, UT	11.47	12.95
Emery, UT	NA	7.48
Hanksville, UT	3.47	5.17
Piute Dam, UT	NA	8.17
Orderville, UT	12.43	14.58
Lees Ferry, AZ	NA	5.94

[1] From Western Region Climate Center (2008).

[2] From Iorns and others (1965).

in table 12, has increased substantially since 1957, except for the Escalante River at mouth near Escalante, Utah. The 1991 results indicate a slight increase in the agricultural component of the dissolved-solids load upstream of the San Juan River near Blanco, New Mexico, and considerable increases below. The 1991 dissolved-solids loads were less than those for the 1914–1957 period at all locations except the San Juan River near Carracas, Colorado. The agricultural component of dissolved solids for the Dirty Devil and the Escalante Rivers increased by about 15 percent. However, the average 1914–1957 and 1991 monitored total loads for the Dirty Devil River differed considerably, which makes the results difficult to compare.

Iorns and others (1965) attributed about 60 percent of the total load for the UCRB as measured at Lees Ferry, Arizona, to natural sources, and 40 percent to agriculture. After removing the apparent reservoir point-source load attributed to Lake Powell, the adjusted predicted 1991 results suggest that 57 percent of the total load at the Colorado at Lees Ferry, Arizona, site is from natural sources and 45 percent is from agricultural sources. The predicted 1991 results are nearly identical with 59 percent from natural sources and 43 percent from agricultural sources. Because of the bootstrap prediction routine applied by the SPARROW model, the sum of mass, in this case dissolved-solids load, attributed to the individual sources may exceed the total predicted load. For the entire UCRB, the amount of irrigated land has increased by more than 315,000 acres, or 22 percent, from 1957 to 1991 (David Eckhart, Bureau of Reclamation Remote Sensing and Geographic Information Group, written commun., September 28, 2006). However, the dissolved-solids load associated with irrigated agriculture has only increased by about 2 percent. The apparent reservoir point-source load attributed to Lake Powell was determined to be 723,000 tons (table 4) and was included in the point-source imports parameter, which was also used to represent the saline springs, in an effort to retain balance in the model. This apparent increase in dissolved solids is not related to 1991 conditions of dissolved-solids sources and transport in the UCRB, and therefore, was removed from the results. The minor apparent reservoir point-source loads associated with the other five reservoirs (table 4) were very small, and no effort was made to remove them from the results presented.

Results from the southwestern U.S. dissolved-solids SPARROW model (Anning and others, 2007), which included the UCRB, were compared with results generated from this study (table 14). The predicted dissolved-solids loads at selected locations generally are similar except for the Colorado River above the Gunnison River. The 1991 adjusted predicted load of 886,000 tons generally agrees with the nearest upstream monitored load of 828,000 tons at Colorado River below Grand Valley Diversion, near Palisade, Colorado, which is approximately 15 mi upstream. The southwestern U.S. model predicts the natural component of the dissolved-solids load to be greater at all but two of the selected locations: Colorado River above Gunnison River, and White and Yampa Rivers above Green River. For the entire UCRB, as measured

Table 14. Dissolved-solids loads and contributions from natural and agricultural sources for 1974–2003 and 1991 for selected locations in the Upper Colorado River Basin.

[An explanation of adjusted predicted and predicted 1991 dissolved-solids loads can be found on page 31. Sum of 1991 natural and agricultural dissolved-solids percent may not always equal 100. NA, data not available]

Location	Area (square miles)	Dissolved-solids load						
					Natural		Agricultural	
		Median 1974–2003 total (tons)	Monitored 1991 total (tons)	Adjusted predicted [predicted] 1991 total (tons)	[1]Median 1974–2003 (percent)	Adjusted predicted [predicted] 1991 (percent)	[1]Median 1974–2003 (percent)	Adjusted predicted [predicted] 1991 (percent)
[2]Colorado River above Gunnison River	9,860	3,170,000	828,000	886,000 [690,000]	75	85 [86]	25	18 [17]
[3]Gunnison River above Colorado River	8,020	1,173,000	1,080,000	830,000 [544,000]	55	32 [45]	45	72 [61]
Colorado River above Green River	26,100	3,421,000	NA	2,510,000 [1,800,000]	[7]68	52 [62]	[7]32	50 [42]
[4]Green River above Yampa River	16,850	931,000	NA	543,000 [556,000]	79	64 [64]	21	36 [36]
[5]White and Yampa Rivers above Green River	13,350	685,000	NA	591,000 [634,000]	61	77 [78]	39	23 [22]
Green River above Colorado River	44,500	2,478,000	NA	1,760,000 [2,050,000]	[7]73	63 [58]	[7]27	38 [42]
[6]San Juan River below Mancos River	13,740	574,000	530,000	695,000 [715,000]	67	64 [59]	33	37 [42]
San Juan River above Colorado River	25,120	744,000	NA	915,000 [972,000]	[7]61	56 [52]	[7]39	45 [49]
Upper Colorado River Basin	108,000	[8]6,393,000	[9]5,760,000	[9]5,300,000 [[9]4,930,000]	[7,8]68	[9]57 [[9]59]	[7,8]32	[9]45 [[9]43]

[1] From Anning and others (2007).
[2] Colorado headwaters hydrologic accounting unit 140100 in Anning and others (2007).
[3] Gunnison hydrologic accounting unit 140200 in Anning and others (2007).
[4] Upper Green hydrologic accounting unit 140401 in Anning and others (2007).
[5] White-Yampa hydrologic accounting unit 140500 in Anning and others (2007).
[6] Upper San Juan hydrologic accounting unit 140801 in Anning and others (2007).
[7] Computed from Anning and others (2007).
[8] Includes Paria River.
[9] 1991 apparent reservoir point-source load for Lake Powell removed.

at Lees Ferry, Arizona, the southwestern U.S. model attributes approximately 68 percent of the dissolved-solids load to natural sources, which is about 10 percent higher than the results of the 1991 UCRB model.

Although both of these efforts developed a dissolved-solids SPARROW model following a similar conceptual model of the sources and transport of dissolved solids, there are fundamental differences associated with the spatial extent, the datasets used, and periods of the studies that should be considered when comparing their results. The UCRB was represented by more than 10,000 stream reaches in the UCRB model. The network of the southwestern U.S. model contained about 5,200 reaches, 1,986 of which were within the UCRB. The finer scale of the UCRB model allowed for a more detailed representation of the various sources and landscape transport characteristics within each incremental catchment. Geology in the southwestern U.S. model was represented by the King and Beikman (1974) 1:2,500,000-scale bedrock geology map of the United States. For the UCRB model, the geologic unit names of the King and Beikman (1974) 1:2,500,000-scale bedrock geology map were assigned to the finer scale units defined by the various 1:500,000-scale state geologic maps. Both modeling efforts incorporated a similar method for grouping the geologic units into distinct geologic source groups; however, this did not ensure that units of the same name were placed in the same geologic source groups. The UCRB model contained three sources of irrigated agricultural lands, classified by lithology, and the agricultural lands in southwestern U.S. model were represented by two sources: cultivated and pasture lands. The UCRB model was developed from monitored dissolved-solids loads from water year 1991 and the southwestern U.S. model was developed from median annual dissolved-solids loads from stations with about 10 or more years of record during the period 1974–2003. Results from the southwestern U.S. effort generally describe the conditions of dissolved solids for the period 1974–2003 (Anning and others, 2007). Results from the UCRB model describe the conditions of dissolved solids in water year 1991.

Application of Results from Water year 1991 to other Years

The UCRB dissolved-solids SPARROW model was calibrated using monitoring data along with precipitation and evaporative transpiration estimates for water year 1991. Potential irrigated lands data for the period 1990–1995 (David Eckhart, Bureau of Reclamation Remote Sensing and Geographic Information Group, written commun., September 28, 2006) were used in defining the irrigated lands sources. The remaining parameters contained in this model are not specific to any period. As previously described, 1991 was selected on the basis of available monitoring data, precipitation that was similar to the 30-year average, streamflows similar to period of record averages in the basin, and the vintage of various geospatial data. A single year was chosen to provide a temporal reference point of dissolved-solids sources and transport in the UCRB to resource managers. Because the hydrologic conditions for water year 1991 were near normal, as determined through comparison with the 30-year average precipitation and selected long-term streamflow records, the results of this modeling effort can be considered representative of an average water year. Although this is generally the case when considering the entire UCRB, there are locations within the basin during water year 1991 that deviated from average precipitation conditions as shown in figure 5. When evaluating predicted dissolved-solids loads under the assumption of average climatic conditions for specific locations, particularly in smaller basins, landscape transport characteristics, particularly the 1991 precipitation estimate, should be examined. When comparing predicted dissolved-solids loads from this model with current conditions in the UCRB, consideration of any changes made within watersheds since 1991, specifically to the irrigated lands and point sources, is required. The results generated from this model are also influenced by the manner in which reservoirs were managed during the 1991 water year. As further described below, the estimated coefficients generated for the various sources and landscape transport characteristics during calibration of the 1991 SPARROW model are representative of basin-averaged conditions.

Limitations and Uncertainty

When interpreting the results and(or) findings of this investigation, as with any modeling exercise, specific limitations and uncertainties associated with the methodologies, data, and techniques used, need to be considered. This report documents the development of a model describing the sources and transport of dissolved solids in the UCRB using a nonlinear weighted least squares regression technique. The results of the model include predictions of water year 1991 dissolved-solids loads for more than 10,000 unique stream reaches with catchment sizes ranging from 1 to 78 mi^2. The estimated coefficients, which represent basin-averaged conditions generated during the nonlinear least-squares calibration, provide understanding into the role the 11 defined sources and 7 defined landscape transport characteristics play in generating and transporting dissolved solids to streams in the UCRB.

The UCRB is a large regional scale drainage. Simplification of real world complexity, especially with natural processes, is necessary when modeling at nearly all scales. This dissolved-solids SPARROW model examined the contributing 108,000 mi^2 drainage of the UCRB and required a number of simplifications, such as grouping 34 geologic units into seven geologic source groups. Moreover, statistically related assumptions were required to apply the techniques of the SPARROW surface-water quality model. In general, there are three sources of uncertainty to consider when evaluating the results of this modeling effort: (1) parameter uncertainty attributed to finite sample size, (2) model uncertainty attributed to unaccounted factors affecting contaminant transport, and (3) measurement error.

SPARROW is a statistically based model used for examining constituent sources, transport, and fate. Because it is not a physical process model, there are some required assumptions related to the behavior of the contaminant being modeled. The nonlinear mathematical representation of the SPARROW model, given by equation 1, is assumed to represent mathematically the means by which the contaminant of interest is produced and transported, and how it evolves. From the results of this modeling effort, particularly the yield R^2 and RMSE values, the model appears to accurately represent a large portion of these processes as related to dissolved solids; however, model uncertainty, evident in the results, indicates there are complexities that are not entirely captured. Model uncertainty theoretically decreases with additional statistically significant explanatory parameters. There are issues related to scale, as describe below, that have some effect on model uncertainty. Statistical techniques often assume that datasets used in the analysis possess statistical characteristics, such as normal unbiased distributions, that are fundamental to applying the technique. The nonlinear weighted least squares technique of SPARROW contains a number of such assumptions. Observation data used for calibration are assumed to be spatially distributed in an unbiased manner, that is, the network of monitoring sites represents all sources of the contaminant completely and in an equal manner. Although the 218 monitoring sites used in this investigation, as shown in figure 1, do not appear to fit this assumption completely, appendix 2 can be used to identify how the sources are represented within the 218 unique calibration reaches. As previously discussed, the coefficient estimates generated in the nonlinear least squares calibration are valid only asymptotically. Parameter uncertainty decreases with larger sample sizes. Therefore, it is assumed that large sample sizes generate results that are unbiased and possess standard normal distributions. The resampled bootstrap analysis indicated a sufficiently large enough sample size to meet these criteria. For a more detailed discussion of the statistical assumptions embedded in the statistical techniques of the SPARROW model, refer to Schwarz and others (2006).

Scale limitations are important to consider when examining the estimated coefficients and predicted loads generated from this modeling effort. Model parameters used in model calibration were computed from geospatial data of varying scales as shown in table 3. When analyzing model parameters for specific locations, it is important to consider the scale from which they were generated. Catchments generated from the modified NHD stream reach network ranged from 1 to 78 mi^2. Calibration catchments, defined as reaches bound by monitoring sites or a combination of monitoring sites and headwater reaches, ranged from 4 to 14,200 mi^2. Predictions of dissolved-solids loads were made for the more than 10,000 stream reaches of the network. Generally, predictions for basins with total drainage areas and source representations within the range of the calibration reaches, as shown in appendix 2, and assuming an unbiased spatial distribution of monitoring sites, possess less uncertainty in the predicted loads than basins outside the range of calibration data, including independent variables. Uncertainty also would be expected to increase as basin size decreases and model required simplifications become less valid. At finer scales, local influences on dissolved-solids loading to streams not represented in the model, such as small-scale water developments that are common in many areas, can cause large differences between model-generated predicted loads and actual loads. When considering limitations related to scale, model required simplifications become increasingly sensitive especially when examining small watersheds. Because coefficients are basin-wide averages, finer scales increase the potential for local geology to possess higher or lower yields than those represented by the coefficients assigned to the seven geologic source groups.

Uncertainties associated with measurement error are inherently contained within both the dependent and independent variables. Measurement errors are difficult to quantify and generally cannot be removed with more observations or variables. Measurement errors associated with the independent variables can lead to biased coefficients. Measurement errors associated with the dependent variable, water year 1991 dissolved-solids loads for the 218 monitoring sites, are difficult to quantify fully because there are a number of error sources. Dissolved-solids loads are derived from analyses of dissolved-solids concentrations, specific-conductance measurements, daily mean streamflow computations, and statistical modeling. Data from all 218 monitoring sites were measured and analyzed by USGS personnel in accordance with USGS standards and techniques as outlined in Rantz and others (1982), U.S. Geological Survey (variously dated), and Fishman and Friedman (1989). Using the measurements and lab analyses obtained at the 218 monitoring sites, annual loads were determined statistically as described in Anning and others (2007), and by using the LOADEST computer program of Runkel and others (2004) adapted for use with S-Plus (Insightful Corporation, 2005) statistical software (Dave Lorenz, U.S. Geological Survey, written commun., 2005) based upon the methods of Runkel and others (2004). The amount of uncertainty associated with measurement error is difficult to quantify; however, because standard procedures were adhered to for the measurements and lab analyses, measurement errors can be assumed to be generally equivalent for each site.

As has been stressed throughout this report, the results of this dissolved-solids SPARROW modeling effort are representative of basin-averaged conditions, as defined by the 218 calibration reaches. Homogeneous yields and properties of the defined sources are assumed. The specified landscape transport characteristics for the various sources provide a means to differentiate between similar sources in different locales. However, it is possible that geologic sources in some basins do not yield the same amount of dissolved solids as in other basins even under similar landscape transport characteristic conditions for a variety of reasons. The presence of dissolvable minerals varies within geologic units, and the natural routing of water in certain landscapes is not necessarily equal in other landscapes. This is especially true when the efficiency of transport in mountainous areas versus areas dominated by mesas or incised canyons is considered.

Summary

The sources and transport mechanisms of dissolved solids in the UCRB have been studied extensively and generally are well understood. The conceptual understanding derived from past investigations of dissolved solids in the UCRB was applied to the approach of the SPARROW surface-water quality model to examine dissolved-solids supply and transport. SPARROW is a spatially referenced regression model that examines the statistical relation between observed contaminant mass, or flux, at monitoring sites within an interconnected stream network to upstream watershed attributes. Attributes consist of sources, landscape transport characteristics, and aquatic transport characteristics. From the well-developed conceptual model of dissolved solids in the UCRB, 11 sources of dissolved solids were defined for examination with the SPARROW model; seven geologic source groups, three irrigated agricultural lands groups, and one point-source associated with saline springs. Twenty-four landscape transport characteristics were statistically examined for significance in predicting dissolved-solids loads in streams of the UCRB through iterative model calibration. From these 24 characteristics, seven were found to be valid predictors: precipitation, evaporative transpiration, soil thickness, hydrologic soil characteristic code, precipitation—maximum catchment elevation ratio, area covered by forest, and minimum catchment elevation. Minimum catchment elevation was specified to the three irrigated agricultural lands sources, and the remaining six characteristics were specified for the seven geologic source groups. The saline springs point source was not specified any landscape transport characteristics.

Dissolved-solids loads for 218 monitoring sites were used to calibrate a dissolved-solids SPARROW model for the UCRB representative of water year 1991 conditions. The calibrated model generally captures the transport mechanisms that deliver dissolved solids to streams in the UCRB as evidenced by R^2 and yield R^2 values of 0.98 and 0.71, respectively. Model prediction error is approximated at 51 percent. Model results indicate that of the seven geologic source groups, the high-yield sedimentary Mesozoic rocks have the largest yield of dissolved solids, about 41.9 tons/mi^2. Irrigated sedimentary-clastic Mesozoic lands have an estimated yield of 1,180 tons/mi^2, about two times greater than the irrigated sedimentary-clastic Tertiary lands. Coefficients estimated for the seven landscape transport characteristics seem to agree well with the conceptual understanding of the role they play in the delivery of dissolved solids to streams in the UCRB.

Predictions of dissolved-solids loads for more than 10,000 stream reaches of the stream reach network used to define the UCRB were generated. From these estimates, the downstream accumulation of dissolved solids, including natural and agricultural components, were examined for selected rivers. Contributions from each of the 11 dissolved-solids sources were examined at selected locations in the Grand, Green, and San Juan Divisions of the UCRB. At the downstream boundary of the UCRB, the Colorado River at Lees Ferry, Arizona, monitoring site, the dissolved-solids contributions of irrigated agricultural lands and natural sources were 45 and 57 percent, respectively. The largest source of dissolved solids in the Grand Division was predicted to be irrigated sedimentary-clastic Mesozoic lands, which account for about 40 percent of the total load above the confluence with the Green River. The bulk of the agricultural loading to the Colorado River occurs below Grand Valley, much of which is attributed to the Gunnison River. The agricultural activities in the Gunnison River basin account for nearly 24 percent or 598,000 tons of the total load for the Grand Division. Irrigated sedimentary-clastic Tertiary lands represent the dominant dissolved-solids source in the Green Division, with 23 percent of the total load above the confluence with the Colorado River.

Model predictions including the contributions of natural and agricultural sources for selected locations in the UCRB were compared with results from Iorns and others (1965) and Anning and others (2007). Generally, dissolved-solids loads for the 1991 UCRB model were less than those in Iorns and others (1965) and were comparable to those in Anning and others (2007). For the Grand Division above the Gunnison River, Iorns and others (1965) attributed more dissolved solids to agriculture than the results from this study. Anning and others (2007) generally associated a larger natural component of the dissolved-solids loads for nearly all selected locations in the UCRB than this study. At the Lees Ferry, Arizona, monitoring site, Iorns and others (1965) attributed a smaller amount of the dissolved-solids loads to irrigated agriculture than the 1991 predictions of this study. This appears to be related to a substantial increase in the amount of irrigated acres in the UCRB since 1957. The agricultural components of the total load at Lees Ferry, Arizona, were 40 percent in Iorns and others (1965), 32 percent in Anning and others (2007), and 45 percent in the 1991 UCRB model.

Results generated from this modeling exercise are bound by specific limitations and uncertainties associated with the methodologies, data, and techniques used. The limitations and caveats presented in this report should be considered when using or interpreting the results generated.

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This report includes an interactive digital map of selected model output that is available at http://pubs.usgs.gov/sir/2009/5007/. A guide to using the digital map is also available at the provided URL.

Appendices 1 and 2

Appendix 1

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.

[CO, Colorado; UT, Utah; WY, Wyoming; NM, New Mexico; AZ, Arizona; A, from Anning and others (2007); L, from Load Estimator (LOADEST) computer program model; nd, none determined]

Surface-water-quality monitoring site		Location			Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit				
09010500	Colorado River below Baker Gulch, near Grand Lake, CO	40°19'33"	105°51'22"	14010001	1,610	A	8.4	nd
09024000	Fraser River at Winter Park, CO	39°54'00"	105°46'34"	14010001	682	A	20.3	nd
09025000	Vasquez Creek at Winter Park, CO	39°55'13"	105°47'05"	14010001	269	A	18.7	nd
09025400	Elk Creek near Fraser, CO	39°55'09"	105°49'31"	14010001	48	A	9.5	nd
09026500	St. Louis Creek near Fraser, CO	39°54'36"	105°52'40"	14010001	859	A	18.5	nd
09032000	Ranch Creek near Fraser, CO	39°57'00"	105°45'54"	14010001	206	A	12.1	nd
09032100	Cabin Creek near Fraser, CO	39°59'09"	105°44'40"	14010001	120	A	16.4	nd
09034250	Colorado River at Windy Gap, near Granby, CO	40°06'30"	106°00'13"	14010001	11,800	A	13.2	nd
09034500	Colorado River at Hot Sulphur Springs, CO	40°05'00"	106°05'15"	14010001	13,400	A	12.8	nd
09034900	Bobtail Creek near Jones Pass, CO	39°45'37"	105°54'21"	14010001	239	A	9.3	nd
09035500	Williams Fork below Steelman Creek, CO	39°46'44"	105°55'40"	14010001	497	A	15.1	nd
09035700	Williams Fork above Darling Creek, near Leal, CO	39°47'50"	106°01'32"	14010001	988	A	14.7	nd
09035800	Darling Creek near Leal, CO	39°48'02"	106°01'33"	14010001	288	A	7.7	nd
09035900	South Fork of Williams Fork near Leal, CO	39°47'45"	106°01'48"	14010001	1,110	A	7.7	nd
09036000	Williams Fork near Leal, CO	39°50'02"	106°03'21"	14010001	3,130	A	9.6	nd
09037500	Williams Fork near Parshall, CO	40°00'01"	106°10'45"	14010001	5,170	A	15.8	nd
09038500	Williams Fork below Williams Fork Reservoir, CO	40°02'07"	106°12'17"	14010001	8,090	A	16.2	nd
09039000	Troublesome Creek near Pearmont, CO	40°13'03"	106°18'45"	14010001	1,350	A	10.2	nd
09041090	Muddy Creek above Antelope Creek, near Kremmling, CO	40°12'09"	106°25'19"	14010001	7,290	L	nd	6.8
09041500	Muddy Creek at Kremmling, CO	40°03'37"	106°23'51"	14010001	26,100	A	35.7	nd
09046490	Blue River at Blue River, CO	39°27'21"	106°01'52"	14010002	1,440	A	35.5	nd
09046600	Blue River near Dillon, CO	39°34'00"	106°02'56"	14010002	6,730	A	25.1	nd
09047500	Snake River near Montezuma, CO	39°36'20"	105°56'33"	14010002	2,720	A	29.8	nd
09047700	Keystone Gulch near Dillon, CO	39°35'40"	105°58'19"	14010002	236	A	24.9	nd
09050100	Tenmile Creek below North Tenmile Creek, at Frisco, CO	39°34'31"	106°06'36"	14010002	23,800	A	60.3	nd
09050700	Blue River below Dillon, CO	39°37'32"	106°03'57"	14010002	21,600	A	16.6	nd
09051050	Straight Creek below Laskey Gulch, near Dillon, CO	39°38'23"	106°02'23"	14010002	859	A	28.1	nd
09052000	Rock Creek near Dillon, CO	39°43'23"	106°07'41"	14010002	577	A	41.5	nd
09052400	Boulder Creek at upper station, near Dillon, CO	39°43'41"	106°10'22"	14010002	532	A	37.0	nd
09052800	Slate Creek at upper station, near Dillon, CO	39°45'47"	106°11'31"	14010002	717	A	30.1	nd

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.—Continued

Surface-water-quality monitoring site		Location			Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit				
09054000	Black Creek below Black Lake, near Dillon, CO	39°47'57"	106°16'04"	14010002	789	A	44.3	nd
09055300	Cataract Creek near Kremmling, CO	39°50'07"	106°18'57"	14010002	581	A	37.4	nd
09057500	Blue River below Green Mountain Reservoir, CO	39°52'49"	106°20'00"	14010002	28,500	A	18.3	nd
09057520	Blue River below Spruce Creek, near Kremmling, CO	39°57'49"	106°21'35"	14010002	19,900	L	nd	10.0
09058000	Colorado River near Kremmling, CO	40°02'12"	106°26'22"	14010001	110,000	A	14.9	nd
09058500	Piney River below Piney Lake, near Minturn, CO	39°42'29"	106°25'34"	14010001	589	A	28.0	nd
09058610	Dickson Creek near Vail, CO	39°42'14"	106°27'25"	14010001	642	A	9.6	nd
09058700	Freeman Creek near Minturn, CO	39°41'54"	106°26'42"	14010001	84	A	21.8	nd
09058800	East Meadow Creek near Minturn, CO	39°43'54"	106°25'34"	14010001	115	A	24.1	nd
09059500	Piney River near state bridge, CO	39°48'00"	106°35'00"	14010001	8,270	A	16.7	nd
09060550	Rock Creek at Crater, CO	39°58'42"	106°42'34"	14010001	1,590	A	12.6	nd
09060770	Rock Creek at McCoy, CO	39°54'44"	106°43'30"	14010001	7,430	A	18.1	nd
09063000	Eagle River at Red Cliff, CO	39°30'30"	106°21'58"	14010003	3,030	A	13.0	nd
09063200	Wearyman Creek near Red Cliff, CO	39°31'20"	106°19'23"	14010003	1,070	A	16.3	nd
09063400	Turkey Creek near Red Cliff, CO	39°31'22"	106°20'08"	14010003	2,810	A	10.7	nd
09063900	Missouri Creek near Gold Park, CO	39°23'25"	106°28'10"	14010003	110	A	15.6	nd
09064500	Homestake Creek near Red Cliff, CO	39°28'24"	106°22'02"	14010003	765	A	17.8	nd
09064600	Eagle River near Minturn, CO	39°33'14"	106°24'07"	14010003	9,570	A	20.7	nd
09065100	Cross Creek near Minturn, CO	39°34'05"	106°24'43"	14010003	974	A	27.5	nd
09065500	Gore Creek at upper station, near Minturn, CO	39°37'33"	106°16'39"	14010003	659	A	14.8	nd
09066000	Black Gore Creek near Minturn, CO	39°35'47"	106°15'52"	14010003	1,180	A	52.3	nd
09066100	Bighorn Creek near Minturn, CO	39°38'24"	106°17'34"	14010003	249	A	16.3	nd
09066150	Pitkin Creek near Minturn, CO	39°38'37"	106°18'07"	14010003	308	A	18.4	nd
09066200	Booth Creek near Minturn, CO	39°38'54"	106°19'21"	14010003	445	A	25.4	nd
09066300	Middle Creek near Minturn, CO	39°38'45"	106°22'54"	14010003	422	A	15.1	nd
09066310	Gore Creek, lower station, at Vail, CO	39°38'28"	106°23'37"	14010003	8,540	A	12.5	nd
09066400	Red Sandstone Creek near Minturn, CO	39°40'58"	106°24'03"	14010003	346	A	13.9	nd
09067000	Beaver Creek at Avon, CO	39°37'47"	106°31'20"	14010003	1,330	A	27.0	nd
09067005	Eagle River at Avon, CO	39°37'54"	106°31'19"	14010003	33,300	A	13.9	nd
09070000	Eagle River below Gypsum, CO	39°38'58"	106°57'11"	14010003	143,000	A	14.8	nd
09070500	Colorado River near Dotsero, CO	39°38'38"	107°04'38"	14010001	381,000	A	13.0	nd

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.—Continued

Surface-water-quality monitoring site		Location			Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit				
09071300	Grizzly Creek near Glenwood Springs, CO	39°43'00"	107°18'35"	14010001	1,240	A	8.7	nd
09071750	Colorado River above Glenwood Springs, CO	39°33'32"	107°17'25"	14010001	519,000	L	nd	2.1
09073300	Roaring Fork River above Difficult Creek, near Aspen, CO	39°08'28"	106°46'25"	14010004	1,790	A	18.5	nd
09073400	Roaring Fork River near Aspen, CO	39°10'48"	106°48'05"	14010004	3,230	A	16.6	nd
09074000	Hunter Creek near Aspen, CO	39°12'21"	106°47'49"	14010004	922	A	21.8	nd
09074800	Castle Creek above Aspen, CO	39°05'15"	106°48'42"	14010004	6,650	A	33.8	nd
09075700	Maroon Creek above Aspen, CO	39°07'25"	106°54'17"	14010004	13,100	A	27.4	nd
09080400	Frying Pan River near Ruedi, CO	39°21'56"	106°49'30"	14010004	18,900	A	19.2	nd
09081600	Crystal River above Avalanche Creek, near Redstone, CO	39°13'56"	107°13'36"	14010004	44,400	A	16.7	nd
09085000	Roaring Fork River at Glenwood Springs, CO	39°32'37"	107°19'44"	14010004	267,000	A	10.9	nd
09085100	Colorado River below Glenwood Springs, CO	39°33'18"	107°20'13"	14010005	991,000	A	14.3	nd
09086000	West Elk Creek near New Castle, CO	39°39'59"	107°37'35"	14010005	201	L	nd	1.8
09086470	Main Elk Creek near New Castle, CO	39°40'41"	107°34'21"	14010005	10,800	L	nd	2.7
09089500	West Divide Creek near Raven, CO	39°19'52"	107°34'46"	14010005	3,780	A	18.6	nd
09093700	Colorado River near De Beque, CO	39°21'45"	108°09'07"	14010005	1,240,000	A	11.3	nd
09095500	Colorado River near Cameo, CO	39°14'21"	108°15'56"	14010005	1,330,000	A	10.7	nd
09105000	Plateau Creek near Cameo, CO	39°11'00"	108°16'02"	14010005	36,600	A	14.2	nd
09106150	Colorado River below Grand Valley Diversion, near Palisade, CO	39°05'55"	108°21'16"	14010005	828,000	A	13.5	nd
09107000	Taylor River at Taylor Park, CO	38°51'37"	106°33'58"	14020001	5,160	A	11.6	nd
09107500	Texas Creek at Taylor Park, CO	38°50'41"	106°34'12"	14020001	1,100	L	nd	2.0
09109000	Taylor River below Taylor Park Reservoir, CO	38°49'06"	106°36'31"	14020001	9,420	A	14.5	nd
09110000	Taylor River at Almont, CO	38°39'52"	106°50'41"	14020001	20,400	A	14.8	nd
09112500	East River at Almont, CO	38°39'52"	106°50'51"	14020001	37,800	A	12.3	nd
09114500	Gunnison River near Gunnison, CO	38°32'31"	106°56'57"	14020002	71,500	A	12.6	nd
09118450	Cochetopa Creek below Rock Creek, near Parlin, CO	38°20'08"	106°46'18"	14020003	5,160	A	16.2	nd
09119000	Tomichi Creek at Gunnison, CO	38°31'18"	106°56'25"	14020003	27,100	A	14.9	nd
09124500	Lake Fork at Gateview, CO	38°17'56"	107°13'46"	14020002	16,000	A	16.5	nd
09126000	Cimarron River near Cimarron, CO	38°15'26"	107°32'46"	14020002	5,410	A	17.1	nd

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.—Continued

Surface-water-quality monitoring site		Location			Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit				
09128000	Gunnison River below Gunnison Tunnel, CO	38°31'45"	107°38'54"	14020002	111,000	A	11.4	nd
09128500	Smith Fork near Crawford, CO	38°43'40"	107°30'22"	14020002	2,380	A	22.8	nd
09132500	North Fork Gunnison River near Somerset, CO	38°55'33"	107°26'01"	14020004	31,900	A	24.4	nd
09134000	Minnesota Creek near Paonia, CO	38°52'12"	107°30'13"	14020004	3,500	A	32.4	nd
09135900	Leroux Creek at Hotchkiss, CO	38°47'53"	107°43'53"	14020004	5,050	A	32.2	nd
09143000	Surface Creek near Cedaredge, CO	38°59'05"	107°51'13"	14020005	2,210	A	27.4	nd
09143500	Surface Creek at Cedaredge, CO	38°54'06"	107°55'14"	14020005	1,500	A	21.1	nd
09144250	Gunnison River at Delta, CO	38°45'11"	108°04'40"	14020005	609,000	A	20.2	nd
09146200	Uncompahgre River near Ridgway, CO	38°11'02"	107°44'43"	14020006	50,000	A	17.8	nd
09147000	Dallas Creek near Ridgway, CO	38°10'40"	107°45'28"	14020006	13,800	A	19.5	nd
09147025	Uncompahgre River below Ridgway Reservoir, CO	38°14'17"	107°45'31"	14020006	81,600	A	11.9	nd
09147500	Uncompahgre River at Colona, CO	38°19'53"	107°46'44"	14020006	83,000	A	20.5	nd
09149500	Uncompahgre River at Delta, CO	38°44'31"	108°04'49"	14020006	263,000	A	17.0	nd
09152500	Gunnison River near Grand Junction, CO	38°59'00"	108°27'00"	14020005	1,080,000	A	16.1	nd
09153290	Reed Wash near Mack, CO	39°12'41"	108°48'11"	14010005	51,100	A	17.0	nd
09163500	Colorado River near Colorado-Utah State Line	39°07'58"	109°01'35"	14010005	2,800,000	A	10.0	nd
09165000	Dolores River below Rico, CO	37°38'20"	108°03'35"	14030002	13,900	A	16.2	nd
09166500	Dolores River at Dolores, CO	37°28'21"	108°29'49"	14030002	46,700	A	12.7	nd
09166950	Lost Canyon Creek near Dolores, CO	37°26'46"	108°28'07"	14030002	889	A	34.8	nd
09169500	Dolores River at Bedrock, CO	38°18'37"	108°53'05"	14030002	41,000	A	37.5	nd
09171100	Dolores River near Bedrock, CO	38°21'25"	108°49'58"	14030002	189,000	A	44.1	nd
09172500	San Miguel River near Placerville, CO	38°02'33"	108°07'54"	14030003	41,100	L	nd	3.1
09177000	San Miguel River at Uravan, CO	38°21'26"	108°42'44"	14030003	105,000	A	23.4	nd
09180000	Dolores River near Cisco, UT	38°47'50"	109°11'40"	14030004	323,000	A	32.9	nd
09180500	Colorado River near Cisco, UT	38°48'38"	109°17'34"	14030005	3,080,000	A	3.9	nd
09184000	Mill Creek near Moab, UT	38°33'44"	109°30'48"	14030005	1,090	A	16.9	nd
09186500	Indian Creek above Cottonwood Creek , near Monticello, UT	37°58'20"	109°31'07"	14030005	333	L	nd	17.5
09209400	Green River near La Barge, WY	42°11'34"	110°09'45"	14040101	263,000	A	19.5	nd
09211200	Green River below Fontenelle Reservoir, WY	42°01'16"	110°02'57"	14040103	293,000	A	14.6	nd
09215550	Big Sandy River below Farson, WY	42°04'24"	109°28'43"	14040104	30,700	A	31.9	nd
09216050	Big Sandy River at Gasson Bridge, near Eden, WY	41°56'51"	109°41'15"	14040104	123,000	A	19.6	nd

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.—Continued

Surface-water-quality monitoring site		Location						
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit	Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
09217000	Green River near Green River, WY	41°30'59"	109°26'54"	14040106	424,000	A	16.0	nd
09224700	Blacks Fork near Little America, WY	41°32'46"	109°41'34"	14040107	101,000	A	24.8	nd
09234500	Green River near Greendale, UT	40°54'30"	109°25'20"	14040106	593,000	A	5.9	nd
09235600	Pot Creek above Diversions, near Vernal, UT	40°46'05"	109°19'06"	14040106	111	A	33.1	nd
09237450	Yampa River above Stagecoach Reservoir, CO	40°16'09"	106°52'49"	14050001	18,900	A	14.0	nd
09237500	Yampa River below Stagecoach Reservoir, CO	40°17'07"	106°49'51"	14050001	19,800	A	7.7	nd
09238900	Fish Creek at upper station, near Steamboat Springs, CO	40°28'30"	106°47'11"	14050001	1,020	A	22.7	nd
09239500	Yampa River at Steamboat Springs, CO	40°29'01"	106°49'54"	14050001	34,900	A	33.5	nd
09240900	Elk River above Clark, CO	40°44'36"	106°51'17"	14050001	5,690	L	nd	5.5
09241000	Elk River at Clark, CO	40°43'03"	106°54'55"	14050001	6,570	L	nd	20.3
09242500	Elk River near Milner, CO	40°30'53"	106°57'12"	14050001	11,500	L	nd	4.6
09243700	Middle Creek near Oak Creek, CO	40°23'08"	106°59'33"	14050001	888	A	19.9	nd
09243900	Foidel Creek at Mouth, near Oak Creek, CO	40°23'25"	106°59'39"	14050001	4,220	A	19.2	nd
09245000	Elkhead Creek near Elkhead, CO	40°40'11"	107°17'04"	14050001	4,030	A	17.9	nd
09246920	Fortification Creek near Fortification, CO	40°44'38"	107°32'25"	14050001	1,170	L	nd	10.5
09247600	Yampa River below Craig, CO	40°28'51"	107°36'49"	14050001	176,000	A	35.7	nd
09249750	Williams Fork at mouth, near Hamilton, CO	40°26'14"	107°38'50"	14050001	44,700	A	26.6	nd
09250507	Wilson Creek above Taylor Creek, near Axial, CO	40°18'53"	107°47'58"	14050002	1,190	L	nd	11.3
09251000	Yampa River near Maybell, CO	40°30'10"	108°01'45"	14050002	251,000	A	32.6	nd
09253000	Little Snake River near Slater, CO	40°59'58"	107°08'34"	14050003	8,930	A	21.5	nd
09255000	Slater Fork near Slater, CO	40°58'57"	107°22'56"	14050003	5,290	A	22.3	nd
09260000	Little Snake River near Lily, CO	40°32'50"	108°25'25"	14050003	76,500	A	35.6	nd
09260050	Yampa River at Deerlodge Park, CO	40°27'06"	108°31'28"	14050002	277,000	A	42.8	nd
09261000	Green River near Jensen, UT	40°24'34"	109°14'05"	14060001	1,060,000	A	24.3	nd
09261700	Big Brush Creek above Red Fleet Reservoir, near Vernal, UT	40°35'20"	109°27'53"	14060002	4,970	A	15.4	nd
09266500	Ashley Creek near Vernal, UT	40°34'39"	109°37'17"	14060002	6,490	A	22.5	nd
09275500	West Fork Duchesne River near Hanna, UT	40°27'01"	110°53'01"	14060003	5,120	A	15.2	nd
09276600	West Fork Duchesne River above North Fork, near Hanna, UT	40°27'42"	110°50'10"	14060003	6,650	L	nd	7.1
09277500	Duchesne River near Tabiona, UT	40°18'01"	110°36'06"	14060003	30,100	L	nd	8.4
09277800	Rock Creek above South Fork, near Hanna, UT	40°33'27"	110°41'50"	14060003	521	L	nd	7.3

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.—Continued

Surface-water-quality monitoring site		Location						
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit	Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
09278000	South Fork Rock Creek near Hanna, UT	40°32'54"	110°41'37"	14060003	577	A	17.8	nd
09279000	Rock Creek near Mountain Home, UT	40°29'36"	110°34'39"	14060003	4,650	A	23.8	nd
09279100	Rock Creek near Talmage, UT	40°18'40"	110°29'36"	14060003	8,670	A	20.5	nd
09279150	Duchesne River above Knight Diversion, near Duchesne, UT	40°16'14"	110°26'31"	14060003	40,000	A	20.7	nd
09285000	Strawberry River near Soldier Springs, UT	40°08'00"	111°01'27"	14060004	3,830	A	12.0	nd
09285900	Strawberry River at Pinnacles, near Fruitland, UT	40°07'38"	110°44'28"	14060004	15,400	L	nd	1.9
09286100	Red Creek above reservoir, near Fruitland, UT	40°19'48"	110°51'43"	14060004	1,020	L	nd	7.2
09286700	Currant Creek below Currant Creek Dam, near Fruitland, UT	40°19'51"	111°02'56"	14060004	1,270	L	nd	6.3
09288000	Currant Creek near Fruitland, UT	40°12'01"	110°54'25"	14060004	6,730	A	10.7	nd
09288180	Strawberry River near Duchesne, UT	40°09'17"	110°33'15"	14060004	39,200	A	11.4	nd
09288400	Strawberry River below Starvation Reservoir, near Duchesne, UT	40°10'26"	110°25'44"	14060004	56,900	L	nd	1.8
09289500	Lake Fork River above Moon Lake, near Mountain Home,UT	40°36'24"	110°31'35"	14060003	1,450	L	nd	21.9
09292500	Yellowstone River near Altonah, UT	40°30'43"	110°20'27"	14060003	4,900	A	21.5	nd
09295000	Duchesne River at Myton, UT	40°12'01"	110°03'47"	14060003	49,000	A	23.1	nd
09299500	Whiterocks River near Whiterocks, UT	40°35'37"	109°55'54"	14060003	2,490	A	31.5	nd
09302000	Duchesne River near Randlett, UT	40°12'56"	109°46'58"	14060003	125,000	A	23.2	nd
09303000	North Fork White River at Burford, CO	39°59'15"	107°36'50"	14050005	47,100	A	7.1	nd
09303300	South Fork White River at Budges Resort, CO	39°50'36"	107°20'03"	14050005	8,050	A	14.0	nd
09303400	South Fork White River near Budges Resort, CO	39°51'51"	107°32'00"	14050005	19,700	A	11.3	nd
09304000	South Fork White River at Buford, CO	39°58'28"	107°37'29"	14050005	30,000	A	9.5	nd
09304200	White River above Coal Creek, near Meeker, CO	40°00'18"	107°49'29"	14050005	88,200	A	10.2	nd
09304500	White River near Meeker, CO	40°02'01"	107°51'42"	14050005	125,000	A	10.1	nd
09304800	White River below Meeker, CO	40°00'48"	108°05'33"	14050005	169,000	A	13.3	nd
09306007	Piceance Creek below Rio Blanco, CO	39°49'34"	108°10'57"	14050006	4,600	A	8.9	nd
09306200	Piceance Creek below Ryan Gulch, near Rio Blanco, CO	39°55'16"	108°17'49"	14050006	14,900	A	12.7	nd
09306222	Piceance Creek at White River, CO	40°04'39"	108°14'07"	14050006	20,300	A	13.7	nd
09306242	Corral Gulch near Rangely, CO	39°55'13"	108°28'20"	14050006	357	A	11.2	nd

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.—Continued

Surface-water-quality monitoring site		Location						
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit	Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
09306255	Yellow Creek near White River, CO	40°10'07"	108°24'02"	14050006	6,300	A	6.9	nd
09306290	White River below Boise Creek, near Rangely, CO	40°10'47"	108°33'53"	14050007	236,000	A	17.3	nd
09306500	White River near Watson, UT	39°58'44"	109°10'41"	14050007	254,000	A	19.5	nd
09310000	Gooseberry Creek near Scofield, UT	39°42'57"	111°17'58"	14060007	4,190	A	35.0	nd
09310500	Fish Creek above reservoir, near Scofield, UT	39°46'28"	111°11'25"	14060007	6,220	A	19.1	nd
09312600	White River below Tabbyune Creek, near Soldier Summit, UT	39°52'33"	111°02'12"	14060007	5,880	A	13.9	nd
09313000	Price River near Heiner, UT	39°43'08"	110°51'55"	14060007	22,700	L	nd	4.1
09315000	Green River at Green River, UT	38°59'10"	110°09'02"	14060008	1,670,000	A	19.5	nd
09326500	Ferron Creek (upper station) near Ferron, UT	39°06'15"	111°12'57"	14060009	17,100	A	12.4	nd
09328500	San Rafael River near Green River, UT	38°51'30"	110°22'10"	14060009	78,200	A	27.0	nd
09329050	Seven Mile Creek near Fish Lake, UT	38°37'40"	111°38'50"	14070003	853	A	14.3	nd
09330000	Fremont River near Bicknell, UT	38°18'25"	111°31'05"	14070003	29,400	A	10.0	nd
09330230	Fremont River near Caineville, UT	38°16'45"	111°03'54"	14070003	29,700	A	17.6	nd
09333500	Dirty Devil River above Poison Spring Wash, near Hanksville, UT	38°05'39"	110°24'24"	14070004	67,700	A	27.6	nd
09337000	Pine Creek near Escalante, UT	37°51'45"	111°38'07"	14070005	443	A	18.3	nd
09337500	Escalante River near Escalante, UT	37°46'41"	111°34'26"	14070005	1,970	A	23.4	nd
09339900	East Fork San Juan River above Sand Creek, near Pagosa Springs, CO	37°23'23"	106°50'26"	14080101	6,170	A	11.6	nd
09342500	San Juan River at Pagosa Springs, CO	37°15'58"	107°00'37"	14080101	23,900	A	21.0	nd
09346000	Navajo River at Edith, CO	37°00'10"	106°54'25"	14080101	10,300	A	20.7	nd
09346400	San Juan River near Carracas, CO	37°00'49"	107°18'42"	14080101	86,200	A	34.5	nd
09349800	Piedra River near Arboles, CO	37°05'18"	107°23'50"	14080102	56,300	A	22.3	nd
09352900	Vallecito Creek near Bayfield, CO	37°28'39"	107°32'35"	14080101	4,530	A	15.5	nd
09354500	Los Pinos River at La Boca, CO	37°00'34"	107°35'56"	14080101	26,700	A	17.7	nd
09355000	Spring Creek at La Boca, CO	37°00'40"	107°35'47"	14080101	8,310	A	23.7	nd
09355500	San Juan River near Archuleta, NM	36°48'05"	107°41'51"	14080101	116,000	A	14.3	nd
09361500	Animas River at Durango, CO	37°16'45"	107°52'47"	14080104	160,000	A	14.5	nd
09363500	Animas River near Cedar Hill, NM	37°02'17"	107°52'25"	14080104	201,000	A	11.4	nd
09364500	Animas River at Farmington, NM	36°43'17"	108°12'05"	14080104	205,000	A	16.3	nd
09365000	San Juan River at Farmington, NM	36°43'23"	108°13'33"	14080105	370,000	L	nd	6.6

Appendix 1. Dissolved-solids load at selected water-quality monitoring sites in the Upper Colorado River Basin, water year 1991.—Continued

Surface-water-quality monitoring site		Location						
Site number	Site name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	Hydrologic accounting unit	Dissolved-solids load (tons)	Dissolved-solids load source	Residual error, as a percent of median daily dissolved-solids concentration	Standard error of prediction, as a percent of daily dissolved-solids load
09367500	La Plata River near Farmington, NM	36°44'23"	108°14'51"	14080105	13,100	L	nd	29.2
09368000	San Juan River at Shiprock, NM	36°47'32"	108°43'54"	14080105	475,000	A	28.6	nd
09371000	Mancos River near Towaoc, CO	37°01'39"	108°44'27"	14080107	22,900	A	29.4	nd
09371002	Navajo Wash near Towaoc, CO	37°12'03"	108°41'50"	14080107	12,600	L	nd	8.7
09371010	San Juan River at Four Corners, CO	37°00'20"	109°02'00"	14080201	530,000	A	20.2	nd
09371500	McElmo Creek near Cortez, CO	37°19'22"	108°40'21"	14080202	79,400	A	15.6	nd
09372000	McElmo Creek near Colorado-Utah state line	37°19'27"	109°00'54"	14080202	84,700	A	13.2	nd
09378170	South Creek above reservoir, near Monticello, UT	37°50'48"	109°22'08"	14080203	79	L	nd	4.4
09378200	Montezuma Creek at golf course at Monticello, UT	37°51'38"	109°20'30"	14080203	63	A	44.3	nd
09378630	Recapture Creek near Blanding, UT	37°45'20"	109°28'33"	14080201	37	A	45.4	nd
09379500	San Juan River near Bluff, UT	37°08'49"	109°51'51"	14080205	655,000	A	24.1	nd
09380000	Colorado River at Lees Ferry, AZ	36°51'53"	111°35'15"	14070006	6,480,000	A	7.6	nd

Appendix 2

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09010500	53.8	0	0	0	0	52.7	0	0.173	0.920	0	0	0
09024000	27.6	0	0	0	0	27.6	0	0	0	0	0	0
09025000	28.2	0	0	0	0	28.2	0	0	0	0	0	0.078
09025400	7.25	0	0.034	0	0.081	7.11	0	0.139	0	0	0	0
09026500	32.9	0	0	0	0	32.2	0	0	0	0.787	0	0.001
09032000	20.0	0	0	0	0	19.8	0	0.222	0	0	0	0
09032100	6.28	0	0	0	0	6.28	0	0	0	0	0	0
09034250	614	0	14.8	2.64	5.42	332	147	85.5	24.9	8.90	0	15.9
09034500	36.0	0	0.934	0.011	0.043	0.737	32.6	2.44	0.146	0	0	0.097
09034900	6.12	0	0	0	0	6.12	0	0	0	0	0	0
09035500	10.3	0	0	0	0	10.3	0	0	0	0	0	0
09035700	18.9	0	0	0	0	18.9	0	0	0	0	0	0
09035800	8.86	0	0	0	0	8.86	0	0	0	0	0	0
09035900	27.7	0	0	0	0	27.7	0	0	0	0	0	0
09036000	17.8	0	0	0	0.106	17.8	0	0	0	0	0	0
09037500	94.3	0	0.876	0.272	0.988	75.7	2.99	10.3	0	3.76	0	1.54
09038500	9.02	0	0.191	0	0	1.23	1.65	6.14	0	0	0	0
09039000	44.7	0	0	0	0.004	39.8	4.45	0.530	0	0	0	0
09041090	148	0	0.207	6.11	0.257	22.9	11.1	19.5	54.9	37.8	0	2.02
09041500	146	0	0.875	6.10	2.01	36.1	5.07	26.3	39.3	35.5	0.658	3.45
09046490	42.5	0	0	0	0	24.3	0	0	0.461	1.93	15.8	0
09046600	80.9	0	0	0	0	54.3	0	0	11.0	9.98	3.57	2.03
09047500	58.1	0	0	0	0	57.1	0	0	1.04	0	0	0
09047700	9.39	0	0	0	0	9.39	0	0	0	0	0	0
09050100	86.6	0	0	0	0	56.7	0.407	0	0	0	29.6	0
09050700	51.3	0	0	0	0	33.9	5.54	0	7.59	3.66	0	0.602
09051050	19.3	0	0	0	0	18.3	0	0	0.985	0.028	0	0
09052000	16.0	0	0	0.014	0	15.3	0	0	0.005	0.756	0	0

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.—Continued

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09052400	8.66	0	0	0	0	8.54	0	0	0	0.124	0	0
09052800	14.5	0	0	0	0	12.4	0	1.91	0.191	0.058	0	0
09054000	15.3	0	0	0	0	14.5	0.123	0.669	0	0	0	0
09055300	12.0	0	0	0	0	10.6	0.275	0.546	0	0.573	0	0
09057500	163	0	1.75	2.93	2.85	77.5	3.00	9.66	50.4	18.5	0	3.81
09057520	61.6	0	0	1.95	0	16.2	0	0.945	10.5	32.7	1.19	0
09058000	379	0	21.7	5.25	4.92	80.5	134	105	16.6	32.9	0.090	9.60
09058500	12.8	0	0	0	0	10.8	0	0	0	0	2.05	0
09058610	3.56	0	0	0	0	0.148	0	0.100	0	0.008	3.31	0
09058700	3.58	0	0	0	0	0.620	0	0.188	0	0	2.77	0
09058800	3.60	0	0	0	0	3.25	0	0	0	0.038	0.312	0
09059500	70.5	0	0.146	0	0.269	10.7	0	7.63	4.14	19.9	28.1	0
09060550	72.9	0	0	0	0	56.4	0	1.58	0	8.42	6.52	0
09060770	128	0	1.19	9.35	1.05	22.9	0	10.6	0	78.1	16.6	0
09063000	76.0	0	0	0	0	28.0	0.055	0	0	0	45.4	2.50
09063200	9.69	0	0	0	0	0.585	0	0.828	0	0	8.27	0
09063400	14.1	0	0	0	0	0.937	0	0.487	0	0	12.7	0
09063900	6.48	0	0	0	0	6.48	0	0	0	0	0	0
09064500	51.9	0	0	0	0	51.0	0.433	0	0	0	0.390	0
09064600	34.4	0	0	0	0	21.4	0	0	0	0	13.0	0
09065100	34.8	0	0	0	0.008	33.5	0	0	0	0	1.30	0
09065500	14.6	0	0	0	0.003	14.3	0	0.006	0	0	0.307	0
09066000	12.5	0	0	0	0	3.55	0	0.842	0	0	8.09	0
09066100	5.65	0	0	0	0.050	5.63	0	0	0	0	0.026	0
09066150	6.19	0	0	0	0.059	4.83	0	0	0	0	1.13	0.237
09066200	6.12	0	0	0	0.021	4.07	0	0	0	0	1.99	0.061
09066300	6.01	0	0	0	0.019	1.79	0	0	0	0	4.18	0.043
09066310	26.0	0	0	0	0.956	1.90	0	4.39	0	0	18.5	1.15

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.—Continued

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09066400	8.49	0	0	0	0	4.05	0	0	0	0	4.44	0
09067000	14.8	0	0	0	0	8.68	0	0	0	0	6.16	0
09067005	73.7	0	0.082	0	0.843	7.32	0	5.50	0	0	58.8	2.09
09070000	549	0	0.057	1.45	14.8	91.4	0	24.6	35.9	77.0	296	24.6
09070500	773	0	1.81	10.5	4.31	209	0.183	89.8	35.5	191	247	0.615
09071300	6.83	0	0	0	0	0.320	0	0	0	0	6.51	0
09071750	137	123,000	0	0	0.147	17.0	0	5.89	0	0.096	114	0
09073300	76.3	0	0	0	0.029	76.3	0	0	0	0	0	0
09073400	29.8	0	0	0	0.158	27.2	0	0	0	0	2.64	0
09074000	41.7	0	0	0	0.04	39.8	0	0	0	0	1.93	0
09074800	32.3	0	0	0	0	18.1	0	0	0	0	14.2	0
09075700	35.8	0	0	0	0	7.92	0	0	0	0	27.9	0
09080400	223	237	0.062	0	0.211	146	2.85	2.40	0	0	72.5	0
09081600	169	0	0.004	0.132	0.118	33.7	0	6.56	21.2	57.2	50.0	0
09085000	833	0	3.93	16.1	32.6	197	0.207	109	19.9	172	296	39.2
09085100	24.4	183,000	0.016	0	0.077	5.25	0	0.277	0	0	18.9	0
09086000	9.53	0	0	0.002	0.011	0	0	0	0	1.07	8.46	0
09086470	91.3	0	0	0	0.022	1.13	0	0	0	0	90.2	0
09089500	64.5	0	0.217	0	0	0.123	0	59.5	4.91	0	0	0
09093700	1,180	0	47.1	7.97	16.6	16.6	144	630	49.7	101	194	49.0
09095500	623	0	10.2	0	3.18	0	285	307	16.7	6.75	0	7.38
09105000	592	0	22.1	3.80	23.0	184	77.3	286	10.7	14.6	0	19.5
09106150	172	0	1.19	0.559	0.236	4.86	1.04	34.8	124	5.54	0	0.916
09107000	129	0	0	0	0.239	118	0.045	0	0	0	6.81	3.60
09107500	44.5	0	0	0	0	42.9	0.110	0	0	0	0.279	1.19
09109000	81.9	0	0	0	0.360	62.8	2.66	0	0	0	9.52	6.91
09110000	223	0	0	0.232	0.709	155	0	0	0	8.53	59.3	0.794
09112500	290	0	2.14	4.57	10.4	68.1	0	17.3	21.9	108	67.1	6.87

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.—Continued

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09114500	245	0	15.9	9.35	5.87	96.6	0	73.4	28.7	39.6	0	6.74
09118450	334	0	5.93	0	9.27	298	0	24.4	0	6.41	0	5.28
09119000	727	0	15.4	4.90	8.72	505	0.044	48.9	0	135	38.5	0
09124500	340	0	0.649	0	1.65	310	0.592	24.9	0	0	0	4.47
09126000	67.2	0	0	0	0	53.8	0	13.5	0	0	0	0
09128000	1,490	588	8.87	4.53	8.17	1,220	22.4	141	2.00	98.3	0	4.34
09128500	43.6	0	0.001	0.232	0	20.9	0	5.60	0	17.1	0	0
09132500	525	0	11.1	0.344	1.44	104	3.27	299	98.0	16.1	0	5.28
09134000	41.8	0	0	0.142	0	8.28	0	5.67	15.7	12.1	0	0
09135900	66.9	0	0.069	2.38	2.17	15.8	2.86	13.4	9.58	18.5	0	6.78
09143000	27.7	0	0	0	0	19.0	1.17	7.36	0.002	0	0	0.114
09143500	14.9	0	0	0.156	1.25	5.89	0.736	0.717	1.99	0.163	0	5.39
09144250	951	0	13.9	73.4	39.0	91.3	9.71	156	103	518	0	73.1
09146200	149	0	0.274	3.29	4.25	87.6	0	12.0	0	29.8	10.1	9.81
09147000	97.6	0	2.30	4.55	0.161	23.7	0	20.1	0	53.7	0	0.001
09147025	18.1	0	0.096	1.40	0.0475	0.208	0	1.91	0	16.0	0	0
09147500	183	0	1.44	3.63	1.30	55.7	0	50.2	0	72.6	1.14	3.26
09149500	667	0	33.0	39.0	30.9	1.49	0.290	128	1.86	489	0	47.1
09152500	1,170	0	3.89	14.0	13.9	51.1	2.91	50.5	139	899	6.78	20.1
09153290	17.7	0	0	9.67	0	0	0	0	0	17.7	0	0
09163500	1,170	0	11.4	53.5	35.5	20.6	51.2	119	346	575	0	60.0
09165000	105	0	0	0	0	13.7	0	5.01	6.72	41.8	37.7	0.529
09166500	399	0	0	2.76	0.540	16.1	0.520	0	64.1	286	32.2	0
09166950	69.3	0	0	0.241	0	0.166	0.263	0	0	68.8	0	0
09169500	1,450	0	2.88	6.91	0.027	4.53	0	41.5	140	1,240	17.3	10.6
09171100	122	132,000	4.34	0.086	0.427	0	0	37.0	23.9	44.1	8.06	8.81
09172500	309	0	0.196	5.51	1.06	80.8	0.111	20.1	13.1	182	12.4	0
09177000	1,190	0	0	43.4	0	16.7	0.482	15.1	24.7	1,130	5.18	0.042

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.—Continued

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09180000	928	3,940	2.60	1.35	0.635	71.3	0.116	37.2	252	489	7.51	71.3
09180500	1,530	0	2.44	2.74	0.998	36.4	235	94.9	407	758	0.029	0
09184000	74.5	0	0	0.496	0	3.46	0	1.68	0	65.0	0	4.31
09186500	30.8	0	0	0	0	4.97	0	7.42	0	18.4	0	0
09209400	3,830	0	365	0.274	13.4	610	149	2,190	0.413	341	154	392
09211200	370	0	7.50	0.716	0	0	118	111	14.8	111	9.22	5.43
09215550	1,130	0	21.0	0	0.288	83.6	456	550	0.891	0.198	0	44.5
09216050	600	0	13.0	0	0	0	492	107	0	0	0	0
09217000	3,800	0	0.215	0	0	0	1,470	1,360	702	269	0	0
09224700	2,980	0	144	3.94	0.350	0	209	2,020	149	384	21.6	206
09234500	2,400	0	37.4	8.38	4.24	0.418	619	1,150	13.2	157	56.5	402
09235600	24.7	0	0	0	0	0	0	11.4	0	1.84	0.066	11.4
09237450	207	0	5.01	14.9	3.05	26.0	0.492	83.0	0.346	93.7	0	3.67
09237500	20.5	0	0.255	0	0	2.86	0	16.5	0	1.08	0	0
09238900	26.0	0	0	0	0	26.0	0.066	0	0	0	0	0
09239500	313	2,570	5.40	0.810	4.32	186	0.623	87.1	8.78	24.9	0	6.20
09240900	123	0	0	0.026	0.210	112	0	0.271	0	8.67	0	2.67
09241000	93.3	0	1.12	0.018	0.206	37.6	0	40.6	0	14.1	0	1.07
09242500	243	0	6.25	6.66	1.59	103	0	45.5	15.1	74.8	0	5.21
09243700	24.7	0	0	0.238	0	0	0	0	21.9	2.86	0	0
09243900	17.7	0	0	0.058	0	0	0	0	17.7	0	0	0
09245000	67.8	0	0	0.094	0	0.986	0	14.7	24.3	27.8	0	0
09246920	40.3	0	1.10	0	0	0.116	0	40.1	0	0	0	0
09247600	952	2,570	19.0	12.0	0.015	38.6	78.4	260	379	195	0	1.24
09249750	458	0	0.207	10.7	0	23.9	0	53.4	161	220	0	0
09250507	20.1	0	0	0.193	0	0	0	0	19.2	0.910	0	0
09251000	776	0	6.28	8.72	0.031	0.149	31.6	269	288	180	5.67	0.991
09253000	252	0	1.86	0.561	0.710	124	0	96.0	14.2	14.6	0	2.53

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.—Continued

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09255000	151	0	2.19	1.94	0	7.78	14.5	106	7.45	15.4	0	0
09260000	3,630	0	39.2	3.61	0.133	89.5	668	2,350	370	109	5.43	38.6
09260050	517	0	6.98	0.099	0	0	30.8	369	20.7	60.0	26.5	9.68
09261000	2,430	0	4.41	0.244	0.425	13.2	428	944	39.2	167	401	435
09261700	87.5	0	0	0.108	0	0	0	30.8	7.53	7.86	30.0	11.3
09266500	101	0	0	0	0	0	0	42.0	0	0.382	11.6	47.3
09275500	63.0	0	0	0.013	0	0	0	23.5	11.1	28.4	0	0
09276600	26.9	0	0	0.134	0	0	0	5.17	2.90	0.490	14.8	3.57
09277500	268	0	9.06	0.417	0.677	0	0	64.3	22.3	51.0	45.5	85.1
09277800	101	0	0	0	0	0	0	0.143	0	0.327	0	100
09278000	16.3	0	0	0	0	0	0	0.093	0	0.261	5.20	10.7
09279000	35.8	0	0.075	0	0	0	0	7.02	1.85	0.294	12.0	14.7
09279100	83.2	0	0.160	0	0	0	0	47.8	3.64	18.2	7.11	6.44
09279150	30.3	0	1.88	0	0	0	0	30.3	0	0.020	0	0
09285000	214	0	0	0	0	0	10.9	149	9.98	31.5	11.1	0.918
09285900	159	0	0.144	0	0	0	25.3	134	0	0	0	0
09286100	31.4	0	0	0	0	0	0	8.00	13.3	10.1	0	0
09286700	47.1	0	0	0	0	0	0	12.5	16.7	17.9	0	0
09288000	119	0	2.61	0	0	0	0	112	6.64	0.989	0	0
09288180	350	0	3.21	0.948	0	0	115	214	0.087	20.9	0	0
09288400	140	0	0.045	0.002	0	0	0	118	0	21.9	0	0
09289500	77.8	0	0	0	0	0	0	0	0	0	0	77.8
09292500	139	0	0.189	0	0	0	0	22.3	0	0.297	4.85	112
09295000	763	0	33.2	14.8	10.6	0	41.5	547	0.747	75.7	7.78	90.3
09299500	124	0	0.167	0	0.058	0	0	16.0	0	0.610	3.55	104
09302000	1,010	0	87.8	30.8	29.9	0	0	544	8.97	118	13.4	322
09303000	259	0	0.010	0	1.29	93.0	0.601	69.7	0	37.6	52.7	5.57
09303300	52.6	0	0	0	0	30.0	0.114	0.208	0	0	22.2	0

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.—Continued

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09303400	75.8	0	0	0	0	22.6	0	0.211	0	0	53.0	0
09304000	51.7	0	0.060	0	1.87	8.91	0	16.0	0	0	22.5	4.34
09304200	208	0	0.588	0.458	1.83	3.21	0.863	11.2	0	34.0	158	0.704
09304500	113	33,100	1.88	5.91	0	0	0	6.38	18.6	83.5	4.54	0
09304800	264	0	6.88	5.75	0	0	31.5	78.7	85.2	51.7	16.6	0
09306007	177	0	1.23	0.093	0	0	28.8	119	21.1	7.46	0.984	0
09306200	328	0	3.57	0	0	0	7.27	321	0	0	0	0
09306222	146	0	1.37	0	0	0	11.0	135	0	0	0	0
09306242	31.7	0	0	0	0	0	14.3	17.4	0	0	0	0
09306255	231	0	0.285	0	0	0	34.8	196	0	0	0	0
09306290	593	0	4.04	0.301	0.284	0	151	190	79.4	125	43.1	4.39
09306500	1,370	0	2.11	1.25	0	0	382	219	607	137	20.8	0
09310000	17.0	0	0	0	0	0	13.0	1.72	2.30	0	0	0
09310500	47.3	0	0	0	0	0	24.7	0	22.3	0.309	0	0
09312600	93.7	0	0	0	0	0	84.2	8.24	1.28	0	0	0
09313000	302	0	0	0.678	0	0	175	0	123	4.33	0	0
09315000	6,800	0	61.3	62.9	0.03	0	2,790	1,850	474	1,530	69.6	76.6
09326500	141	0	0	0	0	0	90.2	0.684	34.4	2.84	0	13.1
09328500	1,520	277	20.5	26.4	0	0	199	121	360	773	8.73	59.2
09329050	24.7	0	0	0	0	11.4	0.249	9.93	0	0.006	0	3.10
09330000	739	0	12.5	10.7	2.56	444	1.44	206	4.92	66.8	0	15.9
09330230	447	0	2.90	1.56	0.643	33.7	0	72.9	86.1	225	9.79	19.5
09333500	2,950	0	12.0	2.54	0	30.3	73.9	229	394	2,190	0.095	30.5
09337000	67.8	0	0	0	0	37.4	0	19.3	0	10.5	0	0.610
09337500	258	0	1.35	0.480	0	15.8	18.4	96.5	8.25	118	0	0.622
09339900	65.8	0	0.135	0.291	0.064	54.0	0	3.31	2.08	5.07	0	1.37
09342500	215	2,180	1.78	4.68	0.416	139	0	30.7	38.2	7.89	0	0
09346000	176	0	1.24	2.21	0.042	66.3	0	46.7	38.0	25.3	0	0
09346400	797	2,180	2.98	10.8	0	80.5	0	102	276	338	0	0

Appendix 2. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reaches as defined for Upper Colorado River Basin SPARROW model.—Continued

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reaches (square miles)	Point source imports (tons)	Irrigated sedimentary-clastic Tertiary lands (square miles)	Irrigated sedimentary-clastic Mesozoic lands (square miles)	Irrigated lands of other lithologies (square miles)	Crystalline and volcanic rocks (square miles)	High-yield sedimentary Cenozoic rocks (square miles)	Low-yield sedimentary Cenozoic rocks (square miles)	High-yield sedimentary Mesozoic rocks (square miles)	Low-yield sedimentary Mesozoic rocks (square miles)	High-yield sedimentary Paleozoic and Precambrian rocks (square miles)	Low-yield sedimentary Paleozoic and Precambrian rocks (square miles)
09349800	654	0	1.23	9.27	2.25	132	0	59.4	70.3	348	36.7	7.06
09352900	80.3	0	0	0	0	51.8	0	0.036	0	0	5.40	23.1
09354500	439	349	18.0	24.1	5.06	105	4.82	72.9	20.5	173	48.4	14.0
09355000	58.6	0	1.60	14.8	0.159	0	0	21.3	0	36.7	0	0.609
09355500	748	0	12.3	0.664	0	0	9.66	719	0	18.9	0	0
09361500	701	0	0.003	0.473	8.20	271	1.43	5.05	25.0	42.9	311	44.9
09363500	401	0	14.6	25.8	7.62	34.3	43.7	67.0	63.3	134	45.5	13.3
09364500	269	0	10.1	0.017	0	0	161	105	0	2.30	0	0
09365000	2,590	0	41.8	0.039	0	0	880	1,700	0	8.48	0	0
09367500	586	0	6.89	15.5	19.1	8.05	89.9	41.9	285	104	9.29	47.8
09368000	5,070	0	19.2	42.9	0	4.32	583	262	2,510	1,720	1.63	0
09371000	528	0	0	14.3	4.49	4.31	0.231	0	337	176	0.746	9.38
09371002	25.5	0	3.93	0.102	0	1.51	0	9.19	2.86	11.9	0	0
09371010	1,130	0	1.38	3.41	0	22.2	17.4	21.2	218	847	0	3.08
09371500	230	0	8.09	46.2	0	0.589	0.052	16.6	9.90	203	0	0
09372000	116	0	0	3.03	0	4.99	0	2.10	4.53	105	0	0
09378170	8.46	0	0	0	0	2.33	0	0.055	0	6.07	0	0
09378200	19.3	0	0	0	0	2.70	0	0.454	0	16.2	0	0
09378630	4.52	0	0	0	0	0.756	0	0	0	3.77	0	0
09379500	8,110	0	1.81	67.4	0	49.3	169	187	1,530	5,410	88.1	681
09380000	14,200	646,000	2.36	6.91	0.03	102	46.2	546	1,660	9,850	285	1,750

Kenney, Gerner, Buto, and Spangler—**Spatially Referenced Statistical Assessment of Dissolved-Solids Load Sources and Transport in Streams of the Upper Colorado River Basin**—Scientific Investigations Report 2009–5007