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

Scientific Investigations Report 2017–5009

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

Cover photograph: View looking southwest down the Colorado River near Moab, Utah. Photograph by Matthew Miller, U.S. Geological Survey, October 2009.

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
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Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Load	
ton per year (ton/yr)	0.9072	metric ton per year
ton per acre	224.17	megagram per square kilometer (Mg/km^2)
ton per square mile (ton/mi^2)	350	kilogram per square kilometer (kg/km^2)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

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

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

Elevation, as used in this report, refers to distance above sea level.

Abbreviations and Acronyms

BLM	Bureau of Land Management
MODIS	Moderate Resolution Imaging Spectroradiometer
RMSE	root-mean-square error
SCP	Salinity Control Program
SPARROW	Spatially Referenced Regressions on Watershed Attributes
SSEBop	Simplified Surface Energy Balance (operational)
STATSGO	State Soil Geographic Database
UCRB	Upper Colorado River Basin
USGS	U.S. Geological Survey

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

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Abstract

Approximately 6.4 million tons of dissolved solids are discharged from the Upper Colorado River Basin (UCRB) to the Lower Colorado River Basin each year. This results in substantial economic damages, and tens of millions of dollars are spent annually on salinity control projects designed to reduce salinity loads in surface waters of the UCRB. Dissolved solids in surface water and groundwater have been studied extensively over the past century, and these studies have contributed to a conceptual understanding of sources and transport of dissolved solids. This conceptual understanding was incorporated into a Spatially Referenced Regressions on Watershed Attributes (SPARROW) model to examine sources and transport of dissolved solids in the UCRB. The results of this model were published in 2009. The present report documents the methods and data used to develop an updated dissolved-solids SPARROW model for the UCRB, and incorporates data defining current basin attributes not available in the previous model, including delineation of irrigated lands by irrigation type (sprinkler or flood irrigation), and calibration data from additional monitoring sites.

Dissolved-solids loads estimated for 312 monitoring sites were used to calibrate the SPARROW model, which predicted loads for each of 10,789 stream reaches in the UCRB. The calibrated model provided a good fit to the calibration data as evidenced by R^2 and yield R^2 values of 0.96 and 0.73, respectively, and a root-mean-square error of 0.47. The model included seven geologic sources that have estimated dissolved-solids yields ranging from approximately 1 to 45 tons per square mile (tons/mi^2). Yields generated from irrigated agricultural lands are substantially greater than those from geologic sources, with sprinkler irrigated lands generating an average of approximately 150 tons/mi^2 and flood irrigated lands generating between 770 and 2,300 tons/mi^2 depending on underlying lithology. The coefficients estimated for six landscape transport characteristics that influence the delivery of dissolved solids from sources to streams, are consistent with the process understanding of dissolved-solids loading to streams in the UCRB.

Dissolved-solids loads and the proportion of those loads among sources in the entire UCRB as well as in major tributaries in the basin are reported, as are loads generated from irrigated lands, rangelands, Bureau of Land Management (BLM) lands, and grazing allotments on BLM lands. Model-predicted loads also are compared with load estimates from 1957 and 1991 at selected locations in three divisions of the UCRB. At the basin scale, the model estimates that 32 percent of the dissolved-solids loads are from irrigated agricultural land sources that compose less than 2 percent of the land area in the UCRB. This estimate is less than previously reported estimates of 40 to 45 percent of basin-scale dissolved-solids loads from irrigated agricultural land sources. This discrepancy could be a result of the implementation of salinity control projects in the basin. Notably, results indicate that the conversion of flood irrigated agricultural lands to sprinkler irrigated agricultural lands is a likely process contributing to the temporal decrease in dissolved-solids loads from irrigated lands.

Introduction

The economic effects of increased salinity (dissolved solids) in the Colorado River have prompted a number of water-quality-related legislative actions and the creation of salinity control programs, implemented by the U.S. Departments of the Interior and Agriculture, to reduce salinity in the river and its tributaries. Salinity in streams of the Upper Colorado River Basin (UCRB), as measured by total dissolved-solids concentration and load, is variable. The Colorado River Basin Salinity Control Program (SCP) Forum has spent between $10 million and $60 million annually between 1988 and 2012 on salinity control projects aimed at reducing salinity loads in surface waters of the Colorado River Basin (U.S. Bureau of Reclamation, 2013). Optimal management and (or) mitigation of salinity requires a sound understanding of the spatial distribution of salinity sources, load accumulation, and transport mechanisms. Sources of salinity to streams in the UCRB can be attributed to natural sources, including the dissolution of salts from underlying geologic formations and point sources from saline springs. Anthropogenic activities in the basin also can influence salinity loading to streams. Most notably, irrigation water applied to agricultural lands enhances the dissolution of salts from underlying soils and geologic formations; these salts are eventually transported to streams. Previous studies have shown that while irrigated lands make up less than 3 percent of the land area in the UCRB, they contribute approximately 40 percent of the dissolved-solids load delivered to the Lower Colorado River Basin (Iorns and others, 1965; Kenney and others, 2009).

In 2009, in collaboration with the SCP and the Bureau of Reclamation (Reclamation), the U.S. Geological Survey (USGS) constructed and published a Spatially Referenced Regressions on Watershed Attributes (SPARROW) model for dissolved solids in UCRB streams (Kenney and others, 2009) to improve understanding of salinity sources and transport. The SPARROW model relates measured constituent loads at monitoring sites to upland catchment attributes including contributing upstream reaches, and generates predictions of dissolved-solids loads for more than 10,000 stream reaches of the stream network used to represent the UCRB. Applying the SPARROW modeling framework to the UCRB has enhanced SCP managers' understanding of dissolved-solids sources and transport throughout the basin. Since its publication, the UCRB dissolved-solids SPARROW model has seen substantial use by SCP scientists and managers to assess salinity loads and sources in the basin, and now plays an integral role in many aspects of SCP planning.

Although the current model has proven to be a useful tool in SCP assessments and planning, program managers are interested in improving model accuracy and utility. The model can now be improved by incorporating recently collected water-quality and streamflow data, and newly available geospatial data sets defining current land and water use in the basin. The UCRB dissolved-solids SPARROW model (Kenney and others, 2009) salinity load estimates represent conditions in water year 1991 (October 1, 1990–September 30, 1991). Water year 1991 was chosen for model development and calibration, in part, because of the relative abundance of streamflow and water-chemistry data available for the UCRB for that period. Although the single-year model provides a temporal reference point to which conditions in the basin for other periods can be compared, most SPARROW applications utilize long-term records and detrend to a base year to estimate loads that are reflective of long-term conditions. Salinity Control Program managers are frequently interested in understanding salinity load distribution under long-term average hydrologic conditions. Salinity loads estimated for monitoring sites in 1991, and represented in the UCRB dissolved-solids SPARROW model (referred to from here on as the 1991 SPARROW model), were generally less than average throughout most of the basin (Kenney and Buto, 2012). In this report we present an updated and enhanced UCRB dissolved-solids SPARROW model that has been constructed and calibrated to improve understanding of current sources and transport of dissolved-solids loads throughout the UCRB. The updated model incorporates data collected during 1984–2012 and defines current basin attributes not available in the 1991 SPARROW model, including delineation of irrigated lands by irrigation type (sprinkler or flood).

Purpose and Scope

This report documents the methods and data used to develop an updated dissolved-solids SPARROW model for the UCRB. The updated model builds on the geospatial basin characteristic datasets and modeling approaches developed by Kenney and others (2009) for the 1991 SPARROW model. Specifically, the updated model incorporates data defining current basin attributes not available in the 1991 SPARROW model, including delineation of irrigated lands by irrigation type (sprinkler or flood). The updated model was calibrated by using estimates of dissolved-solids loads at 312 monitoring stations in the UCRB (fig. 1). Model results for each of 10,789 stream reaches in the UCRB are presented and discussed. Dissolved-solids loads, and the proportion of those loads among sources in the entire UCRB as well as in major tributaries in the basin are reported, as are loads generated from lands under different land management and use categories. Model-predicted loads also are compared with load estimates from 1957 and 1991 for selected locations in three divisions of the UCRB. This report is intended to provide an updated quantitative understanding of the spatial distribution and sources of dissolved-solids loads in the UCRB as a means to enhance management of current and potentially future water resources in the basin. Model estimates can be used to inform the effectiveness of past and ongoing salinity mitigation efforts and to inform the selection of locations for future mitigation work.

Description of Study Area

The UCRB is defined as the drainage basin upstream of the Colorado River at Lee's Ferry, AZ (USGS streamgage 0938000), and drains an area of 108,100 square miles (mi^2), including portions of Wyoming, Utah, Colorado, Arizona, and New Mexico (fig. 1). The basin is topographically complex and ranges in elevation from 3,100 to 14,300 feet (ft) above sea level (averages 6,800 ft). The average annual temperature ranges from 28.7 to 62.5 °F (averages 45.9 °F), and the average annual precipitation ranges from 5.1 to 54.9 inches (in.) (averages 14.5 in.). The western slope of the Rocky Mountains forms the eastern border of the UCRB, and much of the western boundary is bordered by the Wasatch Mountains. The large elevation and climate gradients in the UCRB contribute to a diversity of landscapes, ranging from high elevation alpine areas that receive most of their precipitation as snow, to lower, drier, and warmer areas of the Colorado Plateau. Major rivers in the UCRB include the Colorado, Green, Gunnison, San Juan, White, and Yampa Rivers. Much of the surface-water flow in the UCRB is regulated, including the presence of large

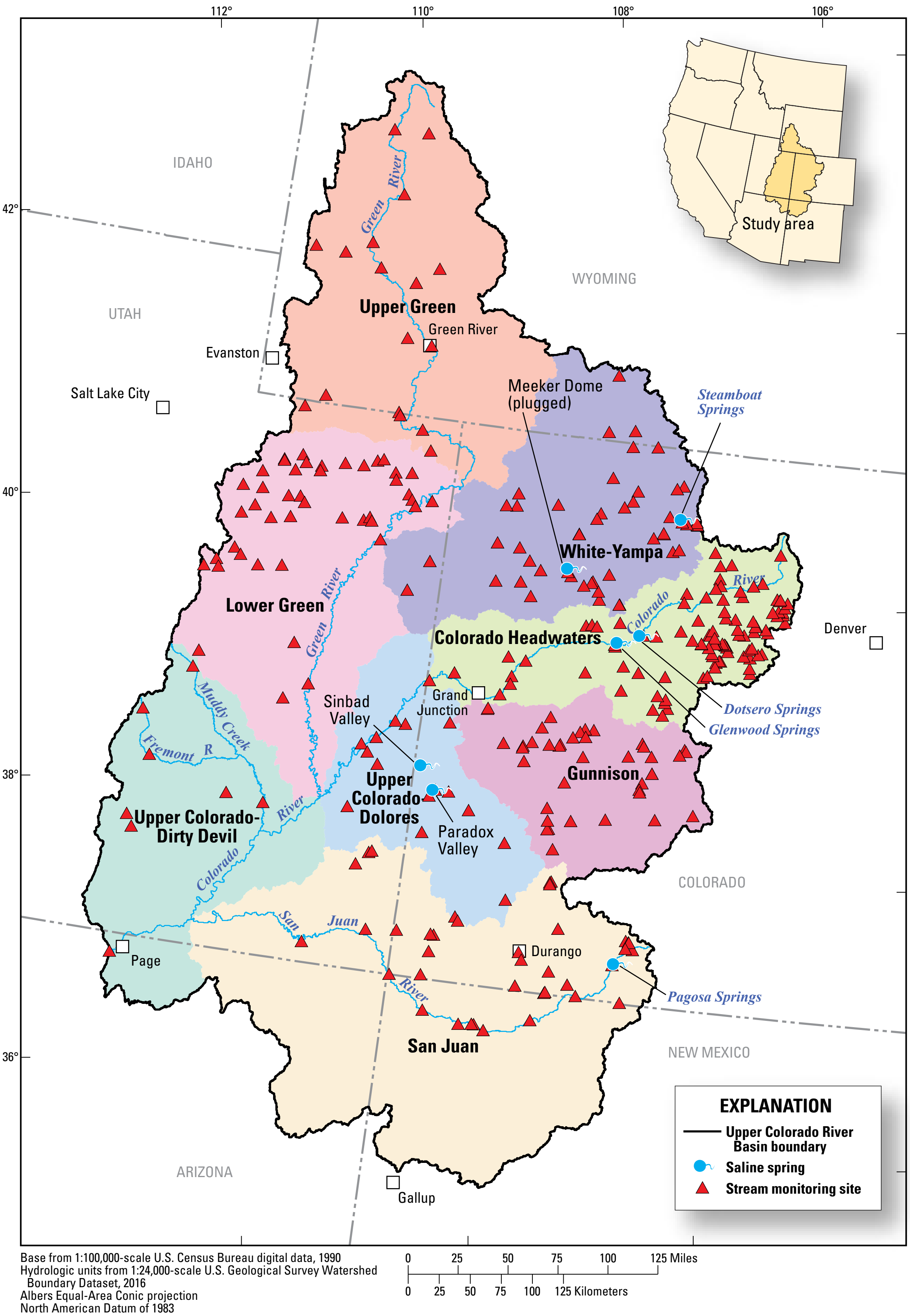

Figure 1. Study area, selected springs, and stream monitoring sites in the Upper Colorado River Basin.

reservoirs, such as Lake Powell (capacity of 2.4 x 10^7 acre-feet [acre-ft]), near the outlet of the UCRB. Approximately 5 percent of the streamflow in the UCRB is diverted to other basins (Liebermann and others, 1989, table 1). Because these diversions tend to occur in high elevation portions of the UCRB where there are minimal sources of dissolved solids, diversions account for less than 1 percent of the dissolved-solids load at Lee's Ferry (Iorns and others, 1965; Anning and others, 2007). There are a number of large springs in the UCRB that discharge high concentrations of dissolved solids to streams (fig. 1, table 2).

Methods

SPARROW Model Description

The SPARROW model relates measured dissolved-solids loads at monitoring stations (calibration data) to upland catchment attributes (sources and landscape transport characteristics), and routes loads through a hydrologic network of streams reaches. SPARROW also has model terms to represent instream and reservoir decay. Dissolved solids are transported conservatively through the stream network in the UCRB (Anning and others, 2007; Kenney and others, 2009). For this reason, instream decay was not considered in the development of the present model. However, reservoir management (changes in storage) can affect the mass of dissolved solids

Table 1. Water year 2010 transbasin diversions accounted for in the SPARROW model.

[CO, Colorado; UT, Utah; WY, Wyoming]

Conveyance name	State of origin	Water year 2010 total export (acre-feet)	Data source
Azotea Tunnel	CO	89,100	U.S. Bureau of Reclamation
H.D. Roberts Tunnel	CO	74,467	Colorado Division of Water Rights
Moffat Water Tunnel	CO	30,879	Colorado Division of Water Rights
Homestake Tunnel	CO	9,011	Colorado Division of Water Rights
C. H. Boustead Tunnel	CO	56,616	Colorado Division of Water Rights
Busk-Ivanhoe Tunnel	CO	3,348	Colorado Division of Water Rights
Twin Lakes Tunnel	CO	46,886	Colorado Division of Water Rights
Wurtz Ditch	CO	1,692	Colorado Division of Water Rights
Alva B. Adams Tunnel	CO	234,220	Colorado Division of Water Rights
Grand River Ditch	CO	13,455	Colorado Division of Water Rights
Hoosier Pass Tunnel	CO	10,984	Colorado Division of Water Rights
Strawberry Tunnel	UT	65,740	Upper Colorado River Commission
Duchesne Tunnel	UT	27,128	Upper Colorado River Commission
Fairview Tunnel	UT	1,300	Upper Colorado River Commission
Ephraim Tunnel	UT	7,120	Upper Colorado River Commission
Spring City Tunnel	UT	2,850	Upper Colorado River Commission
Cheyenne Diversion	WY	11,575	City of Cheyenne, WY

Table 2. Estimated annual dissolved-solids loads for selected springs in the Upper Colorado River Basin.

Saline spring point source	Estimated annual dissolved-solids load (U.S. Bureau of Reclamation, 2013) (tons)	Estimated water year 1991 dissolved-solids load (Kenney and others, 2009) (tons)	Estimated dissolved-solids load used in this report (tons)[1]
Dotsero Springs + Glenwood Springs[2]	517,600	343,000	535,000
Meeker Dome	57,000	37,100	0
Paradox Valley	204,000	148,000	23,000
Steamboat Springs	8,500	5,770	8,500
Pagosa Springs	7,300	4,950	7,300
Sinbad Valley	6,500	4,400	6,500
Total (rounded)	**800,000**	**540,000**	**580,000**

[1] Loads from Dotsero and Glenwood Springs and from the Paradox Valley were estimated using measured loads from nearby monitoring stations. Meeker Dome is reported to have been plugged (Bureau of Reclamation, written commun., March 2016). All other values are from U.S. Bureau of Reclamation (2013).

[2] Dotsero and Glenwood Springs are located near each other and were grouped for modeling purposes in this report.

transported through the network, and a reservoir decay term was tested for inclusion in the model. Model estimated source, landscape transport characteristic, and reservoir decay coefficients were used within the routing constraints of the model to predict dissolved-solids loads in 10,789 reaches of the UCRB. The governing equation that describes mean annual dissolved-solids load (*L*) leaving reach (*i*) is

$$L_i = \left(\sum_{j \in J(i)} L_j^{'}\right) \delta_i A(Z_{\mathrm{i}}^{R}, \theta_R) + \left(\sum_{n=1}^{N_S} S_{n,i} \alpha_n D_n \, (Z_i^{D}; \theta_D)\right) A^{'} \, (Z_i^{R}, \theta_R) \quad (1)$$

where the first summation term represents the dissolved-solids load from all upstream contributing reaches *J(i)* that are delivered to reach *i*. The δ_i term is the dimensionless fraction of upstream flux delivered to reach *i*. δ_i equals 1, unless there is a transbasin diversion of water out of the reach. All major transbasin diversions were accounted for in the model using the δ_i term. The *A* term is the aquatic transport function, representing attenuation of load as it travels through a reach containing a reservoir, and defines the fraction of load entering the upstream end of reach *i* that is delivered to the downstream end of reach *i*. The *A* term is a function of stream reservoir (*R*) characteristics defined by vector $\boldsymbol{Z}_i^R$, with coefficient vector θ_R. The second summation term represents the incremental load contributed to reach *i*. The S_n term represents the specific sources of dissolved solids in reach *i*, with source-specific coefficient α_n. The D_n term is the land-to-water delivery function, which along with $\alpha_{n,}$ determines the load delivered to the stream in reach *i*. The D_n term is a source-specific function of a vector of land-to-water delivery variables defined by vector $\boldsymbol{Z}_i^D$, with a vector coefficient of θ_D. The $A^{'}$ term is the aquatic transport function applied to reach *i*, if it contains a reservoir, and applies to load transport from the midpoint of reach *i* to the outlet of reach *i*. Detailed information and discussion of the theory, development, and application of the SPARROW model is available from Smith and others (1997) and Schwarz and others (2006).

Stream Reach Network

The SPARROW model is based on a geographic information systems (GIS) -based synthetic representation of a stream network used to model the transport of constituent loads downstream through the network. The stream network consists of stream reaches and an associated drainage area or “catchment” that is used to relate landscape characteristics to the network. Each reach extends either from headwater to stream junction, or from one stream junction to another stream junction (Brakebill and others, 2011). Stream junctions, or nodes, are related to each other using a numbering system that identifies the upstream and downstream nodes on each reach. This numbering system is used to define network connectivity and to route flow through the network. The stream and catchment network used for this model was modified from the network used by Kenney and others (2009). Detailed descriptions of methods used to develop the stream network are available in Kenney and others (2009). The earlier stream network was modified for the current model by splitting existing stream reaches and catchments so that new gages not used for calibration in the 1991 SPARROW model were located at or near the outlet of a catchment. New catchments were developed by delineating the drainage area upstream of the gage with the same methods used to develop the earlier network. New catchments were inserted into the previous catchment-stream network and associated reaches split at the catchment outlet. Upstream and downstream nodes were renumbered to maintain properly routed flow through the revised network.

The stream reach network accounted for major water diversions in the UCRB. The transbasin diversions of water out of the basin and listed in table 1 were accounted for by using the fraction of upstream flux delivered to the incremental reach term in the SPARROW model. This approach is consistent with that applied by Kenney and others (2009) and assumes that dissolved solids are removed proportionally to the amount of water removed. The Grand Valley in western Colorado diverts a substantial amount of water from the Colorado River through the Government Highline Canal and Grand Valley diversion structures. These diversions also were accounted for by using the fraction of upstream flux delivered to the incremental reach term. Consistent with the approach applied by Kenney and others (2009), the fraction of flux diverted in the Grand Valley was calculated by using 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. This calculation also accounted for discharge to the Colorado River from USGS streamflow-gaging station 09105000, Plateau Creek near Cameo, Colorado.

Calibration Data

The 1991 SPARROW model was calibrated to 218 independent estimates of dissolved-solids loads for water year 1991. The single-year model provides a temporal reference point to which conditions in the basin for other periods can be compared. Salinity Control Program managers, however, frequently are interested in understanding dissolved-solids load distribution under long-term average hydrologic conditions. To meet this need, updated long-term average dissolved-solids loads were estimated at 323 sites (Tillman and Anning, 2014) that span the range of environmental conditions in the basin.

Details of data compilation and analysis are provided in Tillman and Anning (2014). Briefly, dissolved-solids concentration and streamflow data for USGS monitoring stations in the UCRB were obtained from the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/nwis) for water years 1984–2012. Measures of dissolved solids include specific conductance, residue on evaporation at 180 °C, and the sum of dissolved constituents. Mean annual loads of dissolved solids were estimated using the Fluxmaster program (Schwarz and others, 2006). The ratio of observed to expected loads at the sites ranged from 0.87 to 1.15 (Tillman and Anning, 2014), indicating that bias associated with regression model estimates of loads are not a concern. Fluxmaster load estimates were detrended to a base year of 2010, where possible. Detrending to a base year adjusts for differences among sites in data record lengths, sample sizes, and temporal variability in discharge. Thus, detrended dissolved-solids load estimates represent the load that would occur in the base year (2010 for this study) under average hydrologic conditions, reflecting both the conditions of non-flow factors in the base year and average hydrologic conditions had they prevailed in the base year (Schwarz and others, 2006). This approach provides a robust set of calibration data for use in the development of the SPARROW model. Hereafter, loads detrended to a base year of 2010 are referred to as 2010 loads. It is important to note that these are not measured loads during 2010, but rather detrended loads, as defined above. As such, loads can be interpreted as those loads expected to occur in 2010 had long-term average hydrologic conditions prevailed in 2010. Detrending was not possible at all sites because of limited data near the base year of 2010. Of the 323 sites reported by Tillman and Anning (2014), 100 sites were detrended for both discharge and dissolved solids, 110 sites were detrended for discharge only, and 113 sites were not detrended. The data set was further filtered from 323 to 312 sites to remove sites outside of the basin represented by the SPARROW model and sites with estimated loads that contributed substantial error to the model results (had model residuals greater than 3 or less than -3). The locations of sample sites are shown in figure 1. Dissolved-solids loads used as model calibration data ranged from 6 to 23 million tons per year (tons/yr), with an average of 120,000 tons/yr.

Explanatory Data

Sources

Significant sources of dissolved solids in the UCRB can be categorized generally as natural or anthropogenic. As with the 1991 SPARROW model, the principal natural dissolved-solids sources include geologic units and point sources, mainly saline springs. The largest anthropogenic dissolved-solids source can be ascribed to irrigated agricultural lands (Kenney and others, 2009).

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 (Kenney and others, 2009). Geologic units derived from 1:500,000-scale state geologic maps were grouped into 34 defined units based on the 1:2,500,000-scale King and Beikman (1974) geology of the conterminous United States and further aggregated into 7 source groups that were used to define the geologic units for this model. Development of the geologic data used to define geologic sources in the study area is described in detail in Kenney and others (2009). The seven geologic source groups, identical to the groups used in the 1991 SPARROW model, were defined as follows: crystalline and volcanic rocks, high-yield sedimentary Cenozoic rocks, low-yield sedimentary Cenozoic rocks, high-yield sedimentary Mesozoic rocks, low-yield sedimentary Mesozoic rocks, high-yield sedimentary Paleozoic and Precambrian rocks, and low-yield sedimentary Paleozoic and Precambrian rocks (table 3). Details on the grouping methods and corresponding King and Beikman (1974) and 1:500,000-scale state geologic units that compose each geologic source group are presented in Kenney and others (2009). The grouped geology data are available as a geospatial dataset in the USGS ScienceBase-Catalog at https://www.sciencebase.gov/catalog/.

Agricultural Lands

A geospatial dataset of irrigated lands developed by Buto and others (2014) was used in this investigation to estimate the spatial distribution and lithologic domain of flood and sprinkler irrigated lands in the UCRB. Irrigated agricultural lands are the major anthropogenic source of dissolved solids in the UCRB (Iorns and others, 1965; Liebermann and others, 1989; U.S. Bureau of Reclamation, 2013). Understanding the location, spatial distribution, and the method used to deliver water to agricultural lands is important to help evaluate agriculturally derived dissolved-solids loading to surface water in the UCRB. Irrigation of fields in the UCRB is generally done using one of two methods: flood irrigation or sprinkler irrigation, although other techniques such as drip irrigation are used in the UCRB (Buto and others, 2014). In flood irrigation, water is delivered to a field by a ditch or pipe and flows over the field. In sprinkler irrigation, water is sprayed into the air over fields. Flood irrigation generally results in greater dissolved-solids loading to streams than sprinkler irrigation (Kenney and others, 2009) because the excess water not taken up by plants is either evapotranspired, runs off the land surface, or infiltrates the subsurface picking up solutes. Irrigated lands were classified on the basis of the bedrock lithology previously described and irrigation method. Sprinkler irrigated lands on all lithologies, flood irrigated lands on sedimentary-clastic Mesozoic lithologies, and flood irrigated lands on all other lithologies were identified and input to the SPARROW model (table 3). Overlaying irrigated lands on bedrock lithology assumes that the mineralogy of the irrigated soils is associated with the local underlying bedrock lithology (Kenney and others, 2009). Areas that appeared to be agricultural parcels, but were not actively irrigated during the period for which data were compiled (2007–2010) were not counted as irrigated agricultural lands.

Table 3. Dissolved-solids sources and landscape transport characteristics and associated datasets used in the SPARROW model.

[Elevation refers to distance above sea level. SSEBop, Simplified Surface Energy Balance (operational); MODIS, Moderate Resolution Imaging Spectroradiometer; STATSGO, State Soil Geographic Database]

Variable	Dataset(s) used	Parameters tested
Dissolved-solids sources		
Lithologic groupings	Generalized 1:500,000-scale geology of the Upper Colorado River Basin (Buto and others, 2016)	Crystalline and volcanic rocks
		High-yield sedimentary Cenozoic rocks
		Low-yield sedimentary Cenozoic rocks
		High-yield sedimentary Mesozoic rocks
		Low-yield sedimentary Mesozoic rocks
		High-yield sedimentary Paleozoic and Precambrian rocks
		Low-yield sedimentary Paleozoic and Precambrian rocks
Irrigated lands on selected lithologic groupings	2010 Irrigated lands (Buto and others, 2014), Generalized 1:500,000-scale geology of the Upper Colorado River Basin (Buto and others, 2016)	Sprinkler irrigated lands on all lithologies
		Flood irrigated sedimentary-clastic Mesozoic lands
		Flood irrigated lands of other lithologies
Landscape transport characteristics		
Basin Characterization Model (BCM)	1985–2012 BCM input parameters (Flint and Flint, 2007)	Mean total annual actual evapotranspiration (aet)
		Mean total annual climatic water deficit (cwd)
		Mean total annual excess water (exc)
		Mean total annual snowmelt (mlt)
		Mean total annual snowpack (pck)
		Mean total annual potential evapotranspiration (pet)
		Mean total annual precipitation (ppt)
		Mean total annual recharge (rch)
		Mean total annual runoff (run)
		Mean total annual sublimation (sbl)
		Mean total annual snowfall (snw)
		Mean total annual soil water storage (str)
Elevation and elevation derivatives	1/3 arc-second National Elevation Dataset (Gesch and others, 2009)	Minimum catchment elevation
		Maximum catchment elevation
		Mean catchment elevation
		Median catchment elevation
		Range in catchment elevation
		Minimum catchment percent slope
		Maximum catchment percent slope
		Mean catchment percent slope
Actual evapotranspiration (ET)	SSEBop (Savoca and others, 2013)	MODIS 2000–2012 total ET
		MODIS 2000–2012 maximum ET
		MODIS 2000–2012 mean ET
		Landsat 2010 mean ET
Grazing area	Bureau of Land Management grazing area (Tillman and others, 2015)	Percent of catchment composed of Bureau of Land Management (BLM) grazing allotments

Table 3. Dissolved-solids sources and landscape transport characteristics and associated datasets used in the SPARROW model.—Continued

[Elevation refers to distance above sea level. SSEBop, Simplified Surface Energy Balance (operational); MODIS, Moderate Resolution Imaging Spectroradiometer; STATSGO, State Soil Geographic Database]

Variable	Dataset(s) used	Parameters tested
Land cover	2011 National Land Cover Database (Jin and others, 2013)	Percent of catchment area composed of open water
		Percent of catchment area composed of ice and snow
		Percent of catchment area composed of developed land, open space
		Percent of catchment area composed of developed land, low intensity
		Percent of catchment area composed of developed land, medium intensity
		Percent of catchment area composed of developed land, high intensity
		Percent of catchment area composed of barren land
		Percent of catchment area composed of deciduous forest
		Percent of catchment area composed of evergreen forest
		Percent of catchment area composed of mixed forest
		Percent of catchment area composed of shrub/scrub
		Percent of catchment area composed of grassland/herbaceous
		Percent of catchment area composed of pasture/hay
		Percent of catchment area composed of cultivated crops
		Percent of catchment area composed of woody wetlands
		Percent of catchment area composed of emergent herbaceous wetlands
Rangeland	Rangeland data (Reeves and Mitchell, 2011)	Percent of catchment area composed of rangeland
Rock chemistry [1]	Olson and Hawkins (2012) rock chemistry	Rock calcium oxide concentration as percent (CAO)
		Rock iron oxide concentration as percent (FE)
		Rock potassium oxide concentration as percent (K)
		Rock magnesium oxide concentration as percent (MGO)
		Rock phosphorus concentration as percent (P)
		Rock hydraulic conductivity (PERM)
		Rock sulfur concentration as percent (S)
		Rock silicon dioxide concentration as percent (SI)
		Uniaxial compressive strength (UCS)
Snow cover	MODIS snow cover monthly L3 global 0.05 degree (MOD10CM) data product (Hall and others, 2006)	Mean snow cover (January to April)
		Mean snow cover (April 1)
		Maximum snow cover
Snow water equivalent	Daymet (Thornton and others, 2012)	Total annual (April 1, 1985–2012)
		Maximum (1985–2012)
		Minimum (1985–2012)
		Mean (1985–2012)
		Median (1985–2012)

Table 3. Dissolved-solids sources and landscape transport characteristics and associated datasets used in the SPARROW model.—Continued

[Elevation refers to distance above sea level. SSEBop, Simplified Surface Energy Balance (operational); MODIS, Moderate Resolution Imaging Spectroradiometer; STATSGO, State Soil Geographic Database]

Variable	Dataset(s) used	Parameters tested
Soils [2]	STATSGO (Natural Resources Conservation Service, 2014)	Horizon thickness (hzthk) Total clay (claytotal) Total silt (silttotal) Total sand (sandtotal) Total organic material (om) Saturated hydraulic conductivity (ksat) Available water content (awc) Liquid limit (ll) Plasticity index (pi) Sodium absorption ratio (sar) Electrical conductivity (ec) Percent by weight of carbonate in the less than 2 mm fraction (caco3) Percent by weight of gypsum (gypsum) Cation exchange capacity at pH 7.0 (cec7) Erodability factor (kffact) Slope gradient of the dominant component in the map unit (slopegraddcp) Slope gradient of all components in the map unit (slopegradwta) Minimum depth to bedrock (brockdepmin) Hydrologic group (hydgrpdcd)

[1] Data available from https://www.sciencebase.gov/catalog/item/559301a1e4b0b6d21dd67cb3.

[2] Weighted average for all horizons and value for upper horizon only were tested.

Point Sources

Saline springs represent the largest natural point source of dissolved-solids loading to streams in the UCRB (fig. 1, table 2; Kenney and others, 2009). It has been estimated that greater than 800,000 tons of dissolved solids are discharged annually from the seven springs listed in table 2 to streams and rivers in the UCRB (U.S. Bureau of Reclamation, 2013). However, this estimate is based on loads from Paradox Valley and Meeker Dome prior to the implementation of salinity control efforts. Monitoring sites upstream and downstream of the combined spring discharge from Dotsero and Glenwood Springs, and upstream and downstream of the Paradox Valley were used to estimate the dissolved-solids loading to reaches associated with these spring discharge points. The loads from these monitoring sites are those published in Tillman and Anning (2014), and are the same loads used as calibration data in this report (loads detrended to 2010, where possible). The loads published by the U.S. Bureau of Reclamation (2013) were used to represent loads to reaches associated with discharge from Steamboat Springs, Pagosa Springs, and Sinbad Valley. Meeker Dome has been plugged, and therefore was not identified as contributing a point-source load in the updated SPARROW model. The estimated point-source discharge from the Paradox Valley (approximately 23,000 tons/yr) is less than that estimated prior to salinity control efforts in the basin (approximately 200,000 tons/yr) by a factor of nearly 10 (table 2). It is noteworthy that the average estimated annual point-source load from the Paradox Valley for 1997–2015 using high-frequency (daily) specific-conductance data collected at monitoring sites that bracket the Paradox Valley, is approximately 43,000 tons/yr (Alisa Mast, U.S. Geological Survey, written commun., May 20, 2016). The discrepancy between this estimate and the value of 23,000 tons/yr that is used to represent the Paradox Valley point-source load in this report is because different datasets were used to estimate the annual loads (daily measured specific-conductance values vs. daily modeled estimates of dissolved solids obtained from discrete measurements). The use of computed daily values from nearly continuous measurements of specific conductance to estimate loads is a more accurate approach than the use of daily modeled estimates from discrete measurements of either specific conductance or total dissolved solids. However, to maintain consistency with the approach used to estimate loads at the other monitoring stations (the calibration data), the value of 23,000 tons/yr, which is representative of the load in year 2010 under long-term average hydrologic conditions, was used to represent the dissolved-solids load from the Paradox Valley. Further, overall model performance and model-predicted coefficients are nearly identical regardless of which estimated point-source load for the Paradox Valley is used in the model. The total annual point-source dissolved-solids load from all of the saline springs in the UCRB was estimated to be approximately 580,000 tons (table 2). This value is similar to the estimate of approximately 540,000 tons reported for the year 1991 (Kenney and others, 2009).

Landscape Transport Characteristics

Conceptually, climatic, physical drainage basin, land cover, and soil characteristics may play a role in the delivery of dissolved solids from sources to streams in the UCRB (Kenney and others, 2009). On the basis of our conceptual understanding of processes that contribute to the delivery of dissolved solids to streams, and the previous work in the UCRB by Kenney and others (2009), 10 broad landscape transport characteristics were evaluated as predictors of dissolved-solids loads in UCRB streams (table 3). Each transport characteristic consists of one or more parameters tested within the model. For example, 16 land cover classes compose the broad land cover characteristic input to the model. Transport characteristics were represented by GIS data of varying sources and scales (table 3). Each characteristic was evaluated against the catchment network using GIS tools and analysis methods.

Calibration of Upper Colorado River Basin Dissolved-Solids Model

A UCRB dissolved-solids SPARROW model was calibrated using the calibration and explanatory data described above. Calibration data were weighted depending on if they were detrended for dissolved solids and discharge, discharge only, or not detrended. Sites that were detrended for dissolved solids and discharge were given the highest weighting (weighting = 99), followed by sites detrended for discharge only (weighting = 83), and sites that were not detrended for dissolved solids or discharge (weighting = 66), thereby giving sites that were detrended more influence on the model. Landscape transport characteristics were mean-adjusted and transformed (log transform) as needed to approximate normal distributions. Exploratory models were developed using nonlinear least-squares regression. Variables tested for potential inclusion in the models were determined based on our conceptual understanding of dissolved-solids transport in the basin and variables included in previous models for the UCRB (Kenney and others, 2009). Sources of dissolved solids were added to the models first, followed by landscape transport characteristics. Kenney and others (2009) used data from a single year—1991, to calibrate the 1991 model. Therefore, it was necessary to account for the short-term (annual) effects of reservoir storage on dissolved-solids loads.

In the present model, which is based on a long time series of data, this approach was not feasible and is not required given that the periods of record used to compute loads are greater than reservoir residence times. Instead, a more traditional approach to assessing the effects of reservoir storage on loads was applied, whereby a reservoir decay term, estimated as a function of areal hydraulic load in reservoirs (mean annual flow divided by reservoir surface area), was tested. This term was not identified as a significant process, and therefore, was not included in the final model. All source variables were constrained to be non-negative, as this is consistent with the conceptual understanding that these are sources of dissolved solids. Landscape transport characteristics and the reservoir decay term were not constrained, as it is possible for these variables to interact with sources to either increase or decrease the relative delivery of dissolved solids to streams. All variables listed in table 3 were tested for potential inclusion in the final model. Decisions regarding which variables to include in the final model were based on overall model performance (root-mean-square error [RMSE]), geographic and spatial distribution of residuals, statistical significance of each variable, and collinearity among variables. Only statistically significant ($p < 0.05$) landscape transport characteristics were retained in the final model. However, for conceptual reasons, all tested sources were retained in the final model regardless of statistical significance. Following selection of the final set of model variables, a nonparametric bootstrapping procedure with 200 iterations was used to define 90-percent confidence intervals for each model coefficient (Schwarz and others, 2006). The model coefficients and associated predictions reported below are the mean values estimated by the resampled bootstrap analysis. Spatial autocorrelation among model residuals was assessed by using Geary's C statistic (Geary, 1954).

Source terms in the model were specified as the area of each source. Coefficients can be interpreted as the mean dissolved-solids yield from a given source, assuming that spatially variable landscape transport terms are uniformly distributed at average conditions throughout the reach. Landscape transport coefficients are applied to each source, thereby increasing (for positive coefficients) or decreasing (for negative coefficients) model-estimated dissolved-solids fluxes from reaches with greater values of the landscape transport variable. Dissolved-solids flux from irrigated lands is related to the amount of water applied for crop irrigation. Spatially distributed estimates of the amount of irrigated water applied are not available. Conceptually, the amount of water applied to agricultural lands is a function of growing season and climate, with less irrigation water needed in cooler and wetter areas with shorter growing seasons. To approximate the spatial variability in the amount of water needed for crop irrigation in the UCRB, mean elevation was used as a landscape transport variable specific to irrigated agricultural land sources. The remaining landscape transport characteristics were specified for the geologic source categories. The final calibrated model was used to predict spatially distributed dissolved-solids fluxes in the UCRB. In the 1991 SPARROW model, predicted dissolved-solids fluxes at monitoring sites were adjusted to match the calibration data. This approach was not applied in the present modeling effort because this approach would preclude the use of the model for simulating water-quality conditions under alternative land use/management scenarios (Schwarz and others, 2006).

Dissolved Solids in the Upper Colorado River Basin

The calibrated dissolved-solids SPARROW model provided a good fit to the calibration data (table 4). Volume R^2 values show that the model explained 96 percent of the variance in dissolved-solids load. The model yield R^2, which is a more appropriate indicator of model fit because it acts to remove area-flux correlations, was 0.73. Model RMSE was 0.47. These values compare favorably with the model fit statistics reported for the 1991 SPARROW model of $R^2 = 0.98$, yield $R^2 = 0.71$, and RMSE = 0.51. Diagnostic plots provide further indication that there was a good fit of the model to the calibration data (fig. 2). There was good correspondence between observed and predicted dissolved-solids loads and yields, with points centered along the 1:1 line (fig. 2*A* and *B*). Further, residuals were normally distributed as a function of predicted dissolved-solids load and yield (fig. 2*C* and *D*). Geary's C was 0.83 ($p = 0.14$), indicating that there was not spatial autocorrelation in the residuals.

Sources of Dissolved Solids

The dissolved-solids SPARROW model contained 11 source variables, including point sources as a single variable, 7 different geologic sources, and 3 irrigated lands sources (table 4). The *p*-values for all source variables with the exception of sprinkler irrigated lands ($p = 0.22$) were less than 0.05. However, it was important to represent this source in the model, and this variable was retained. The dimensionless point-source coefficient was 0.78. A value of 1 indicates that the estimates of point-source loads (loads from saline springs shown in table 2) are accurate. Although the coefficient of 0.78 indicates that the estimated loads from saline springs may be too large, the 90-percent confidence intervals determined from the bootstrapping analysis contain 1.0, indicating that the point-source coefficient is not significantly different than 1.0. Consistent with the 1991 SPARROW model, the high-yield sedimentary Mesozoic rocks had the largest coefficient, and therefore, the highest yield (44.9 tons/mi^2) of the seven geologic groups. The predicted yield from this group for the 1991

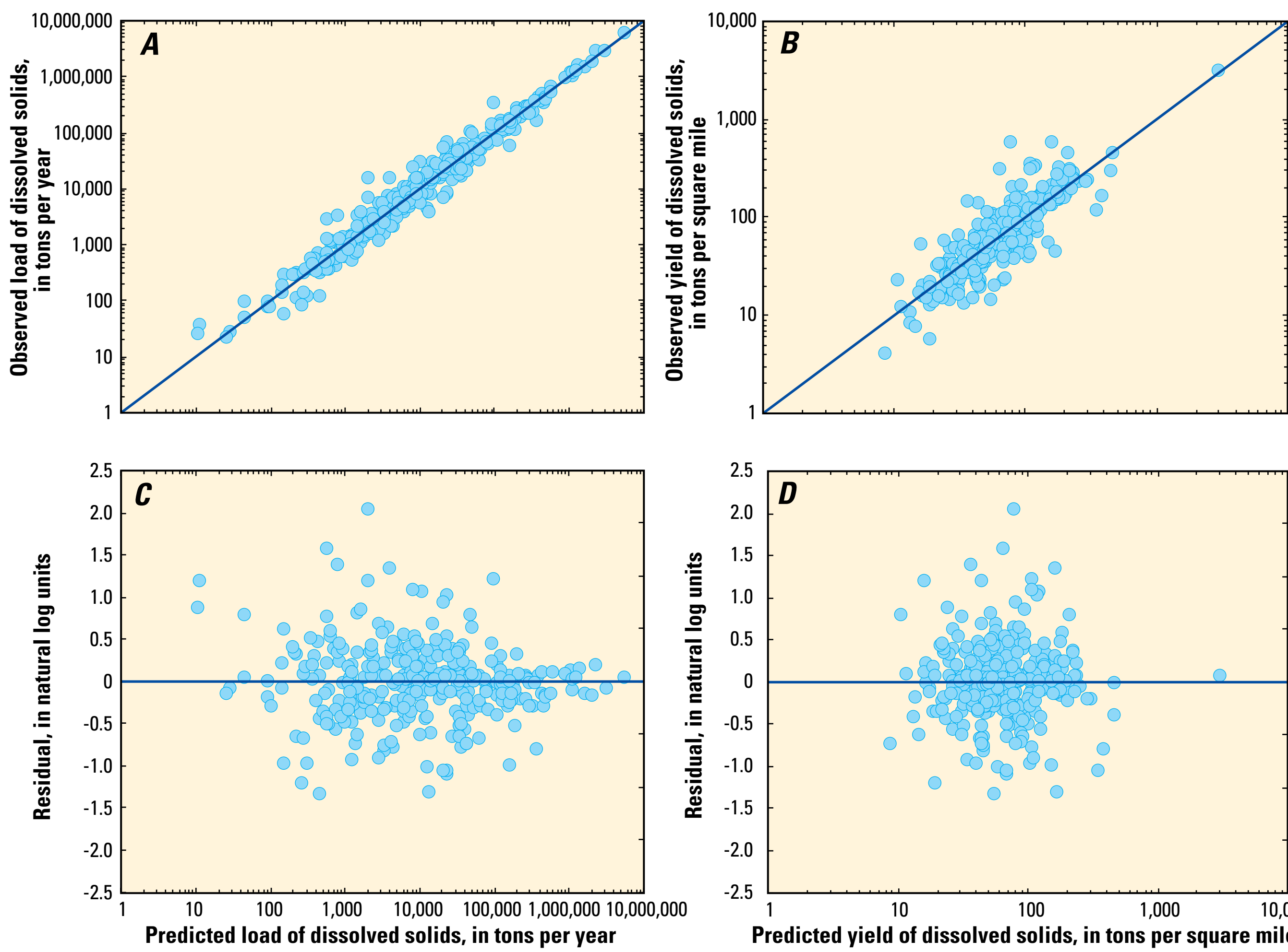

Figure 2. Dissolved-solids SPARROW model, showing *A,* observed versus predicted load of dissolved solids, *B*, observed versus predicted yield of dissolved solids, *C*, residuals versus predicted load of dissolved solids, and *D*, residuals versus predicted yield of dissolved solids.

Table 4. SPARROW model coefficients and statistics.

[D, dimensionless; ton/mi², tons per square mile; <, less than; ln, natural log; in/yr, inch per year; ft, feet; sqrt, square root; %, percent; in., inch; RMSE, root-mean-square error]

Model parameter	Coefficient units	Lower bound 90-percent confidence interval	Mean coefficient	Upper bound 90-percent confidence interval	Standard error	p-value	Variance inflation factor
Dissolved-solids sources							
Point-source imports	D	0.47	0.78	1.34	0.29	<0.001	1
Crystalline and volcanic rocks	ton/mi²	2.68	4.61	6.17	1.15	<0.001	7.5
Sedimentary rocks							1.4
High-yield Cenozoic	ton/mi²	19.3	32.1	43.9	6.93	<0.001	1.4
Low-yield Cenozoic	ton/mi²	13.8	20.2	25.9	4.03	<0.001	2.1
High-yield Mesozoic	ton/mi²	23	44.9	63.3	11.7	<0.001	1.9
Low-yield Mesozoic	ton/mi²	6.06	14.4	20.1	1.9	0.01	1.5
High-yield Paleozoic and Precambrian	ton/mi²	19.5	35.1	48.9	8.98	<0.001	4.4
Low-yield Paleozoic and Precambrian	ton/mi²	0.51	1.5	2.23	0.54	0.01	1.8
Sprinkler irrigated lands	ton/mi²	-420	150	434	298	0.22	1.2
Flood irrigated sedimentary-clastic Mesozoic lands	ton/mi²	798	2,296	3,477	842	<0.001	1.3
Flood irrigated lands of other lithologies	ton/mi²	159	773	1,313	495	0.04	1.3
Landscape transport characteristics							
Mean catchment precipitation minus mean catchment actual evapotranspiration	(ln[in/yr])⁻¹	0.86	1.06	1.25	0.12	<0.001	20.3
Mean catchment elevation	ft⁻¹	-0.007	-0.004	-0.0001	0.0002	0.03	1.3
Mean catchment slope	(sqrt[%])⁻¹	0.17	0.23	0.3	0.04	<0.001	4.3
Mean catchment cumulative thickness of soil	in.⁻¹	-0.04	-0.03	-0.01	0.01	<0.001	2.9
Rock iron oxide concentration	(ln[%])⁻¹	0.12	0.38	0.65	0.16	0.005	1.9
Fraction of catchment area covered by rangeland	D	0.17	0.81	1.4	0.35	0.01	8.4

Number of observations	R^2	Yield R^2	RMSE	Eigen spread
312	0.96	0.73	0.47	144

SPARROW model was 41.9 tons/mi². The high-yield sedimentary Cenozoic and low-yield Paleozoic and Precambrian rock groups also had high yields of 32.1 and 35.1 tons/mi², respectively. The low-yield sedimentary rock groups had dissolved-solids yields ranging from 1.5 tons/mi² for low-yield Paleozoic and Precambrian rocks to 20.2 tons/mi² for low-yield Cenozoic rocks.

Irrigated lands were divided into three source groups on the basis of irrigation type and underlying lithology: sprinkler irrigated lands (regardless of underlying lithology), flood irrigated sedimentary-clastic Mesozoic lands, and flood irrigated lands of other lithologies. Flood irrigated lands were apportioned among geologic groupings because Mesozoic lands are expected to generate greater yields than lands of other lithologies. This apportionment was not possible for sprinkler irrigated lands because of the small land area covered by sprinkler irrigated lands. Flood and sprinkler irrigated lands occupy 1,836 mi² of the UCRB; this equates to 1.7 percent of the total land area in the UCRB. Sprinkler irrigated, flood irrigated sedimentary-clastic Mesozoic, and flood irrigated lands of other lithologies occupy 564 mi², 374 mi², and 899 mi², respectively. Drip irrigated lands occupy 0.42 mi² of the UCRB. The small area of drip irrigated lands precluded their inclusion as sources in the model. Similarly, the small area of sprinkler irrigated lands precluded the division of this group among underlying geologic groups. All three irrigated land source groups had substantially higher coefficients than the geologic source groups (table 4). The sprinkler irrigated lands yielded 150 tons/mi², whereas the flood irrigated sedimentary-clastic Mesozoic lands yielded 2,296 tons/mi², and the flood irrigated lands of other lithologies yielded 773 tons/mi². These results are consistent with those reported for the 1991 SPARROW model, in that irrigated lands on sedimentary-clastic Mesozoic rocks produce the highest dissolved-solids yields. Data differentiating irrigation type (sprinkler vs. flood) were not available at the time when the 1991 SPARROW model was constructed. The predicted yields among irrigation types in the present model are consistent with the conceptual understanding and expectation that sprinkler irrigated lands have lower dissolved-solids yields than flood irrigated lands.

Landscape Transport of Dissolved Solids

The dissolved-solids SPARROW model includes six landscape transport characteristics (table 4). These variables interact with the source terms to either increase (for positive landscape transport coefficients) or decrease (for negative landscape transport coefficients) the predicted loads. All landscape transport characteristics included in the model were statistically significant ($p < 0.05$). Mean coefficients from the resampled bootstrap analysis, and the 90-percent confidence intervals from the resampled bootstrapping excluded zero, further indicating their significance.

Mean catchment elevation was the only landscape transport variable set to interact with the three irrigated land sources. As described above, this variable serves as a proxy for the amount of water applied for crop irrigation, with the assumption that less irrigation water is needed at higher elevations that are cooler, wetter, and have shorter growing seasons. The negative coefficient associated with mean catchment elevation (table 4, -0.004) is consistent with this concept, and indicates that higher elevations are associated with a decrease in dissolved-solids loads from irrigated land sources.

The remaining five landscape transport characteristics were applied to the seven geologic source categories. The coefficient for mean catchment cumulative thickness of soil was negative (table 4, -0.03), which is consistent with the negative coefficient for this variable reported in the 1991 SPARROW model (-0.05). As suggested by Kenney and others (2009), possible interpretations of the inverse relation between soil thickness and dissolved-solids load include thinner soils indicating less weathered rock, and therefore greater dissolved-solids loads, and thicker weathered soils impeding movement into unweathered rocks. Another possible process contributing to this finding is the storage of dissolved solids in areas with greater soil thickness. High elevation catchments tend to have greater precipitation, less evapotranspiration, and steeper slopes than low elevation catchments. The positive coefficients for precipitation minus actual evapotranspiration (1.06) and mean catchment slope (0.23) indicate that higher elevations produce more dissolved solids than lower elevations. This interpretation is also consistent with the findings in the 1991 SPARROW model. The positive coefficients associated with rock iron oxide concentration (0.38) and fraction of the catchment area covered by rangeland (0.81) indicate that larger values of these variables are associated with increases in dissolved-solids loads from geologic sources. The positive rangeland coefficient may be reflective of increased loads from disturbed lands.

Predicted Fluxes to Lower Colorado River Basin and Major Tributaries

The SPARROW model estimates that approximately 6.4 million tons/yr of dissolved solids are delivered from the UCRB to the Lower Colorado River Basin (table 5). This value compares favorably with the estimate of 6.1 million tons/yr obtained from monitoring data at USGS streamflow-gaging station 09380000, Colorado River at Lees Ferry, AZ (Tillman and Anning, 2014). It is important to remember that the model is calibrated to the dissolved-solids flux for a base year of 2010 under long-term mean hydrologic conditions. Therefore, the model estimated fluxes represent the typical dissolved-solids flux under such conditions, and may not match annual fluxes, which vary over time. Six percent of the basin-scale dissolved-solids load was from point sources such as springs, 62 percent was from geologic sources, 2.5 percent was from sprinkler irrigated lands, 17 percent was from flood irrigated sedimentary-clastic Mesozoic lands, and 12 percent was from flood irrigated lands of other lithologies (table 5). Although sprinkler and flood irrigated lands compose only 1.7 percent of the total land area in the UCRB, they contribute 32 percent of the total dissolved-solids load.

Dissolved-solids loads and yields among the eight hydrologic unit code level 4 (HUC4) watersheds in the UCRB (see fig. 1) were variable (table 6). The Colorado Headwaters had the largest dissolved-solids load (1.6 million tons/yr) and yield (163 tons/mi^2), whereas the Upper Colorado-Dirty Devil had the lowest load (230,000 tons/yr) and yield (19 tons/mi^2). The relative importance of different sources of dissolved solids to streams in the UCRB also varied among HUC4 watersheds (fig. 3). Geologic sources contributed the largest fraction of the total load in all eight watersheds, ranging from 40 percent of

Table 5. Estimated annual total dissolved-solids loads from sources in the Upper Colorado River Basin.

Dissolved-solids source	Dissolved-solids load (tons/per year)
Point-source imports	410,000
Geologic sources	
Crystalline and volcanic rocks	290,000
High-yield sedimentary Cenozoic rocks	690,000
Low-yield sedimentary Cenozoic rocks	870,000
High-yield sedimentary Mesozoic rocks	920,000
Low-yield sedimentary Mesozoic rocks	620,000
High-yield sedimentary Paleozoic and Precambrian rocks	540,000
Low-yield sedimentary Paleozoic and Precambrian rocks	28,000
Irrigated land sources	
Sprinkler irrigated lands	160,000
Flood irrigated sedimentary-clastic Mesozoic lands	1,100,000
Flood irrigated lands of other lithologies	750,000
Total (rounded)	**6,400,000**

the load in the Gunnison watershed to 92 percent of the load in the Upper Colorado-Dirty Devil watershed. Point sources including springs, contributed 31 percent of the load in the Colorado Headwaters watershed, which contains Dotsero and Glenwood Springs. This is the only watershed for which point sources composed greater than 10 percent of the total watershed load, contributing to the finding that this watershed had the largest estimated dissolved-solids load and yield (table 6). Dissolved-solids loads from sprinkler irrigated lands contributed less than 10 percent of the total load in each of the eight watersheds. Flood irrigated lands (those on sedimentary-clastic Mesozoic lands combined with those on other lithologies) contributed between 5 percent (Upper Colorado-Dirty Devil watershed) and 60 percent (Gunnison watershed) of the total load to the watersheds.

Table 6. Estimated annual total dissolved-solids loads and yields from watersheds in the Upper Colorado River Basin.

Dissolved-solids source	Dissolved-solids load[1] (tons per year)	Dissolved-solids yield (tons per mile)
Colorado Headwaters	1,600,000	163
Gunnison	800,000	99
Upper Colorado-Dolores	410,000	49
Upper Green	890,000	53
White-Yampa	880,000	66
Lower Green	1,000,000	69
Upper Colorado-Dirty Devil	230,000	19
San Juan	910,000	37

[1] Loads represent the sum of incremental loads generated in each reach within each watershed and do not account for diversions. Therefore, the sum of loads from all watersheds is greater than the total load delivered to the Lower Colorado River Basin.

Predicted Yields Among Land Use and Management Categories

Dissolved-solids yields from four different land use/management categories were estimated and mapped to provide information on the relative yields from lands experiencing different land use/management. The four categories include irrigated lands, rangelands, Bureau of Land Management (BLM) managed lands, and grazing allotments on BLM managed lands (see table 3 for information on data sources). Estimated yields from the latter three categories were restricted to those generated from geologic sources. As described above, irrigated lands occupy a small fraction (less than 2 percent) of the land area in the UCRB, but contribute 32 percent of the dissolved-solids load. This is a result of the large yields produced by irrigated lands (table 4, fig. 4). The average dissolved-solids yield produced by irrigated lands was 113 tons/mi^2, with a maximum yield of 3,800 tons/mi^2 in the Grand Valley of Colorado. High dissolved-solids yields (greater than 1,000 tons/mi^2) from irrigated agricultural lands are present in parts of the Gunnison, Colorado Headwaters, and Lower Green watersheds (fig. 4).

Yields generated from geologic sources were generally less than those generated on irrigated lands in the UCRB. In contrast to the large yields estimated from irrigated lands, the average dissolved-solids yield from geologic sources was 34 tons/mi^2, with a maximum yield of 680 tons/mi^2 near Aspen, Colorado. The spatial distribution of geologic yields from rangelands, BLM managed lands, and grazing allotments on BLM managed lands is shown in figures 5, 6, and 7, respectively. Geologic sources on rangelands, BLM managed lands, and grazing allotments on BLM managed lands contributed

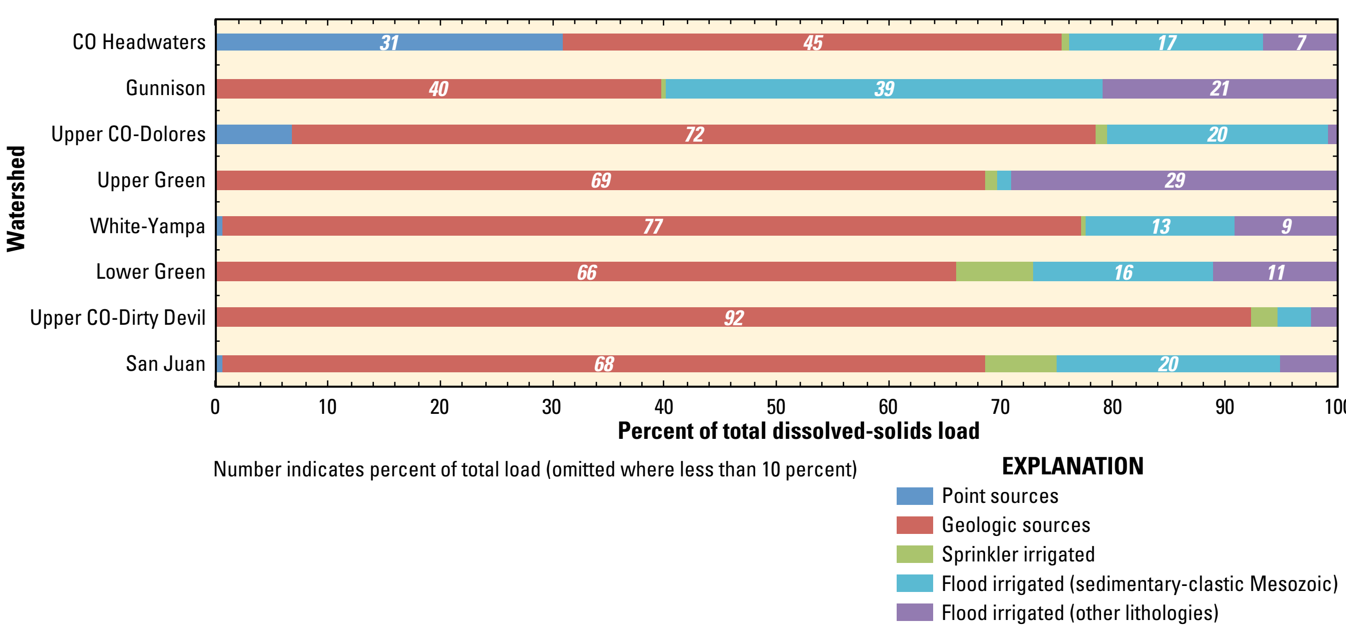

Figure 3. Estimated shares of dissolved-solids loads to watersheds in the Upper Colorado River Basin from modeled sources.

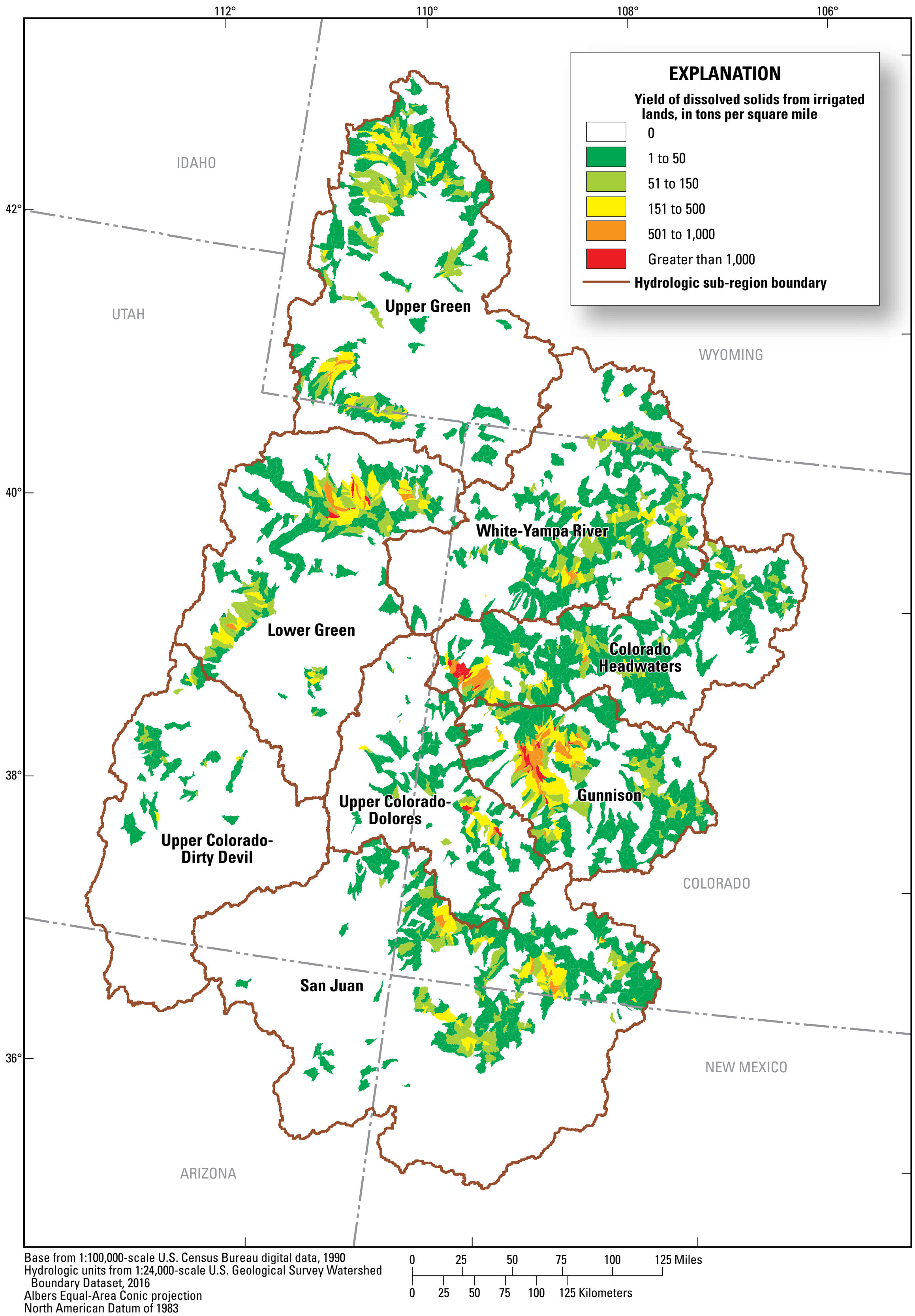

Figure 4. Estimated incremental dissolved-solids yields from irrigated lands in the Upper Colorado River Basin.

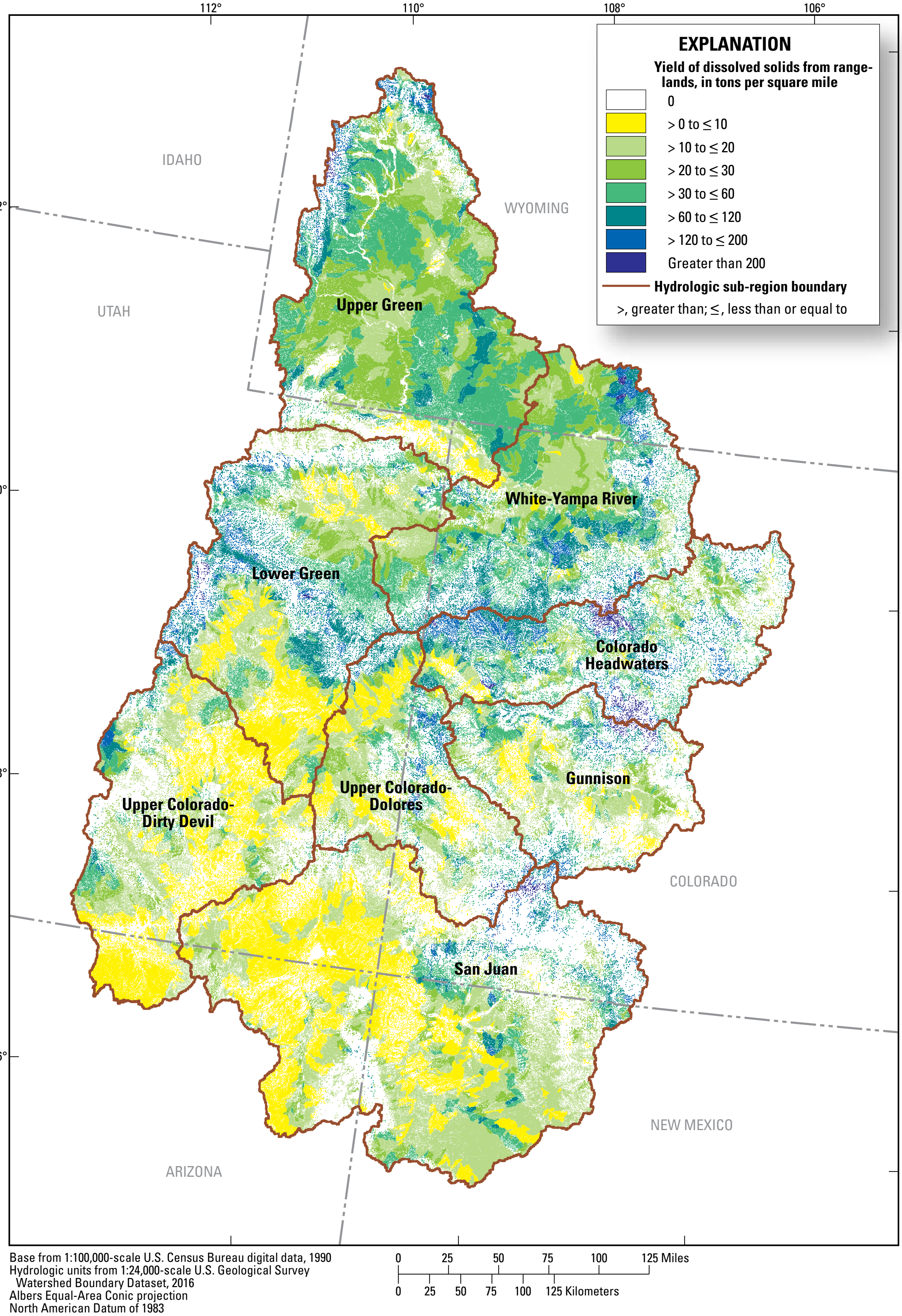

Figure 5. Estimated incremental dissolved-solids yields from rangelands in the Upper Colorado River Basin.

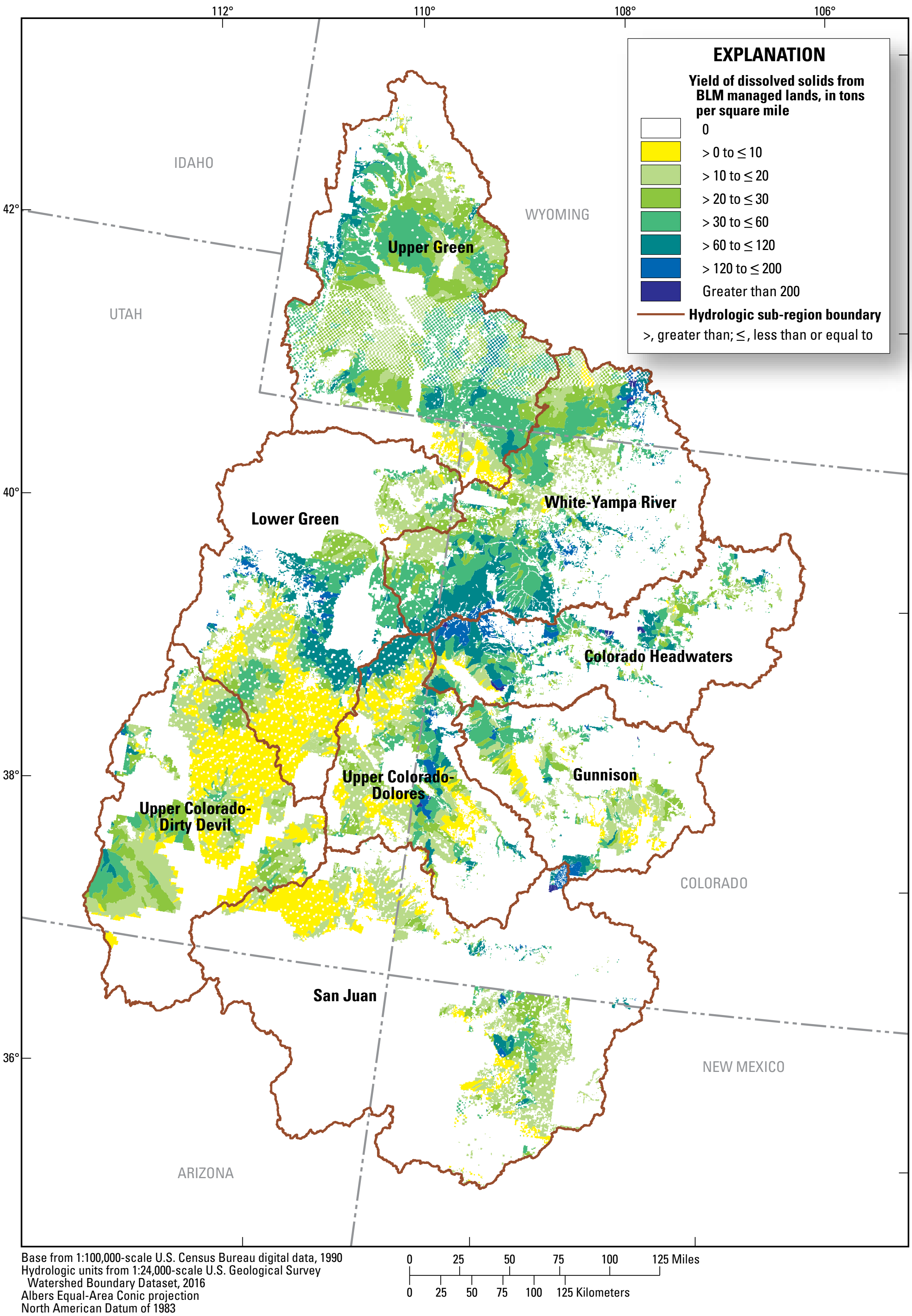

Figure 6. Estimated incremental dissolved-solids yields from BLM managed lands in the Upper Colorado River Basin.

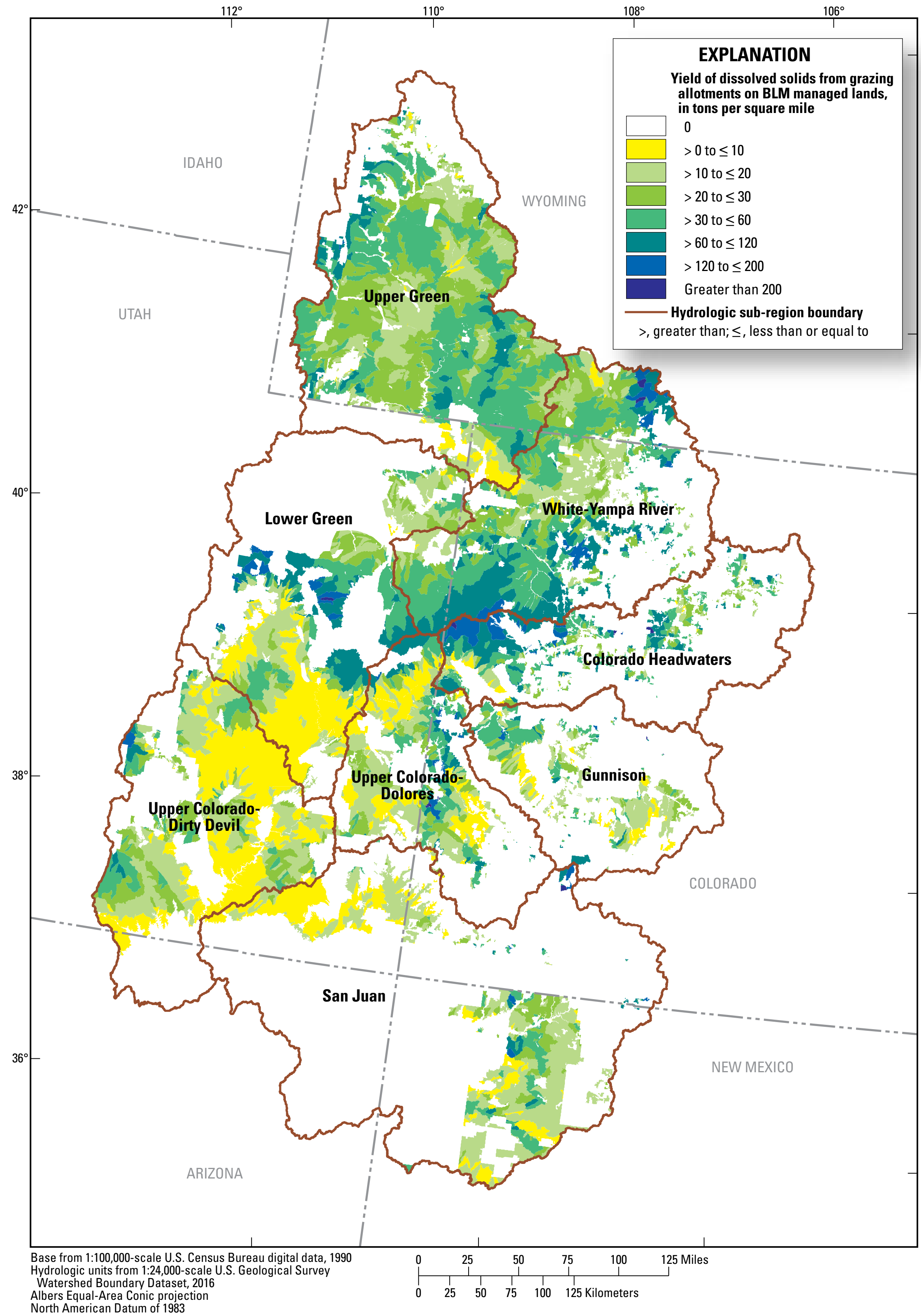

Figure 7. Estimated incremental dissolved-solids yields from grazing allotments on BLM managed lands in the Upper Colorado River Basin.

1.7 million tons/yr, 1.3 million tons/yr, and 1.5 million tons/yr of dissolved solids, respectively. The basin-scale geologic yield from rangelands was 30 tons/mi^2, and was 32 tons/mi^2 for both BLM managed lands and grazing allotments on BLM managed lands. These estimates are intended to provide an assessment of how loads and yields vary as a function of land use and management. However, it is important to note that there is substantial spatial overlap among these groups (figs. 5, 6, and 7), and therefore adding loads from different groups may result in double counting of loads.

Comparison of Dissolved-Solids Load Predictions with Other Studies at Selected Locations in the Upper Colorado River Basin

Predicted dissolved-solids loads from the present modeling effort were compared with loads estimated as part of previous assessments, including those estimated from the 1991 SPARROW model. The probable amounts of dissolved solids from natural and human sources, on the basis of irrigated land areas and yields, were estimated from the 1914–1957 annual average, and adjusted to 1957 for selected locations in three divisions of the UCRB (Iorns and others, 1965). These estimates were compared with estimates from the 1991 SPARROW model in Kenney and others (2009). Where possible, the 1957 and 1991 estimates are compared with those from the present (base year of 2010) model (table 7). Dissolved-solids loads vary from year to year depending on watershed conditions, most notably the amount of precipitation. Additionally, the 1914–1957 period predates the construction of many large reservoirs in the UCRB. For these reasons, care must be taken when comparing the absolute values of estimated loads among years at a given site. A more robust comparison of variability among years at a given site is provided by the percentages of predicted loads from natural and agricultural sources.

In general, the 1991 and 2010 models attributed a smaller percentage of the dissolved-solids loads from agricultural sources in the Grand Division as compared with the 1957 estimates (table 7). The 1991 and 2010 agricultural sources of dissolved-solids loads in the Grand Division were within 10 percent of one another, with the exception of Plateau Creek near Cameo, CO (USGS streamgage 09105000) where the models attributed a smaller fraction of total load to agricultural sources in 2010 (41 percent) than in 1991 (62 percent).

In the Green Division, the shares of dissolved-solids loads from agricultural sources in 1957 were generally similar to those estimated for 1991 and 2010. Exceptions to this included the Yampa River near Maybell, CO (USGS streamgage 09251000) where the percent of agricultural loads increased from 14 percent in 1957 to 33 percent in 1991 to 37 percent in 2010, and the White River near Watson UT (USGS streamgage 09306500) where the percent of agricultural loads decreased from 50 percent in 1957 to 15 and 18 percent in 1991 and 2010, respectively. These patterns may be driven in part by changes in irrigated agricultural areas. It is estimated that the amount of irrigated agricultural land in the Yampa basin in 1957 was 80 mi^2 (table 7). This area increased to 108 mi^2 in 1991, and decreased to 81 mi^2 in 2010. The opposite pattern was observed in the White River basin, where the amount of irrigated agricultural land decreased over time from 47 mi^2 in 1957, to 40 mi^2 in 1991, and 37 mi^2 in 2010.

Although temporal patterns in irrigated agricultural areas track patterns in the fraction of loads from irrigated agricultural lands, it is important to note that the irrigated lands dataset used in the 1991 model was mapped by a variety of agencies using a variety of source materials, scales, and mapping methods. Therefore, differences in scale, mapping methods, and image interpretation may account for some discrepancies between reported agricultural lands between the 1991 and 2010 models. Notable differences in the percent of load attributed to agricultural sources between the 1991 and 2010 models included a decrease from 60 percent in 1991 to 45 percent in 2010 at the Green River near La Barge, WY (USGS streamgage 09209400), a decrease from 74 percent in 1991 to 54 percent in 2010 at the Duchesne River near Randlett, UT (USGS streamgage 09302000), and a decrease from 42 percent in 1991 to 30 percent in 2010 at the Green River at Green River, UT (USGS streamgage 09315000). The conversion of flood to sprinkler irrigated lands in these basins, most notably the Duchesne basin, where over half of the irrigated agricultural lands in 2010 were irrigated by sprinklers (table 7), is a likely process contributing to the observed decreases in the fraction of loads from irrigated lands.

The San Juan River near Bluff, UT (USGS streamgage 09379500) was the only site in the San Juan Division with estimates of the percent of load from agricultural sources in all three years. The share of dissolved-solids load from agricultural sources at this location increased from 29 percent in 1957 to 49 percent in 1991, and then decreased to 32 percent in 2010 (table 7). This pattern is consistent with the pattern of change in irrigated agricultural areas in this basin. Sixty-four percent of the irrigated agricultural lands draining to the San Juan River near Bluff, UT in 2010 were sprinkler irrigated, highlighting the likely role of conversion from flood to sprinkler irrigated lands in mitigating salinity loads from agricultural lands. The share of dissolved-solids load from agricultural sources at the Dirty Devil River above Poison Spring Wash, near Hanksville, UT (USGS streamgage 09333500), where sprinkler irrigated lands were estimated to make up 81 percent of the irrigated land area in 2010, decreased from 42 percent in 1991 to 13 percent in 2010 (table 7).

The share of dissolved-solids load from irrigated agricultural sources at the Colorado River at Lees Ferry, AZ (USGS streamgage 09380000) was similar in 1957 (40 percent) and 1991 (43 percent), and decreased to 32 percent in 2010 (table 7). This basin-scale decrease in the share of dissolved-solids loads from agricultural sources may be a reflection of the implementation of numerous salinity control projects in the UCRB. The idea that salinity control projects are contributing to this decrease in dissolved-solids loads is supported by

Table 7. Dissolved-solids loads and contributions from natural and agricultural sources for 1914–1957, adjusted for 1957, 1991, and 2010, for the Grand Division above the Gunnison River, Colorado, the Green Division of the Upper Colorado River Basin, and the San Juan Division of the Upper Colorado River Basin.

[**Abbreviations:** mi^2, square miles; WY, Wyoming; UT, Utah; NM, New Mexico; AZ, Arizona; NA, data not available]

Location	Drainage area[1] (mi^2)	Irrigated area, 1957[2] (mi^2)	Irrigated area, 1991[2] (mi^2)	Flood and sprinkler irrigated area, 2010[3] (mi^2)	Sprinkler irrigated area, 2010[3] (mi^2)	Dissolved-solids load: Average 1914–1957 total[2] (tons)	Monitored 1991 total[1] (tons)	Monitored 2010 total[4] (tons)	Natural: Average 1914–1957[2] (percent)	Natural: Predicted 1991[5,6] (percent)	Natural: Predicted 2010[4] (percent)	Agricultural: Average 1914–1957[2] (percent)	Agricultural: Predicted 1991[5,6] (percent)	Agricultural: Predicted 2010[4] (percent)
Grand Division above the Gunnison River, Colorado														
Colorado River at Hot Sulphur Springs, CO	825	25	24	15	0	18,300	13,400	15,300	62	90	83	38	10	17
Roaring Fork at Glenwood Springs, CO	1,451	49	53	26	11	299,900	267,000	275,000	69	92	92	31	11	8
Colorado River near Cameo, CO	8,050	255	269	140	27	1,578,000	1,330,000	1,430,000	76	88	92	24	13	8
Plateau Creek near Cameo, CO	592	45	49	22	5	66,100	36,600	49,400	43	52	59	57	62	41
Colorado River below Grand Valley Divide, near Palisade, CO[7]	8,753	301	320	163	32	1,644,100	828,000	1,020,000	76	86	91	24	16	9
Green Division of the Upper Colorado River Basin														
Green River near La Barge, WY	3,910	NA	378	231	6	NA	263,000	243,000	NA	41	55	NA	60	45
Green River near Green River, WY	9,740	237	420	264	29	504,000	424,000	346,000	63	63	70	37	37	30
Green River near Greendale, UT	15,390	399	620	400	41	847,400	593,000	664,000	63	62	67	37	38	33
Yampa River near Maybell, CO	3,410	80	108	81	4	2,188,000	251,000	281,000	86	68	63	14	33	37
Little Snake River near Lily, CO	3,730	32	50	34	2	120,500	76,500	126,000	75	81	84	25	19	16
Duchesne River near Randlett, UT	4,250	212	227	201	108	460,200	125,000	175,000	29	29	46	71	74	54
White River near Watson, UT	4,020	47	40	37	2	330,600	254,000	221,000	50	85	82	50	15	18
Green River at Ouray, UT	31,540	828	1,116	572	95	2,407,000	1,010,000	1,300,000	61	62	69	39	39	31
Green River at Green River, UT	40,890	860	1,183	854	234	2,652,000	1,670,000	1,790,000	61	59	70	39	42	30
San Juan Division of the Upper Colorado River Basin														
San Juan River near Carracas, CO	1,230	NA	25	14	1	NA	86,200	61,400	NA	84	85	NA	17	15
San Juan River near Archuleta, NM	3,260	NA	114	67	10	NA	116,000	124,000	NA	66	66	NA	34	34
San Juan River near Bluff, UT	23,000	323	480	335	213	997,000	655,000	514,000	71	51	68	29	49	32
Dirty Devil River above Poison Spring Wash, near Hanksville, UT	4,160	NA	45	31	25	NA	67,700	141,000	NA	59	87	NA	42	13
Entire Upper Colorado River Basin														
Colorado River at Lees Ferry, AZ	108,000	2,203	2,698	1,836	564	8,642,000	5,760,000	6,000,000	60	59	68	40	43	32

[1] From Kenney and others (2009).
[2] Calculated from Iorns and others (1965), as reported in Kenney and others (2009).
[3] Area actively irrigated during period of data compilation (2007–2010).
[4] Detrended to a base year of 2010, from Tillman and Anning (2014), and used in this report.
[5] Non-adjusted loads from Kenney and others (2009).
[6] Sum of predicted 1991 natural and agricultural dissolved-solids load percent may not always equal 100, see Kenny and others (2009).
[7] Colorado River Basin above Gunnison River in Iorns and others (1965).

(1) the results of Anning and others (2007) who demonstrated that there was a greater decrease in dissolved-solids concentrations downstream of salinity control units relative to upstream changes in the southwestern United States, (2) the aforementioned decrease in dissolved-solids loads from Paradox Valley, and (3) SCP estimates of approximately 1 million tons of dissolved solids reduced between 1980 and 2010 as a result of salinity control projects in the basin (James Prairie, U.S. Bureau of Reclamation, written commun., August 3, 2016). Conversion from flood to sprinkler irrigated lands in the UCRB (31 percent of irrigated lands in the UCRB are sprinkler irrigated) is a likely process contributing to the temporal decrease in dissolved-solids loads from irrigated lands.

Limitations and Uncertainty

When interpreting the results presented here, as well those from any modeling study, it is important to recognize the limitations and uncertainties associated with the model data, coefficients, and predictions. A detailed discussion of the assumptions and simplifications inherent to SPARROW is provided in Schwarz and others (2006). Briefly, there are three main sources of uncertainty that should be considered when interpreting the results of SPARROW modeling. These include parameter uncertainty (uncertainty in source and land to water characteristic coefficients), model uncertainty attributed to unaccounted for sources or landscape transport characteristics, and measurement error. Predicted dissolved-solids loads from the present SPARROW model are based on calibration data during 2010 under long-term mean hydrologic conditions. Therefore, the model estimated loads represent the typical dissolved-solids loads under such conditions, and may not match annual fluxes, which vary over time. Uncertainty in model predictions is expected to be greater in smaller watersheds than in major rivers draining large watersheds. Further, model coefficients are basin-wide averages. For these reasons, care must be taken when interpreting results from specific locations, especially those draining small watersheds. Although it is important to recognize the model limitations and uncertainties, SPARROW is a useful watershed modeling tool that relates estimates of mean annual loads in a network of monitoring stations to watershed attributes, and routes mass through the basin under mass-balance constraints. Therefore, when interpreted in the context of basin-wide average conditions, SPARROW model results can be used as a tool to identify sources of, and landscape transport characteristics influencing, dissolved-solids transport in the UCRB.

Summary

Spatially Referenced Regressions on Watershed Attributes (SPARROW) modeling was used to provide an improved understanding of the spatial distribution of salinity sources, load accumulations, and transport mechanisms in the Upper Colorado River Basin (UCRB). The model builds upon a previously published dissolved-solids SPARROW model developed for the UCRB, which represented conditions in the 1991 water year. The updated model incorporates data defining current basin attributes not available in the previous SPARROW model, including delineation of irrigated lands by irrigation type (sprinkler or flood), and was calibrated to dissolved-solids load estimates for 312 monitoring stations in the UCRB—an increase from 218 monitoring sites in the 1991 SPARROW model. The model was used to estimate dissolved-solids loads for more than 10,000 stream reaches in the UCRB. The load estimates were used as calibration data in the updated model, and the resultant model predictions represent dissolved-solids loads in 2010, under long-term average hydrologic conditions.

Eleven sources of dissolved solids in the basin were included in the model: seven geologic source groups, three irrigated agricultural land source groups, and one point source associated with saline springs. Seventy-eight landscape transport characteristics representing climatic, physical drainage basin, land cover, and soil characteristics that conceptually, may play a role in the delivery of dissolved solids from sources to streams, were tested for potential inclusion in the model. Six of these 78 landscape transport characteristics were identified as valid predictors of dissolved-solids loads. The calibrated model provided a good fit to the calibration data as evidenced by R^2 and yield R^2 values of 0.96 and 0.73, respectively, and a root-mean-square error of 0.47. Of the geologic source groups, high-yield sedimentary Mesozoic rocks had the largest dissolved-solids yield of 44.9 tons/mi^2. The three irrigated agricultural land sources had substantially larger yields than the geologic source groups, with estimates of 150 tons/mi^2, 2,296 tons/mi^2, and 773 tons/mi^2 for sprinkler irrigated lands, flood irrigated sedimentary clastic Mesozoic lands, and flood irrigated lands of other lithologies, respectively. The larger yields from irrigated agricultural lands relative to geologic sources, and the larger yields from flood irrigated lands relative to sprinkler irrigated lands are consistent with the conceptual understanding of dissolved-solids sources in the UCRB. The coefficients estimated for the six landscape transport characteristics are also consistent with the conceptual understanding of dissolved-solids delivery to streams in the UCRB.

The SPARROW model estimated that approximately 6.4 million tons/yr of dissolved solids are delivered from the UCRB to the Lower Colorado River Basin. Six percent of the basin-scale dissolved-solids load was estimated to be from saline springs, 62 percent was from geologic sources, and 32 percent was from irrigated agricultural land sources, which compose less than 2 percent of the total land area of the UCRB. The fraction of load estimated to have originated from irrigated agricultural lands for the present model (32 percent) is less than that estimated by the 1991 SPARROW model (43 percent). This decrease may be a result of the implementation of salinity control projects in the UCRB.

Dissolved-solids loads and yields among the eight HUC4 watersheds in the UCRB were variable, as was the relative importance of different sources of dissolved solids to streams in the UCRB. For example, saline springs contributed 31 percent of the load in the Colorado Headwaters watershed, but composed less than 10 percent of the load in the remaining seven watersheds. Irrigated agricultural lands contributed 60 percent of the dissolved-solids load in the Gunnison watershed, and between approximately 10 and 35 percent of the load in the remaining seven watersheds. Dissolved-solids loads and yields from geologic sources among three land use/management categories were similar. Geologic sources contributed between 1.3 million and 1.7 million tons/yr of dissolved solids on rangelands, BLM managed lands, and grazing allotments on BLM managed lands in the UCRB, and yields were approximately 30 tons/mi^2 for each of these land use/management categories.

The percentages of SPARROW model-predicted loads from natural and agricultural sources at selected locations in three divisions of the UCRB were compared with estimates from 1957 and 1991. In general, the 1991 and 2010 models attributed a smaller percentage of the dissolved-solids load from agricultural sources in the Grand Division above the Gunnison River, Colorado, as compared to the 1957 estimates. Shares of dissolved-solids loads from agricultural sources in the Green Division of the UCRB were generally similar across the three years, with the exception of the Yampa River near Maybell, CO, where the percent of agricultural loads increased from 14 percent in 1957 to 33 percent in 1991 and 37 percent in 2010, and the White River near Watson, UT, where the fraction of loads from agricultural lands decreased from 50 percent in 1957 to 15 and 18 percent in 1991 and 2010, respectively. The share of dissolved-solids loads from agricultural sources at the San Juan River near Bluff, UT, increased from 29 percent in 1957 to 49 percent in 1991, and then decreased to 32 percent in 2010. The estimated shares of agricultural loads at the basin scale were 40 percent in 1957, 43 percent in 1991, and 32 percent in 2010. Patterns of change in the fraction of loads from irrigated agricultural lands are likely driven, in part, by changes in the amount of irrigated lands over time. Notably, results indicate that the conversion of flood irrigated lands to sprinkler irrigated lands is a likely process contributing to the temporal decrease in dissolved-solids loads from irrigated lands.

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