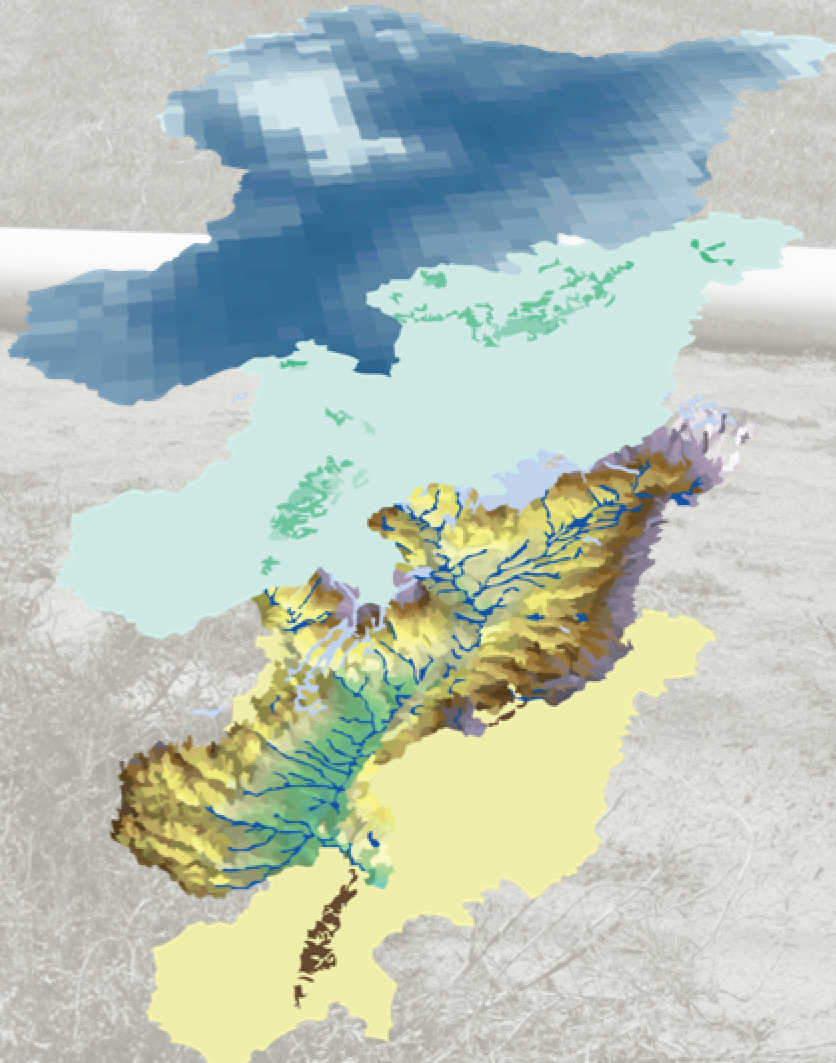
Prepared in cooperation with the Bureau of Reclamation and the Colorado River Water Conservation District

Ranking Contributing Areas of Salt and Selenium in the Lower Gunnison River Basin, Colorado, Using Multiple Linear Regression Models



Scientific Investigations Report 2013–5075

U.S. Department of the Interior
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COVER. Inset left: Measuring the streamflow of a tributary in the Lower Gunnison River Basin, Colo. (Photograph taken by Laetitia Linard); Inset right: Example geospatial data used in the report (Photograph taken by Joshua Linard, U.S. Geological Survey); Background: a field typical of those found in the Lower Gunnison River Basin, Colo. (Photograph taken by Judith Thomas, U.S. Geological Survey).

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SALLY JEWELL, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2013

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton, long (2,240 lb)	1.016	megagram (Mg)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

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).

Elevation, as used in this report, refers to distance above the vertical datum.

Water year, as used in this report, refers to the period October 1–September 30 and is designated by the year in which it ends.

Ranking Contributing Areas of Salt and Selenium in the Lower Gunnison River Basin, Colorado, Using Multiple Linear Regression Models

By Joshua I. Linard

Abstract

Mitigating the effects of salt and selenium on water quality in the Grand Valley and lower Gunnison River Basin in western Colorado is a major concern for land managers. Previous modeling indicated means to improve the models by including more detailed geospatial data and a more rigorous method for developing the models. After evaluating all possible combinations of geospatial variables, four multiple linear regression (MLR) models resulted that could estimate irrigation-season salt yield, nonirrigation-season salt yield, irrigation-season selenium yield, and nonirrigation-season selenium yield. The adjusted r-squared and the residual standard error (in units of log-transformed yield) of the models were, respectively, 0.87 and 2.03 for the irrigation-season salt model, 0.90 and 1.25 for the nonirrigation-season salt model, 0.85 and 2.94 for the irrigation-season selenium model, and 0.93 and 1.75 for the nonirrigation-season selenium model. The four models were used to estimate yields and loads from contributing areas corresponding to 12-digit hydrologic unit codes (HUCs) in the lower Gunnison River Basin study area. Each of the 175 contributing areas was ranked according to its estimated mean seasonal yield of salt and selenium.

Introduction

Mitigating the effects of salt and selenium on water quality in the Grand Valley and lower Gunnison River Basin in western Colorado is a major concern for land managers. Salt and selenium are known to limit municipal uses of water, reduce agricultural productivity, and, in the case of selenium, lead to mortality, abnormalities, and reproductive failure in waterfowl and fish (Leib and others, 2012; Tuttle and Grauch, 2009; Presser and Luoma, 2006; Butler and others, 1996). High levels of salt and selenium were conceptually associated with irrigated land overlying marine shale (Leib and others, 2012; Tuttle and Grauch, 2009; Butler and others, 1996; Butler and others, 1991; Duffy, 1984; Evangelou and others, 1984), which is common in the Grand Valley and the lower Gunnison River Basin.

Land-management practices aimed at limiting the amount of salt and selenium that reaches the stream have focused on improving the methods by which irrigation water is conveyed and distributed. Federal land managers implement these practices, termed control projects, in the Grand Valley and lower Gunnison River Basin in accordance with the Colorado River Basin Salinity Control Act in 1974, which directs Federal land managers to enhance and protect the quality of water available in the Colorado River. The Bureau of Reclamation (USBR) manages improvements in conveyance through canals, ditches, and pipes. Distribution is improved by the U.S. Department of Agriculture Natural Resource Conservation Service (NRCS) through enhancing the methods by which irrigation water is applied to fields.

Because of the spatial variability of irrigation and marine shale throughout the Grand Valley and lower Gunnison River Basin, different areas produce different amounts of salt and selenium. The implication of the effect of irrigation and geology on the spatial distribution of in-stream salt load (in units of weight per time) was explored by Kenney and others (2009) through their application of the SPAtially Referenced Regressions On Watershed attributes (SPARROW) model (Schwarz and others, 2006). Geology, land use (including irrigated land), climate, and topography were used in a model designed to estimate salt load within the entire Upper Colorado River Basin, within which the Grand Valley and lower Gunnison River Basin are located, for the water year 1991. (Water year, as used in this report, refers to the period October 1–September 30 and is designated by the year in which it ends.) In their final report, they indicated the lack of higher resolution data that accounted for irrigation-water diversions led to an under-estimation of salt load downstream from the confluence between the Colorado and Gunnison Rivers. The in-stream salt load was estimated just upstream from the confluence for the Gunnison River near Grand Junction, Colorado (streamgage 09152500) and was 252,000 ton/yr. The measured load was 1,080,000 ton/yr and the error in estimation propagated errors downstream between estimated and measured load.

Although the data needed to describe the geospatial distribution of irrigation-water diversions were unavailable for the entire Upper Colorado River Basin, the data were available for the Grand Valley and lower Gunnison River Basin. In a study related to the work of Kenney and others (2009), Leib and others (2012) examined the statistical relations between a variety of geospatial information and loads of salt and selenium measured in streams of the Grand Valley and lower Gunnison River Basin from water year 1989 to water year 2004. The geospatial information represented basin attributes related to topography, climate, geology, irrigated land, irrigation-water applied, and irrigation channels. As part of that work, multiple linear regression (MLR) statistical models were developed to test the ability of geospatial variables to estimate in-stream loads of salt and selenium at locations co-located with water-quality samples. Four models were developed that estimated loads of salt and selenium for the irrigation (April–October) and nonirrigation (November–March) seasons. The annual mean salt load estimated for the Gunnison River near Grand Junction (streamgage 09152500) was 1,047,000 ton/yr, compared to a measured load of 1,011,000 ton/yr. Although these estimates were similar to the measured values, the collinearity of the explanatory variables and the weight of subbasin area as a predictor resulted in a search for more robust methods to estimate loads of salt and selenium.

Methods for improving the MLR models were identified following their relative success at estimating loads of salt and selenium. Improving the input data sets and refining the statistical methods used to develop models were identified as a means of improving estimates of salt and selenium production. With inherent uncertainty in any simulated estimate in mind, Leib and others (2012) purported that the models may best be used as tools to rank different areas according to their estimated production of salt and selenium. This information is essential to land managers trying to target areas where control projects might best limit the production of salt and selenium. Therefore, the U.S. Geological Survey (USGS), in cooperation with the USBR and the Colorado River Water Conservation District, conducted a study to improve the MLR models developed for the Grand Valley and lower Gunnison River Basin and to rank the estimated production of salt and selenium of 175 contributing areas within the study area.

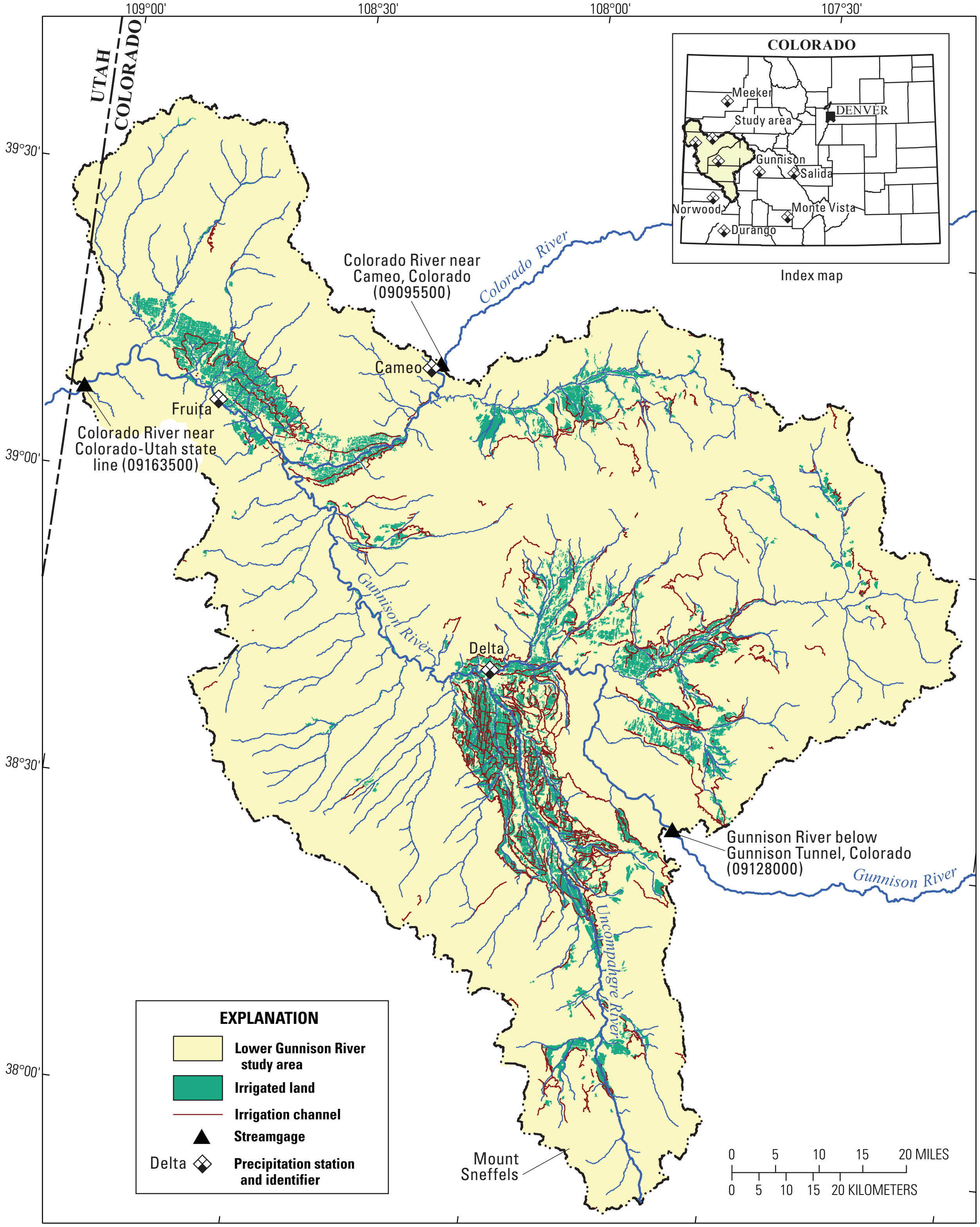
Purpose and Scope

This report documents the methods used to improve and refine the MLR models developed by Leib and others (2012), hereinafter referred to as the previous study, to estimate seasonal in-stream salt and selenium yields and rank 175 contributing areas in terms of the estimated salt and selenium production. Inclusive to this report is a detailed description of the revised methods used to select, process, and relate water-quality and geospatial data. Geospatial data and stream water-quality data were used to develop MLR models to predict seasonal in-stream salt and selenium yields. The models were then applied to contributing areas defined by 12-digit Hydrologic Unit Codes (HUCs). The estimates from the models were subsequently ranked to identify areas in the Grand Valley and lower Gunnison River Basin more likely to produce more salt and selenium than other areas.

Description of Study Area

The Grand Valley and lower Gunnison River Basin study area, herein referred to as the lower Gunnison River Basin study area, consists of the Gunnison River Basin below Gunnison Tunnel (streamgage 09128000) and the area draining to the Colorado River from below the streamgage near Cameo, Colo. (streamgage 09095500), to the Utah-Colorado state line (streamgage 09163500) (fig. 1). The study area contains 5,897 mi^2, of which 3,963 mi^2 drain directly to the lower Gunnison River. Elevation ranges from 14,153 ft at the summit of Mt. Sneffels to 4,333 ft at the Utah-Colorado state line. Areas contributing to water quality are, in this report, defined by the topography and are represented as subbasins (the total drainage area upstream from a location on a stream) and by HUC contributing areas designated in the Watershed Boundary Dataset (U.S. Geological Survey, 2008). In contrast to subbasins, HUC contributing areas are defined from point to point along a stream channel, and only the most upstream HUC contributing areas are composed of the total upstream drainage area. Subbasins in the lower Gunnison River Basin study area ranged in size from 0.78 to 5,897 mi^2, and HUC contributing areas ranged from 5 to 136 mi^2.

In addition to physical characteristics of the topography, the characteristics of climate, land use, geology, and soils were assumed to influence water quality in the lower Gunnison River Basin study area. Considered to have an arid climate, the lower Gunnison River Basin study area averaged 7.2 in. of rain per year from 1971 to 2000 (determined by methods described in Daly and others, 1994). A dense network of irrigation canals and ditches crossing many streams and topographic boundaries was constructed to provide water to facilitate the conversion of natural vegetation to agriculture (fig. 1). The Colorado River is the source of irrigation water in the Grand Valley and reservoirs are the initial source of water in the lower Gunnison River Basin, although water flows into and out of the irrigation network at many points within the network. The converted agricultural land is common in near-stream areas and occupies 7.3 percent of the study area (fig. 1; TechniGraphicS, Inc., 2004). The amount of irrigation water applied can vary widely (0–60 in.) during the growing season (April–October) within a subbasin depending on the irrigation method. The Mancos Shale is a Cretaceous marine shale occupying 1,090 mi^2 or 18.5 percent of the study area, and weathered Mancos Shale residuum is the dominant soil in near-stream areas and agricultural fields (fig. 2).



Base modified from U.S. Geological Survey digital 2012, 2,000,000
Albers Equal-Area Conic projection
Standard parallels 29°30′ and 45°30′, central meridian -96°
Latitude of origin 23°
North American Datum of 1983 (NAD83)

Figure 1. Map showing the lower Gunnison River Basin study area and the irrigated land and irrigation network, Colorado.

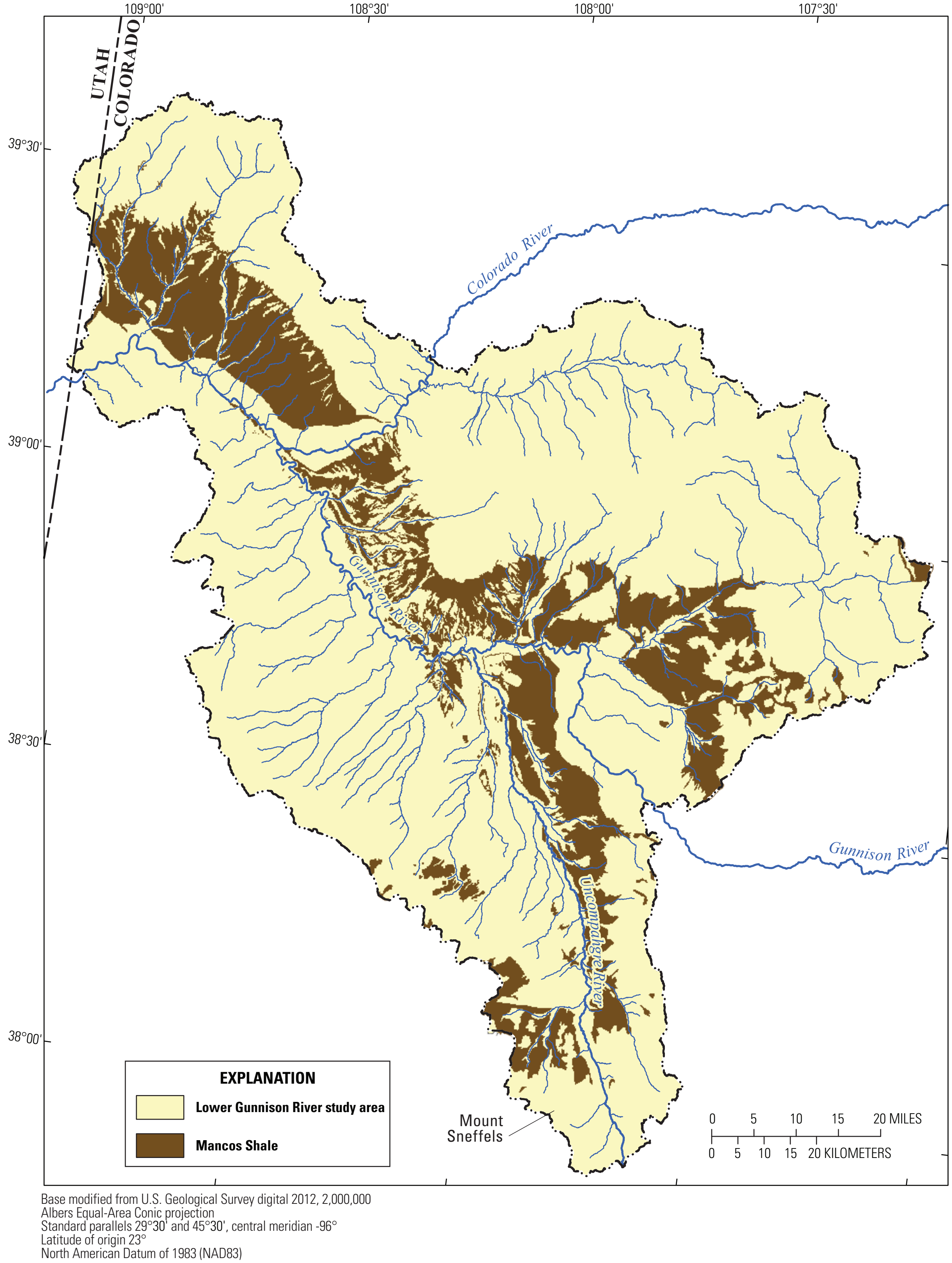


Figure 2. Map showing Mancos Shale in the lower Gunnison River Basin study area, Colorado.

Types of Information Used

The information used in this study included the data used in the previous study (Leib and others, 2012), updated versions of some previously used geospatial data, and some new geospatial data. The raw water-quality data remained consistent, although, as described below, its use in model development was changed. Detailed descriptions of the geospatial data used previously are presented in Leib and others (2012), and explicit variables analyzed in this study are presented below. Updated geospatial data included higher resolution elevation and precipitation data. A digital elevation model (DEM) of 10-m resolution, instead of the 30-m resolution data used previously, was incorporated. The new precipitation data were of 800-m resolution, compared to the previous 4,000-m resolution data, and were representative of precipitation during the years 1971–2000 rather than 1961–1990 as was used previously. Geospatial data representing irrigation efficiency, frost-free days, and effective precipitation, which were used to estimate the amount of irrigation water applied, were also updated. These geospatial data and the geospatial data used in the previous study to estimate the amount of irrigation water applied were also incorporated into the new model development to examine if the changes in how the geospatial data were represented affected their relation to salt and selenium. Additional new geospatial data that were incorporated into the analysis consisted of coarse- and fine-resolution soils data.

Water-Quality Data

The number of sites (231) and the period of record (water years 1989–2004) considered in the current study were identical to that of the previous study. Sites were removed from the model-development data on the basis of the ability to define a topographic boundary constrained by the study area and on the number of samples collected at a site. Water-quality data were divided into two seasons: an irrigation season (April–October) and a nonirrigation season (November–March). A minimum selection criterion of five samples in a season was used to select sites from which models would be developed. This number of samples was subjectively chosen with the goal of ensuring that a large statistical sample (greater than 30 sites) of the population was used to develop the seasonal models (Helsel and Hirsch, 1992). To establish the relations between geospatial data and salt yields measured during the irrigation season, 46 sample sites were used, and for the nonirrigation season, 37 sites were used. Selenium yields during the irrigation season were compared to geospatial data at 51 sample sites, and for the nonirrigation season, 48 sample sites were used (table 1). The mean seasonal salt and selenium water-quality data measured at each site were used to represent each sample site.

The major difference in the use of water-quality data between the previous and current study was the conversion from loads (units of weight per time) to yields (units of weight per area per time). A drawback to using loads was that subbasins with large areas would naturally produce large loads simply because of the area available to contribute salt and selenium. Salt and selenium are naturally produced as runoff moves through surface and subsurface media prior to entering the stream. Following the conceptual understanding that irrigated areas underlain by marine shale are principal sources of salt and selenium, a small area with those attributes could produce the same load as a large area without irrigation or marine shale. Faced with such a situation, land managers using loads as a means of determining where to implement control projects would have to rely on alternative methods to make their decisions.

Table 1. Summary of water-quality data used to develop multiple linear regression models for the lower Gunnison River Basin, Colorado.

[--, not applicable]

Model	Number of water-quality sampling sites with data	Number of water-quality sampling sites used in model development[1]	Minimum yield (weight[2] per year per acre)[3]	Maximum yield (weight[2] per year per acre)[3]
Salt, irrigation season	99	46	1.32E-04	2.28E-02
Salt, nonirrigation season	156	37	9.04E-05	7.00E-03
Selenium, irrigation season	99	51	1.74E-06	7.68E-04
Selenium, nonirrigation season	163	48	1.05E-07	4.88E-04
Total number of sites	231	58	--	--

[1]Includes sites with more than five samples and had defined boundaries not complicated buy a irrigation network.

[2]Weight is in units of tons for salt models and pounds for selenium models.

[3]Values are based on data for water-quality sampling sites used in model development.

From a modeling perspective, changing from loads to yields helped to ensure that the explanatory variables used in the models were not confirming that large areas produce large loads. The previous study indicated that of the geospatial variables that were significantly related to in-stream salt and selenium, almost all of them were in units of area. Converting the water-quality data to units of yield made the response variable independent of the influence of subbasin size.

The range of seasonal salt and selenium yield data used to develop the models also limited the ability of the model to estimate yields. It was not expected that the models would accurately estimate yields for HUC contributing areas whose explanatory variables resulted in yield estimates exceeding the limits of the original data. The minimum salt yields were 0.0001 (ton/acre)/d for the irrigation season and 0.0003 (ton/acre)/d for the nonirrigation season. The maximum salt yields were 0.03 (ton/acre)/d for the irrigation season and 0.008 (ton/acre)/d for the nonirrigation season. The minimum selenium yields were $2.3x10^{-6}$ (lb/acre)/d for the irrigation season and $1.8x10^{-6}$ (lb/acre)/d for the nonirrigation season. The maximum selenium yields were 0.0007 (lb/acre)/d for the irrigation season and 0.0005 (lb/acre)/d for the nonirrigation season.

Geospatial Data

The process of quantifying the relations between geospatial data and salt and selenium data began with the delineation of subbasin boundaries as defined by elevation data. With the aid of a geographic information system (GIS), a DEM from the USGS National Elevation Dataset (U.S. Geological Survey, 1999a) was used to define the geographic extent of 168 subbasins (fig. 3). The outlet of each subbasin was determined on the basis of water-quality sample locations provided by the National Water Information System (U.S. Geological Survey, 1998) database and stream networks defined by the USGS National Hydrography Dataset (U.S. Geological Survey, 1999b). The subbasins delineated for each sample site were used as a basis for extracting geospatial data from larger geospatial datasets of the entire study area.

Once the subbasins were defined, topographic characteristics of each subbasin were extracted. Geospatial variables associated with elevation were significantly related to salt and selenium in the previous study. The minimum, mean, and maximum elevations were extracted from the new DEM for each subbasin. Additionally, the mean aspect and the minimum, mean, and maximum slope were extracted to ascertain whether these geospatial attributes were related to yields of salt and selenium. The change in elevation within subbasins ranged from just over 400 to almost 10,000 ft for the entire lower Gunnison River Basin study area. The range of values for mean subbasin aspect (230 degrees to 120 degrees) confirmed that most subbasins drain to the north. Nearly all subbasins had minimum slopes of 0 percent; however, maximum slopes varied with some subbasins having slopes exceeding 3,000 percent.

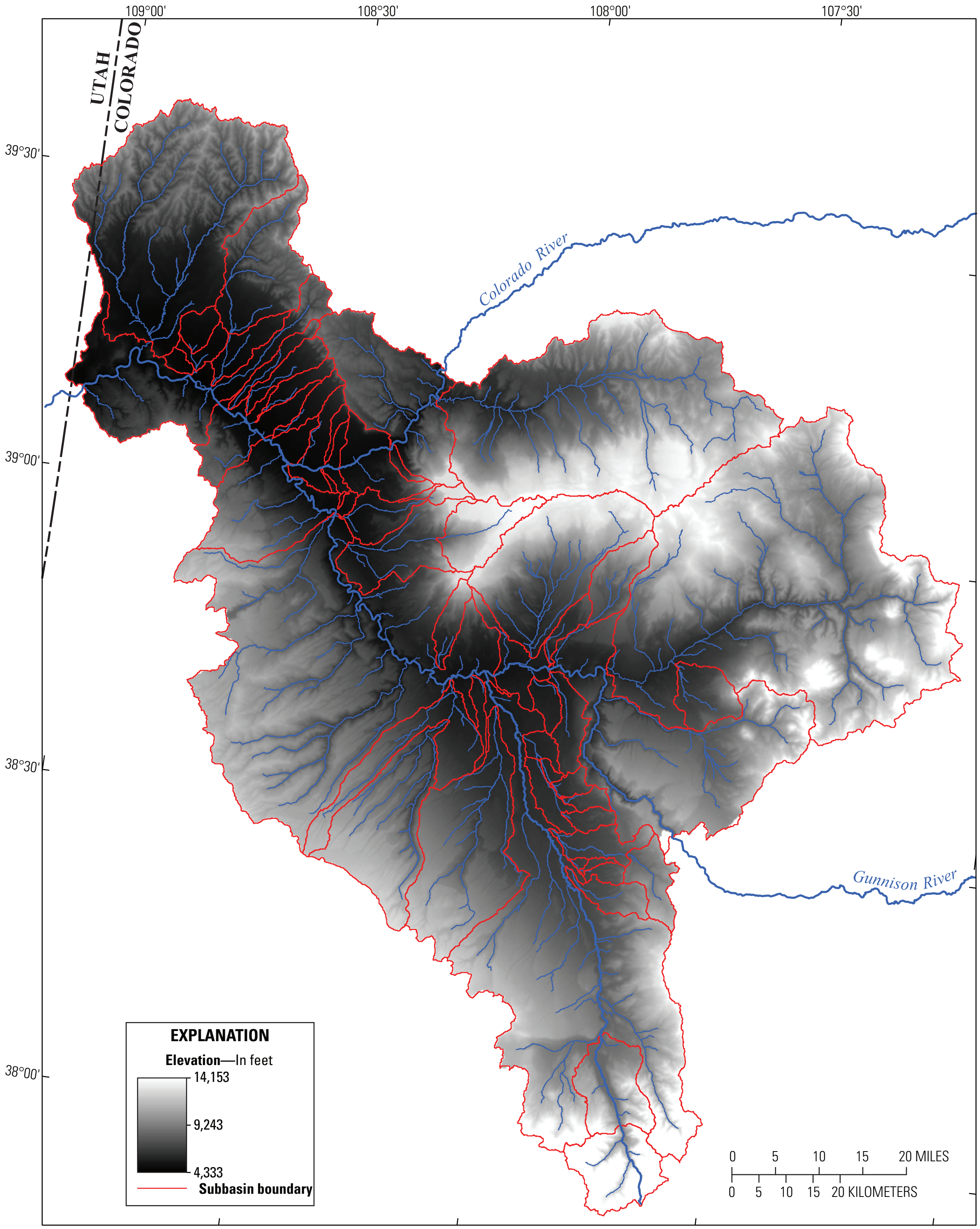
Precipitation

Precipitation in the lower Gunnison River Basin study area varies spatially and temporally. The subbasin precipitation data used in the previous study were available at 4-km resolution for the period from 1961 to 1990 and were significantly related to loads of salt and selenium (Daly and others, 2002). Precipitation-elevation Regressions on Independent Slopes Model (PRISM) data were available at 800-m resolution for the period from 1971 to 2000 (Daly and others, 2002). PRISM data consisting of mean monthly precipitation were used to develop maps of seasonal precipitation for the lower Gunnison River Basin study area. Subbasins at lower elevations received less precipitation than those at higher elevations, and within a subbasin, precipitation increased with elevation. The seasonal minimum, mean, and maximum precipitations were extracted from the new PRISM data for each subbasin. Minimum subbasin precipitation ranged from 4.9 to 13.7 in. during the irrigation season and from 2.2 to 10.2 in. during the nonirrigation season. Mean subbasin precipitation ranged from 5.4 to 18.9 in. during the irrigation season and from 2.7 to 18.4 in. during the nonirrigation season. Maximum subbasin precipitation ranged from 5.6 to 23.9 in. during the irrigation season and from 2.9 to 29.9 in. during the nonirrigation season.

Agricultural Land Use

Land use has been linked to surface-water quality in the lower Gunnison River Basin study area. Mayo (2008) documented the importance of land use, irrigation, and land-use conversion to in-stream salt. To ascertain the effect of land use and irrigation on salt and selenium transport, land uses within each subbasin were analyzed. Geospatial data from “Colorado’s decision support system—2000 irrigated parcels” (TechniGraphicS, Inc., 2004) were used to define the irrigated land within the lower Gunnison River Basin study area. Evaluation of this dataset provided estimates of irrigated land by subbasin, in units of percentage of subbasin area. This dataset used 11 agricultural land-use categories: alfalfa, corn grain, dry beans, grapes, grass pasture, orchard, small grains, sod farm, sunflowers, vegetables, and wheat. The irrigated lands within the study area typically are near streams and close to an irrigation network (fig. 1) and could occupy as much as 75 percent of the area of a subbasin. Land-use categories that occupied less than 0.01 percent of the lower Gunnison River Basin study area (grapes, sod farm, and sunflowers) were excluded from further analysis. The most common agricultural crop in the subbasins was alfalfa, although corn and pasture occupied a greater percentage of subbasin area in specific subbasins.

Complicating the effects of crop type on salt and selenium transport is the application of irrigation water, which changes physical and chemical hydrogeologic processes.



Base modified from U.S. Geological Survey digital 2012, 2,000,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -96°
Latitude of origin 23°
North American Datum of 1983 (NAD83)

Figure 3. Map showing subbasins corresponding to water-quality data used to develop the multiple linear regression models of the lower Gunnison River Basin, Colorado. Subbasins extend from the subbasin outlet to the topographic divide.

Irrigation methods differ spatially, which can result in spatially differing amounts of water percolating through the soil. The Colorado Decision Support System irrigated-lands dataset (TechniGraphicS, Inc., 2004) specifies crop type and irrigation method for each irrigated-lands area. Data that quantify the amounts of irrigation water applied are not directly available; however, using the available geospatial data and empirical relations, the amounts of water applied can be estimated. Identical to the previous study, the water applied to each crop was estimated using the following equation:

$$I_i = [(W_i \times G_i) - P]/M, \qquad (1)$$

where

- I_i is the amount of irrigation water applied to a crop *i* during the growing season, in inches;
- W is the mean consumptive water use for crop *i*, in inches of water per growth-season day;
- G is the mean growth season, in days, and varied by crop;
- P is the mean effective precipitation, in inches of water per growth season; and
- M is the decimal percent efficiency of the irrigation method.

The values of consumptive water use, *W*, and mean growth season, *G*, for each crop were obtained from the U.S. Department of Agriculture Soil Conservation Service Colorado irrigation guide (U.S. Department of Agriculture Soil Conservation Service, 1988). The mean effective precipitation (the precipitation available to plants for consumptive use), *P*, was calculated for nine towns in Colorado (Cortez, Delta, Durango, Fruita, Gunnison, Meeker, Monte Vista, Norwood, and Salida) using data provided in Broner and Schneekloth (2003) and in U.S. Department of Agriculture Soil Conservation Service (1988) (fig. 1). Leib and others (2012) described a simple linear regression to relate mean effective precipitation (in inches per growth season) to mean precipitation (in inches per growth season) for the nine towns. On the basis of these relations, mean effective precipitation for any site in the study area can be estimated from mean precipitation using the following equation:

$$P = 0.3266P_R + 1.24, \qquad (2)$$

where

- P is the mean effective precipitation, in inches of water per growth season, and
- P_R is the mean precipitation, in inches of water per growth season.

The mean percentage efficiency of the irrigation method in equation 1, *M*, was determined by Waskom (1994) for five irrigation methods—flood (25 percent), furrow (40 percent), gated pipe (65 percent), sprinkler (75 percent), and drip (90 percent). The spatial distribution of irrigation methods was obtained using attribute data contained in the "Colorado's decision support system—2000 irrigated parcels" (TechniGraphicS, Inc., 2004) dataset. These data were updated using geospatial information from the U.S. Department of Agriculture NRCS Conservation Innovation Grants (CIG) program that accounted for changes in irrigation method that occurred after the creation of the irrigated-land geospatial dataset (Colorado River District, 2010).

Equations 1 and 2 provide a means for estimating the amount of irrigation water applied to areas with a specific land use and irrigation type. The amount of water applied ranged from 40.0 to 83.8 in., depending on the method of irrigation-water application and the land use. Summing these values for areas within a given subbasin provided data that were related with yields measured at subbasin outlets, as demonstrated in the following equation:

$$I_T = \sum_{i \to 1}^{n} (A_i I_i), \qquad (3)$$

where

- I_T is the total irrigation water applied in the subbasin for crops 1 to *n,* in acre-feet;
- A_i is the area of crop *i,* in acres; and
- I_i, is the amount of irrigation water applied to crop *i,* in feet.

The methods described above produced geospatial data representative of effective precipitation, consumptive use, irrigation efficiency, and irrigation water applied that occurred over agricultural land in the lower Gunnison River Basin study area during the irrigation season. The previous study produced the same types of geospatial data, although different methods were used to create them. Geospatial data created in this study and in the previous study each represented different possible spatial distributions, and thus, the geospatial variables extracted from both types of geospatial data were related with salt and selenium yields. Effective precipitation in the previous study ranged from 3.0 to 5.2 in. and in this study ranged from 1.6 to 4.3 in. Consumptive use in the previous study ranged from 19.4 to 35.8 in. and in this study ranged from 16.9 to 32.0 in. The range of values for irrigation efficiency for both studies was the same; however, the geospatial data representing irrigation efficiency was adjusted on the basis of CIG data as mentioned above. The irrigation water applied in the previous study ranged from 43.3 to 89.6 in. and in this study ranged from 40.0 to 83.8 in.

Geology

The geologic age, lithology, and chemistry in each subbasin can affect the physical availability (abundance and ease of mobilization) of salt and selenium within the subbasin. To define the spatial distribution and abundance of potential salt and selenium sources, digital geologic maps of Utah (Hintze and others, 2000) and the Gunnison, Grand Mesa, and Uncompahgre National Forests (Day and others, 1999) were combined into a single dataset. Known relations and anecdotal relations described by Butler and others (1996) concerning geochemical and physical properties were used to categorize geologic units into 3 groups and 34 subgroups, identical to those used in the previous study.

Soils

The soils in the lower Gunnison River Basin study area vary spatially, and because they were formed from predominantly Cretaceous marine shale, they are possible sources of salt and selenium. In this study, the spatial variability of soil was represented using the 1:250,000-scale State Soil Geographic (STATSGO) database (U.S. Department of Agriculture, 1994) and the 1:24,000-scale Soil Survey Geographic (SSURGO) database (U.S. Department of Agriculture, 1995). Each database contained geospatial data associated with numerous soil types. Each subbasin has multiple soil types, and subbasin statistics (minimum, mean, and maximum) were calculated from the geospatial variable data associated with each soil type. The geospatial variables that were evaluated were the available water content, percent clay, percent organic matter, electrical conductivity, amount of sodium relative to calcium and magnesium in the water extract from saturated soil paste, frost-free days, depth of the restrictive layer, depth to the bottom of the soil, erodibility factor quantifying the susceptibility of soil particles to detachment and movement by water, hydraulic conductivity, percent sand, and the drainage class as classified in the SSURGO database.

The values for each geospatial variable of a soil type varied spatially and with depth. Spatially, variations would be expected in the SSURGO database, but some variation was related to the different soil surveys compiled to form the database (fig. 4). Soils classified as the same type were commonly assigned different variable values depending on where and when the soil surveys were conducted. Additionally, several soil types delineated in the SSURGO database lacked attribute data and occupied 7.4 percent of the lower Gunnison River Basin study area. The data for these areas were supplemented with STATSGO data. Because of the variability in soil depth and number of soil layers for each soil type, the information from the various depths and layers were combined into single values for the geospatial variables for each soil type. For the STATSGO data, this involved calculating a mean value from geospatial variable values for each soil layer that were weighted by layer thickness. High, medium, and low values were available in the databases for geospatial variables representing available water content, hydraulic conductivity, and depth of the restrictive layer. Mean values, weighted by the thickness of the soil layer, were calculated for each of these types of geospatial variables.

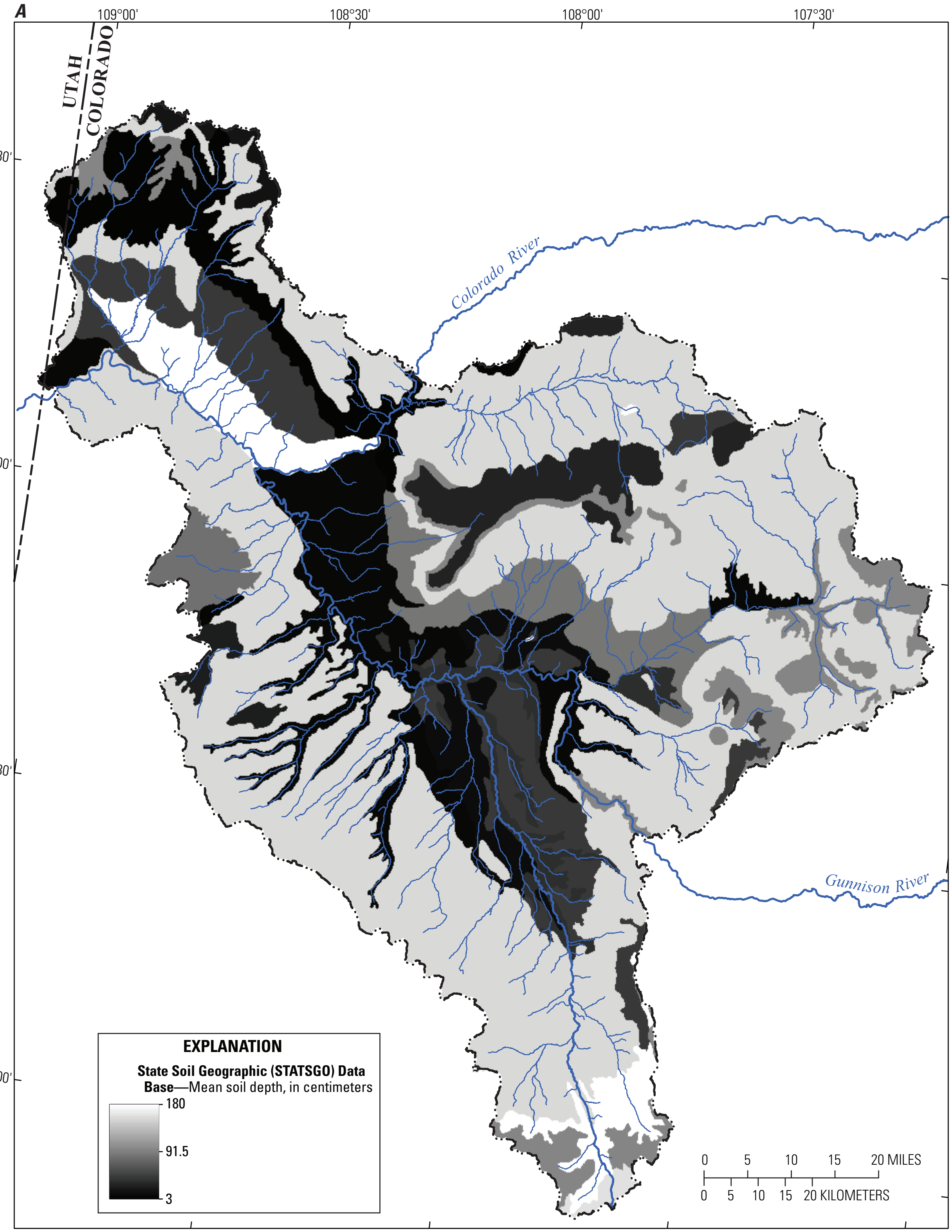
Statistical Analysis Methods

Extraction of geospatial data for each subbasin produced geospatial variables that could be related to water-quality data at corresponding sample sites. The values extracted for each geospatial variable ranged widely between subbasins. The mean available water content in the data extracted from the STATSGO database, for example, ranged from 0.06 to 0.17, whereas the area of subbasins ranged from about 500 to 3,800,000 acres. To minimize the disparity in geospatial variables, values were standardized into units of standard deviation by subtracting the values from their mean and dividing by their standard deviation. These standardized values, for each geospatial variable, were then regressed against the natural logarithm of mean seasonal yields of salt and selenium.

By assessing all possible combinations of the geospatial variables using standard evaluation statistics, MLR models were developed. Relations were calculated using the weighted least-squares method (Helsel and Hirsch, 1992). Weights were based on the number of water-quality samples available for each sample site for each season. Water-quality data from 58 samples sites were regressed against 110 different geospatial variables. The optimal combination of explanatory variables was found using the standard error, adjusted r-squared, Cp, and Press statistics. Ideally, an optimal model is found when the adjusted r-squared is greatest and the standard error, Cp, and Press statistics are minimized (Helsel and Hirsch, 1992). Unfortunately, the use of these methods to identify optimal models was not straightforward because the maximum or minimum of the evaluation statistics rarely corresponded to the same model. To supplement the evaluation statistics, statistical significance (p-value) was calculated for each explanatory variable and plots of residuals were analyzed to subjectively assess the occurrence of desirable characteristics such as homoscedasticity (similarity of variance) and normal distribution.

The leverage and influence of each sample site was determined for each of the models to further evaluate the occurrence of potential outliers. Combinations of explanatory variables that result in either very low or very high values in the x direction have high leverage and can affect the slope of the regression (Ott and Longnecker, 2001). A high leverage point that corresponds to an outlier in the y direction is a point that has high influence (Ott and Longnecker, 2001). Leverage was calculated using the leverage statistic h_i, and influence was calculated using the $DFFITS_i$ statistic as defined by Helsel and Hirsch (1992). Different combinations of explanatory variables changed the leverage and influence each sample site had on a regression equation. Criterion used to assess whether sample sites had high leverage or high influence were those defined by Helsel and Hirsch (1992). Sample sites exhibiting high leverage and influence were individually evaluated on the ability of the water-quality data to represent the upstream drainage area. The number of samples at each sample site and the subjective understanding of how the irrigation network influenced the measured water-quality data were used to exclude sites.

To ensure that explanatory variables used in the models were statistically independent of each other, the collinearity between variables was evaluated. Severe collinearity can result



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Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -96°
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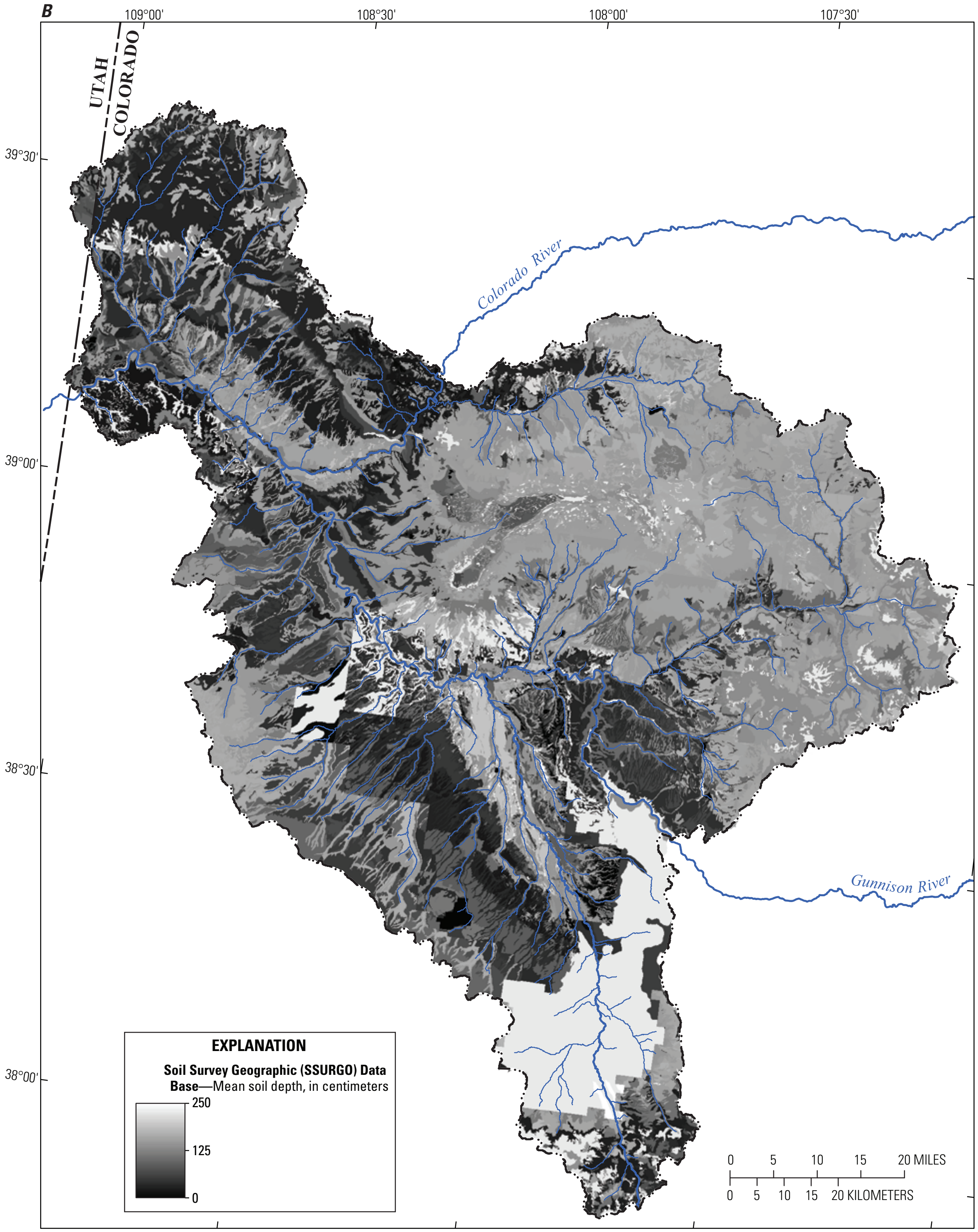
Figure 4. Maps showing mean soil depth, in centimeters, based on *A*, State Soil Geographic (STATSGO) soils database and *B*, Soil Survey Geographic (SSURGO) soil database spatial resolution using mean soil depth, in centimeters, lower Gunnison River Basin, Colo.



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in very large standard errors (Ott and Longnecker, 2001) that would be undesirable. The collinearity of explanatory variables was determined using the variance inflation factor (*VIF*) statistic (Helsel and Hirsch, 1992). Explanatory variables were considered collinear when the *VIF* statistics were greater than 10 (Helsel and Hirsch, 1992). The explanatory variables in the final models were chosen such that instances of collinearity did not occur.

Several geospatial variables represented the same geospatial characteristics although they differed in terms of either the resolution used to describe the geospatial variable, the time when the geospatial dataset was created, or a combination thereof. An example of geospatial variables in this condition are irrigation season, high-resolution maximum-precipitation data, and coarse-resolution mean-precipitation data. Incorporating geospatial variables that were not collinear but represented the same geospatial characteristic was undesirable, and such redundant geospatial variables were not allowed in the MLR models.

After developing MLR models able to estimate yields of salt and selenium from subbasins, the models were applied to contributing areas defined by HUCs (Seaber and others, 1987). Explanatory variables were extracted for each contributing area and used in the MLR models to estimate seasonal yields of salt and selenium. It was assumed that the mean and standard deviation calculated for each explanatory variable of the model-development data would correspond to those of the HUC contributing areas. Each HUC contributing area was ranked using the estimated mean seasonal yields. HUC contributing areas with the greatest yields received the smallest rank, and the HUC contributing areas with the lower yields received higher ranks. As Marshall and Spiegelhalter (1998) indicated, ranks based on samples of a population rather than the entire population can lead to an inaccurate ranking. To assist in understanding how the yields of different contributing areas compare to each other, confidence intervals determined for each estimate of HUC contributing area yield were calculated using methods defined by Helsel and Hirsch (1992).

Multiple Linear Regression Models

After evaluating all possible combinations of geospatial variables, four MLR models resulted that best estimated irrigation-season salt yield, (S_I), nonirrigation-season salt yield, (S_{NI}), irrigation-season selenium yield, (Se_I), and nonirrigation-season selenium yield (Se_{NI}). The adjusted r-squared and the residual standard error (in units of log-transformed yield) of the models were, respectively, 0.87 and 2.03 for the irrigation-season salt model, 0.90 and 1.25 for the nonirrigation-season salt model, 0.85 and 2.94 for the irrigation-season selenium model, and 0.93 and 1.75 for the nonirrigation-season selenium model (fig. 5). Each model had 8 explanatory variables, except the model for the nonirrigation-season selenium yield, which had 11 explanatory variables. Several of the explanatory variables occurred in each of the four models, and a total of 18 different explanatory variables were used (table 2).

Salt Irrigation-Season Model

The eight explanatory variables used to estimate salt yield during the irrigation season (S_I) were related to geology, soil, physical characteristics, canals, the irrigation network, and irrigation application (table 2). The equation takes the form:

$$\ln(S_I) = -6.16 - 0.54z_{Grp3.3} + 0.43z_{IM} - 0.37z_{clay2} + 0.41z_{hzdepb2} - 2.28z_{ksat2} + 0.17z_{aspect} - 0.33z_{C.type1} + 1.18z_{ETrev} \quad (4)$$

where

z is the standardized value of the explanatory variable.

Geology in the form of Quaternary alluvial deposits near streams (*Grp3.3*) and irrigated Mancos Shale (*IM*) are sources of salt, and it was expected these types of data would relate well to salt measured in streams. The mean percent clay (*clay2*) in the lower Gunnison Basin can relate to hydrologic and geochemical processes. Clay in soils can increase the water-holding capacity and decrease the saturated hydraulic conductivity. The clay in soils originating in the lower Gunnison River Basin study area tends to contain easily mobilized salt (Wright and Butler, 1993). A subbasin with a relatively high mean saturated hydraulic conductivity (*ksat2*) could transport more salt than a subbasin with a lower *ksat2* but may not have the contact time necessary to dissolve the salt. The mean aspect of a subbasin (*aspect*) affects the ability of the soil to retain moisture. North-facing slopes receive less solar radiation than south-facing slopes and are able to retain soil moisture longer as a result. Differences in soil moisture are also evident between west- and east-facing slopes; cooler temperatures on the east-facing slopes allow the underlying soils to retain soil moisture longer than the west-facing slopes. This increased residence time allows more salt to enter into solution than in soils underlying south-facing slopes. The area of a subbasin occupied by large canals (*C.type1*) can raise the level of local groundwater, which shortens the path that percolating water has to travel to reach groundwater. Subbasins with a greater area of canals have a higher potential for an increased level of groundwater than subbasins with fewer canals. Evapotranspiration from irrigated lands (*ETrev*) can concentrate salt in the soil (Brouwer and others, 1985). (*ETrev* is the sum of consumptive use for all crops in a subbasin.) The subbasins with more irrigated land are able to concentrate more salt in the soil than subbasins with less irrigated land.

Salt Nonirrigation-Season Model

The eight explanatory variables used to estimate salt yield during the nonirrigation season (S_{NI}) were related to geology, irrigated land, soils, physical characteristics, and the irrigation network (table 2). The equation takes the form:

$$\ln(S_{NI}) = -6.39 - 0.36z_{Grp3.3} - 0.35z_{IM} + 0.78z_{Irr.land} - 1.24z_{ffday2} + 0.61z_{sand2} - 0.59z_{elev} + 0.45z_{aspect} + 0.28z_{C.type1} \quad (5)$$

where

z is the standardized value of the explanatory variable.

Half the processes represented in the explanatory variables used in the salt irrigation-season model were retained in the salt nonirrigation-season model. The inclusion of the percent of a subbasin classified as irrigated land (*Irr.land*) into the S_{NI} model accounts for the different groundwater systems in irrigated and unirrigated areas. Irrigated land typically has a higher water-table elevation than unirrigated land and will flush more salt after the irrigation season ends and water-table elevations decrease. Similar to *ETrev*, frost-free days (*ffday2*) represents the number of days moisture is removed from the soil. Subbasins with a greater number of frost-free days have more time to evapoconcentrate salt than subbasins with fewer frost-free days. Mean percent sand in a subbasin (*sand2*) is associated with higher hydraulic conductivities than finer-textured soils, and subbasins with less sand typically will yield less salt than subbasins with more sand. The mean subbasin elevation (*elev*) potentially accounts for multiple factors affecting salt yield. Higher elevations tend to receive less irrigation and, conceptually, the depth to groundwater is considered to increase with elevation.

Selenium Irrigation-Season Model

The eight explanatory variables used to estimate selenium yield during the irrigation season (Se_I) were related to geology, precipitation, soils, physical characteristics, and irrigation application (table 2). The equation takes the form:

$$\ln(Se_I) = -10.00 - 0.74z_{Grp3.3} - 0.33z_{IM} - 1.15z_{PIhires} - 0.832_{Zhzdepb2} - 1.05z_{kwfact2} + 0.49z_{aspect} + 0.43z_{slope} + 1.25z_{ETrev} \quad (6)$$

where

z is the standardized value of the explanatory variable.

Five of the processes represented in the explanatory variables used in the salt models also corresponded to processes associated with selenium and were retained in the selenium irrigation-season model. The mean irrigation-season precipitation received by a subbasin (*PIhires*) had a negative relation to selenium yield. Other than the fact that *PIhires* is related to elevation in the lower Gunnison River Basin study area, it is unclear why the negative relation exists. The inclusion of the mean erodibility of subbasins (*kwfact2*) as an explanatory variable was supported by studies by Hedlund (1994) and Evangelou and others (1984) that indicated surface runoff laden with selenium in either dissolved or particulate forms can contribute to subbasin yield. The mean subbasin slope (*slope*) accounts for the amount of percolation and subsequent interaction with selenium source material. This interaction would cause subbasins with lower slopes to yield more salt and selenium than subbasins with higher slopes.

Selenium Nonirrigation-Season Model

The 11 explanatory variables used to estimate selenium yield during the nonirrigation season (Se_{NI}) were related to geology, irrigated land, soils, physical characteristics, and the irrigation network (table 2). The equation takes the form:

$$\ln(Se_{NI}) = -10.64 + 0.83z_{Grp1.10} + 0.63z_{Grp3.2} - 0.45z_{Grp3.3} - 0.74z_{IM} + 0.73z_{Irr.land} - 2.38z_{clay2} + 5.27z_{ksat2} + 1.56z_{resdepth2} + 0.45z_{kwfact2} + 0.45z_{aspect} + 0.92z_{C.type1} \quad (7)$$

where

z is the standardized value of the explanatory variable.

The inclusion of the percent of subbasin area occupied by Tertiary (Uinta, Green River, and Wasatch) and Cretaceous (Mesaverde and Mancos Shale) geologic formations (*Grp3.2*) into the S_{NI} model further indicates the importance of the different selenium sources. The mean depth to a restrictive layer in a subbasin (*resdepth2*) indicated subbasins with a shallower restrictive layer yielded more selenium than subbasins with deeper restrictive layers. A shallow restrictive-layer depth decreases the time required for percolating water to interact with unweathered geologic formations. Soils saturated above the restrictive layer would provide a quicker pathway to a stream through lateral throughflow rather than through a deeper groundwater path.

Rankings of Contributing Areas

The four seasonal salt and selenium models were used to estimate yields and loads from contributing areas corresponding to 12-digit HUCs in the lower Gunnison River Basin. Given the explanatory variables and their relations to salt and selenium, the HUCs along stream corridors were expected to yield more salt and selenium than HUCs draining headwater areas. Mean seasonal yields for the 175 HUC contributing areas are illustrated in figure 6, and summary statistics are

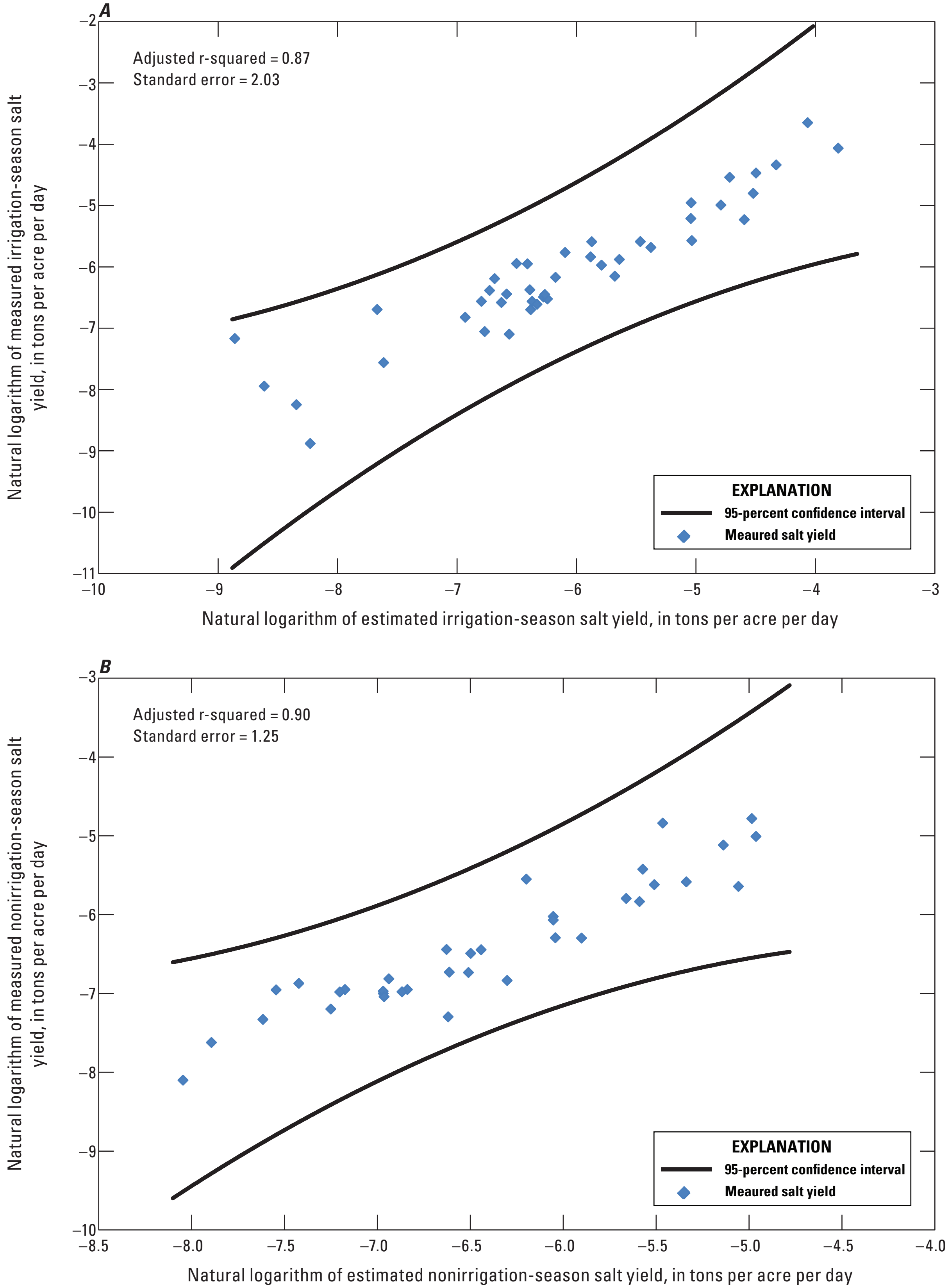
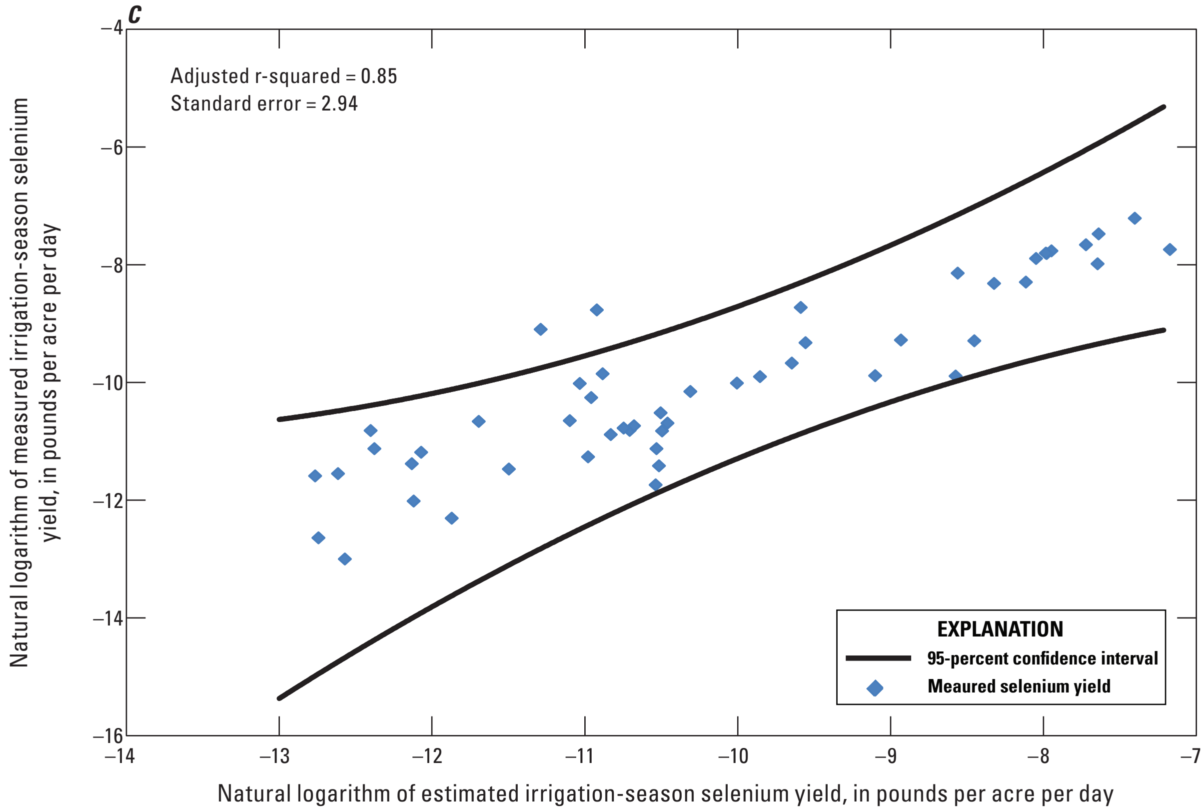


Figure 5. Graphs showing relation of mean measured yields to model-estimated yields for the lower Gunnison River Basin, Colorado. *A*, Irrigation-season salt yield. *B*, Nonirrigation-season salt yield. *C*, Irrigation-season selenium yield. *D*, Nonirrigation-season selenium yield.



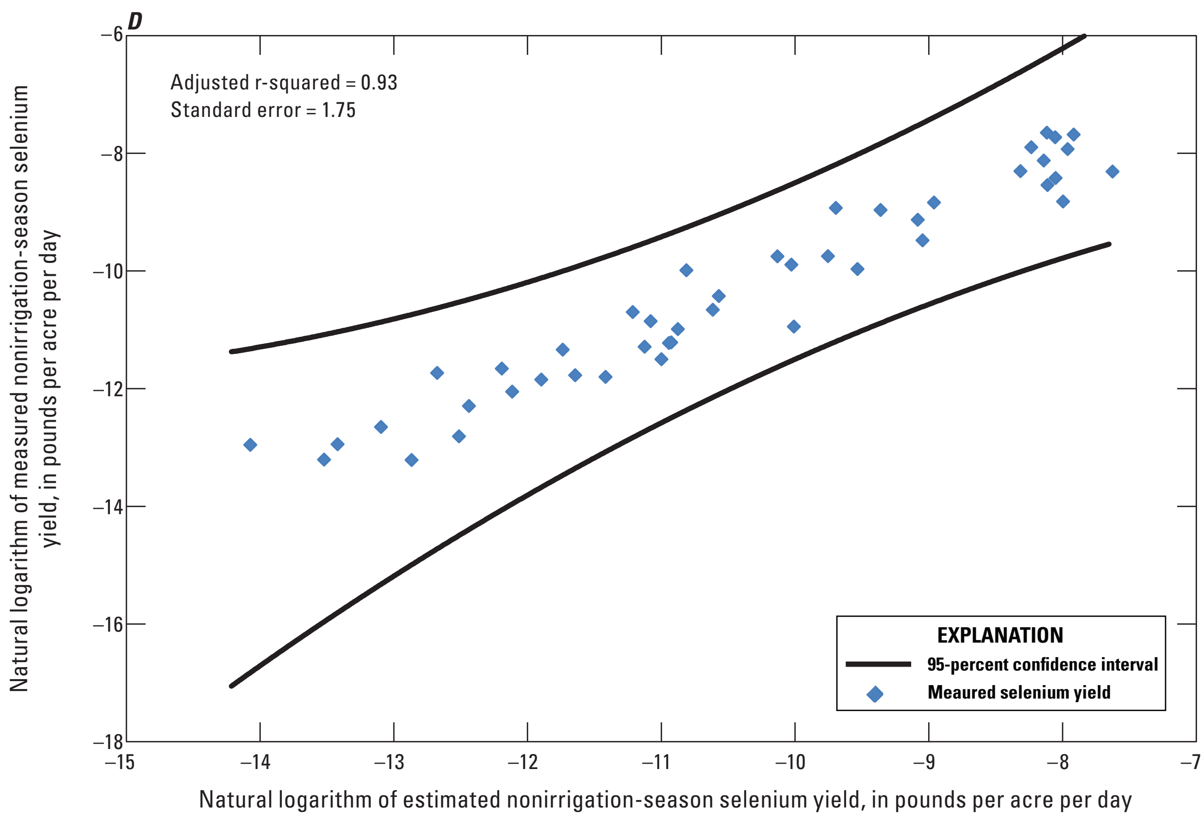


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Table 2. Multiple linear regression model explanatory variables and their associated statistics for the lower Gunnison River Basin, Colorado.

[P-values indicate explanatory variable significance (P less than 0.01 is significant); SI, irrigation-season salt model; SNI, nonirrigation-season salt model; SeI, irrigation-season selenium model; SeNI, nonirrigation-season selenium model; <, less than; SSURGO, Soil Survey Geographic database; ft^3/s, cubic foot per second; --, not applicable]

Explanatory variable	Variable description	P-value				Correlation coefficient			
		SI	SNI	SeI	SeNI	SI	SNI	SeI	SeNI
elev	Mean subbasin elevation	--	<0.0001	--	--	--	–0.72	--	--
aspect	Mean subbasin aspect	0.107	0.000	0.001	0.001	0.02	0.34	0.19	0.34
slope	Mean subbasin slope	--	--	0.013	--	--	--	–0.49	--
Grp1.10	Percent of basin occupied by Mancos Shale	--	--	--	0.002	--	--	--	0.79
Grp3.2	Percent of basin occupied by Uinta, Green River, Wasatch, Mesa Verde, and Mancos Geologic formations	--	--	--	0.000	--	--	--	0.53
Grp3.3	Percent of subbasin occupied by Quaternary alluvial deposits near streams	<0.0001	0.001	0.000	0.001	–0.32	–0.24	–0.30	–0.26
IM	Percent of basin occupied by irrigated Mancos	<0.0001	0.000	0.038	0.001	0.62	0.61	0.56	0.47
PIhires	High-resolution irrigation season mean precipitation	--	--	<0.0001	--	--	--	–0.73	--
clay2	SSURGO mean percent clay	0.061	--	--	<0.0001	0.01	--	--	–0.09
ffday2	SSURGO mean frost-free days	--	0.003	--	--	--	0.39	--	--
hzdepb2	SSURGO mean soil depth	0.073	--	0.010	--	–0.02	--	–0.06	--
kwfact2	SSURGO mean erodibility	--	--	0.067	<0.0001	--	--	0.37	0.50
ksat2	SSURGO mean saturated hydraulic conductivity	0.004	--	--	<0.0001	–0.29	--	--	–0.56
resdepth2	SSURGO mean depth to a restrictive layer	--	--	--	0.002	--	--	--	–0.04
sand2	SSURGO mean percent sand	--	0.071	--	--	--	–0.53	--	--
Irr_land	Percent of irrigated land in the subbasin	--	<0.0001	--	<0.0001	--	0.63	--	0.49
ETrev	Revised evapotranspiration from irrigated land	<0.0001	--	<0.0001	--	0.80	--	0.68	--
C.type1	Percent of small (1–100 ft^3/s) canals in the subbasin	0.004	0.002	--	<0.0001	0.44	0.52	--	0.53

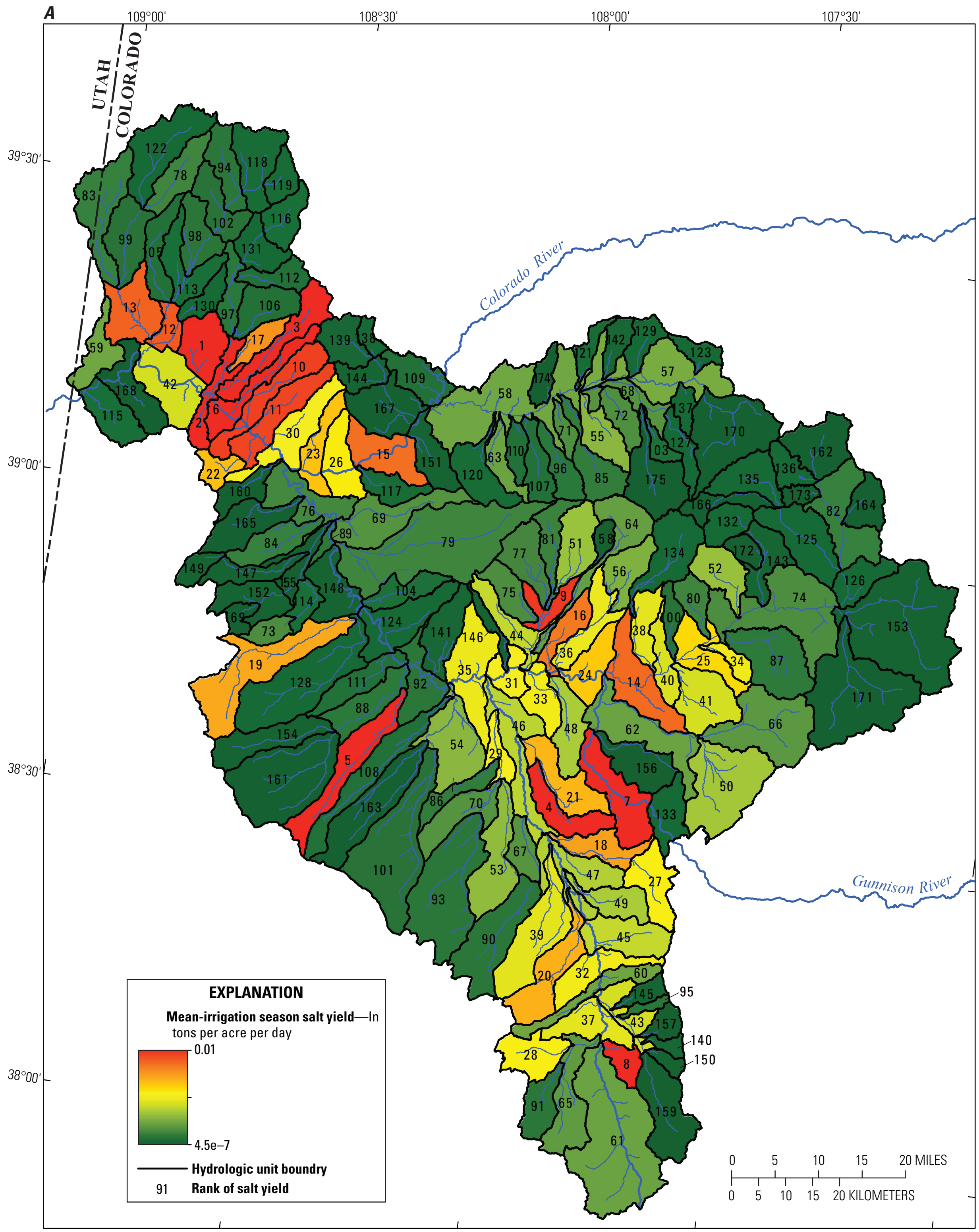

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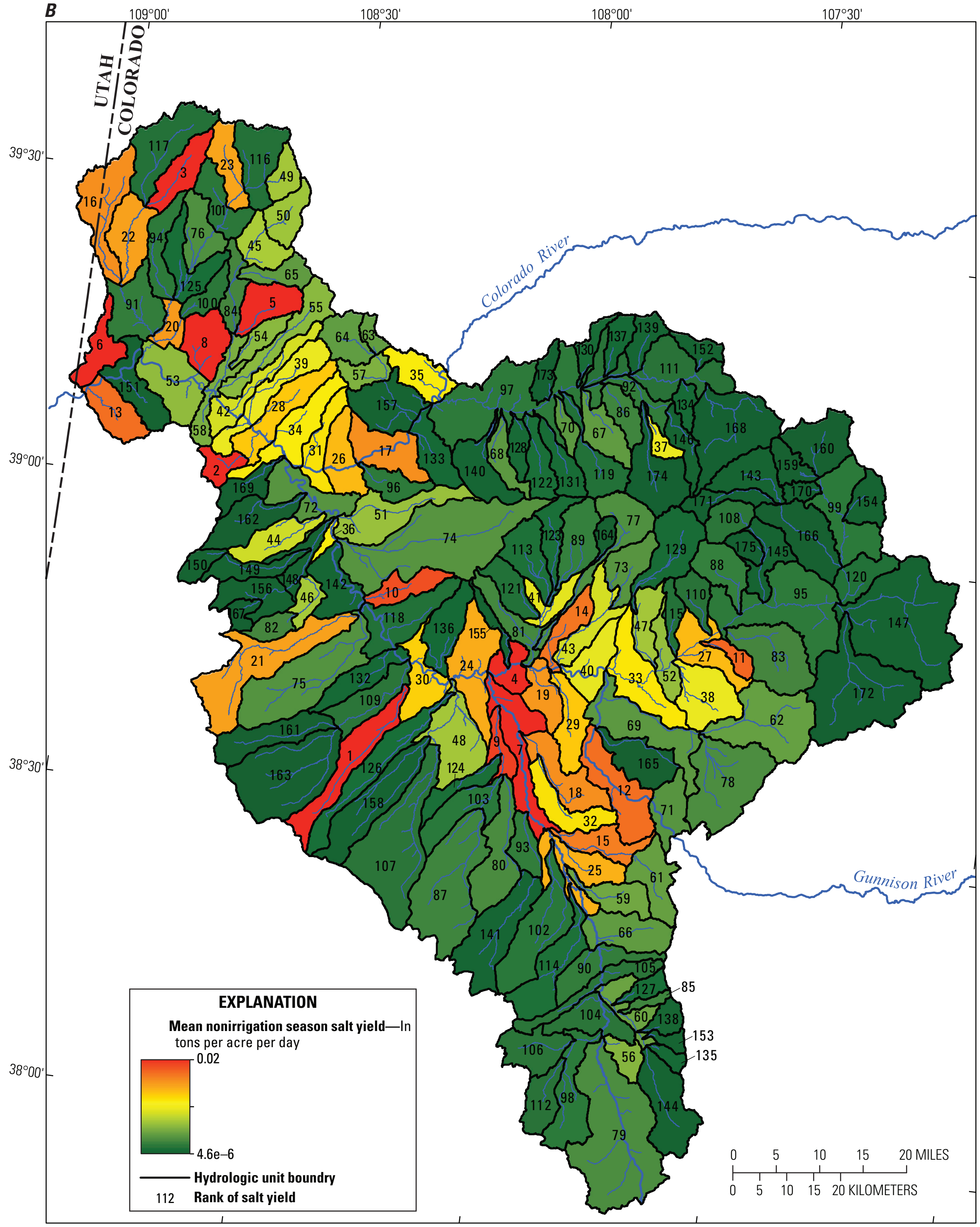
Figure 6. Maps showing seasonal yield estimates from the hydrologic unit code (HUC) contributing areas in the lower Gunnison River Basin study area, Colorado. *A,* Irrigation-season salt yield. *B,* Nonirrigation-season salt yield. *C,* Irrigation-season selenium yield. *D,* Nonirrigation-season selenium yield. Ranks are indicated by the numbers in each HUC contributing area.



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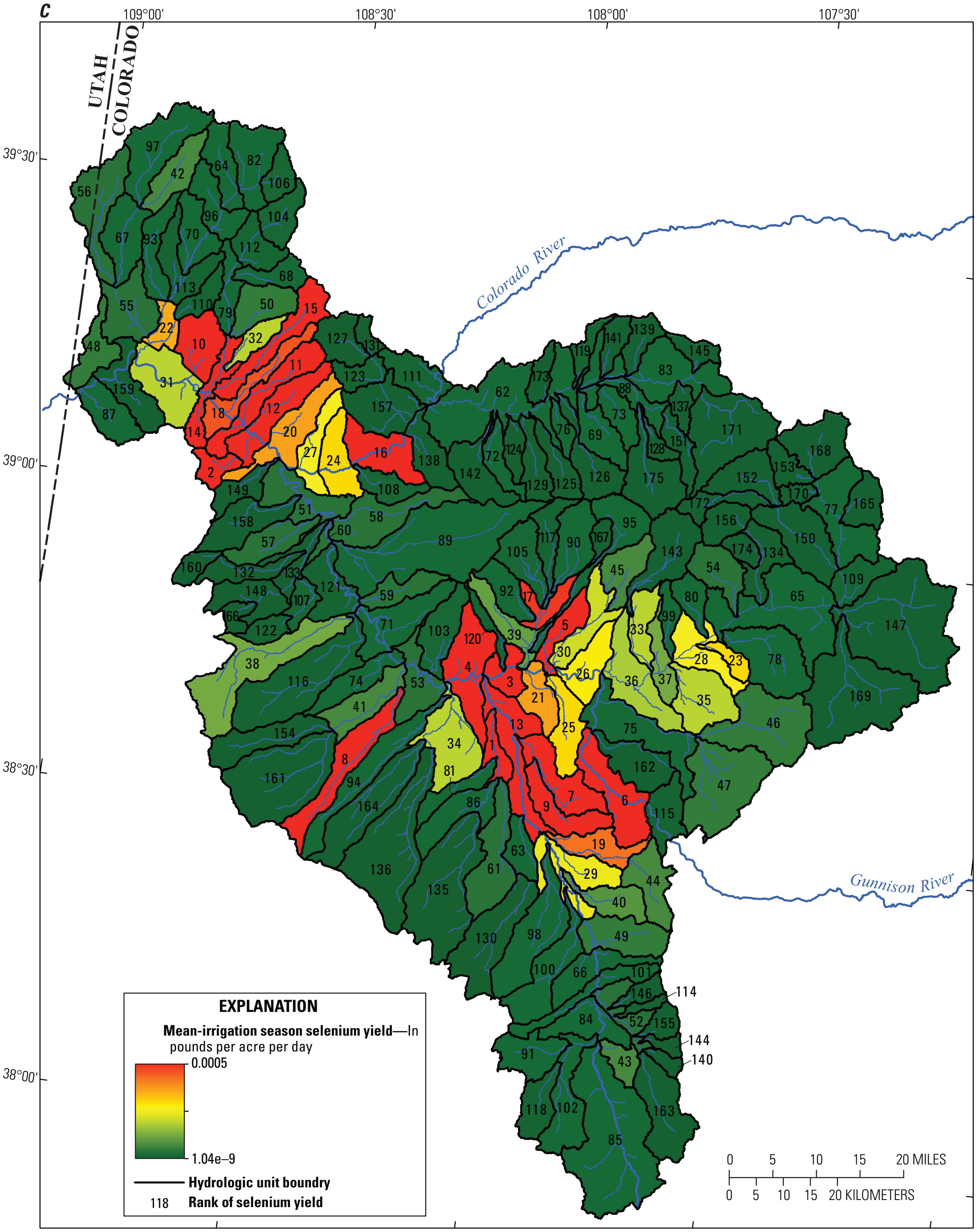

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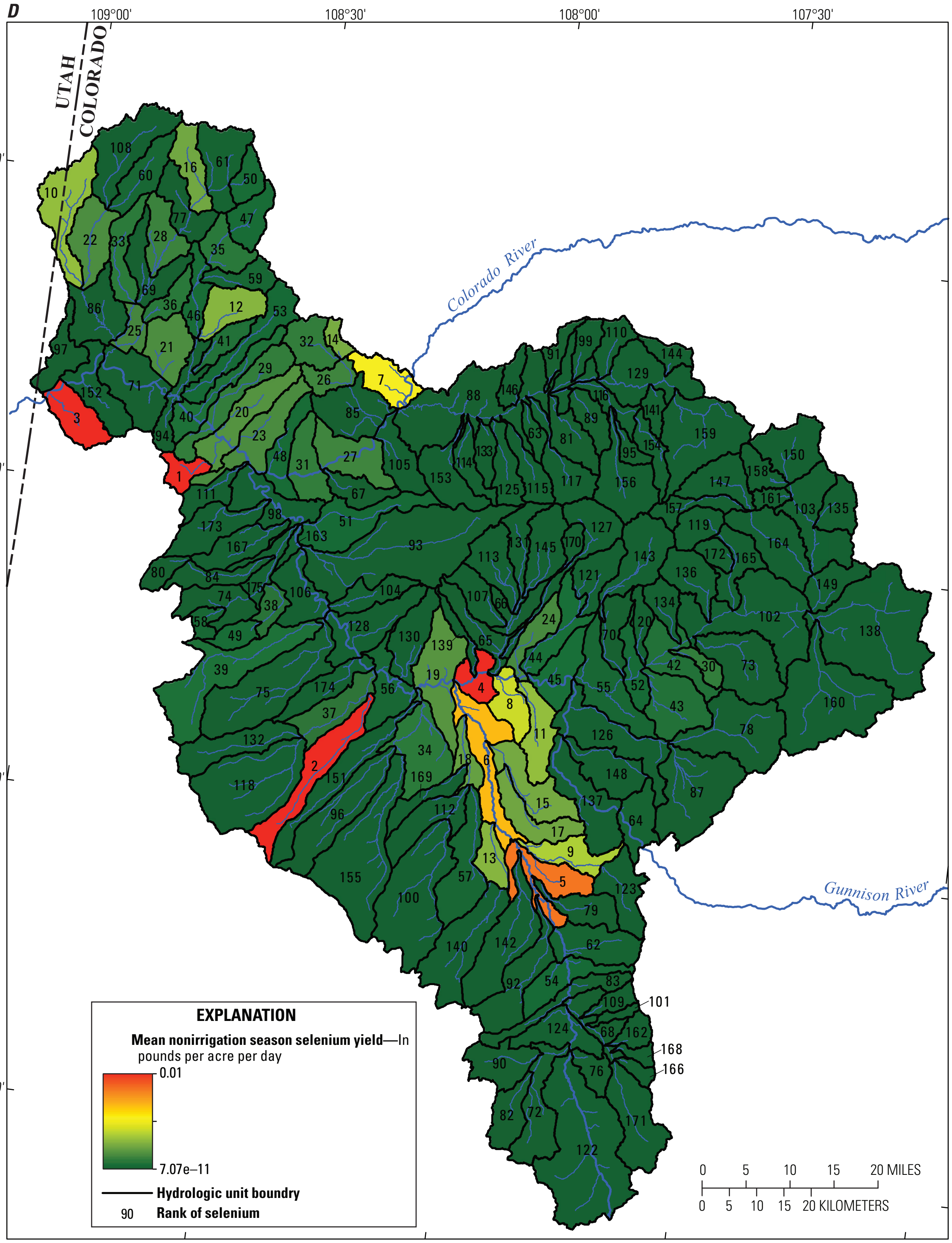

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provided in appendix 1. HUC contributing areas with the highest yields generally were in low-lying, irrigated areas of the Gunnison River Basin, Uncompahgre River, and below the confluence of the Gunnison and Colorado Rivers. HUC contributing areas with the lowest yields generally were in headwater areas and areas without irrigation. The same general conclusions were evident in maps of estimated loads, although the influence of HUC contributing area size was apparent (fig. 7).

Instances where yield estimates from HUC contributing areas exceeded the limits of the model-development data occurred for each model. The model-development data, ideally, are comprised of a large enough amount of data such that uncertainty in response-variable estimates is minimized. Estimates greater or less than those limits of the model-development data are a result of combining values of explanatory variables that did not occur in the model-development data and uncertainty increases at these extremes (Helsel and Hirsch, 1992). The upper and lower limits were exceeded in each model, except for the maximum yields of the irrigation-season salt and selenium models (appendix 1 and figure 8). The majority of estimates outside the limits of the model-development data were from HUC contributing areas whose yields were lower than the minimums used in model development.

Each HUC contributing area was ranked according to its estimated mean seasonal yield of salt and selenium (appendix 1). Within the upper and lower limits of the model-development data, the natural logarithms of the yield estimates rank linearly (fig. 8). Ranks based on such statistical samples are commonly used, although prone to misinterpretation (Marshall and Spiegelhalter, 1998). In addition, when considering the confidence intervals determined for each ranked yield estimate it is necessary to understand that the ‘true’ mean seasonal yield from any one HUC contributing area could be higher or lower than the presented yield estimates of numerous other HUC contributing areas.

Summary

Mitigating the effects of salt and selenium on water quality in the Grand Valley and lower Gunnison River Basin in western Colorado is a major concern for land managers. Land-management practices aimed at limiting the amount of salt and selenium that reaches the stream have focused on improving the methods by which irrigation water is conveyed and distributed. Because of the spatial variability of irrigation and marine shale throughout the Grand Valley and lower Gunnison River Basin, different areas produce different amounts of salt and selenium. The implication of the effect of irrigation and geology on the spatial distribution of in-stream salt and selenium was explored in a previous modeling study. Following the relative success of preliminary MLR models, methods for improving the models were identified; improving the input datasets and refining the statistical methods used to develop models could improve estimates of salt and selenium production. Therefore, the U.S. Geological Survey (USGS), in cooperation with the USBR and the Colorado River Water Conservation District, conducted a study to improve the MLR models developed for the Grand Valley and lower Gunnison River Basin and to rank the estimated production of salt and selenium of 175 contributing areas within the study area.

The information used in this study included the data used in the previous study, updated versions of some previously used geospatial data, and some new geospatial data. Water-quality data from 231 sample sites representing water years 1989–2004 were considered. The major difference in the use of water-quality data between the previous and current studies was the conversion of data from loads to yields. From a modeling perspective, changing from loads to yields helped to ensure the explanatory variables used in the models were not confirming that large areas produce large loads. To establish the relations between geospatial data and salt loads measured during the irrigation season, 46 sample sites were used, and for the nonirrigation season, 37 sample sites were used. Selenium loads during the irrigation season were compared to geospatial data at 51 sample sites, and for the nonirrigation season, 48 sample sites were used.

The process of quantifying the relations between geospatial data and salt and selenium data began with the delineation of subbasin boundaries as defined by elevation data. Geospatial variables representing subbasin attributes related to topography, precipitation, agricultural land use, geology, and soils were extracted. Seasonal MLR models able to estimate salt and selenium were developed by assessing all possible combinations of the geospatial variables using standard evaluation statistics. The leverage and influence of each sample site were determined for each of the models to further evaluate the occurrence of potential outliers. To ensure that explanatory variables used in the models were independent of each other, the collinearity between variables was evaluated.

After evaluating all possible combinations of geospatial variables, four MLR models resulted that could estimate irrigation-season salt yield, nonirrigation-season salt yield, irrigation-season selenium yield, and nonirrigation-season selenium yield. The adjusted r-squared and the residual standard error of the models were, respectively, 0.87 and 2.03 for the irrigation-season salt model, 0.90 and 1.25 for the nonirrigation-season salt model, 0.85 and 2.94 for the irrigation-season selenium model, and 0.93 and 1.75 for the nonirrigation-season selenium model.

The four seasonal salt and selenium models were used to estimate yields and loads from 12-digit HUC contributing areas in the lower Gunnison River Basin. Instances where yield estimates from HUC contributing areas exceeded the limits of the model-development data occurred for each model. The majority of estimates outside the limits of the model-development data were from HUC contributing areas whose yields were lower than the minimums used in model development. Each HUC contributing area was ranked

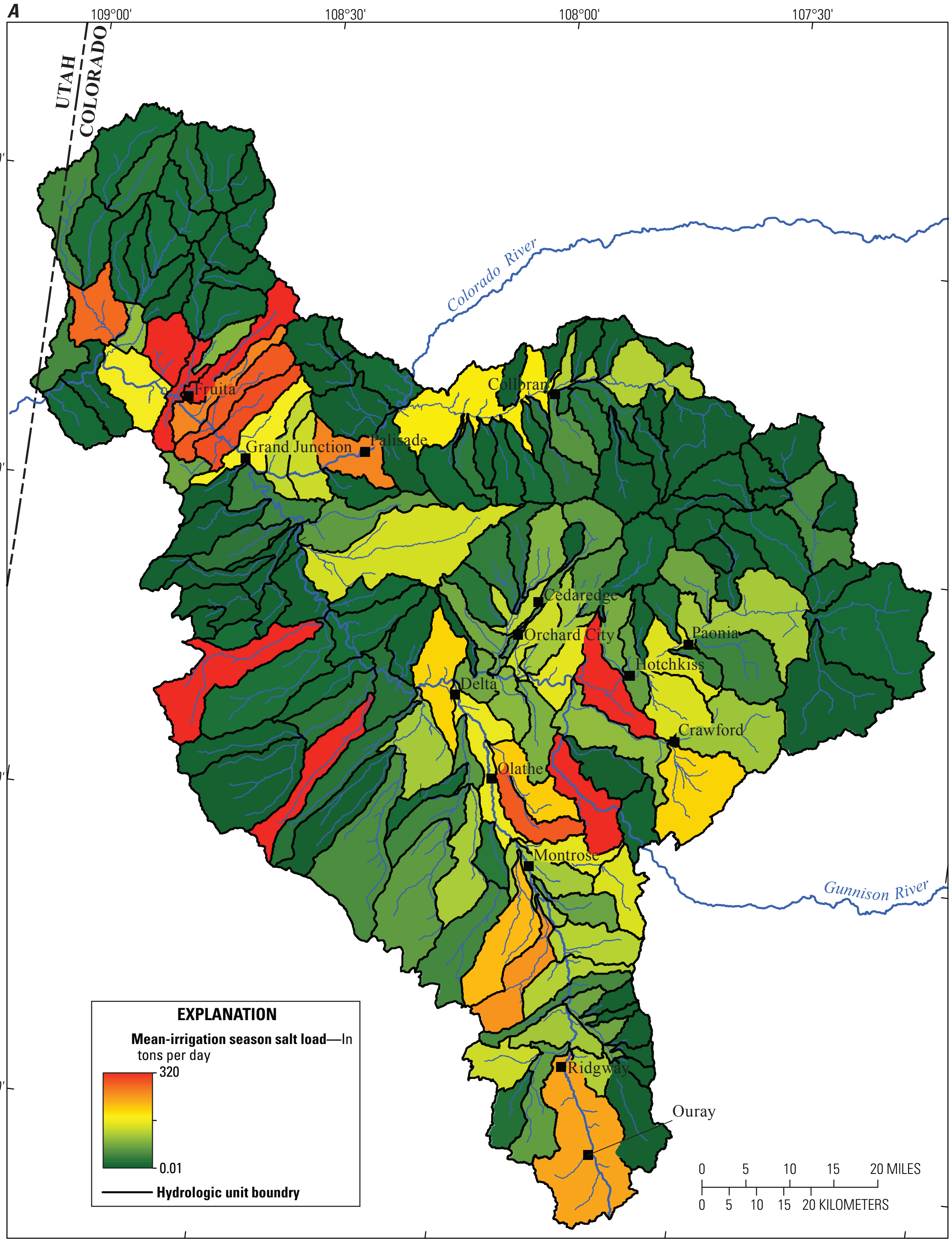

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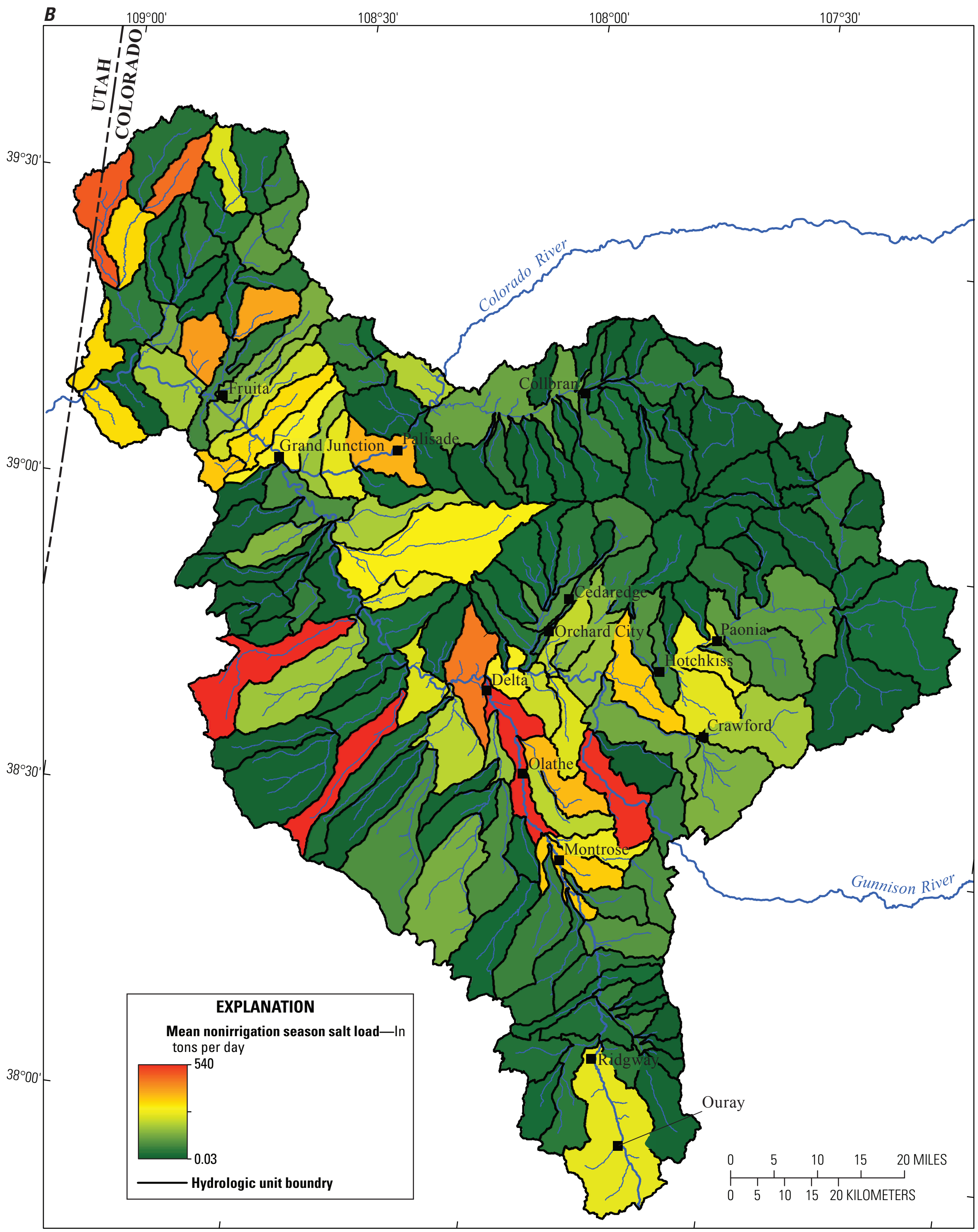
Figure 7. Maps showing seasonal load estimates from the hydrologic unit codes (HUC) contributing areas in the lower Gunnison River Basin study area, Colorado. *A,* Irrigation-season salt load. *B,* Nonirrigation-season salt load. *C,* Irrigation-season selenium load. *D,* Nonirrigation-season selenium load.



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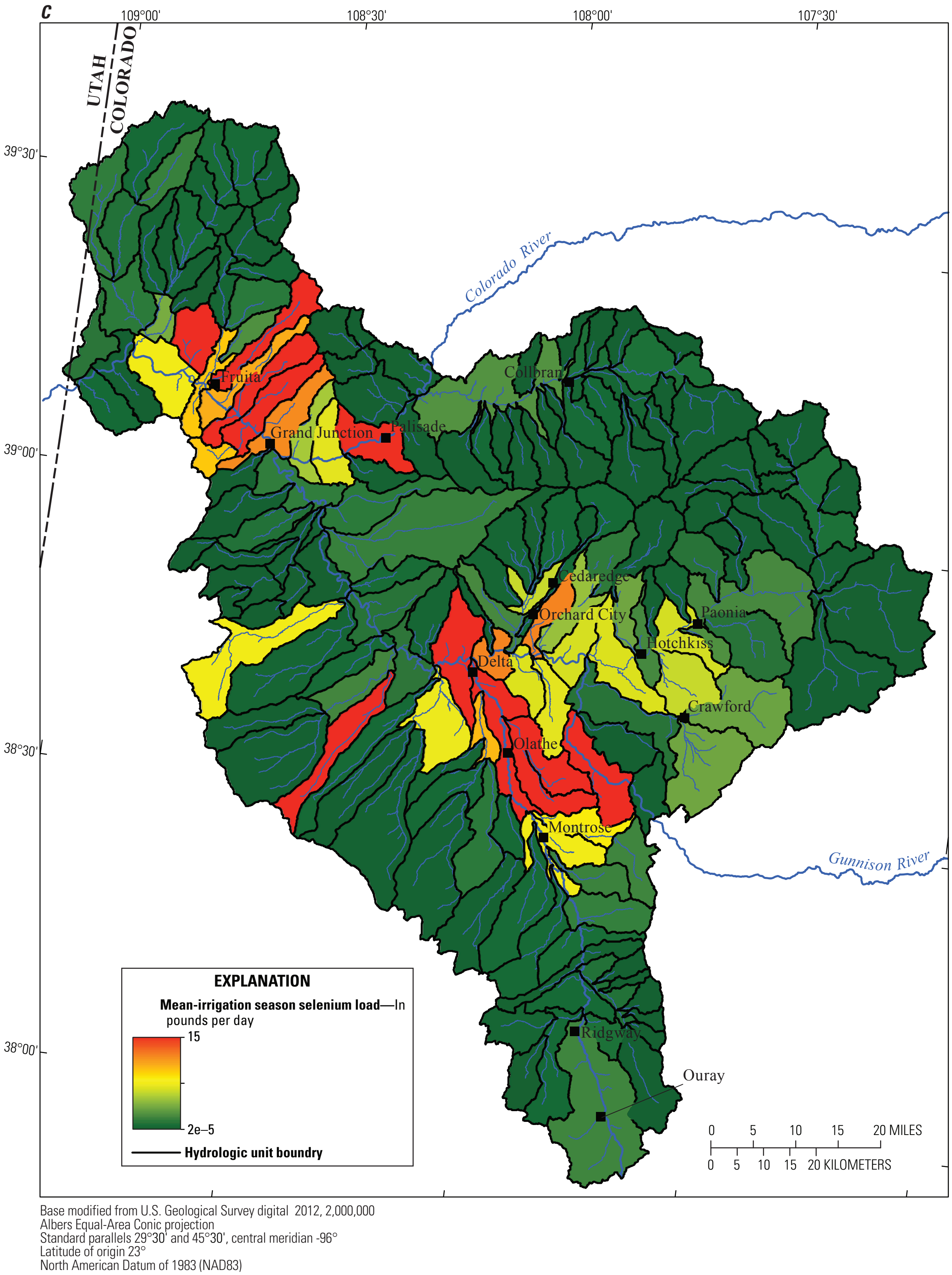

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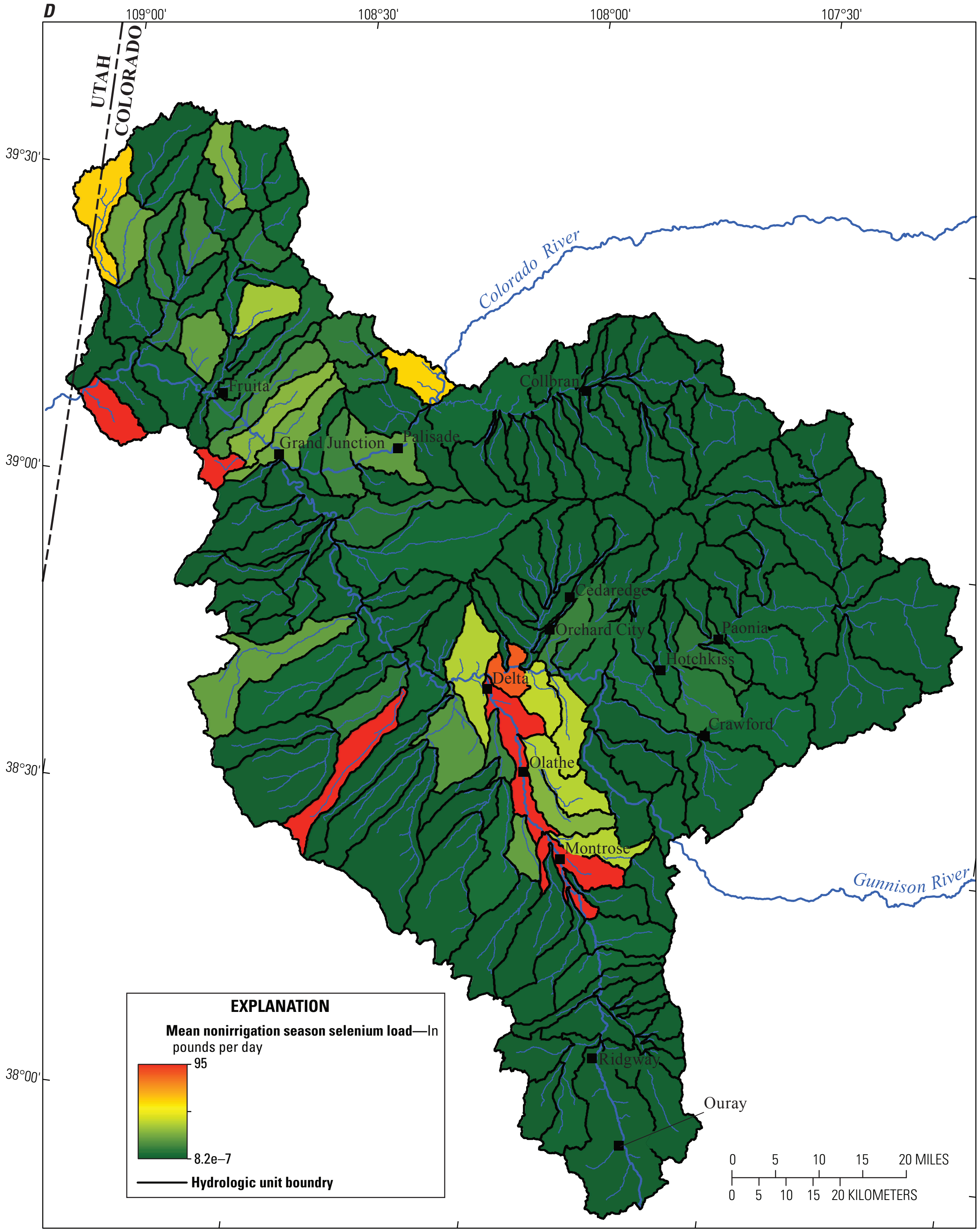

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Standard parallels 29°30' and 45°30', central meridian -96°
Latitude of origin 23°
North American Datum of 1983 (NAD83)

Figure 7. Maps showing seasonal load estimates from the hydrologic unit codes (HUC) contributing areas in the lower Gunnison River Basin study area, Colorado. *A,* Irrigation-season salt load. *B,* Nonirrigation-season salt load. *C,* Irrigation-season selenium load. *D,* Nonirrigation-season selenium load.—Continued

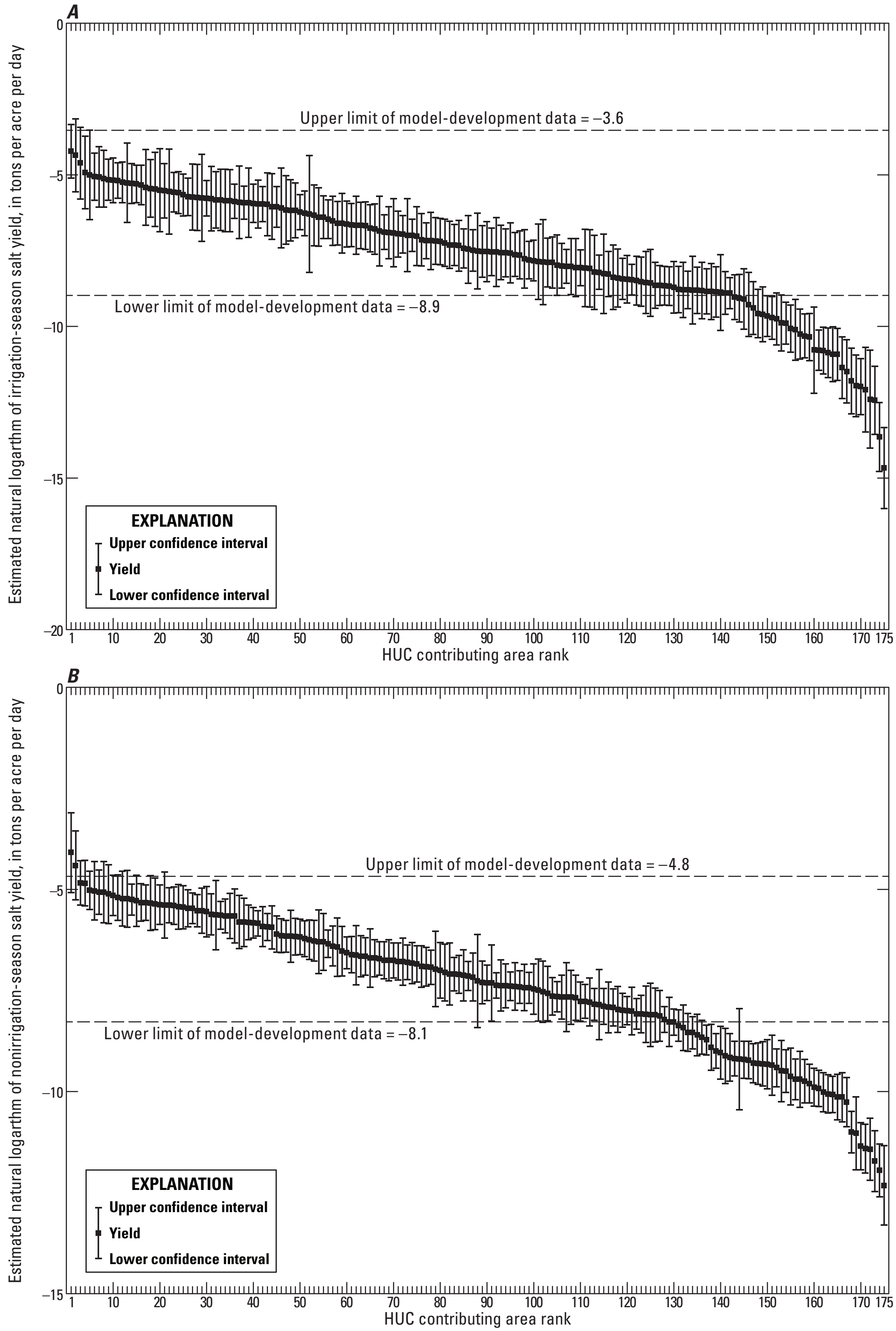
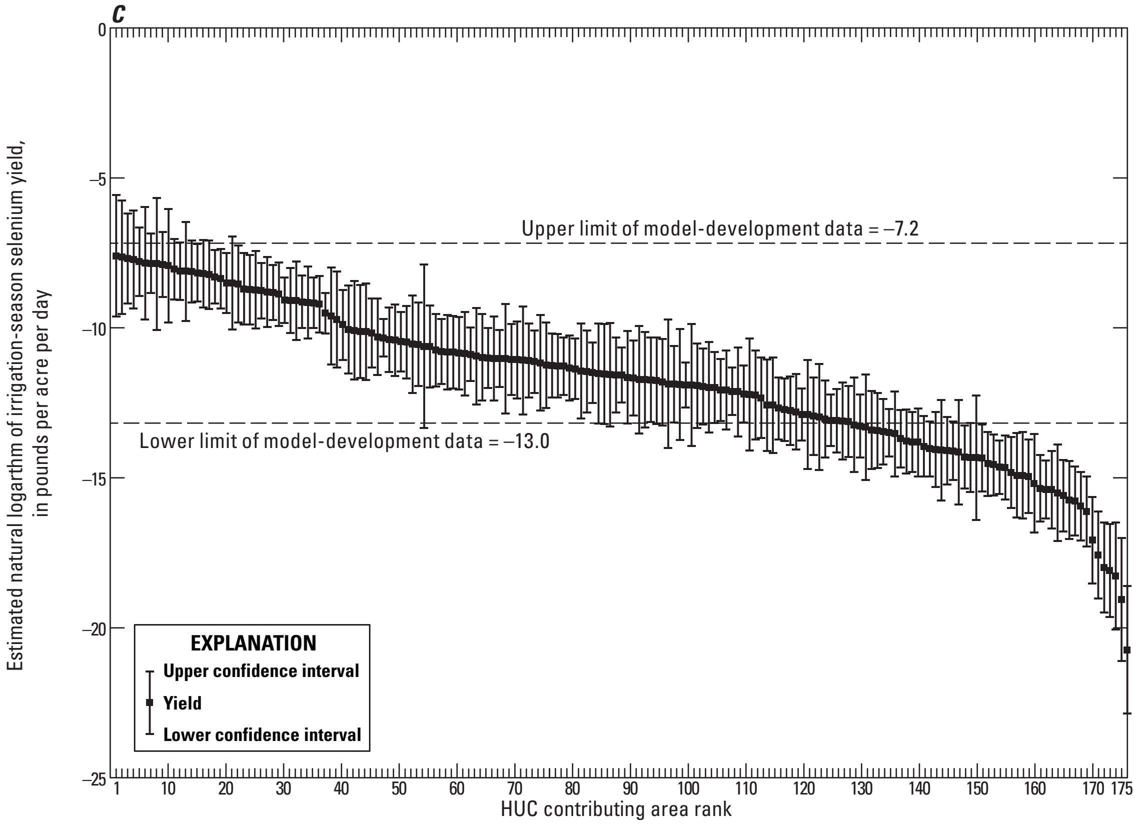


Figure 8. Graphs showing ranked seasonal yield estimates from hydrologic unit codes (HUC) contributing areas in the lower Gunnison River Basin, Colo., study area with corresponding confidence intervals. *A,* Irrigation-season salt yield. *B,* Nonirrigation-season salt yield. *C,* Irrigation-season selenium yield. *D,* Nonirrigation-season selenium yield.



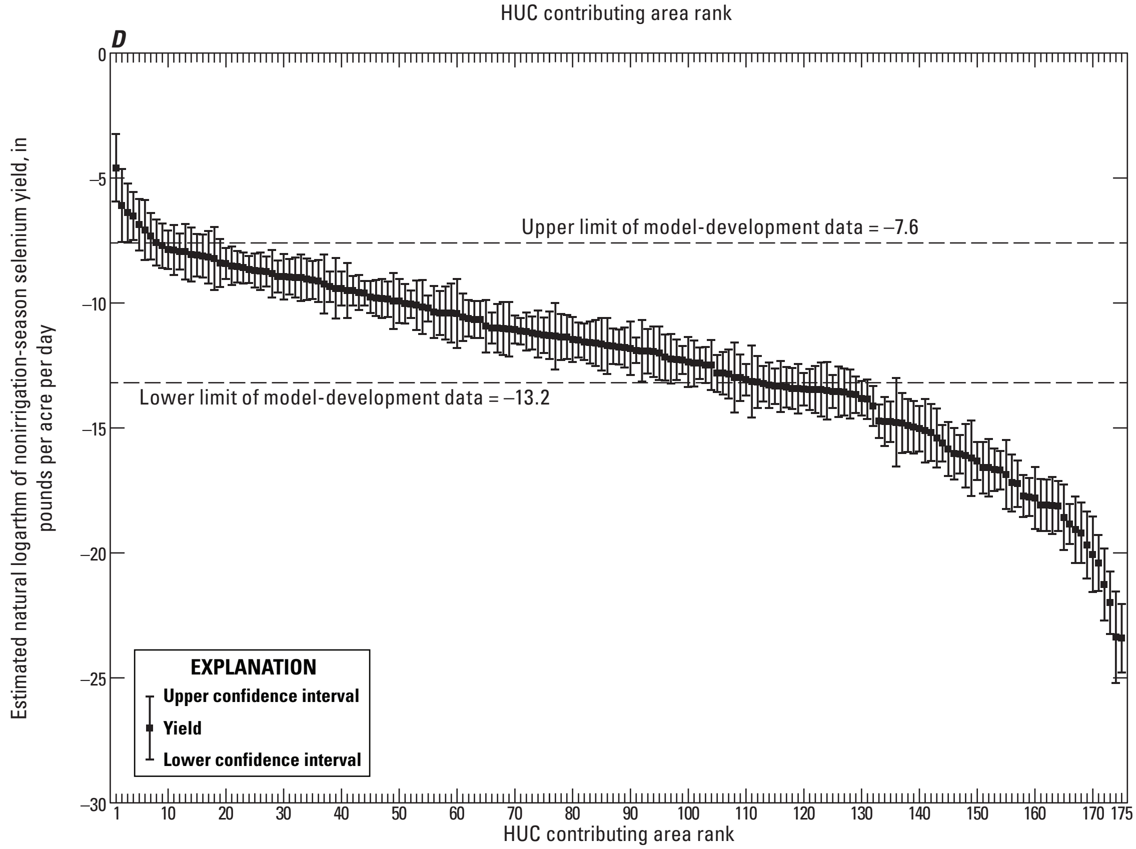


Figure 8. Graphs showing ranked seasonal yield estimates from hydrologic unit codes (HUC) contributing areas in the lower Gunnison River Basin, Colo., study area with corresponding confidence intervals. *A,* Irrigation-season salt yield. *B,* Nonirrigation-season salt yield. *C,* Irrigation-season selenium yield. *D,* Nonirrigation-season selenium yield.—Continued

according to its estimated mean seasonal yield of salt and selenium. When considering the confidence intervals determined for each ranked yield estimate, it is necessary to understand that the 'true' mean-seasonal yield from any one HUC contributing area could be higher or lower than the presented yield estimates of numerous other HUC contributing areas.

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Appendix

Appendix 1. Estimates of HUC seasonal salt and selenium yield and their corresponding ranks.

[bold yield values indicate yields that exceeded the upper or lower limit of the calibration data]

Hydrologic unit code	Salt yield (tons per acre per day)		Selenium yield (pounds per acre per day)		Rank of salt yield (figure 6*A* and 6*B*)		Rank of selenium yield (figure 6*C* and 6*D*)	
	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season
140100050801	1.50E-4	1.34E-3	**2.12E-6**	1.31E-4	139	64	127	32
140100050802	**1.22E-4**	1.73E-3	**2.30E-6**	1.70E-4	144	57	123	26
140100050806	1.51E-4	1.34E-3	**1.60E-6**	3.29E-4	138	63	131	14
140100050807	3.34E-4	3.65E-3	5.12E-6	**6.81E-4**	109	35	111	7
140100050904	**1.09E-5**	**6.41E-5**	**3.50E-7**	9.10E-6	167	157	157	85
140100050905	**6.38E-5**	**2.04E-4**	**1.07E-6**	2.83E-6	151	133	138	105
140100050906	2.43E-4	6.35E-4	5.70E-6	1.73E-5	117	96	108	67
140100050907	5.27E-3	5.06E-3	2.92E-4	1.66E-4	15	17	16	27
140100050909	3.46E-3	4.41E-3	1.72E-4	1.33E-4	26	26	24	31
140100050910	4.02E-3	3.79E-3	1.58E-4	5.49E-5	23	31	27	48
140100050911	3.30E-3	3.65E-3	2.15E-4	1.92E-4	30	34	20	23
140100050912	**2.20E-5**	**1.69E-5**	**6.34E-7**	2.04E-6	160	169	149	111
140100050913	5.92E-3	4.15E-3	3.17E-4	2.28E-4	11	28	12	20
140100050914	5.97E-3	3.11E-3	3.40E-4	1.35E-4	10	39	11	29
140100050915	4.11E-3	**1.27E-2**	5.08E-4	**1.05E-2**	22	2	2	1
140100051001	2.31E-4	2.18E-3	6.02E-6	5.08E-5	119	49	106	50
140100051003	2.36E-4	3.80E-4	1.12E-5	2.67E-5	118	116	82	61
140100051004	5.47E-4	4.71E-3	1.79E-5	3.08E-4	94	23	64	16
140100051005	4.01E-4	5.83E-4	7.41E-6	1.25E-5	102	101	96	77
140100051008	4.47E-4	1.04E-3	1.66E-5	1.53E-4	98	76	70	28
140100051009	2.86E-4	**3.15E-4**	3.65E-6	1.65E-5	113	125	113	69
140100051010	1.75E-4	5.97E-4	5.20E-6	1.12E-4	130	100	110	36
140100051011	3.63E-4	6.46E-4	8.49E-6	1.30E-4	105	94	93	33
140100051012	5.57E-3	4.82E-3	2.06E-4	1.72E-4	12	20	22	25
140100051101	2.71E-4	2.17E-3	6.59E-6	5.63E-5	116	50	104	47
140100051102	1.63E-4	2.33E-3	4.65E-6	1.18E-4	131	45	112	35
140100051103	3.25E-4	1.28E-3	1.72E-5	3.14E-5	112	65	68	59
140100051104	5.08E-4	8.56E-4	1.26E-5	5.72E-5	97	84	79	46
140100051105	3.54E-4	6.86E-3	3.04E-5	3.67E-4	106	5	50	12
140100051106	4.73E-3	1.93E-3	1.19E-4	7.74E-5	17	54	32	41
140100051107	1.36E-2	1.68E-3	3.13E-4	6.68E-6	2	58	14	94
140100051108	1.05E-2	1.92E-3	3.00E-4	4.33E-5	3	55	15	53
140100051109	6.73E-3	2.80E-3	2.62E-4	8.45E-5	6	42	18	40
140100051401	2.17E-4	3.79E-4	7.34E-6	2.38E-6	122	117	97	108
140100051402	8.08E-4	8.26E-3	4.43E-5	3.10E-5	78	3	42	60
140100051403	7.05E-4	5.07E-3	2.27E-5	3.97E-4	83	16	56	10
140100051404	4.29E-4	4.74E-3	1.73E-5	2.02E-4	99	22	67	22
140100051406	5.49E-3	6.96E-4	2.57E-5	8.50E-6	13	91	55	86
140100051501	1.55E-2	6.54E-3	3.81E-4	2.08E-4	1	8	10	21
140100051503	2.72E-3	1.97E-3	1.19E-4	1.53E-5	42	53	31	71
140100051504	**7.97E-6**	**9.13E-5**	**2.68E-7**	**6.48E-8**	168	151	159	152
140100051505	1.44E-3	6.78E-3	3.25E-5	5.03E-6	59	6	48	97
140100051506	2.73E-4	5.55E-3	9.98E-6	**1.75E-3**	115	13	87	3
140100051701	1.45E-3	6.29E-4	1.98E-5	8.07E-6	58	97	62	88

Appendix 1. Estimates of HUC seasonal salt and selenium yield and their corresponding ranks.—Continued

[bold yield values indicate yields that exceeded the upper or lower limit of the calibration data]

Hydrologic unit code	Salt yield (tons per acre per day)		Selenium yield (pounds per acre per day)		Rank of salt yield (figure 6*A* and 6*B*)		Rank of selenium yield (figure 6*C* and 6*D*)	
	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season
140100051702	**1.25E-6**	**8.47E-6**	**1.23E-8**	**1.13E-7**	174	173	173	146
140100051703	2.25E-4	**2.63E-4**	2.68E-6	7.05E-6	121	130	119	91
140100051709	1.76E-3	1.27E-3	1.67E-5	1.07E-5	55	67	69	81
140100051710	6.34E-4	3.54E-4	**2.16E-6**	**1.62E-6**	85	119	126	117
140100051711	1.02E-3	1.21E-3	1.37E-5	2.44E-5	71	70	76	63
140100051712	5.15E-4	**2.42E-4**	**2.18E-6**	**1.69E-6**	96	131	125	115
140100051713	3.48E-4	3.24E-4	**1.82E-6**	**1.36E-6**	107	122	129	125
140100051714	3.33E-4	**2.81E-4**	**2.20E-6**	**4.20E-7**	110	128	124	133
140100051715	1.34E-3	1.22E-3	1.63E-5	**1.75E-6**	63	68	72	114
140100051716	2.27E-4	**1.24E-4**	**8.34E-7**	**5.97E-8**	120	140	142	153
140100051804	1.08E-3	6.56E-4	9.96E-6	**1.68E-6**	68	92	88	116
140100051805	1.85E-4	**1.03E-4**	**5.15E-7**	**5.88E-8**	127	146	151	154
140100051806	3.95E-4	3.13E-3	**1.89E-6**	6.29E-6	103	37	128	95
140100051807	**4.51E-7**	**6.72E-6**	**1.04E-9**	**3.53E-8**	175	174	175	156
140100051808	1.01E-3	8.23E-4	1.55E-5	7.87E-6	72	86	73	89
140100051901	1.56E-3	4.40E-4	1.08E-5	**1.20E-6**	57	111	83	129
140100051902	1.53E-4	**2.03E-4**	**1.09E-6**	**2.84E-7**	137	134	137	141
140100051903	**1.44E-4**	**1.70E-4**	**8.50E-7**	4.81E-6	142	137	141	99
140100051904	1.82E-4	**1.29E-4**	**1.06E-6**	2.20E-6	129	139	139	110
140100051905	2.10E-4	**8.55E-5**	**7.95E-7**	**1.71E-7**	123	152	145	144
140100051906	**6.62E-6**	**1.74E-5**	**1.63E-8**	**1.99E-8**	170	168	171	159
140200020501	1.19E-3	1.38E-3	3.57E-5	1.21E-5	66	62	46	78
140200020502	2.09E-3	1.02E-3	3.45E-5	8.43E-6	50	78	47	87
140200020503	1.36E-3	1.22E-3	1.39E-5	**1.35E-6**	62	69	75	126
140200021001	1.60E-4	1.18E-3	3.29E-6	2.42E-5	133	71	115	64
140200021002	**4.31E-5**	**4.13E-5**	**2.18E-7**	**1.04E-7**	156	165	162	148
140200021003	6.70E-3	5.60E-3	4.14E-4	**3.87E-7**	7	12	6	137
140200040701	**5.41E-5**	**9.51E-5**	**6.51E-7**	**3.49E-7**	153	147	147	138
140200040702	**5.96E-6**	**1.14E-5**	**4.05E-8**	**1.91E-8**	171	172	169	160
140200040901	7.07E-4	6.14E-4	1.35E-5	3.93E-6	82	99	77	103
140200040902	**1.92E-5**	**7.85E-5**	**1.53E-7**	**4.07E-7**	164	154	165	135
140200040903	**2.17E-5**	**5.28E-5**	**1.06E-7**	**8.50E-8**	162	160	168	150
140200040904	1.57E-4	**5.77E-5**	**4.64E-7**	**2.08E-8**	136	159	153	158
140200040905	**4.21E-6**	**1.23E-5**	**2.47E-8**	**1.45E-8**	173	170	170	161
140200041101	9.69E-4	6.39E-4	1.76E-5	4.22E-6	74	95	65	102
140200041102	5.91E-4	8.62E-4	1.33E-5	1.42E-5	87	83	78	73
140200041103	1.95E-3	7.29E-4	2.60E-5	**3.96E-7**	52	88	54	136
140200041104	1.87E-4	3.50E-4	5.28E-6	**9.48E-8**	126	120	109	149
140200045501	2.02E-4	**4.12E-5**	**6.31E-7**	**1.40E-8**	125	166	150	164
140200045502	1.58E-4	**1.07E-4**	**4.99E-7**	**1.11E-7**	135	143	152	147
140200045503	**1.23E-5**	**1.15E-5**	**1.48E-8**	**3.43E-8**	166	171	172	157
140200045601	**1.26E-4**	**1.04E-4**	**1.45E-6**	**8.90E-9**	143	145	134	165
140200045602	1.60E-4	4.88E-4	**3.50E-7**	**1.54E-6**	132	108	156	119
140200045603	**4.35E-6**	**4.65E-6**	**5.61E-9**	**6.07E-10**	172	175	174	172

Appendix 1. Estimates of HUC seasonal salt and selenium yield and their corresponding ranks.—Continued

[bold yield values indicate yields that exceeded the upper or lower limit of the calibration data]

Hydrologic unit code	Salt yield (tons per acre per day)		Selenium yield (pounds per acre per day)		Rank of salt yield (figure 6*A* and 6*B*)		Rank of selenium yield (figure 6*C* and 6*D*)	
	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season
140200045801	1.59E-4	**2.65E-4**	**8.13E-7**	**2.13E-7**	134	129	143	143
140200045802	2.85E-3	2.21E-3	1.14E-4	1.63E-5	38	47	33	70
140200045803	7.92E-4	4.40E-4	1.23E-5	**4.12E-7**	80	110	80	134
140200045805	4.22E-4	3.88E-4	7.19E-6	**1.50E-6**	100	115	99	120
140200045806	3.06E-3	5.74E-3	1.77E-4	1.35E-4	34	11	23	30
140200045807	2.72E-3	3.12E-3	1.11E-4	7.14E-5	41	38	35	43
140200045808	3.68E-3	4.39E-3	1.56E-4	7.74E-5	25	27	28	42
140200045809	2.77E-3	2.03E-3	7.82E-5	4.50E-5	40	52	37	52
140200045810	5.36E-3	3.70E-3	1.05E-4	3.80E-5	14	33	36	55
140200050801	6.91E-4	2.75E-3	2.19E-5	**5.46E-9**	84	44	57	167
140200050802	**1.91E-5**	**4.66E-5**	**3.40E-7**	**2.95E-10**	165	162	158	173
140200050803	8.35E-4	1.18E-3	2.97E-5	4.84E-6	76	72	51	98
140200050901	3.03E-3	4.56E-3	4.67E-4	2.32E-4	35	24	4	19
140200050902	**1.45E-4**	**1.81E-4**	6.60E-6	**1.03E-6**	141	136	103	130
140200050903	5.62E-4	4.05E-3	2.77E-5	3.28E-5	92	30	53	56
140200050904	3.31E-4	**2.30E-4**	1.49E-5	**7.38E-11**	111	132	74	174
140200050905	2.05E-4	3.60E-4	1.63E-5	**1.24E-6**	124	118	71	128
140200051301	**9.92E-5**	**6.86E-5**	2.66E-6	**3.28E-7**	146	155	120	139
140200051303	2.50E-3	8.98E-4	6.33E-5	1.85E-5	44	81	39	65
140200051304	9.42E-4	3.46E-4	8.55E-6	2.77E-6	75	121	92	107
140200051305	8.10E-4	4.08E-4	6.07E-6	**1.86E-6**	77	113	105	113
140200051306	7.57E-4	3.21E-4	3.04E-6	**1.01E-6**	81	123	117	131
140200051307	2.00E-3	7.02E-4	9.06E-6	**1.38**E-7	51	89	90	145
140200051308	**3.51E-5**	**4.40E-5**	**1.26E-7**	**2.02E-9**	158	164	167	170
140200051309	1.34E-3	1.03E-3	7.84E-6	**1.33E-6**	64	77	95	127
140200051310	1.66E-3	1.15E-3	4.04E-5	**1.49E-6**	56	73	45	121
140200051311	2.98E-3	2.78E-3	1.21E-4	6.95E-5	36	43	30	44
140200051312	2.21E-3	4.14E-3	1.70E-4	3.96E-4	48	29	25	11
140200051313	3.94E-3	3.07E-3	1.66E-4	6.03E-5	24	40	26	45
140200051314	5.08E-3	5.45E-3	4.36E-4	1.81E-4	16	14	5	24
140200051316	6.05E-3	3.03E-3	2.82E-4	1.73E-5	9	41	17	66
140200051317	3.12E-3	4.93E-3	2.15E-4	**5.31E-4**	33	19	21	8
140200051318	3.24E-3	8.18E-3	4.86E-4	**1.53E-3**	31	4	3	4
140200051501	8.02E-4	1.13E-3	9.23E-6	6.86E-6	79	74	89	93
140200051502	1.06E-3	2.07E-3	2.14E-5	4.59E-5	69	51	58	51
140200051503	3.95E-4	6.04E-3	2.13E-5	3.92E-6	104	10	59	104
140200051504	**7.34E-5**	**1.10E-4**	2.52E-6	2.83E-6	148	142	121	106
140200051505	5.70E-4	3.64E-3	2.06E-5	**1.42E-8**	89	36	60	163
140200054001	**6.81E-6**	**3.65E-5**	**1.50E-7**	3.18E-5	169	167	166	58
140200054002	9.75E-4	8.70E-4	2.46E-6	5.09E-5	73	82	122	49
140200054003	**7.14E-5**	**9.30E-5**	**2.27E-7**	1.09E-5	149	150	160	80
140200054004	2.86E-4	2.23E-3	5.80E-6	9.05E-5	114	46	107	38
140200054005	**6.15E-5**	**6.41E-5**	**6.35E-7**	1.37E-5	152	156	148	74
140200054006	**8.85E-5**	**9.41E-5**	**1.56E-6**	9.51E-6	147	149	132	84

Appendix 1. Estimates of HUC seasonal salt and selenium yield and their corresponding ranks.—Continued

[bold yield values indicate yields that exceeded the upper or lower limit of the calibration data]

Hydrologic unit code	Salt yield (tons per acre per day)		Selenium yield (pounds per acre per day)		Rank of salt yield (figure 6*A* and 6*B*)		Rank of selenium yield (figure 6*C* and 6*D*)	
	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season	Irrigation season	Nonirrigation season
140200054007	**4.48E-5**	**9.45E-5**	**1.50E-6**	**7.07E-11**	155	148	133	175
140200057301	4.43E-3	4.76E-3	7.13E-5	8.46E-5	19	21	38	39
140200057302	1.84E-4	1.11E-3	3.14E-6	1.30E-5	128	75	116	75
140200057501	**2.20E-5**	**4.46E-5**	**2.20E-7**	**1.55E-6**	161	163	161	118
140200057502	**5.35E-5**	**5.09E-5**	**4.59E-7**	**7.60E-7**	154	161	154	132
140200057503	7.11E-3	**1.75E-2**	4.05E-4	**2.31E-3**	5	1	8	2
140200057504	5.78E-4	4.83E-4	4.55E-5	1.01E-4	88	109	41	37
140200057701	4.06E-4	4.89E-4	**1.19E-6**	**4.92E-8**	101	107	136	155
140200057702	**2.02E-5**	**6.13E-5**	**1.78E-7**	5.35E-6	163	158	164	96
140200057703	3.47E-4	**3.14E-4**	8.23E-6	**6.50E-8**	108	126	94	151
140200057704	1.77E-3	2.21E-3	1.12E-4	1.22E-4	54	48	34	34
140200060301	1.41E-3	4.95E-4	6.95E-6	9.68E-6	60	105	101	83
140200060302	3.12E-3	6.98E-4	1.73E-5	4.01E-5	32	90	66	54
140200060303	2.48E-3	1.28E-3	3.18E-5	2.54E-5	45	66	49	62
140200060701	7.69E-3	3.73E-3	3.97E-4	2.94E-4	4	32	9	17
140200060702	4.21E-3	5.02E-3	4.12E-4	3.19E-4	21	18	7	15
140200060704	2.40E-3	6.55E-3	3.16E-4	**8.69E-4**	46	7	13	6
140200064001	5.65E-4	**1.14E-4**	**1.74E-6**	**3.09E-7**	90	141	130	140
140200064002	2.84E-3	5.61E-4	7.27E-6	**2.65E-7**	39	102	98	142
140200064003	4.30E-3	4.06E-4	7.13E-6	6.93E-6	20	114	100	92
140200064004	3.41E-3	1.40E-3	4.23E-5	**1.47E-6**	27	61	44	123
140200064005	2.21E-3	1.52E-3	5.31E-5	1.21E-5	49	59	40	79
140200064006	4.54E-3	5.30E-3	2.46E-4	4.67E-4	18	15	19	9
140200064007	2.25E-3	4.52E-3	1.48E-4	**1.07E-3**	47	25	29	5
140200064010	1.12E-3	6.52E-4	1.87E-5	3.66E-4	67	93	63	13
140200064801	**3.39E-5**	**1.06E-4**	**1.96E-7**	**1.43E-9**	159	144	163	171
140200064802	**6.75E-5**	**1.92E-4**	**9.20E-7**	**6.84E-9**	150	135	140	166
140200064803	1.48E-4	**7.87E-5**	**8.00E-7**	**4.77E-9**	140	153	144	168
140200064804	**3.74E-5**	**1.42E-4**	**3.86E-7**	**1.44E-8**	157	138	155	162
140200064805	5.42E-4	8.38E-4	3.65E-6	4.23E-6	95	85	114	101
140200064806	**1.19E-4**	**3.08E-4**	**7.59E-7**	2.37E-6	145	127	146	109
140200064807	2.70E-3	1.47E-3	2.79E-5	1.69E-5	43	60	52	68
140200065001	5.49E-4	8.04E-4	**1.40E-6**	4.43E-6	93	87	135	100
140200065002	1.05E-3	5.35E-4	1.00E-5	1.98E-6	70	103	86	112
140200065003	6.13E-4	3.20E-4	1.14E-5	**2.93E-9**	86	124	81	169
140200065004	1.87E-3	9.47E-4	2.03E-5	3.18E-5	53	80	61	57
140200065005	3.34E-3	6.25E-3	5.29E-4	2.77E-4	29	9	1	18
140200067901	1.36E-3	9.80E-4	1.03E-5	**1.48E-6**	61	79	85	122
140200067902	6.26E-3	1.83E-3	4.28E-5	1.30E-5	8	56	43	76
140200067903	1.23E-3	6.18E-4	6.83E-6	1.51E-5	65	98	102	72
140200067904	5.62E-4	4.32E-4	2.93E-6	9.93E-6	91	112	118	82
140200067905	3.37E-3	4.90E-4	8.56E-6	7.66E-6	28	106	91	90
140200067906	2.88E-3	5.00E-4	1.05E-5	**1.40E-6**	37	104	84	124

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