science for a changing world

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

Land Disturbance Associated with Oil and Gas Development and Effects of Development-Related Land Disturbance on Dissolved-Solids Loads in Streams in the Upper Colorado River Basin, 1991, 2007, and 2025

Scientific Investigations Report 2010-5064

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

Cover: Foreground image: Photograph to the north showing a pumping well in the Drunkards Wash gas field near Price, Utah. Photograph by Susan G. Buto, August, 2009. Background image: 2006 National Agricultural Imagery Program image showing oil- and gas-related land disturbance near the Green and White Rivers in Uintah County, Utah.

Land Disturbance Associated with Oil and Gas Development and Effects of Development-Related Land Disturbance on Dissolved-Solids Loads in Streams in the Upper Colorado River Basin, 1991, 2007, and 2025

By Susan G. Buto, Terry A. Kenney, and Steven J. Gerner

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

Scientific Investigations Report 2010–5064

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:
Buto, S.G., Kenney, T.A., and Gerner, S.J., 2010, Land disturbance associated with oil and gas development and effects of development-related land disturbance on dissolved-solids loads in streams in the Upper Colorado River Basin, 1991, 2007, and 2025: U.S. Geological Survey Scientific Investigations Report 2010-5064, 56 p. Available at http://pubs.usgs.gov/sir/2010/5064.

Contents

Figures

Tables

Appendix tables

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl), (petroleum, 1 barrel = 42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)

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).

Abbreviations and Acronyms Used in the Text

(Clarification or additional information given in parentheses)

ANSI	American National Standards Institute
API	American Petroleum Institute
BLM	Bureau of Land Management
BMP	Best Management Practices
CS	Common Status
DLG	Digital Line Graph
DOQ	Digital Orthophoto Quadrangle
EA	Environmental Assessment
EIS	Environmental Impact Statement
EPCA	Energy Policy and Conservation Act
FY	Fiscal Year
GAP	Geographic Area Plan
GIS	Geographic Information System
GPS	Global Positioning System
HUC	Hydrologic Unit Code
LOP	Life of Project
MDP	Master Development Plan
NAIP	National Agricultural Imagery Program
NED	National Elevation Dataset (USGS)
NEPA	National Environmental Policy Act of 1969
NHD	National Hydrography Dataset
NWIS	National Water Information System (USGS)
PLSS	Public Land Survey System
PRISM	Precipitation-elevation Regressions on Independent Slopes Model (Oregon State University)
RFD	Reasonably Foreseeable Development
RMP	Resource Management Plan
ROW	Right of Way
SMA	Surface Management Agency
SPARROW	Spatially Referenced Regressions on Watershed Attributes (USGS)
UCRB	Upper Colorado River Basin
U.S.	United States
USBR	U.S. Bureau of Reclamation
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

Land Disturbance Associated with Oil and Gas Development and Effects of Development-Related Land Disturbance on Dissolved-Solids Loads in Streams in the Upper Colorado River Basin, 1991, 2007, and 2025

By Susan G. Buto, Terry A. Kenney, and Steven J. Gerner

Abstract

Oil and gas resource development in the Upper Colorado River Basin (UCRB) has increased substantially since the year 2000. The UCRB encompasses several significant oil and gas producing areas that have the potential for continued oil and gas resource development. Land disturbance associated with oil and gas resource development is caused by activities related to constructing drill pads to contain drilling and well maintenance equipment and roads to access the drill pad. Land disturbed by oil and gas development has the potential to cause increased erosion, stream degradation, habitat fragmentation and alteration, and increase public use of areas that may be environmentally sensitive. Land disturbance resulting from oil and gas resource development has not been monitored and mapped on a regional scale in the UCRB. However, information on the location and age of oil and gas wells in the UCRB is available. These data combined with geographic data analysis and modeling techniques were used to estimate the total area of disturbed land associated with oil and gas resource development in 1991 and in 2007 in the UCRB. Additional information about anticipated oil and gas development in the UCRB was used to project land disturbance to the year 2025. Results of the analysis indicate that approximately 117,500 acres (183 mi^2) of total land disturbance was associated with drill pads and related roads in the UCRB in 1991. The estimated area of disturbed land associated with oil and gas development increased 53 percent to 179,400 acres (280 mi^2) in 2007. Projecting oil and gas development through 2025 results in a potential near doubling of the land disturbance to approximately 319,300 acres (500 mi^2).

Estimated land disturbance for 1991 and 2007 were input to a contaminant transport model developed for the UCRB to assess the statistical significance of energy-related land disturbance to contributing dissolved solids to basin streams. The statistical assessment was an observational study based on an existing model and available water-quality monitoring data for the basin. No new data were collected for the analysis. The source coefficient calibrated for the disturbed lands associated with oil and gas development in 2007 was zero, which indicated that estimated land disturbance from oil and gas development is not statistically significant in explaining dissolved solids in UCRB streams. The lack of significance in the contaminant transport modeling framework may be due to the amount of available monitoring data, the spatial distribution of monitoring sites with respect to land disturbance, or the overall quantity of land disturbance associated with oil and gas development basin wide. Finally, dissolved-solids loads derived from natural landscapes may be similar to loads derived from lands disturbed by oil and gas resource development. The model recalibration done for this study confirms calibration results from Kenney and others (2009): the most significant contributor to dissolved solids in the UCRB is irrigated agricultural land, which covers an area substantially larger than the estimated area disturbed by oil and gas development and is subjected to artificially applied water.

Introduction

The inland sedimentary basins of the United States contain significant sources of oil and natural gas (U.S. Bureau of Land Management, 2006). Federal onshore lands contain an estimated 20 percent of the oil and 25 percent of the nation’s undiscovered natural gas resources (U.S. Bureau of Land Management, 2006). The Bureau of Land Management (BLM) has indicated that the oil and gas industries are interested in continuing to develop the Upper Colorado River Basin (UCRB; U.S. Bureau of Land Management, 2002). Oil and gas development areas in the UCRB include the Uinta-Piceance Province in northwestern Colorado and northeastern Utah, the San Juan Province in northwestern New Mexico and southwestern Colorado, the southwestern Wyoming Province, and the Paradox Basin in southern Utah and southwestern Colorado (fig. 1).

A significant volume of known and potential oil and gas reserves occur in the sedimentary basins in the UCRB. In 2002, the U.S. Geological Survey (USGS) estimated 21 trillion ft^3 of gas, 60 million barrels of oil, and 43 million barrels of

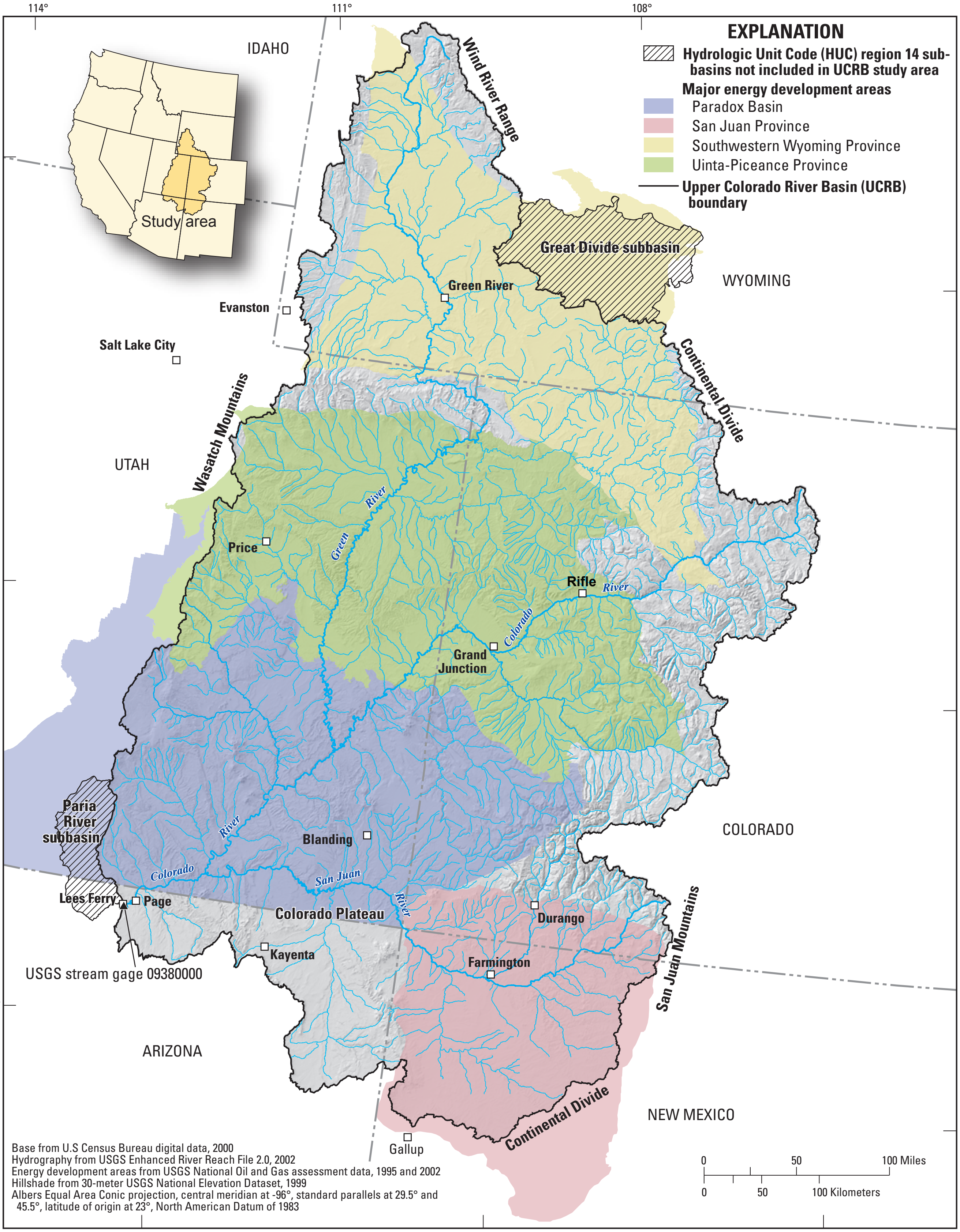

Figure 1. Major oil and gas development areas in the Upper Colorado River Basin study area.

natural gas liquids remain undiscovered in the Uinta-Piceance Province (U.S. Geological Survey, 2002a). In addition, the USGS estimated the San Juan Province could contain about 50 trillion ft^3 of gas, 19 million barrels of oil, and 148 million barrels of total natural gas liquids (U.S. Geological Survey, 2002b). The southwestern Wyoming Province could contain 84 trillion ft^3 of gas, 131 million barrels of oil, and 2.6 billion barrels of total natural gas liquids (U.S. Geological Survey, 2002c). No recent estimates of undiscovered reserves were available for the Paradox Basin. Huffman (1995) indicates the Aneth field, discovered in the Paradox Basin in 1956, contains approximately 1 billion barrels of proven oil reserves.

The pace of oil and gas development in the UCRB has increased substantially since 2000. An average of 4,527 wells were started per year on Federal land in the five UCRB states in fiscal years 2006 and 2007 (FY, October 1 to September 30) (U.S. Bureau of Land Management, 2008). An average of 2,462 wells per year were drilled between FY 2000 and 2005. In contrast, an average of 1,284 wells were drilled per year in the preceding 10-year period, FY 1990 to 1999. Wyoming had the largest increase and the largest number of wells drilled since 2000 (fig. 2). According to BLM statistics, two wells were started on Federal land in Arizona between FY 1990 and 2007.

Oil, natural gas, and coal bed methane exploration and reserve development occurs on both Federal and non-Federal lands in the UCRB. Calculations based on BLM and other National digital datasets (U.S. Bureau of Land Management, 2006; John Reitsma, Bureau of Land Management, written commun., October 23, 2007; National Atlas of the United States, 2006a,b) indicate that approximately 60 percent of UCRB lands are Federally owned. Another 15 percent of lands are tribal owned. State-owned lands make up about 3.5 percent of the area and approximately 4.5 percent of land in the UCRB is split-estate land. Split-estate lands occur when the surface and mineral rights are owned by separate entities, usually one Federal and one non-Federal. Non-Federal entities include private landholders. On split-estate lands, the surface owner or managing agency controls the surface uses but the mineral estate is the dominant estate (U.S. Bureau of Land Management, 2006). The remaining 17 percent of land is private or managed by local governmental entities.

Oil and gas resource development requires construction of drill pads for well drilling and operation. A drill pad is a level area, usually several acres, that is constructed to provide a platform for drilling and then operating and maintaining a completed, producing well. A low traffic volume, single lane resource road is usually constructed to access each drill pad. Roads can erode land, degrade streams, fragment and alter habitat and increase public use of an area (U.S. Bureau of Land Management, 2007). Drill pads may have similar environmental effects. Drill pads and roads can be reclaimed

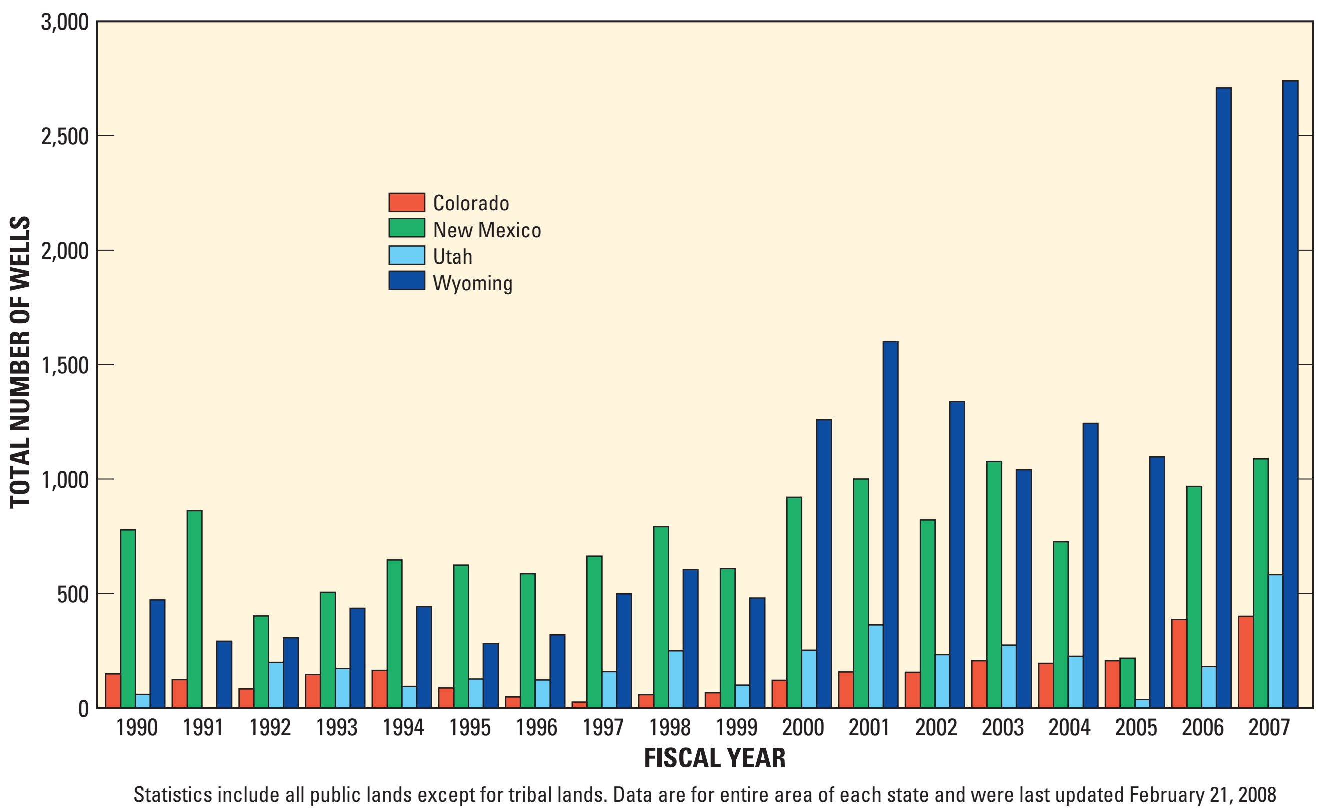

Figure 2. The number of oil and gas wells started on Federal lands annually in Colorado, New Mexico, Utah, and Wyoming Fiscal Years 1990 to 2007.

after the well is abandoned but reclamation may take decades to be completed in the arid landscapes of the UCRB. The rate at which plant communities recover during reclamation partly depends on climatic and vegetation conditions at each site. Even moderate disturbance in a site dominated by desert scrub can take 60 years to reach predisturbance biomass and 180 years for reasonable recovery of species diversity, even on noncompacted soils (U.S. Bureau of Land Management, 2009a).

Salinity in steams, as measured by dissolved-solids concentration, can be affected by natural conditions, such as geology, precipitation patterns, or land cover, and by anthropogenic activities, such as land use and irrigation practices. Increased drill pad and road construction in the UCRB in recent years has raised concerns that the land disturbance associated with oil and gas development could increase erosion and soil material transport in the basin. Increased erosion and soil material transport has the potential to adversely affect water quality and dissolved-solids load in the surface waters of the UCRB by increasing the volume of readily dissolved mineral salts transported from drill pads and roads to streams.

The USGS Spatially Referenced Regressions on Watershed Attributes (SPARROW) surface water-quality model relates measured chemical constituents at monitoring stations to upland catchment attributes, such as land use, land cover, or geology (Smith and others, 1997). The USGS, in cooperation with U.S. Department of the Interior—Bureau of Reclamation (USBR) and BLM, has developed a dissolved-solids SPARROW model of the UCRB to assess the sources and transport mechanisms of dissolved-solids loads in streams throughout the basin (Kenney and others, 2009). Land disturbance from oil and gas development in the UCRB has been estimated using geographic information system (GIS) analysis and modeling techniques. Results from the estimation have been input to the UCRB dissolved-solids SPARROW or UCRB SPARROW model to assess the statistical significance of land disturbance related to oil and gas development on dissolved-solids transport in the UCRB.

Purpose and Scope

Regional-scale compilation, synthesis, and analysis of data defining land disturbance related to oil and gas development and its effects on water quality may help to improve understanding of the potential cumulative effects of oil and gas development in the UCRB. Land disturbance associated with oil and gas well drilling is not regularly or consistently mapped at state or regional scales in the study area. This report consolidates information about oil and gas resource development in the UCRB and uses the information to estimate the amount of land disturbance related to energy development in the study area. Future potential disturbance was projected on the basis of information from BLM resource management plans (RMP) and reasonably foreseeable development (RFD) scenarios. The statistical significance of estimated current oil- and gas-related land disturbance on contributing dissolved solids to surface water in the study area was evaluated within the USGS SPARROW surface water-quality model for the UCRB.

This report is organized into two major sections. The first section of the report describes methods used to model the amount of land disturbed by oil and gas development in the UCRB and gives the results of land disturbance estimates for existing disturbance in 1991 and 2007 and for projected future land disturbance by 2025. The second section of the report documents the statistical assessment of the contribution of oil and gas development-related land disturbance on dissolved-solids transport in streams and rivers in the UCRB. The statistical assessment was an observational study based on an existing UCRB SPARROW model and on available water-quality monitoring data for the basin. No new data were collected for this analysis.

Description of Study Area

The UCRB drains parts of Arizona, Colorado, New Mexico, Utah, and Wyoming (fig. 1). For this study and for the earlier SPARROW model described by Kenney and others (2009), the UCRB is defined as the contributing drainage basin of Hydrologic Unit Code (HUC) region 14 upstream of USGS streamflow-gaging station 09380000, Colorado River at Lees Ferry, Arizona. The 2,505,000-acre (3,900-mi^2) Great Divide subbasin (HUC 14040200), northeast of the continental divide in Wyoming, is part of HUC 14 but is a closed basin and does not contribute runoff to the UCRB. The Great Divide subbasin has been excluded from the extent of the UCRB for this study. The 914,000-acre (1,400-mi^2) Paria River subbasin (HUC 14070007) also has been excluded from this study because surface-water flows from the subbasin discharge below the USGS gage at Lees Ferry, Arizona. The UCRB, for the purposes of this study, has a contributing drainage area of about 69,200,000 acres (108,000 mi^2). Major river drainages in the UCRB include the Green, San Juan, and Colorado Rivers.

The UCRB is bounded by the Wasatch Mountains in northern and central Utah to the west, the San Juan Mountains of Colorado and New Mexico to the southeast, and the Wind River Range in west-central Wyoming to the north (fig. 1). Basin landscapes vary, ranging from high alpine to arid desert. Annual precipitation ranges from about 40 inches, mostly as snow, near the continental divide to less than 10 inches on the Colorado Plateau (PRISM Group, Oregon State University, 2007). Land cover in the basin is characterized by mixed desert scrub and rangeland, irrigated agriculture, and forested highlands. The largest urban area in the UCRB is Grand Junction, Colorado with a population of approximately 42,000 according to the 2000 Census (U.S. Census Bureau, 2000).

Sources of Dissolved Solids

Geologic formations, particularly sedimentary rocks, are the largest natural source of dissolved solids transported to streams in the UCRB (Iorns and others, 1965; Liebermann and others, 1989; U.S. Department of the Interior, 2003; Anning and others, 2007; Kenney and others, 2009). Dissolved solids are produced from geologic formations containing soluble minerals that are dissolved by surface runoff and groundwater flow (Kenney and others, 2009). Saline springs discharge substantial quantities of dissolved solids from groundwater and may contribute as much as 800,000 tons of dissolved solids per year to UCRB streams (U.S. Department of the Interior, 2003). Irrigated agricultural lands are the major anthropogenic source of dissolved solids in the UCRB (Iorns and others, 1965; Liebermann and others, 1989; U.S. Department of the Interior, 2003). Irrigation in arid environments can alter the natural rate at which solids are dissolved and transported to streams.

Dissolved-solids concentrations in streams differ throughout the study area as a result of varying climatic, hydrologic, and geologic conditions. A significant factor determining the composition of dissolved-solids concentrations is the predominant rock types and the soils derived from those rock types within a drainage basin. In general, sedimentary rock assemblages of Mesozoic and Cenozoic age yield the largest volumes of dissolved solids in the UCRB (Kenney and others, 2009). The middle and lower reaches of the Colorado, Green, and San Juan Rivers are underlain by sedimentary rocks that contain soluble minerals that have the potential to contribute to dissolved-solids loads in the UCRB (Iorns and others, 1965).

Removing native vegetation and disturbing and compacting native soils to construct unpaved, or loose-surface, roads and drill pads can increase erosion from both wind and water at the disturbed site. Arid-land soils are often stabilized by chemical and biological crusts. Even a slight disturbance of these crusts can lead to active erosion of a previously stable ground surface (Wilshire and others, 1996). Compaction of soils from road construction, drill pad construction, and vehicular traffic may alter soil structure and thereby reduce infiltration capacity, which can increase runoff, erosion, and transport of loose soil material. Bare ground associated with drill pads and access roads may aid the efficiency of dissolved-solids transport from high-yield sedimentary assemblages by increasing the total sediment load of runoff waters. Dissolved solids are produced from sediment load by chemical dissolution of soluble mineral components in the sediment during fluid transport of eroded materials. Efforts are made to mitigate the potential for erosion from drill pads and access roads. BLM construction guidelines suggest, when appropriate, trapping well location runoff and sediments by using sediment fences or water retention ponds (U.S. Bureau of Land Management, 2007).

Estimation of Area Disturbed by Oil and Gas Development

Estimates of land disturbance associated with oil and gas resource development in the UCRB were developed in several phases. First, documents relating to oil and gas Best Management Practices (BMP) and development plans for the UCRB were reviewed and information about common oil and gas drill pad and resource road construction practices were compiled. Second, oil and gas well data from public, state-managed databases were assembled to create a single dataset of well locations for the study area. Information from the state databases was used to identify wells that were likely to be associated with active land disturbance related to drilling and maintaining the well. Third, A GIS-based calibration dataset was developed to show the pattern and extent of oil and gas-related land disturbance in the study area. The calibration dataset was also used to assess the completeness and accuracy of existing GIS-based road datasets for the study area. Finally, an oil- and gas-related land disturbance model for 2007 was created using GIS tools and techniques. The modeled disturbance included land disturbance created by the construction of drill pads and resource roads. The accuracy of the model was evaluated and compared with oil- and gas-related land disturbance data from the calibration dataset. The same methods used to estimate oil- and gas-related land disturbance for 2007 were used to estimate oil- and gas-related disturbance for 1991 and to project potential land disturbance to the year 2025. Each phase is described in detail in the remainder of this section.

Review of Oil and Gas Development Plans and Best Management Practices

Proposed drilling and leasing areas on Federal lands are subject to an evaluation of potential environmental impact under the National Environmental Policy Act of 1969 (NEPA) before sites are cleared and drilling commences. NEPA requires Federal agencies to assess the environmental effects of proposed actions before making decisions (Council on Environmental Quality, 2007). Environmental Assessments (EA) and Environmental Impact Statements (EIS) related to oil and gas development generally outline the number of proposed drill pads for a project or lease area and the average pad size during initial well development and during the life of the project (LOP). EA and EIS documents may also contain descriptions of total anticipated resource road length and width for the initial well development phase and for the LOP. NEPA and other guidance documents were reviewed to identify common drill pad and resource road construction practices in the UCRB. The information gathered and summarized from the reviewed documents was used in conjunction with high resolution aerial imagery showing oil- and gas-related land disturbance to devise the methods used to estimate the extent of land disturbance from oil and gas development described in this report.

A total of 20 draft and final EIS documents for Utah and Wyoming and 8 Master Development Plans (MDP) for Colorado were reviewed and summarized (appendixes 1A–C). MDPs are EA documents developed by BLM Colorado field offices under guidance from onshore oil and gas orders implemented jointly by the U.S. Departments of Interior and Agriculture (U.S. Forest Service and U.S. Bureau of Land Management, 2007). All reviewed documents were obtained from the BLM. No EIS or EA directly related to oil and gas development and implemented exclusively by the U.S. Forest Service (USFS) were evaluated. No EIS or EA for Arizona or New Mexico were reviewed. Initial drill pad size reported for Colorado, Utah, and Wyoming was approximately 3.9 acres, but in-state averages varied widely (table 1). All three states indicated that the average drill pad size throughout the LOP was 1.5 acres or smaller. The average widths of LOP resource roads were less than 30 ft; initial widths were as much as 60 ft. The larger initial width allows large equipment to access the drill pad. The road is partially reclaimed to a narrower width after the well is completed. During the draft EIS and EA process, several alternative plans are usually suggested with one scenario identified as the preferred development plan. Resource road and drill pad dimensions summarized in table 1 are based on the preferred alternative proposed in the draft document or are based on the final EIS if available.

Suggested BMPs regarding drill pad and resource road construction are outlined in the BLM Gold Book (U.S. Bureau of Land Management, 2007) and Manual 9113 (U.S. Bureau of Land Management, 1985). The Gold Book recommends that drill pads be located in level areas away from narrow ridges and steep slopes. The Gold Book further recommends that operations be avoided or properly mitigated in riparian areas, floodplains, playas, lakeshores, wetlands, and areas subject to severe erosion and mass soil movement. Documents reviewed for this study recommend that a 500-ft wide buffer of undisturbed land will be maintained between construction areas and perennial stream channels or open water. The buffer area is usually reduced to 100 ft for ephemeral and intermittent stream channels. BLM guidelines suggest that resource road gradients should not exceed 8 percent except for short lengths to minimize the environmental effects of erosion.

Compilation of Oil and Gas Well Data

The location and current status of oil and gas wells in the UCRB is maintained in oil and gas well databases by each state in the region. Well information is also available from private companies that maintain subscription-based oil and gas well databases. The privately managed databases have restrictions on reuse and dissemination of the data. Because of these restrictions, state information held in publicly available databases was used in this study as the basis for estimating the total area of oil- and gas-related land disturbance in the UCRB. Colorado, New Mexico, Utah, and Wyoming maintain well records online (Colorado Oil and Gas Conservation Commission, 2007; New Mexico Institute of Mining and Technology Petroleum Recovery Research Center, 2007; Utah Division of Oil, Gas, and Mining, 2007; Wyoming Oil and Gas Conservation Commission, 2007). Arizona maintains records that are available upon request (Steve Rauzi, Arizona Geological Survey, written commun., August 7, 2007). Records in the databases represent wells permitted on state, local, private, Tribal, and Federal lands in each state. Well information contained in the state databases includes American Petroleum Institute (API) identification numbers, the geographic location of the well, and information about the well's status, and spud date. The spud date is the date drilling began (Schlumberger Limited, 2009).

Tabular well data from the state oil and gas databases were acquired in the summer of 2007. The data from each state was migrated to a new table that was composed of a standard set of attributes, including the location of each well, the unique API number of the well, the spud date of each well, and the current status of the well. Attributes in a table or database are columns or fields of information that are used to describe the features in the table. Each state well record included an alphabetic code used to describe the status of the well. The state well status codes were modified before inclusion in the

Table 1. Average oil and gas drill pad and resource road dimensions reported in reviewed Bureau of Land Management National Environmental Policy Act documents for states in the Upper Colorado River Basin.

[A list of reviewed documents is in Appendixes 1A–C. LOP, life of project; ROW, right of way; ft, feet]

	State			State average
	Utah	Colorado	Wyoming	
Average estimated initial pad size (acres)	2.50	5.00	4.10	3.9
Average estimated LOP pad size (acres)	1.40	1.25	1.50	1.4
Lifetime average pad size by State (acres)	1.95	3.13	2.80	2.6
Average estimated initial ROW width (ft)	32.50	59.00	52.00	47.8
Average estimated LOP ROW width (ft)	21.00	26.00	28.00	25.0
Lifetime average ROW width by State (ft)	26.75	42.50	40.00	36.4

new table by appending the two letter American National Standards Institute (ANSI) state alpha code (U.S. Census Bureau, 2008) to the state status code. Appending the state ANSI code to the state status code prevented confusion when two states used the same set of letters to identify different well status conditions. For example, the well status code SP identifies a spudded well in the Wyoming state database and a plugged and abandoned storage well in the Arizona state database. These codes were modified to WY-SP and AZ-SP to maintain the state definitions and create unique well status codes in the new table. Most of the wells in the state databases were either categorized as drilled and completed as producing wells, or drilled and abandoned at the time the state data were acquired. Some wells in the state databases were permitted but not drilled at the time the data were acquired.

The state databases included spud dates and status dates. Status dates could be associated with either database maintenance or with the date when the well's status changed. Status date was not clearly defined for any of the state databases. The attribute "status date" was maintained in the new table to provide temporal information for wells where spud dates were missing or incomplete. API numbers and well locations expressed in latitude and longitude were transferred directly from the state databases to the new table. Attributes used to identify the disturbance classification and location source information for each well were included in the new table and determined for this study.

Each state table was converted to a point feature class stored in a geodatabase. A feature class is a dataset, or collection of geographic features, that have the same geometry type (such as point, line, or polygon), the same attribute fields, and the same spatial reference (Environmental Systems Research Institute, 2009a). A geodatabase is a database used to store, query, and manipulate spatial data (Environmental Systems Research Institute, 2009a). Each point in the feature class represented a well location based on the latitude, longitude, and datum information supplied by the states. Latitude or longitude information was missing for over 2,000 New Mexico well records. The New Mexico database included Public Land Survey System (PLSS) township, range, and section with each well record. The location of wells with incomplete location information was estimated from the PLSS information using the BLM township geocoder. The township geocoder allows township, range, section, and quarter section values to be converted into latitude and longitude (U.S. Bureau of Land Management and U.S. Forest Service, 2008a). The location returned by the geocoder is the centroid of the section or quarter section polygon that is input to the geocoder interface. Well locations estimated using the PLSS information were identified in the well feature classes in an attribute named "location source." The individual feature classes were projected to Albers Equal Area Projection, merged into a single feature class, and clipped to the boundary of the study area to create the final 2007 UCRB oil and gas well dataset. The final well dataset contained 89,282 points representing well locations in the study area.

A simplified common status (CS) code attribute was added to the 2007 UCRB oil and gas well dataset and defined for four well types: "active", "inactive", "abandoned–disturbed", and "abandoned–not disturbed." State status codes identifying a well as producing, spudded, or active were assigned the CS code "active." Wells with state status codes indicating the well had been permitted but not yet drilled or identifying the well as an abandoned location were assigned the CS code "inactive." About 20,000 wells in the 2007 UCRB oil and gas well dataset had a state status code indicating the well had been plugged and abandoned. CS codes were assigned to each plugged and abandoned well location on the basis of visual inspection of randomly selected wells plotted on top of 2005–2007 1-meter resolution National Agricultural Imagery Program (NAIP) imagery (U.S. Department of Agriculture, 2006). Land disturbance was clearly visible in the NAIP imagery at the locations of most inspected well locations drilled in the mid-1970s and later. Land disturbance was less evident or absent at older well locations. Wells dated from 1975 or later were assigned the CS code "abandoned–disturbed" on the basis of this observation. Plugged and abandoned wells dated before 1975 were coded "abandoned–not disturbed." Status date was substituted for spud date when assigning the CS code to 30,764 wells because spud dates were missing in the source data. Substituting status date for spud date assumes that the well's status date has some relation to drilling activity and is not simply related to database maintenance activities. Both spud date and status date were missing for 7,162 wells in the 2007 UCRB oil and gas well dataset and several wells had invalid date information, such as 7/1/5003 and 12/1/2402. Plugged and abandoned wells with no status or spud date or with invalid status or spud dates were assigned the CS code "abandoned–not disturbed." Lack of date information or substitution of dates can affect the accuracy of the CS code a well was assigned.

Common status codes were used to further classify each well as "disturbed" or "not disturbed." For the purposes of this study, an oil and gas well that is classified as "disturbed" is assumed to be associated with an area of active land disturbance related to the drill pad constructed to contain drilling equipment and the road used to access the drill pad. The land is disturbed by removing the natural vegetation and modifying natural topography to accommodate drilling and well maintenance activities. The disturbed drill pad area and road are maintained for access to the well head if the well becomes a producing well. Wells with CS codes "active" or "abandoned–disturbed" were classified as "disturbed." Wells with all other CS codes were classified "not disturbed." In the database, 61,780 wells (69 percent of the total) are classified as "disturbed" (fig. 3). The 2007 UCRB oil and gas well dataset can be downloaded from the USGS at http://water.usgs.gov/GIS/metadata/usgswrd/XML/sir2010_5064_UCRB_ogdb.xml.

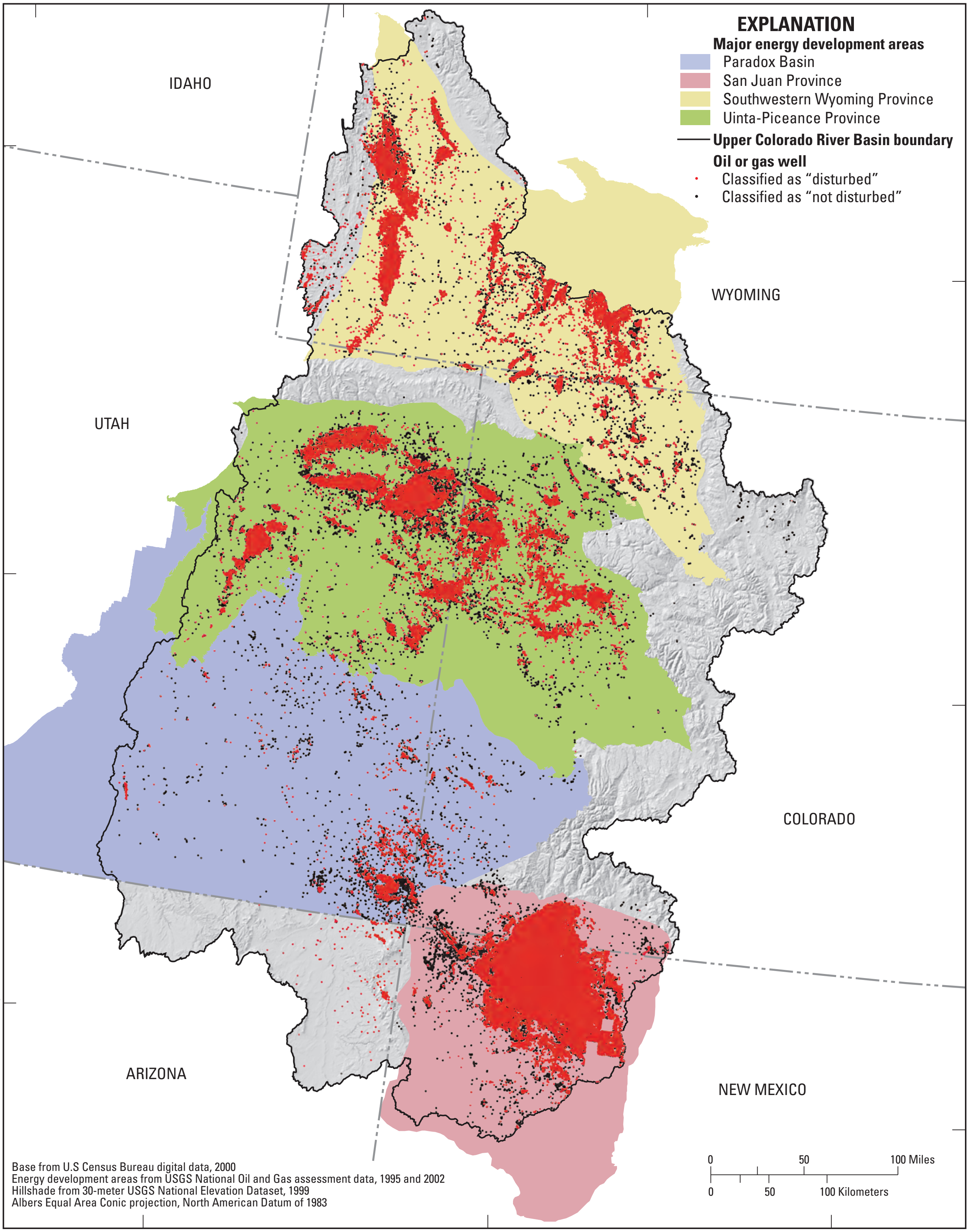

Figure 3. Oil and gas well locations classified as "disturbed" and "not disturbed" in the Upper Colorado River Basin, 2007.

Developing a Calibration Dataset to Measure Land Disturbance from Constructing Oil and Gas Drill Pads and Resource Roads

A calibration dataset was developed to help systematically measure resource road and drill pad geometry across the UCRB, to verify information gathered from BMP and development plans, and to calibrate and assess the accuracy of the methods used to estimate oil- and gas-related land disturbance in the study area described in the report section titled “Methods Used to Estimate Land Disturbance Associated with Oil and Gas Development.” The extent of the calibration data were constrained by 100-km^2 (38.6-mi^2) calibration cells that were randomly selected from a feature class containing a continuous grid of cells distributed across the study area. To select the calibration cells, 100 randomly placed points were produced within the boundaries of the continuous grid. The points were created using a GIS tool that randomly generates a specified number of points within a user-defined area (Environmental Systems Research Institute, 2009b). No constraint was placed on the number of points that could be placed within a single grid cell. Grid cells that contained one or more randomly generated points were selected as calibration cells. The final selection consisted of 76 cells, each of which was assigned a unique identifying number (fig. 4).

The land area within each of the 76 calibration cells was inspected for visible surface disturbance that could be attributed to oil and gas development. Each calibration cell was examined on a computer screen against a backdrop of 2005–2007 NAIP imagery (U.S. Department of Agriculture, 2006). Sixty of the selected calibration cells contained oil- and gas-related land disturbance. The remaining 16 contained no land disturbance that could be attributed to oil and gas development.

Land disturbance that could be attributed to oil and gas development within the boundaries of each calibration cell was manually digitized into the calibration dataset. Visible drill pads were digitized into the calibration dataset as polygons (fig. 5). The extent of the digitized polygon was constrained by the boundary of the calibration cell; therefore, only the part of the drill pad inside the calibration cell was digitized. Well locations from the UCRB oil and gas database were used to help identify bare areas visible in the NAIP imagery as oil and gas drill pads. Bare areas that showed characteristics common to drill pad construction, such as the presence of a pit for containment of drilling fluids or a characteristic rectangular shape with a visible access road, were digitized even if no well point fell within or near the bare area.

Resource roads were digitized from the road’s origin at the edge of the drill pad to the location where the resource road intersected an existing road contained in a USGS Digital Line Graph (DLG) dataset (fig. 5). DLG data are digital representations of cartographic information converted from maps and related sources (U.S. Geological Survey, 1996a). The DLG data used to represent existing, or baseline, roads for this analysis were produced from USGS 1:100,000-scale 30- by 60-minute topographic quadrangle maps and BLM 1:100,000-scale planimetric maps. The DLG roads were used to represent existing roads for this study to maintain continuity with the earlier SPARROW study for the UCRB (Kenney and others, 2009), for which the DLG roads were used to calculate road densities in the study area. For this study, the DLG road datasets were compared with more recent road datasets, including the 2001 National land cover data impervious surface (Multi-Resolution Land Characteristics Consortium, 2001) and Bureau of Transportation Statistics roads data (U.S. Geological Survey, 2007) and found to be of similar resolution and quality. None of the datasets evaluated as potential baseline road layers accurately captured the extent of the unpaved road network visible in the NAIP imagery in the study area. Resource roads were digitized into the calibration dataset as lines representing the approximate centerline of the road and classified as either primary or secondary oil and gas roads (fig. 5). The extent of the digitized line representing an oil and gas road was constrained by the boundary of the calibration cell so that only the part of the road inside the cell was digitized. If the source drill pad was alone or far from other drill pads, a single primary resource road was designated for the drill pad and other roads directly connected to the drill pad were classified as secondary access roads. If the drill pad was part of a large network of drill pads, roads that appeared to be directly connected in a network and could be used for primary access to the drill pads were digitized and classified as primary roads. Secondary roads were digitized only when directly associated with a drill pad. Additional roads that connected with the primary resource road or secondary access roads were assumed to have been created by other activities, such as recreational driving, grazing access, or short cutting between pads, and not directly associated with oil and gas development.

Methods Used to Estimate Land Disturbance Associated with Oil and Gas Development

Land disturbance associated with oil and gas development is not regularly or consistently mapped in the UCRB at state or regional scales. Accurately mapping oil- and gas-related land disturbance is difficult because of the large spatial extent of the study area. Land disturbance estimates developed for this study were based on information gathered from existing oil and gas well databases, information from EIS and other guidance documents, and observations made from aerial imagery rather than from mapping the precise extent and location of all oil and gas-related land disturbance in the study area. Estimates of land disturbance from drill pads are described in the next section followed by a description of the methods used to model land disturbance from resource roads.

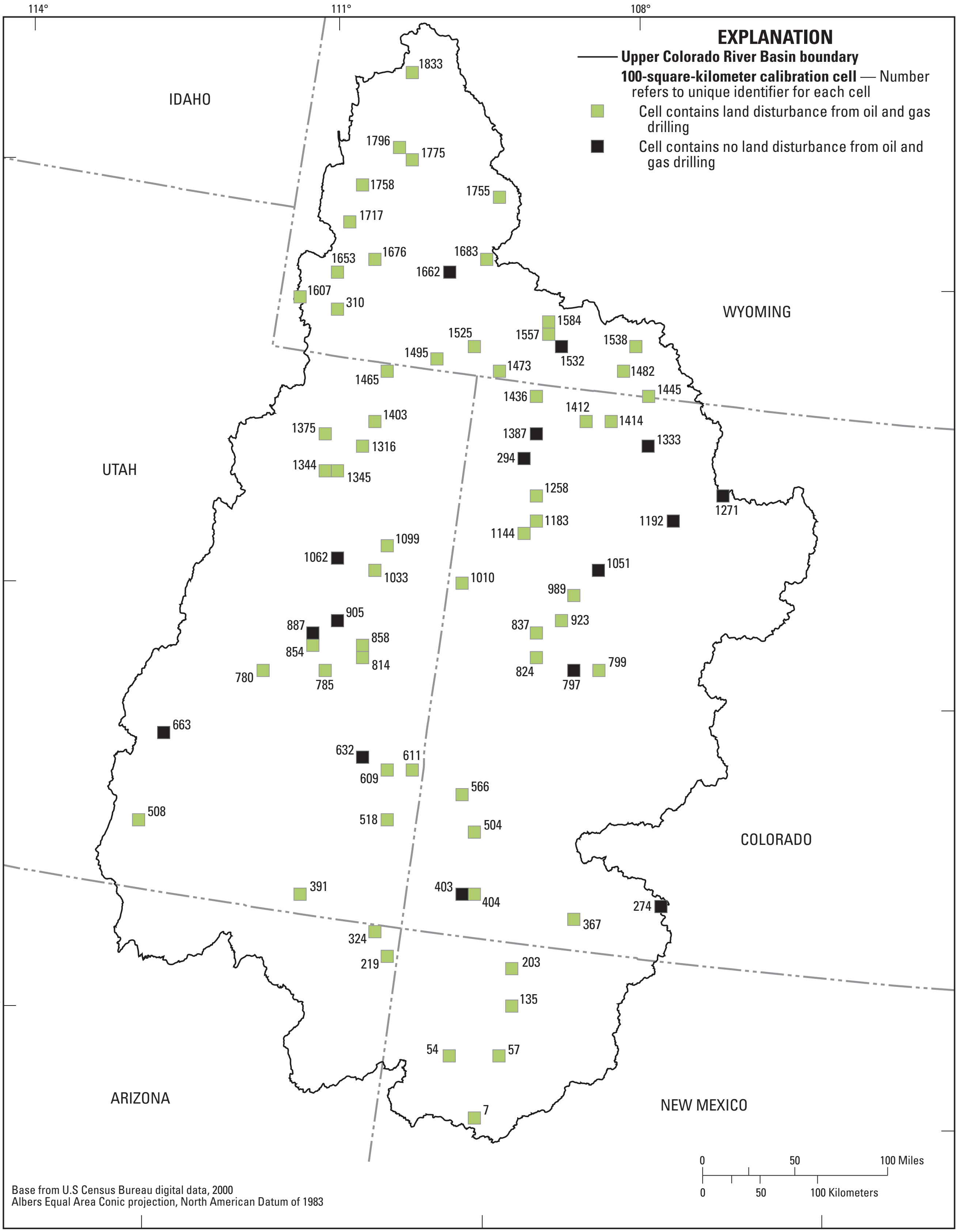

Figure 4. Location of 76 cells used to create the oil- and gas-related land disturbance calibration dataset, Upper Colorado River Basin.

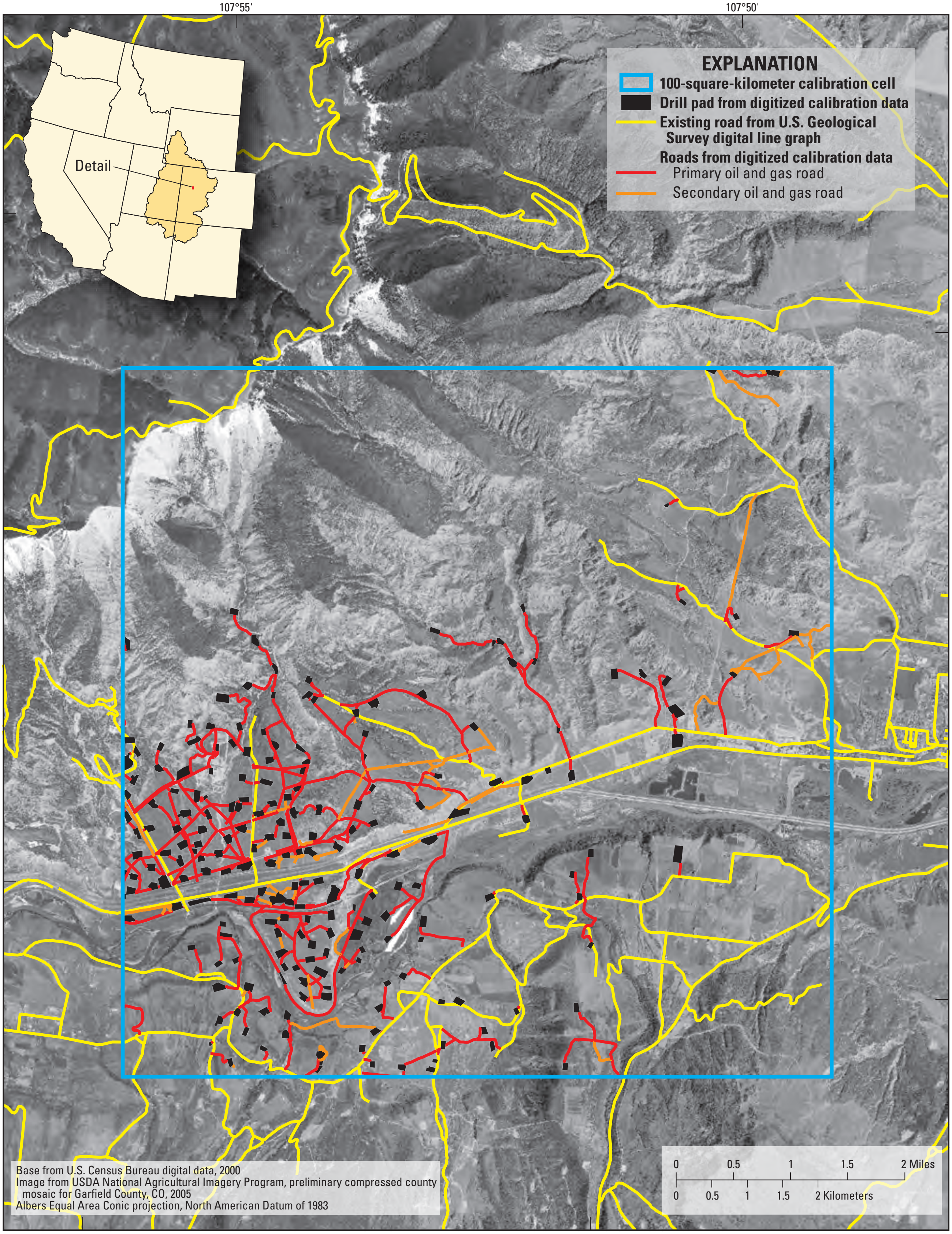

Figure 5. Digital line graph roads, primary and secondary oil and gas roads, and drill pads in a calibration cell near Rifle, Colorado, 2007.

Description of Methods Used to Estimate Land Disturbance Associated with Oil and Gas Drill Pads

Information from the reviewed NEPA and BMP documents and measurements based on the calibration dataset were used in conjunction with the UCRB oil and gas well dataset to develop estimates of land disturbance from oil and gas drill pad construction. A circular buffer was created around each well classified as “disturbed” in the 2007 UCRB oil and gas well dataset and stored in a GIS feature class. The buffer is a circular polygon with the well point at the center of the polygon. The radius of the circle is the specified buffer size. Areas where buffers overlapped were treated as a single area of disturbance.

A series of differently sized buffer polygons ranging in radius from 175.5 to 182.1 ft (53.5 to 55.5 m) were compared to the calibration dataset. The selected buffer sizes correspond to a drill pad model that ranges in size between 2 and 2.5 acres. Buffer sizes were selected to correspond with average pad sizes reported in reviewed NEPA documents (table 1, appendix 1A-1C) and with measurements taken from the calibration dataset. The total modeled pad area from each tested buffer size was compared with the total pad area digitized in the calibration dataset. A 177.2-ft (54-m) radius buffer underestimated the total drill pad disturbance measured in the calibration dataset by less than 1 percent. The area of a circle with a 177.2-ft radius equals 2.26 acres. The area of land disturbed by oil and gas drill pads in the UCRB for 2007 was modeled by applying a 177.2-ft radius buffer to wells in the 2007 UCRB oil and gas well dataset that were classified as “disturbed” (fig. 6).

Description of Methods Used to Estimate Land Disturbance Associated with Oil and Gas Resource Roads

BLM road construction guidelines suggest that a single resource road should be constructed to access a drill pad. Additional roads connected to drill pads may be the result of shortcuts created by drilling and well service personnel or by recreational driving and off-road vehicle traffic that is unrelated to oil and gas development. For this analysis, road disturbance from resource roads is assumed to occur on a single access road originating at a drill pad and terminating at an existing road mapped in the 1:100,000-scale USGS DLG roads dataset previously described.

GIS least-cost distance tools were used to model the location of the single, primary resource road used to access each oil and gas drill pad. The least-cost path method models a path from a source to a destination based on a raster, or cell-based cost surface (Environmental Systems Research Institute, 2008). The cost surface is created by applying a weight to each raster cell. The weight assigned to each cell represents the difficulty associated with travel through the cell. Higher weights are assigned to cells where travel should be restricted. For example, when modeling the fastest route between destinations on an existing street network, the cost surface may be constructed using existing speed limits as weights. Raster cells representing roads with slower speed limits would be assigned a higher cost value so that the slowest routes correspond with the highest cost of travel. Costs are usually based on inherent features in the location (Environmental Systems Research Institute, 2008). High costs may be assigned to travel on steep slopes or across protected land cover classes, such as wetlands or riparian areas, to restrict the location of modeled paths. Paths created using this method are GIS-based representations of road locations and do not represent actual road locations constructed to access drill pads.

Several cost surfaces based on slope or a combination of slope and simulated riparian areas were tested for this analysis. First, a percent-slope dataset was calculated for the study area from 1 arc-second USGS National Elevation Data (NED; U.S. Geological Survey, 1999a). The NED is a raster representation of elevation. The raster is composed of a grid of square cells each of which is assigned a value representing the average elevation of the area covered by that cell. A raster cell in the 1 arc-second NED represents an area approximately 30 m (98.4 ft) on each side. The percent-slope dataset was reclassified into four separate cost surface datasets. The first dataset contained four classes of slope values. Each class was assigned an arbitrarily chosen integer value that increased with increasing slope. The value assigned to each class represented the cost to travel across the raster cell. The next group contained seven classes. The final two datasets contained 14 and 30 classes respectively. Increasing the number of classes in the cost surface dataset allowed for finer control over the routes created across the cost surface by the model.

A least-cost path model was created using each of the cost surfaces described above. Locations of the oil and gas wells classified as “disturbed” in the 2007 UCRB oil and gas well database were input to the model as destinations. The 1:100,000-scale DLG roads data were input to the model as the sources so that a path was created to each well location from the nearest DLG road along a path calculated by the model. The results were visually inspected and compared with digitized resource roads from the calibration dataset. In all cases, the least-cost path model based on slope cost surfaces created paths that meandered in riparian areas and in areas with shallow slopes.

A buffer area around perennial and intermittent stream courses was created and combined with the cost surfaces to better control the behavior of the cost path model. Stream courses mapped in the medium-resolution National Hydrography Dataset (NHD; U.S. Geological Survey, 1999b) were used to model the riparian areas. The NHD contains codes that identify perennial, intermittent, and other types of stream courses. Stream lines coded as perennial water courses were buffered by 500 ft, and intermittent stream lines were buffered by 100 ft. The buffered streams, representing riparian areas, were converted to raster format, assigned the highest cost value from the slope cost surface, and combined with

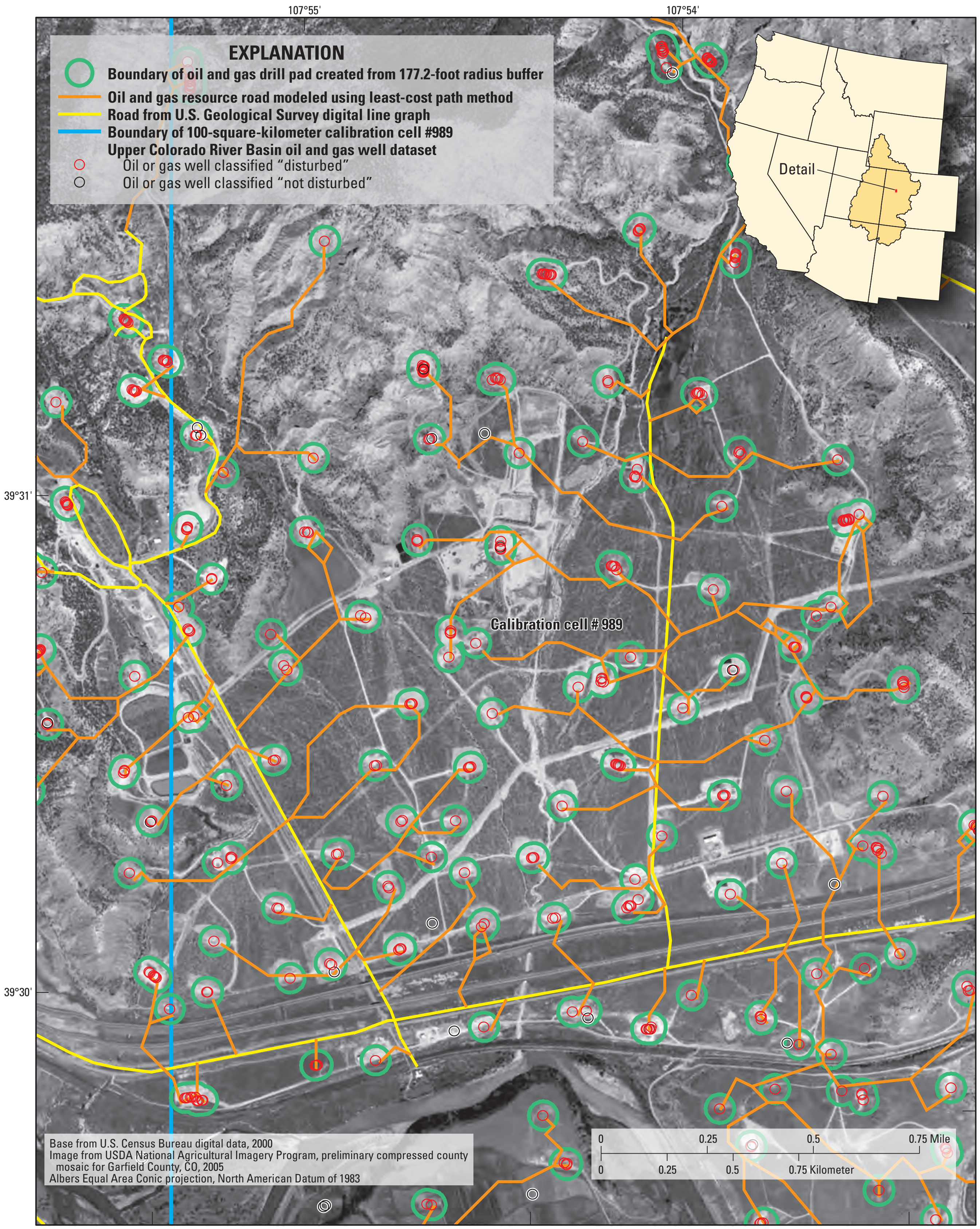

Figure 6. Model of oil and gas drill pads and resource roads overlying National Aerial Imagery Program imagery, near Rifle, Colorado, 2007.

the 14- and the 30-class slope cost surfaces. A least-cost path model was created for each of the riparian-slope cost rasters. The 1:100,000-scale DLG roads were input to the cost path model as the source, and the destination was set to the oil and gas wells that had been classified as “disturbed” in the 2007 UCRB oil and gas well dataset. The results were visually compared to NAIP imagery and the calibration dataset. Paths created from the riparian-slope cost rasters tended to create more direct routes from the source road to the destination well. The 2007 least-cost path datasets were compared with the total length of primary resource roads digitized in the calibration dataset. The path dataset based on 30 slope classes combined with riparian areas most closely matched the total length of primary resource roads measured in the calibration dataset. As previously noted, roads created using least-cost path methods are representations of the primary resource roads (fig. 5) constructed to access drill pads and do not match the exact location of actual roads (fig. 6). If a road in the source DLG dataset was less than 98.4 ft (30 m) from the well destination, no path to the well was calculated in the model because a path already existed. Because of this, the total resource road length estimate does not take into account resource roads that were present in the USGS 1:100,000-scale DLG dataset.

Resource road right of way (ROW) widths were measured in selected calibration cells in the study area. Measured road widths incorporated all visible disturbance, including the main road surface and drainage ditches and berms on either side of the primary roadway. The average measured ROW width was approximately 35 ft, which compares favorably with ROW widths reported in NEPA documentation (table 1, appendix 1A-1C). The total area of land disturbance associated with oil and gas resource roads for 2007 in the UCRB was estimated by creating a 17.5-ft buffer on both sides of each modeled resource road and summing the area of the buffer polygons. A 17.5-ft buffer results in a 35-ft-wide polygon around the modeled resource road.

Description of Methods Used to Estimate Land Disturbance from Past Oil and Gas Development

Estimates of land disturbance associated with oil and gas development through 1991 were required as input to the UCRB SPARROW model (Kenney and others, 2009), which was calibrated to monitoring data for water year 1991 (October 1990–September 1991; a water year is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends). Land disturbance associated with oil and gas development through 1991 was estimated by identifying wells dated 1991 or earlier in the 2007 UCRB oil and gas well dataset. Wells were first selected on the basis of spud year or, if the well had no spud date, status year. Wells that had no spud or status date or had erroneous dates were included in the 1991 estimation. The resulting selection contained 48,073 well locations. Status codes for these wells were assessed in the same manner as that used to assess codes in the 2007 UCRB oil and gas well dataset. Each well was assigned a CS code to indicate whether the well was classified as “disturbed” or “not disturbed.” Wells plugged and abandoned before 1960 were assigned CS code “abandoned–not disturbed” and classified “not disturbed.” Wells plugged and abandoned between 1960 and 1991 were assigned CS code “abandoned–disturbed” and classified “disturbed.” Wells with no spud or status date or with erroneous dates kept their previously assigned CS code “abandoned–not disturbed” and were classified “not disturbed.” In 1991, 36,483 wells were classified “disturbed” and 11,590 wells were classified “not disturbed.” The area disturbed by oil and gas drill pads and resource roads in 1991 was estimated using the same methods as those used to estimate land disturbance in 2007.

Description of Methods Used to Project Land Disturbance from Future Oil and Gas Development

Oil and gas development on public lands in the western United States has increased in the last decade, and will likely continue in the UCRB (U.S. Bureau of Land Management, 2008). The 2007 UCRB oil and gas well dataset and BLM forecasts of potential future oil and gas development were used to project land disturbance from oil and gas development activities through 2025. RMPs are developed to guide management decisions for large areas of Federal land in the western United States. RMPs often cover a span of 10 to 15 years and are usually developed by BLM field offices but may also be produced as cooperative agreements between multiple land-management stakeholders in a region. An example of a cooperative management plan is the San Juan Public Lands RMP developed jointly by the USFS and BLM (U.S. Bureau of Land Management, 2009b). RMPs commonly include RFD documents outlining the amount and types of resource extraction activity expected for the life of the RMP. Seventeen RMPs were reviewed to estimate future oil and gas development in the UCRB (appendix 2).

Information from RMPs was integrated into a single table identifying the projected development expected within the resource area covered by the RMP (table 2). The BLM field offices reported RMP information in different ways, some offices presenting minimum and maximum anticipated development and others presenting a single value representing expected development. This study did not revise or modify BLM estimates derived from the RMPs but did use conservative methods to calculate average anticipated development within the study area. RMP estimates were usually associated with known resource areas or with USGS “plays” identified in the National oil and gas assessment (U.S. Geological Survey, 2009). A “play” is a set of known or postulated oil and/or gas accumulations sharing similar geologic, geographic, and temporal properties (U.S. Geological Survey, 1996b). Most of the RMP documents examined were published between the years 2000 and 2008.

Table 2. Summary of oil and gas development forecasts from Bureau of Land Management resource management plans for the Upper Colorado River Basin.

[BLM, Bureau of Land Management; RMP, Resource Management Plan]

Resource area	Anticipated number of wells reported in BLM RMP		BLM field office	RMP date	Length of RMP (years)	Comments
	Minimum	Maximum				
San Juan Basin (New Mexico and Colorado)	12,461	16,615	Farmington, Columbine	2001	20	Based on New Mexico estimates of expected subsurface completions.
Glenwood Springs-Roan Plateau	2,976	3,691	Glenwood Springs	2006	20	Maximum value is based on number of wells in proposed alternative. Minimum value is based on number of wells estimated in no action alternative.
Grand Junction operational area	300	1,000	Grand Junction	1985	20	Assumed same drilling densities from 1985 RMP.
Kemmerer gas	2,680		Kemmerer	2008	20	Coal and non-coal gas totals.
Little Snake operational area	3,031		Little Snake	2007	20	
Moab operational area	150	600	Moab	2005	15	Sum of all reported areas in Moab field office RMP.
Colorado San Juan public lands	1,185		Multiple - see comments	2007	15	San Juan public lands RMP. Covers parts of Dolores, Columbine, and Pagosa Springs BLM field offices.
Jonah	500	3,100	Pinedale	2008	20	
LaBarge and south central	120	2,000	Pinedale	2008	20	Counts calculated based on 20 to 100 wells per township density.
Merna	1,152	2,304	Pinedale	2008	20	Counts calculated based on 1 to 2 wells per 40 acres.
Pinedale Anticline	900	2,450	Pinedale	2008	20	
Pinedale coalbed gas	600		Pinedale	2008	20	Based on estimate of 600 wells in low potential areas.
Emery-Book Cliffs-Price operational area	940		Price	2004	20	Sum of Book Cliffs/Emery and remainder of Price planning area.
Tavaputs Plateau - Price	600		Price	2004	20	
Rawlins area	8,822		Rawlins	2008	20	
Richfield area 1, 2a, and 3b	94		Richfield	2005	15	Area 4c (potential 360 wells) is largely outside the study area and was omitted from these estimates.
LaBarge - Rock Springs west	80	400	Rock Springs	1997	20	Based on Pinedale LaBarge and south-central estimates.
Rock Springs central and east	3,000		Rock Springs	1997	20	Estimate based on density of drilling in Rawlins RMP.
Altamont-Bluebell	425		Vernal	2008	15	Oil, gas, and coalbed gas.
East Tavaputs Plateau	677		Vernal	2008	15	
Manila-Clay Basin	42		Vernal	2008	15	
Monticello operational area	75	315	Monticello	2008	15	Total of reported values for Paradox fault and fold belt, Blanding subbasin, and Monument upwarp.
Monument Butte - Red Wash	4,658		Vernal	2008	15	
Tabiona-Ashley Valley	28		Vernal	2008	15	
West Tavaputs Plateau	454		Vernal	2008	15	
White River operational area	18,200	21,650	White River	2007	20	Oil and gas plus coalbed methane wells included in estimate.

One plan was from 1997 and one from 1985. Oil and gas development estimates outlined in older documents were included in the analysis with the assumption that development activities in these geographic areas would continue 20 more years at the pace outlined in the older document. The average number of wells reported for each resource area or play was calculated from the minimum and maximum number of wells reported in each RMP. If no minimum was reported, the average was calculated as half the reported number of expected wells. In some cases, the expected development was reported as the anticipated density of wells within a known resource area. These data were converted to an expected number of wells on the basis of the total area of anticipated development cited in the RMP. The RMP for the Farmington, New Mexico, field office area reported development in terms of expected subsurface completions. The reported values were used with the assumption that each completion would be associated with a single drill pad. Calculating the number of disturbed drill pads using the average number of subsurface completions may result in overestimating drill pad densities in the geographic area covered by the RMP.

Existing oil and gas resource areas were identified from digital state oil and gas maps (De Bruin, 2002; Chidsey and others, 2004; Wray and others, 2005), resource areas from the 2006 BLM Energy Policy and Conservation Act (EPCA) report (U.S. Bureau of Land Management, 2006), and BLM township and range polygons (U.S. Bureau of Land Management and U.S. Forest Service, 2008b). Known oil and gas development areas were selected and cross-referenced with the areas reported in the reviewed RMP documents. The selected areas were merged with a GIS dataset of leasable land parcels from the BLM EPCA report. Merging the selected oil and gas development areas with leasable land parcels created a dataset which represented resource areas where future oil and gas drilling is likely to occur. The resource areas represented areas of anticipated activity in the total area reported in the RMP and occasionally extended outside the UCRB boundary. The average annual number of wells anticipated for each resource area was estimated by dividing the calculated average number of wells for each resource area by the number of years covered by the RMP pertaining to that resource area (table 2). The calculated average annual number of wells was used to estimate the total number of wells that are projected to be drilled in each resource area between 2007 and 2025 (fig. 7).

To estimate the total cumulative number of wells associated with active disturbance that could be expected in 2015, the 2007 UCRB oil and gas well dataset was modified by assuming that disturbance associated with wells in the dataset that had been plugged and abandoned between 1975 and 1983 would be successfully restored to natural or near natural conditions between 2007 and 2015. These wells, previously assigned CS code "abandoned–disturbed", were selected and assigned CS code "abandoned–not disturbed." Random points representing new wells were generated within the resource area polygons. The number of random well points generated within a resource area equaled the calculated number of wells anticipated for the 8-year period between 2007 and 2015. The new wells were assigned CS code "active" and classified as "disturbed." The wells were clipped to the study area boundary and merged with the modified 2007 UCRB oil and gas well dataset to create an oil and gas well dataset representing an estimated number of oil and gas wells in the UCRB projected to 2015. The process was repeated in two additional time steps for the periods 2015 to 2020 and 2020 to 2025. Wells in the 2007 UCRB oil and gas well dataset that had state status codes identifying them as plugged and abandoned and with CS codes "abandoned–disturbed" were reassigned CS code "abandoned–not disturbed" in 5-year time steps as the future development scenarios progressed forward. Reassignment of CS codes was based on the assumption that disturbed land area would be successfully reclaimed and that disturbance would no longer be evident at well locations more than 30 years old. Disturbance was modeled for all wells in the final 2025 dataset using the same methods as those used to estimate disturbance for the 2007 UCRB oil and gas well dataset. Modeled resource roads were created from existing DLG roads to the new set of wells classified as "disturbed" using the same methods as those used to create resource roads for the 2007 UCRB oil and gas well dataset.

Estimated Current and Projected Future Land Disturbance from Oil and Gas Development

A total of 36,483 wells were classified as "disturbed" in 1991. The total modeled pad area (2.26 acres each) associated with these wells was about 78,800 acres (123 mi^2) (fig. 8A). In 2007, 61,780 wells were classified as "disturbed" and the modeled disturbance from drill pads increased to about 120,400 acres (188 mi^2). Disturbance projections based on BLM RMPs indicate that the number of wells classified as "disturbed" could increase to about 109,500 by 2025, and projected land disturbance from constructing new oil and gas drill pads could increase to as much as 222,800 acres (348 mi^2) by 2025.

The total length of oil and gas resource roads in the study area was estimated to be about 9,000 mi in 1991 and about 13,500 mi in 2007. The length estimate is based on the assumption that a single access road was constructed to each well location classified as "disturbed" in the 2007 UCRB oil and gas well dataset for those years (fig. 8B). The total length of resource roads could increase to 22,500 mi by 2025 if average anticipated development scenarios are met. The modeled resource road length was based on calculating the shortest path from a well site classified as "disturbed" to the nearest mapped DLG road and pairing each well site with a single primary access road. Assuming a 35-ft ROW width, the total area disturbed by resource roads associated with wells classified as "disturbed" was approximately 38,700 acres (60 mi^2) in 1991 and was projected to be 58,950 acres (92 mi^2) by 2007. Road disturbance could increase to 96,500 acres (151 mi^2) by 2025.

The total modeled area of land disturbance from drill pads and roads was 117,500 acres (183 mi^2) for 1991 and 179,350 acres (280 mi^2) for 2007 (fig. 8C). The total area disturbed by oil and gas resource development could increase to over 319,000 acres (500 mi^2) by 2025. The predicted rate of growth is linear because the prediction method assumes an average number of wells drilled per year calculated from RMP averages. Actual yearly disturbance is likely to vary over time as resource development varies in response to commodities prices and resource demand.

GIS datasets containing information about Surface Management Agency (SMA) and landowners were acquired from the BLM and the National Atlas of the United States (U.S. Bureau of Land Management, 2006; John Reitsma, Bureau of Land Management, written commun., October 23, 2007; National Atlas of the United States, 2006a, b). The datasets were combined to create a single SMA dataset. The 2007 UCRB oil and gas dataset was merged with the SMA

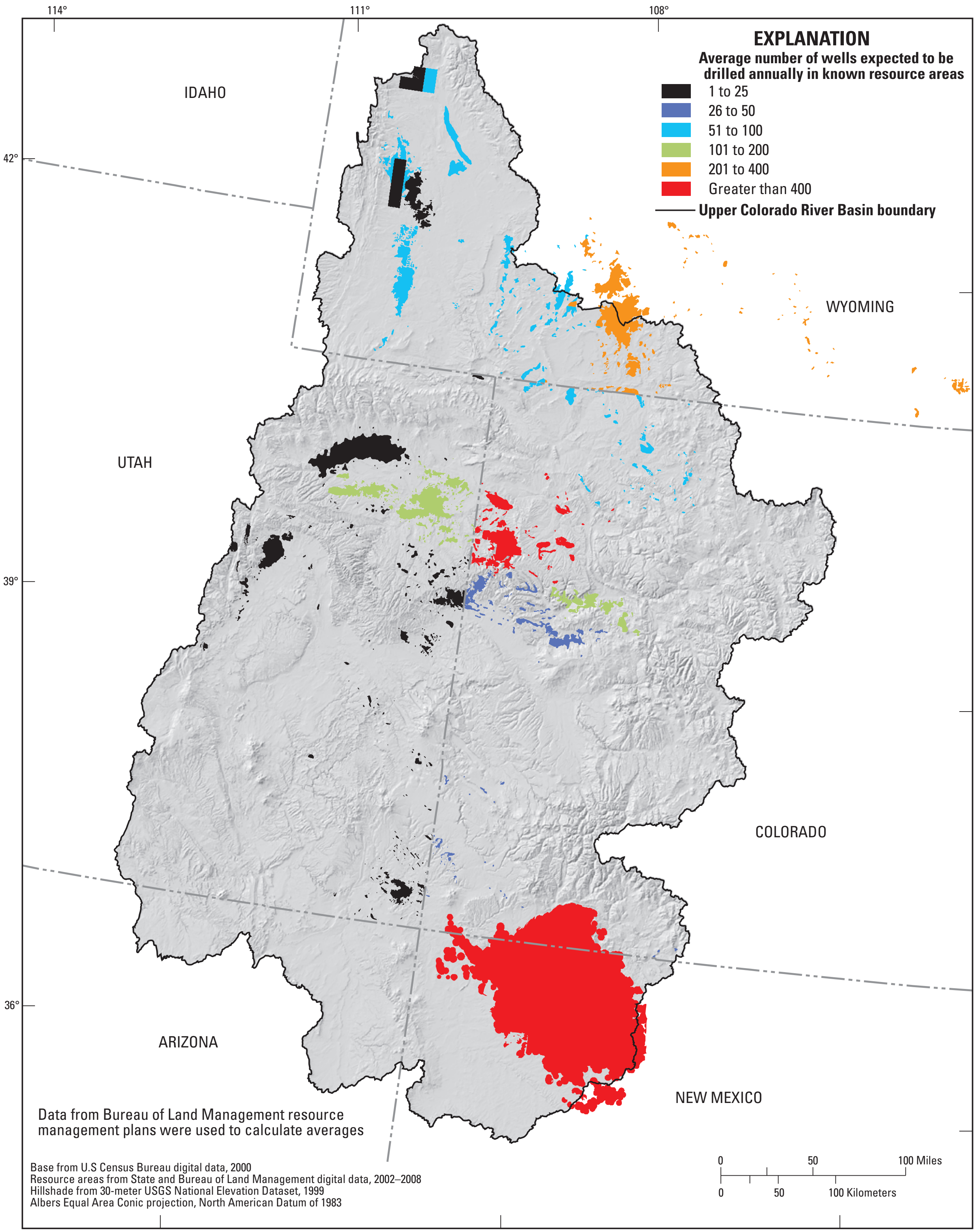

Figure 7. Calculated average annual number of new oil and gas wells anticipated in known oil and gas resource areas, Upper Colorado River Basin and parts of surrounding area.

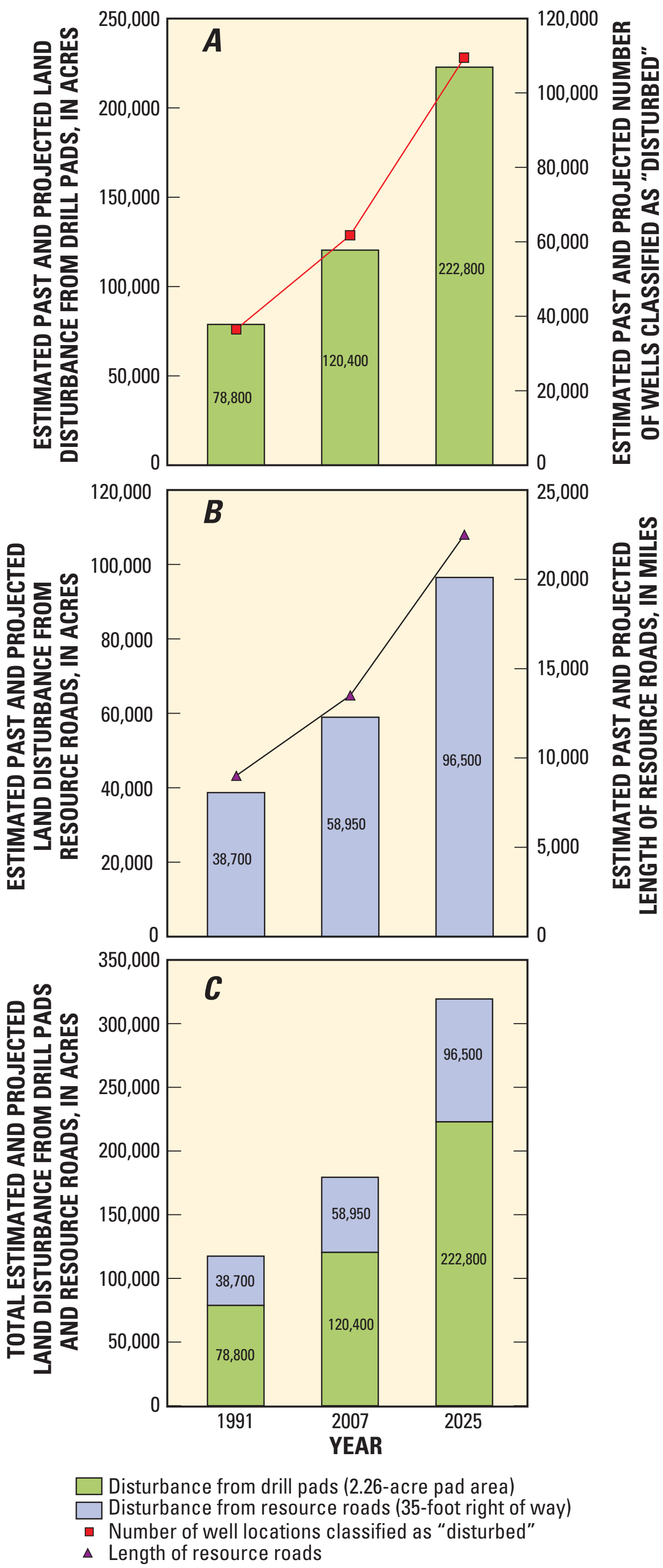

Figure 8. *A*, Number of oil and gas wells classified as "disturbed" and the total estimated area of land disturbed by oil and gas drill pads and *B*, roads, and *C*, by both drill pads and roads, Upper Colorado River Basin, 1991, 2007, and 2025.

dataset to examine the relation between well locations and the SMA. The data show that approximately 48 percent of wells classified as "disturbed" were located on BLM managed land and 25 percent were on private or assumed private land (fig. 9). Assumed private lands are lands within the UCRB that had no assigned SMA or landowner in the SMA dataset. Bureau of Indian Affairs lands contained 13 percent of the wells classified as "disturbed" and approximately 5 percent of wells classified as "disturbed" were on split-estate lands. The distribution of all wells drilled in the study area, classified as "disturbed" and classified as "not disturbed" on each SMA compares well to the percentages of well locations classified as "disturbed" reported above (table 3).

Well densities are highest in New Mexico, where about 35 percent of wells classified as "disturbed" are located (table 4). About 9 percent of the UCRB area is in New Mexico. Approximately 26 percent of wells classified as "disturbed" are in Colorado, and about 18 percent of wells classified as "disturbed" are in Wyoming. About 36 percent and 16 percent of UCRB lands are in Colorado and Wyoming, respectively. Approximately 21 percent of the wells classified as "disturbed" are in Utah, which comprises about 33 percent of the total UCRB land area. Less than 1 percent of wells classified as "disturbed" are in Arizona, which is about 6 percent of the total UCRB area.

Limitations and Considerations of Methodology

The methods described in this report produce estimates of current and projected land disturbance from oil and gas development and do not map the precise locations and extent of all oil- and gas-related land disturbance. This section describes limitations of these methods and attempts to assess some of the uncertainties associated with the land disturbance estimates. Errors in the modeling methods can be related to incorrect well locations and dates and classification methods that generalized actual conditions on the basis of reported well status information. Using a model to create drill pads of uniform size may introduce errors because drill pad sizes vary spatially and temporally. The method used to estimate the impact of resource roads is based on creating modeled paths from the source well to an existing road. The paths are only an estimate of the length and location of resource roads, and the actual length of a road constructed to access an oil or gas well may be over- or underestimated. In addition, ROW widths used to estimate the total area of resource roads were uniform, whereas actual road widths can vary spatially and temporally.

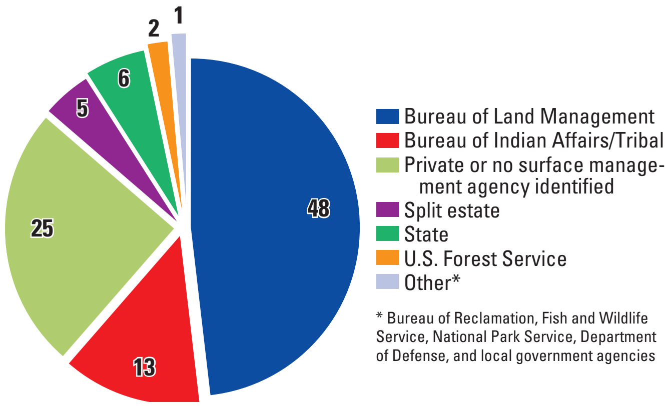

Figure 9. Percentage of oil and gas wells classified as "disturbed" by Surface Management Agency or landowner, Upper Colorado River Basin, 2007.

Table 3. Percentage of all oil and gas wells classified as "disturbed" and "not disturbed", by Surface Management Agency or landowner, Upper Colorado River Basin, 2007.

Surface Management Agency or landowner	Number of wells ("disturbed" and "not disturbed")	Percentage of total
Bureau of Land Management	42,503	48
Bureau of Indian Affairs/Tribal	12,795	14
Private or no SMA identified	21,379	24
Split estate	4,238	5
State	5,256	6
U.S. Forest Service	2,006	2
Other[1]	1,105	1

[1] Bureau of Reclamation, Fish and Wildlife Service, National Park Service, Department of Defense, and local government agencies.

Table 4. Percentage of the oil and gas wells classified as "disturbed" and the percentage of the area in each state contained in the 2007 Upper Colorado River Basin (UCRB) study area.

State	Percentage of 2007 wells classified as "disturbed"	Percentage of total area of UCRB
Arizona	0.3	6
Colorado	26.2	36
New Mexico	35.2	9
Utah	20.6	33
Wyoming	17.7	16

Errors Associated with Well Locations in the 2007 Upper Colorado River Basin Oil and Gas Well Dataset

Well locations from the state databases were randomly checked and verified against 2005–2007 NAIP imagery but no systematic error analysis was made on the source data. The actual location of the oil and gas well may vary from the reported location because of field conditions at the time the well was spudded, map and Global Positioning System (GPS) errors at the time the well was sited, or data entry errors. For example, in the active oil and gas development area near Rifle, Colorado, most wells classified as "disturbed" are located in areas where well-pad disturbance is visible and most wells classified as "not disturbed" are located in areas where pad disturbance is not visible or next to a well classified as "disturbed" (fig. 10). Some wells appear to be mislocated and some bare areas that may be a drill pad have no well point associated with them. Recently permitted wells are likely to be sited more accurately than older wells in the database because of available GPS technology and rule changes requiring that locations submitted during the permitting process are more accurate. Location reporting requirements vary by state and by the age of the well (Utah Division of Oil, Gas, and Mining, 2004; Wyoming Oil and Gas Conservation Commission, 2008; Colorado Oil and Gas Conservation Commission, 2009).

The method used to model areas disturbed by oil and gas development depends on accurate well locations. Although the regional estimate of land disturbance is within 1 percent of the total land disturbance measured in the calibration dataset, locational errors in the 2007 UCRB oil and gas well dataset may translate to over- or underestimating the land disturbed by oil and gas development at local scales. Imagery dates may play a minor role in the error of the estimation. Wells drilled after the NAIP imagery was acquired were not digitized into the calibration data but would have been included as wells classified as "disturbed" in the 2007 UCRB oil and gas well dataset and modeled as areas of land disturbance.

Assessment of Methods Used to Model Land Disturbance from Oil and Gas Drill Pads

Oil and gas drill pads are not constructed with uniform dimensions or areas. State and Federal permitting rules, topographic and environmental conditions at the well site, construction practices, and equipment requirements dictate the actual area and dimensions of drill pads. The estimate of land disturbance from oil and gas development described in this report relies on a model that created drill pads of uniform dimensions that may be larger or smaller than the dimensions of the actual disturbed area. Individual drill pads vary in size over time as the pad areas are partially reclaimed during the production phase of the well and as final reclamation efforts take place.

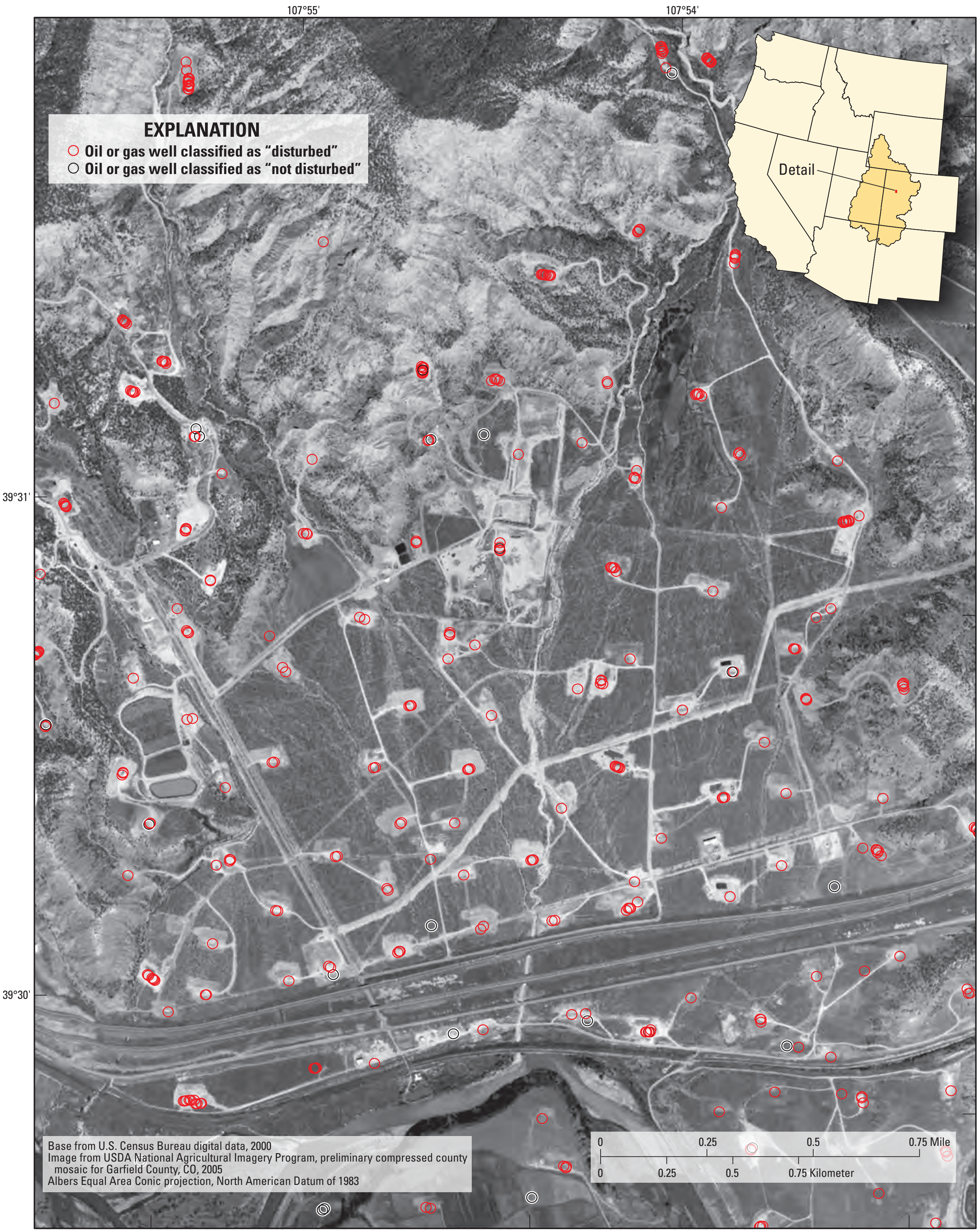

Figure 10. 2005 National Agricultural Imagery Program imagery for an area near Rifle, Colorado, and well locations from the 2007 Upper Colorado River Basin oil and gas well dataset.

The total area of modeled drill pads is within less than 1 percent of the total area of measured drill pads in the calibration cells in 2007. Errors vary within individual calibration cells (fig. 11A). The average total measured pad disturbance for all calibration cells is about 44 acres compared with 54 acres in the land disturbance model (fig. 11B). The median measured disturbance is 7.2 acres compared with 7.9 acres in the modeled data. The maximum disturbed area from drill pads measured in a calibration cell was 558 acres and the maximum modeled area from drill pad disturbance in a calibration cell was 665 acres. Disturbed area from drill pads was underestimated in 41 of 76 calibration cells and overestimated in 24 calibration cells (fig. 11C). No disturbance was measured in 16 calibration cells. No disturbance was estimated in 11 calibration cells so 5 calibration cells that had no measured disturbance contained some estimated disturbance. Figure 11D shows the measured pad areas for all 76 calibration cells compared with the modeled pad areas. The data are generally clustered along the linear trend line with a few outliers.

The model underestimated land disturbance from drill pads most often in Wyoming and Utah, where disturbance was underestimated in 81 percent and 61 percent of the calibration cells, respectively. In Colorado, the model underestimated drill pad disturbance in 36 percent of the calibration cells, overestimated in 36 percent of the calibration cells and was correct in 28 percent of the cells. In Arizona, the model underestimated disturbance in one of the two cells and overestimated it in the other cell. The model overestimated drill pad disturbance in all five calibration cells in New Mexico. Over- or underestimation of land disturbance from oil and gas drill pads may be due to statewide differences in drill pad construction practices or to errors in the source databases used to site the wells. Overestimation in New Mexico may be because of well locations derived from township and range information or because a large number of oil and gas wells are located in agricultural and urban areas around the city of Farmington where mixed land use made land disturbance from drill pads difficult to identify in the NAIP imagery.

Large differences between measured and modeled land disturbance from drill pads were examined to identify reasons for over- or underestimating disturbance. The largest differences were in calibration cell #780 (fig. 4). The disturbance model assigned 17.5 acres of land disturbance to this calibration cell. Calibration cell #780 contained 1.8 acres of measured disturbance from drill pads. The cell contained 13 well locations from the Utah oil and gas database. Two wells were undated. The Utah oil and gas database indicated that the remaining wells were drilled between 1965 and 1985. The two undated wells were identified as abandoned locations in the source database. Of the 11 drilled wells in this calibration cell, disturbed area around only one well drilled in 1984 was visible in the NAIP imagery. No disturbance could be seen near wells located approximately 1.5 mi northwest of the 1984 well and spudded between 1977 and 1985. The lack of visible disturbance may be due to location or date errors in the oil and gas database, differences in the terrain on which the wells were sited, differences in the way the drill pads were constructed, or differences in reclamation activity and success on the drill pads. Lack of visible disturbance may also be because wells were never actually drilled at those locations.

The second largest error occurred in calibration cell #404, which contained 48 wells from the Colorado oil and gas well database. The measured drill pad disturbance in this cell was 4.5 acres. Twenty acres were modeled in calibration cell #404. Only one well in the calibration cell had a spud date and seven wells had neither a spud date nor a status date. The earliest status date was 1911 and the latest date was 1990. Thirty nine of the wells were classified as “not disturbed” and nine were classified as “disturbed” in the 2007 UCRB oil and gas well dataset. Five of the wells classified as “disturbed” were dated between 1976 and 1985 and located in an area where several houses were visible in the NAIP imagery. All well locations were within 300 ft of U.S. Highway 160. Neither the houses nor any disturbance were visible in digital orthophoto quadrangles (DOQ) acquired in the mid-1990s (U.S. Geological Survey, 2006). A minor network of roads connecting the well sites was visible in the NAIP imagery and in the DOQ. The remaining wells classified as “disturbed” were distributed throughout the calibration cell.

Analysis of the differences between modeled and measured land disturbance in calibration cells highlights a limitation of the method used to estimate drill pad disturbance. The disturbance estimation relies on accurate locations, well status, and date information in the source oil and gas databases and assumes that reclamation activities will be uniformly successful across the widely varying landscape of the UCRB.

Assessment of Methods Used to Model Land Disturbance from Oil and Gas Resource Roads

Length of resource roads was modeled using least-cost path methods to create a simulated road network. The disturbed area associated with resource roads was estimated by applying a uniform ROW width to the simulated roads. The following discussion of sources of error in the resource model will focus on the total length of measured roads compared with the total length of modeled roads because road lengths were digitized into the calibration dataset to test the methods used to model roads. Actual road area was not measured in the calibration data, and the accuracy of the area estimate will not be directly assessed.

The total length of modeled primary resource roads within all 76 calibration cells was approximately 395 mi. The total length of primary resource roads measured and digitized in the calibration cells was 364 mi. The total length of primary resource roads estimated by the least-cost path model was approximately 8.5 percent more than the total length of primary resource roads measured in all calibration cells. As with the pad disturbance estimation, the difference between modeled and measured primary road lengths varies by calibration cell. Measured and modeled road lengths correlate well when plotted against each other (fig. 12A). The average

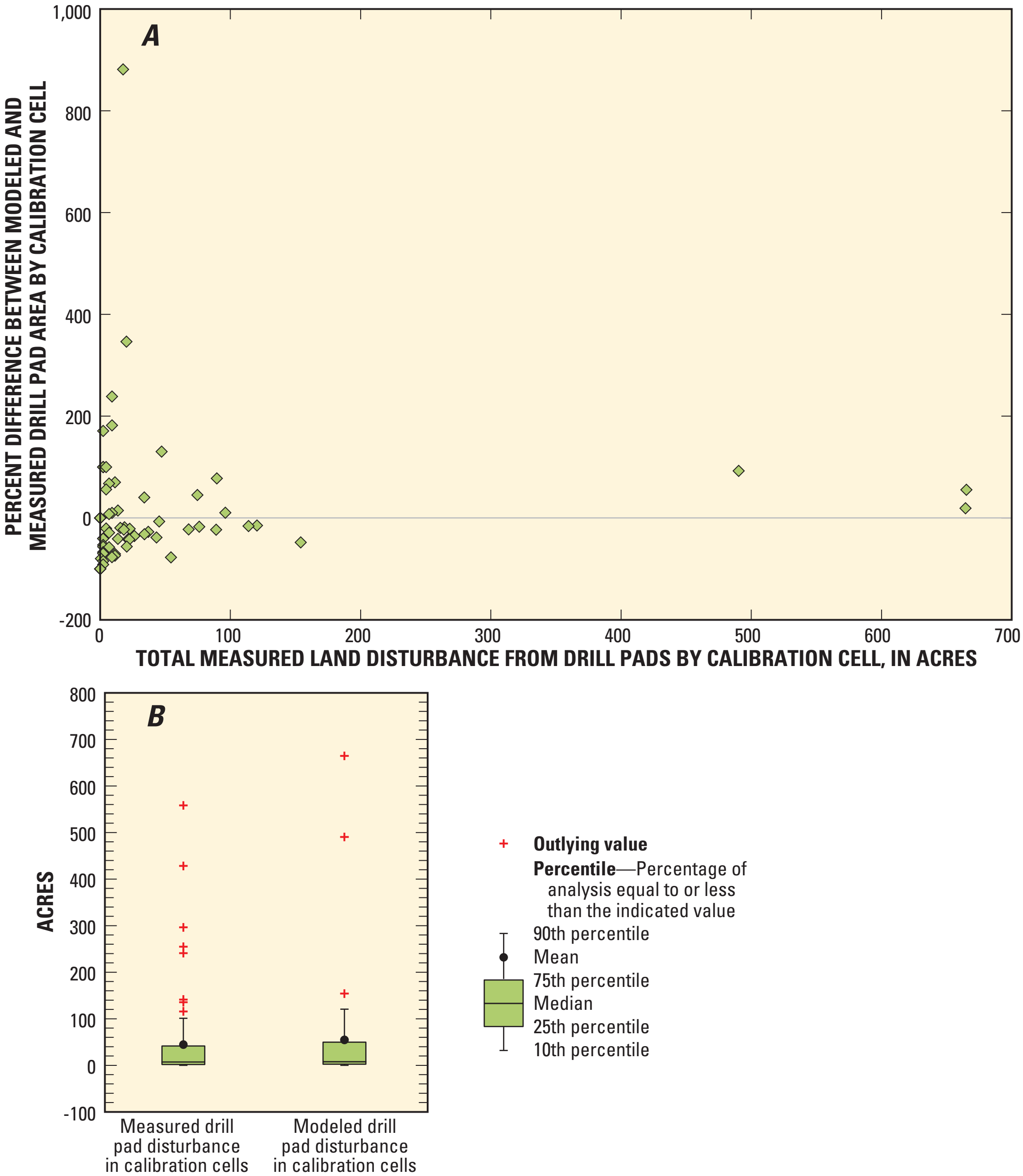

Figure 11. *A*, Percent difference between modeled and measured land disturbance from oil and gas drill pads, *B*, summary of measured and modeled area of land disturbance from oil and gas drill pads, *C*, distribution of difference between modeled and measured land disturbance from oil and gas drill pads, and *D*, correlation between modeled and measured land disturbance from oil and gas drill pads in 76 calibration cells, Upper Colorado River Basin, 2007.

measured road length for all calibration cells was 6.5 mi compared with 7.1 mi in the least-cost path model (fig. 12B). The maximum length of roads measured in a single cell was 51.6 mi compared with the maximum modeled length of 57.4 mi. The median measured road length was 2.0 mi compared with the median modeled road length of 2.4 mi.

Although the above analysis indicates that the least-cost path model overestimates the total length of resource roads in the UCRB, the model likely underestimates the actual impact of resource roads in the study area because the model does not account for secondary roads created as a result of oil and gas development. Thirty seven of the 60 calibration cells that contained visible oil- and gas-related land disturbance contained unpaved roads that were digitized as secondary oil and gas resource roads. The total length of measured secondary roads in these calibration cells varied from as little as 230 ft in a cell to as much as 34 mi in a cell. In the 37 calibration cells that contained secondary roads, the average length these roads was 3.5 mi per calibration cell.

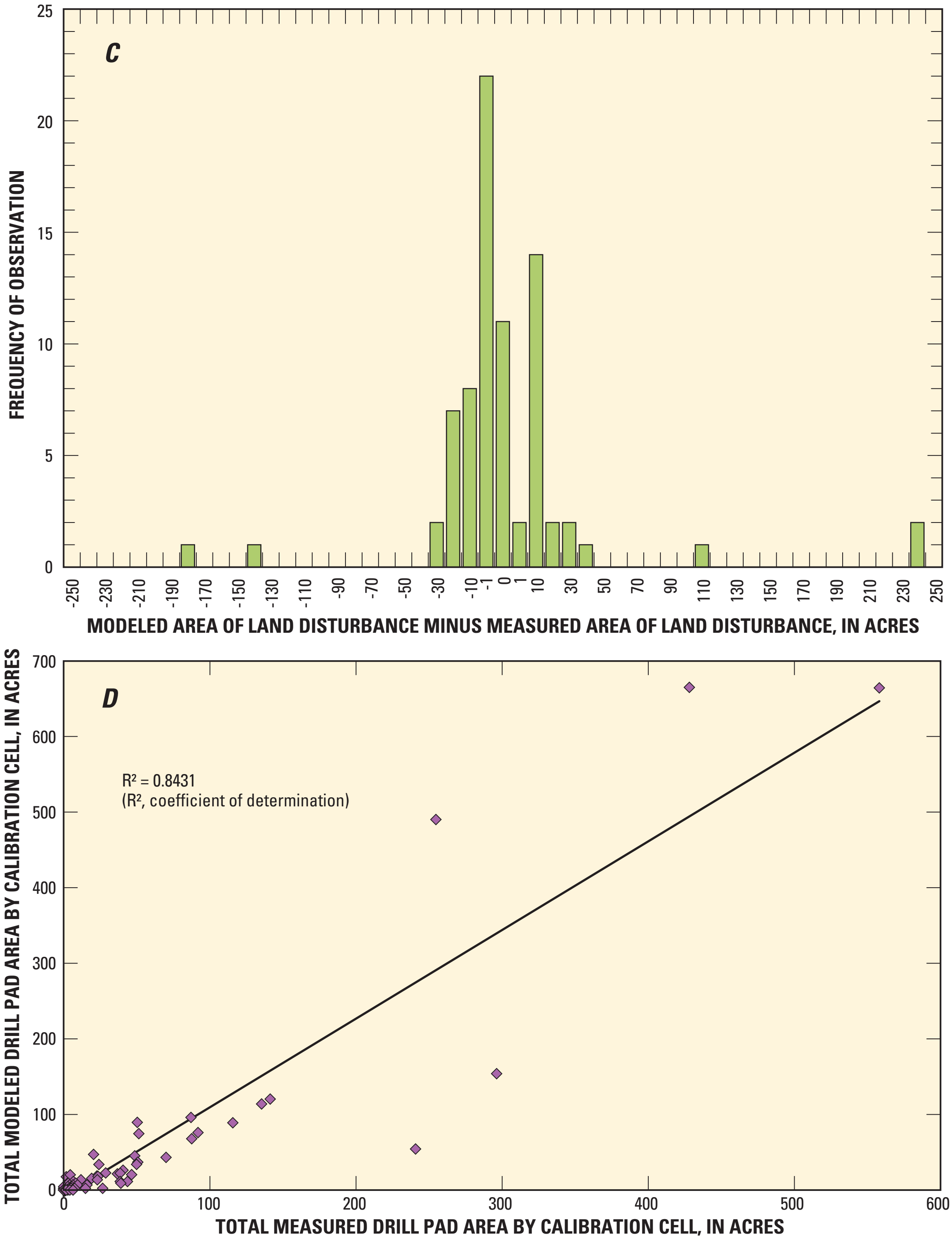

Figure 11. *A*, Percent difference between modeled and measured land disturbance from oil and gas drill pads, *B*, summary of measured and modeled area of land disturbance from oil and gas drill pads, *C*, distribution of difference between modeled and measured land disturbance from oil and gas drill pads, and *D*, correlation between modeled and measured land disturbance from oil and gas drill pads in 76 calibration cells, Upper Colorado River Basin, 2007.—Continued

Errors in the location and extent of roads in the DLG dataset used as the source of existing roads in the least-cost path model could cause the model to over- or underestimate the length of resource roads at local scales. The DLG dataset was often incomplete, and comparisons to roads visible in the NAIP imagery indicated locational errors. A mislocated or missing source road in the DLG dataset could affect the total length of modeled resource roads by either lengthening or shortening the modeled path created to access the drill pad. In addition, an unknown length of resource roads was included in the DLG dataset as unpaved roads. These roads would not have been modeled as resource roads and would not be included in the road disturbance estimates.

Fifteen of the 76 calibration cells described earlier were randomly selected (fig. 13) and used to estimate the extent of existing resource roads in the DLG data. All visible roads—resource roads, paved roads, and unpaved local roads visible in the NAIP imagery—in these cells were manually digitized

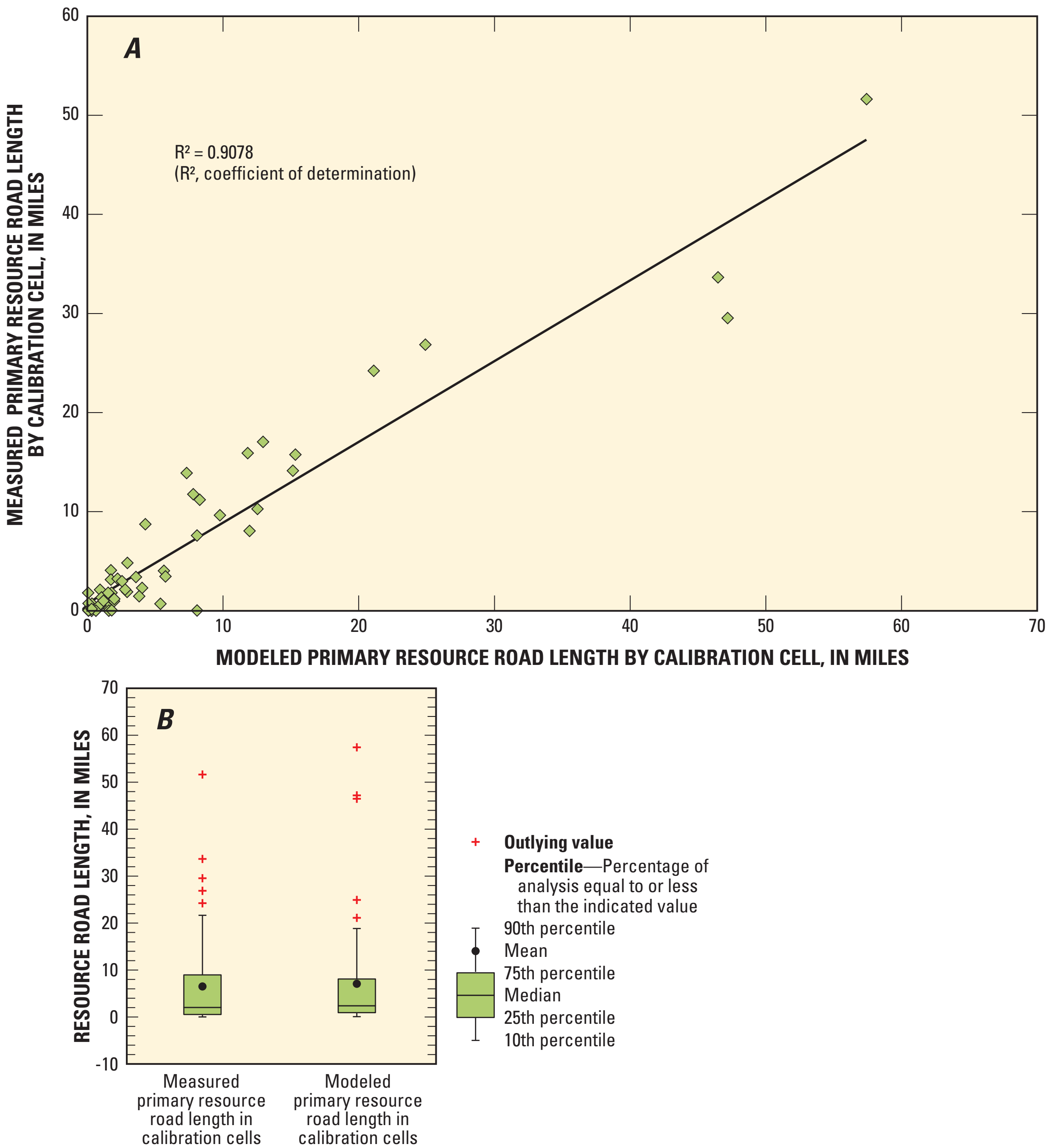

Figure 12. *A*, Correlation between modeled and measured oil and gas resource road length and *B*, summary of modeled and measured resource road length in 76 calibration cells, Upper Colorado River Basin, 2007.

into a DLG assessment dataset. Roads in the DLG assessment dataset were digitized as the centerline of the road visible in the NAIP imagery. Each digitized line was classified as a paved road, a local unpaved road, or a resource road. A single resource road was designated for each drill pad that had more than one road associated with it. All other roads associated with the drill pad were classified as local unpaved roads. It was also noted whether the digitized road existed in or was absent from the DLG dataset.

Oil and gas resource roads were present in the DLG dataset in 10 of the 15 DLG calibration cells. The total length of resource roads per calibration cell included in the DLG dataset ranged from 0.25 mi to 6.9 mi. The average length of resource roads in the 10 DLG calibration cells that contained resource roads was 2 mi. Resource roads in the DLG dataset are a source of error for the resource road model because these roads are omitted from the modeled length of resource roads.

The total length of all unpaved roads in the model was underestimated by 4 percent to 72 percent when compared with road lengths measured in the 15 tested calibration cells. On average, the total length of unpaved roads mapped in the DLG dataset was underestimated by 50 percent when compared with the total length of unpaved roads measured in the 15 selected calibration cells. Missing or badly located roads can affect the route created by the least-cost path model and cause the total length of roads actually constructed to access a drill pad to be over- or underestimated at local scales.

Assessment of Methods Used to Project Future Land Disturbance from Oil and Gas Development

Projected future land disturbance estimates were based on the average number of wells presented in the BLM RMPs. Total projected drill pad area may be underestimated if the maximum number of wells drilled approaches the maximum number of wells in the RMP projections. Conversely, disturbance will be overestimated if the expected drilling only meets the minimum anticipated number of wells. Resource development depends on future energy demands and will vary over time. In addition, development projections are often based on undiscovered resources and the actual resource may be more or less abundant than anticipated. The calculated area of land disturbance from oil and gas development was derived from GIS-based modeled drill pads, some of which overlapped and were treated as a single area. The analysis assumes that each well is associated with 2.26 acres of disturbed ground, even when multiple wells were drilled on a single drill pad. If the total number of discrete drill pads reaches the averages calculated from RMP documents and used for this analysis, the total disturbed area could be larger than that estimated. Future well locations are not actual well locations and were only created to simulate potential overall land disturbance from future oil and gas development. Well densities in areas where simulated wells were created to approximate future conditions may be higher than that allowed by state, local, and Federal regulations. In addition, BLM RMP data are projections of expected activity and may not correctly predict the actual development for an area.

Statistical Assessment of Dissolved-Solids Sources, Loads, and Transport in the Upper Colorado River Basin

The USGS in cooperation with the USBR and the BLM, developed a dissolved-solids SPARROW model specific to the UCRB for water year 1991 (Kenney and others, 2009). The SPARROW surface water-quality model uses a mass balanced approach to examine the production and transport of instream constituent mass, or flux, on the basis of a nonlinear, weighted least-squares regression technique (Schwarz and others, 2006). Coefficients for defined load sources, landscape transport characteristics, and aquatic transport characteristics are derived through iterative calibration with loads from stream-monitoring sites. The determined coefficients represent average conditions based upon the role each source term and characteristic play throughout the basin of interest, assuming an unbiased distribution of the monitoring sites used in model calibration (Kenney and others, 2009). These coefficients are then applied to the SPARROW model, and constituent load estimates can be generated for each of the incremental stream reaches of the basin of interest.

The UCRB dissolved-solids SPARROW or UCRB SPARROW model was calibrated using dissolved-solids loads calculated for 218 stream-monitoring sites (fig. 14). Prediction error is approximated at 51 percent (Kenney and others, 2009). The 11 defined sources for the model were 7 geologic source groups, 3 agricultural lands groups, and a point-source imports group that was composed of 7 large saline springs and 6 reservoirs. Six landscape transport characteristics, including terms associated with climate, soils, vegetation, and elevation, were statistically significant in describing the transport of dissolved solids to streams in the UCRB.

Effects of Land Disturbance from Oil and Gas Development on Dissolved-Solids Loads in the Upper Colorado River Basin

The 1991 UCRB SPARROW model was used to assess the effects of land disturbance from oil and gas development on dissolved-solids loads in the basin. The calibration routine of the SPARROW model generates basin-averaged coefficients for sources, landscape transport characteristics, and aquatic transport characteristics that statistically explain the production, transport, and fate of the constituent of interest. Modeled land disturbance attributed to oil and gas development for 1991 and 2007 was examined as a source of dissolved solids in streams in the UCRB. The 1991 UCRB

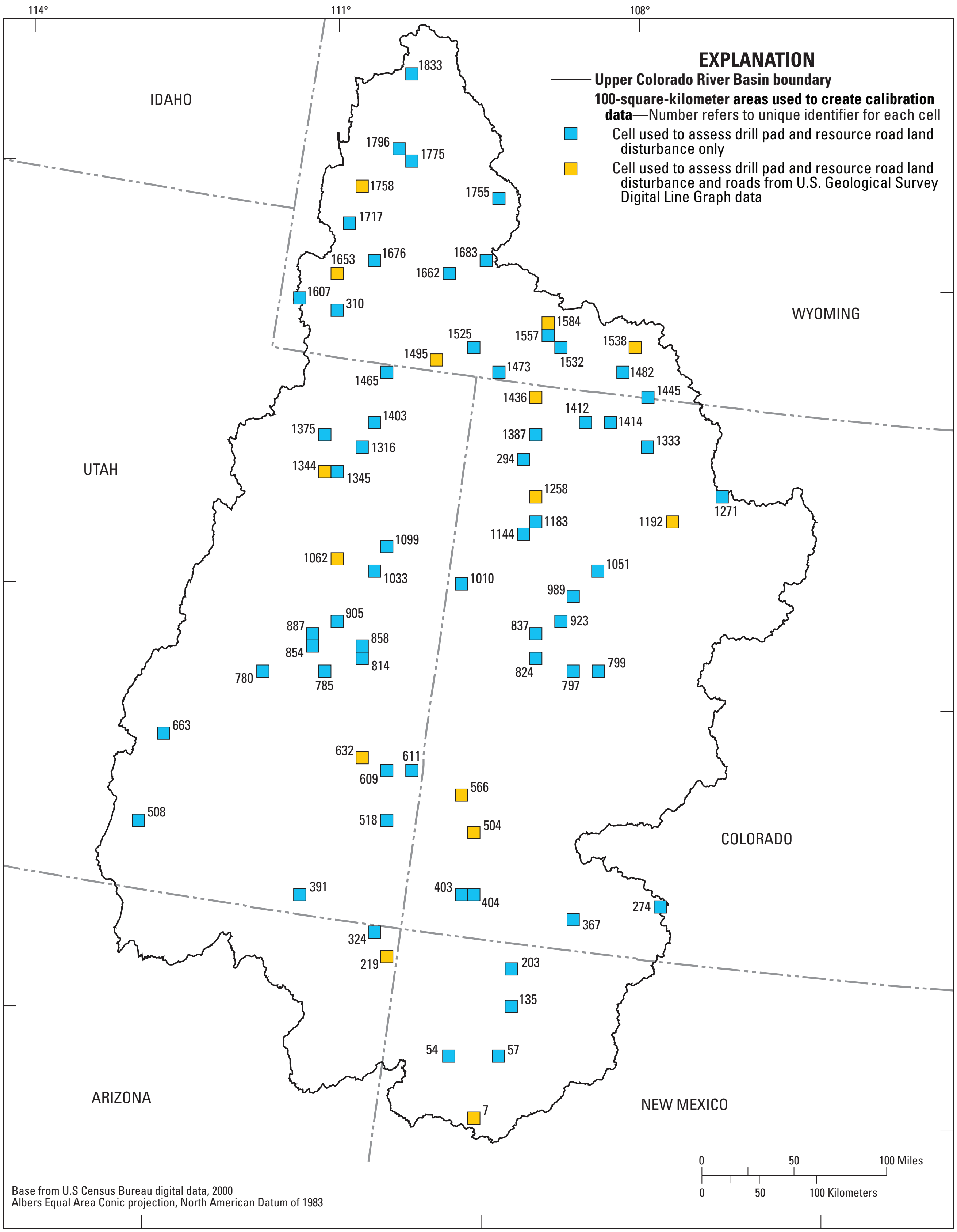

Figure 13. Location of calibration cells chosen to create the Digital Line Graph assessment dataset, Upper Colorado River Basin.

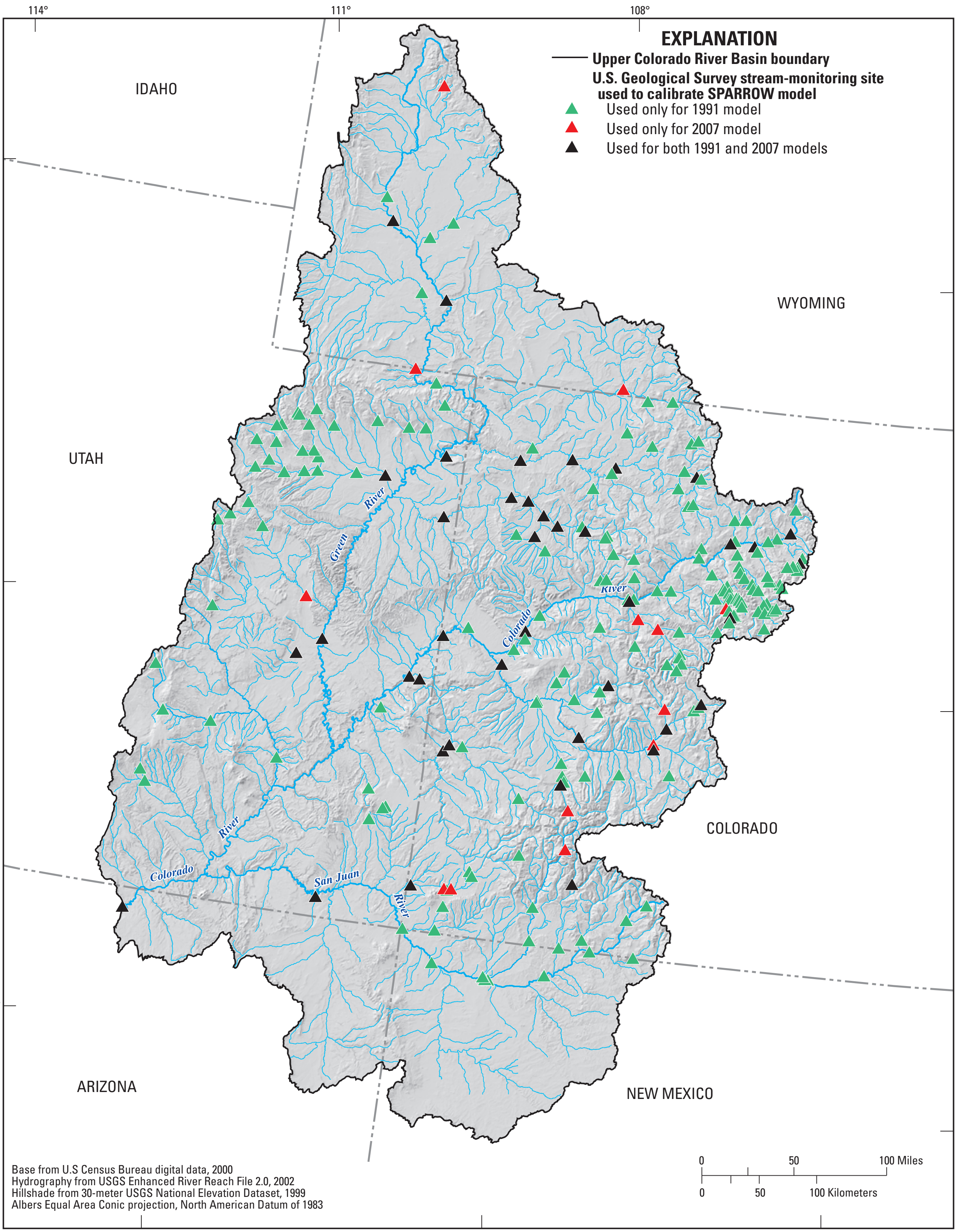

Figure 14. Location of U.S.Geological Survey stream-monitoring sites with dissolved-solids monitoring data used for the 1991 Upper Colorado River Basin (UCRB) dissolved-solids SPARROW model and the 2007 exploratory UCRB dissolved-solids SPARROW model.

SPARROW model (Kenney and others, 2009) and a similar, exploratory SPARROW model specific to monitoring data for water year 2007 were used for this analysis. The estimated total area of land disturbed by oil and gas development was calculated for each catchment and stream reach in the UCRB SPARROW stream network for 1991 and 2007 as an input to the models (fig. 15). A catchment, or contributing area, is the land-surface area that contributes flow to a stream segment. All runoff from a catchment is discharged from the same outlet.

Annual dissolved-solids loads were available for 218 monitoring sites for the 1991 UCRB SPARROW model compared with 53 monitoring sites for the 2007 model (fig. 14). Mean daily and annual dissolved-solids loads for the 53 sites were determined by using a multiple linear regression model included in the computer model LOADEST (Runkel and others, 2004) adapted for use with TIBCO Spotfire S+ statistical software (TIBCO Software Inc., 2008) (appendix 3). Explanatory variables in the regression models included various functions of streamflow and time. The LOADEST models were calibrated by using dissolved-solids concentration data (sometimes estimated from specific-conductance measurements) and associated streamflow values obtained from the USGS National Water Information System (NWIS) database. For each site, a time series of daily mean streamflow values was applied to the formulated regression model to estimate dissolved-solid loads.

The land disturbance source input to the UCRB SPARROW model included the total area of land disturbance estimated for drill pads and resource roads. Including the land disturbance source with the defined sources of the 1991 UCRB SPARROW model increased the source groups to 12. The 6 landscape transport characteristics applied to the original 11 source groups were unchanged. However, different combinations of landscape transport characteristics applied to the land disturbance source were examined in the 1991 and the 2007 SPARROW models. In each of these models, the source coefficient estimated for the disturbed lands associated with oil and gas development was zero (null). Within the framework of the SPARROW model, the coefficient indicates that the land area disturbed by oil and gas development was not statistically significant in explaining dissolved-solids loads in UCRB streams. The other source groups had coefficients that were similar to those reported by Kenney and others (2009).

Interpretation of Results

To understand the null result of the effect of land disturbance from oil and gas development on dissolved-solids loads in the UCRB requires a more thorough examination of the data network and the limitations of the UCRB SPARROW model. The null result indicates that land disturbance associated with oil and gas development does not contribute to dissolved-solids loads in streams in the UCRB. However, this examination of the relation between land disturbance associated with oil and gas development and dissolved solids is an observational study, not an experimental study. The study design was limited to available data that may not have been ideal for properly testing the hypothesis that land disturbance associated with oil and gas development increases dissolved solids in streams in the UCRB. When the result of an observational study does not overtly confirm the hypothesis, care must be taken when drawing a conclusion. As described in detail below, the null result is likely caused by the inherent limitations of the data used in the model. Further, because SPARROW is a spatially referenced statistical model, results are scaled to the data network supporting the model. The model results were affected by the available monitoring data, distribution of monitoring sites with respect to land disturbance, the total area of disturbed lands associated with oil and gas development basin wide and within the reaches used for model calibration, and the potential yield of dissolved solids from disturbed lands compared with the natural yield.

Total land disturbance associated with oil and gas development in the study area was estimated at 117,500 acres (183 mi^2) for 1991 and 179,350 acres (280 mi^2) for 2007. This accounts for 0.17 and 0.26 percent, respectively, of the 108,000 mi^2 in the UCRB. For perspective, the defined sources represented in the 1991 UCRB SPARROW model are shown in table 5 (Kenney and others, 2009). The smallest represented source group in the 1991 UCRB SPARROW model, irrigated lands of other lithologies, consisted of 268,800 acres (420 mi^2), or 0.39 percent of the UCRB. As discussed by Kenney and others (2009), the probability was high that the estimated coefficient for the irrigated lands of other lithologies group was zero (p-value), or insignificant in explaining dissolved solids in UCRB streams, but it was retained in the model for continuity. The next smallest source group, irrigated sedimentary-clastic Mesozoic lands, was 576,000 acres (900 mi^2), roughly three times the size of the disturbed lands associated with oil and gas development in 2007. The total area of disturbed lands associated with oil and gas development modeled in 1991 and 2007 may be too small for a regional scale model, such as the UCRB SPARROW model, to capture their contribution to instream dissolved-solids loads. The total land disturbance in 2025 is projected to be approximately 319,000 acres (500 mi^2), an areal extent that is about 19 percent larger than the irrigated lands of other lithologies source in the 1991 UCRB SPARROW model. It is important to note that substantially more water is artificially applied to irrigated lands than naturally falls on the disturbed lands associated with oil and gas development in the UCRB. Artificially applied water substantially increases the production and transport of dissolved solids. Further, transport paths from irrigated lands and lands disturbed by oil and gas development differ in length. Irrigated lands are generally much closer to streams in the UCRB than the lands disturbed by oil and gas development. From the exploratory efforts of examining land disturbance associated with oil and gas development for 1991 and 2007, it is expected that the projected 2025 RFD land disturbance would also likely be too small to be a significant explanatory variable as a source of dissolved solids in streams in the UCRB.

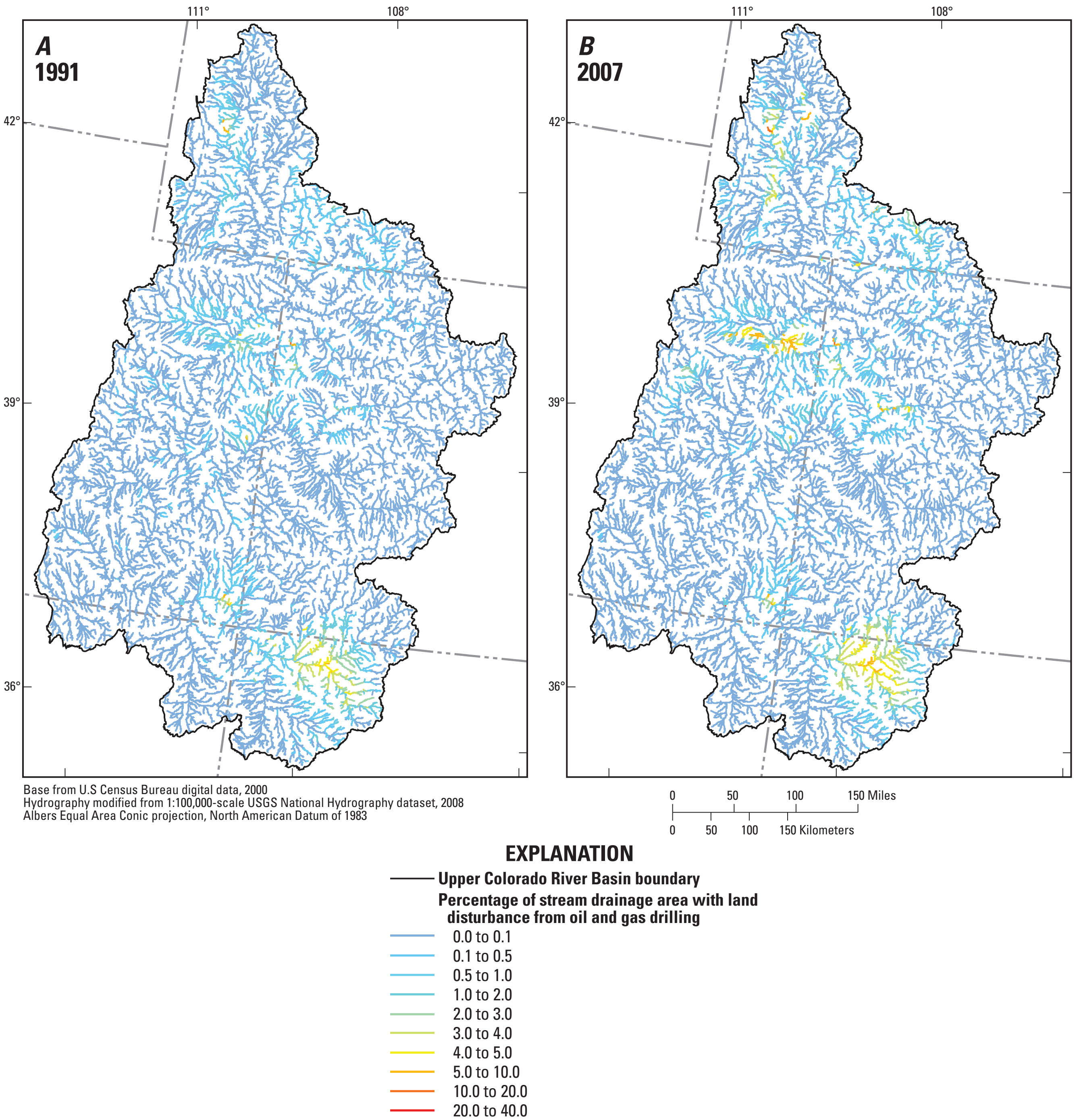

Figure 15. Upper Colorado River Basin SPARROW stream network indicating the percentage of the total contributing land area for each stream reach that was disturbed by oil and gas development in *A*, 1991 and *B*, 2007, Upper Colorado River Basin.

Table 5. Area of dissolved-solids source groups defined for the 1991 Upper Colorado River Basin (UCRB) dissolved-solids SPARROW model and the 2007 UCRB exploratory dissolved-solids SPARROW model.

Source group	Total area of source group		Percentage of Upper Colorado River Basin [1]
	Acres	Square miles	
Crystalline and volcanic rocks [2]	6,195,200	9,680	8.96
High-yield sedimentary Cenozoic rocks [2]	7,872,000	12,300	11.4
Low-yield sedimentary Cenozoic rocks [2]	16,448,000	25,700	23.8
High-yield sedimentary Mesozoic rocks [2]	8,960,000	14,000	13
Low-yield sedimentary Mesozoic rocks [2]	23,168,000	36,200	33.5
High-yield sedimentary Paleozoic and Precambrian rocks [2]	2,694,400	4,210	3.89
Low-yield sedimentary Paleozoic and Precambrian rocks [2]	3,795,600	5,930	5.5
Irrigated sedimentary-clastic Tertiary lands [2]	883,200	1,380	1.3
Irrigated sedimentary-clastic Mesozoic lands [2]	576,000	900	0.83
Irrigated lands of other lithologies [2]	268,800	420	0.39
Disturbed lands, 1991 [3]	117,500	183	0.17
Disturbed lands, 2007 [4]	179,350	280	0.26

[1] Sum of values does not add to 100 percent because data sources overlap.

[2] Value used in 1991 and 2007 models.

[3] Value used in 1991 model.

[4] Value used in 2007 model.

Data for annual dissolved-solids loads were available at 218 and 53 monitoring sites during water years 1991 and 2007, respectively. As explained by Kenney and others (2009), within the SPARROW modeling framework these monitoring sites correspond to 218 and 53 unique calibration reaches from which SPARROW estimates model coefficients. The distribution of model parameters, including sources, within the calibration reaches provides some insight as to how well each parameter is being represented during the model calibration process. For the 1991 data, the drainage area for calibration reaches ranged from 2,278 acres (3.56 mi^2) to 9,088,000 acres (14,200 mi^2) and the average area was 316,800 acres (495 mi^2). For the 2007 data, the drainage area of calibration reaches ranged from 12,800 acres (20 mi^2) to 14,336,000 acres (22,400 mi^2) and the average area was 1,305,600 acres (2,040 mi^2).

Appendixes 4 and 5 show how the source groups, including land disturbance associated with oil and gas development and excluding the point-source imports, were represented within each of the calibration reaches. The percentage of the calibration reach area represented by each source was computed and the maximum, minimum, mean, and median were reported for all non-zero source groups (table 6) for the 1991 and 2007 data. The maximum percentage of land disturbance within a calibration reach was 2.81 percent for the 1991 data and 0.95 percent for the 2007 data. For both years, the maximum percentage of the land disturbance sources is much smaller than any other defined sources, which indicates that land disturbance associated with oil and gas development may not be represented well in the calibration reach data. The distribution of stream-monitoring sites used to calibrate the 1991 model and the 2007 exploratory model are shown in figure 16. Ideally, the monitoring sites would be evenly distributed throughout the study area including areas with land disturbance from oil and gas development. A lack of stream-monitoring sites within areas with land disturbance from oil and gas development indicates that the stream-monitoring network may have a biased distribution toward areas without oil- and gas-related land disturbance such that contributions of dissolved solids from disturbed lands are not adequately represented in the model. Inadequate representation may produce a null result.

The potential yield of dissolved solids from land disturbed by oil and gas development is a function of the natural yield of the local geologic units. Land disturbance on high-yield geologic units would contribute more to dissolved-solids loads than similar disturbance on low-yield geologic units. Dissolved-solids yield from geologic units in the UCRB SPARROW model are represented by seven geologic source groups. Statistically significant coefficients, which represent basin-averaged yields, were estimated for each of these seven source groups. These yields ranged from 1.26 to 41.9 tons of dissolved solids per square mile (Kenney and others, 2009). For comparison, the UCRB SPARROW model contained three irrigated lands sources with predicted yields of 22.8, 662, and 1,180 tons per square mile (Kenney and others, 2009).

Table 6. Representation of dissolved-solids source groups in 1991 Upper Colorado River Basin (UCRB) dissolved-solids SPARROW model and 2007 exploratory UCRB dissolved-solids SPARROW model calibration reaches.

[Statistical analyses of sources in calibration reaches were done on all non-zero source areas. Max., maximum; Min., minimum]

	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	Crystalline and volcanic rocks	Sedimentary Cenozoic rocks		Sedimentary Mesozoic rocks		Sedimentary Paleozoic and Precambrian rocks		Land disturbance associated with oil and gas development
					High-yield	Low-yield	High-yield	Low-yield	High-yield	Low-yield	
	Percentage of the calibration reach area										
1991											
Max.	15.4	54.6	8.39	100	90.6	100	100	100	98.795	100	2.81
Min.	0.0004	0.001	0.0002	0.017	0.006	0.041	0.007	0.018	0.0020	0.003	0.0008
Mean	1.59	2.309	0.994	42.6	14.2	25.5	16.5	26.5	24.1	9.92	0.167
Median	0.865	0.666	0.350	29.8	4.28	16.4	10.5	15.3	8.76	2.59	0.032
2007											
Max.	14.0	21.9	7.07	98.9	46.8	92.5	44.4	93.0	59.8	32.5	0.947
Min.	0.051	0.018	0.001	0.186	0.004	0.045	0.013	1.26	0.002	0.079	0.001
Mean	1.84	1.80	1.23	34.1	10.1	25.5	12.4	28.0	11.1	5.10	0.199
Median	1.24	0.927	0.706	24.4	6.55	16.8	10.4	14.9	4.31	2.44	0.118

The large yields associated with irrigated lands are due to the application of water, which increases the dissolution and transport of solids to streams. The amount of water applied greatly exceeds natural precipitation in these areas.

The seven geologic source groups, which represent the natural landscape, are subject to natural precipitation and associated weathering that dissolve solids at rates that are much smaller than those for irrigated lands. Disturbed lands associated with oil and gas development, aside from being barren, are similar to the natural landscapes of the UCRB. Barren surfaces exposed by construction of drill pads and resource roads may provide access to previously unweathered materials soon after the initial disturbance. However, with time, the yield of these disturbed materials may approach that of the surrounding geology. Most of the disturbed lands associated with oil and gas development in the UCRB are buffered by undisturbed lands containing sparse arid-environment vegetation types. This vegetation may impede the transport of dissolved solids to streams by slowing down overland flow of water and sediment, and encouraging infiltration.

Another factor that likely affected the results of the UCRB SPARROW model was that about 73 percent of the wells classified as “disturbed” in the 2007 UCRB oil and gas well dataset were located on one of three low-yield sedimentary lithologies of the 1991 UCRB SPARROW model (Kenney and others, 2009). Approximately 27 percent of wells classified as “disturbed” were located on one of the three high-yield sedimentary lithologies (fig. 17). The null result for the land disturbance coefficient in the UCRB SPARROW model would in this case represent the effects of the location of much of the oil and gas land disturbance on low-yield geologic units.

There are a number of possible reasons why the disturbed lands associated with oil and gas development were not a significant explanatory variable for the production of dissolved solids in the UCRB dissolved-solids SPARROW model. The null result is likely due to a combination of factors and indicates that the UCRB SPARROW model has a streamflow data network that probably is not extensive enough to fully assess the contribution of dissolved solids from land disturbed by oil and gas development. A true test of the hypothesis would require more monitoring data representative of locations that have significant land disturbance from oil and gas development.

Summary

The Bureau of Land Management (BLM) has identified the Upper Colorado River Basin (UCRB) as an area with potential for continued oil and gas development on the basis of interest expressed by the oil and gas industries. Oil and gas development has increased substantially in the UCRB since 2000. Lands disturbed by oil and gas development can harm the environment through erosion, air pollution, stream degradation, habitat fragmentation and alteration, and increased public use of potentially environmentally sensitive areas. Monitoring and mapping land disturbance from oil and gas development has not been synthesized on a regional scale in the UCRB but data on the location and age of oil and gas wells are available from state-maintained databases for the five states partly within the UCRB. GIS analysis and modeling techniques were used to map the location and estimate the

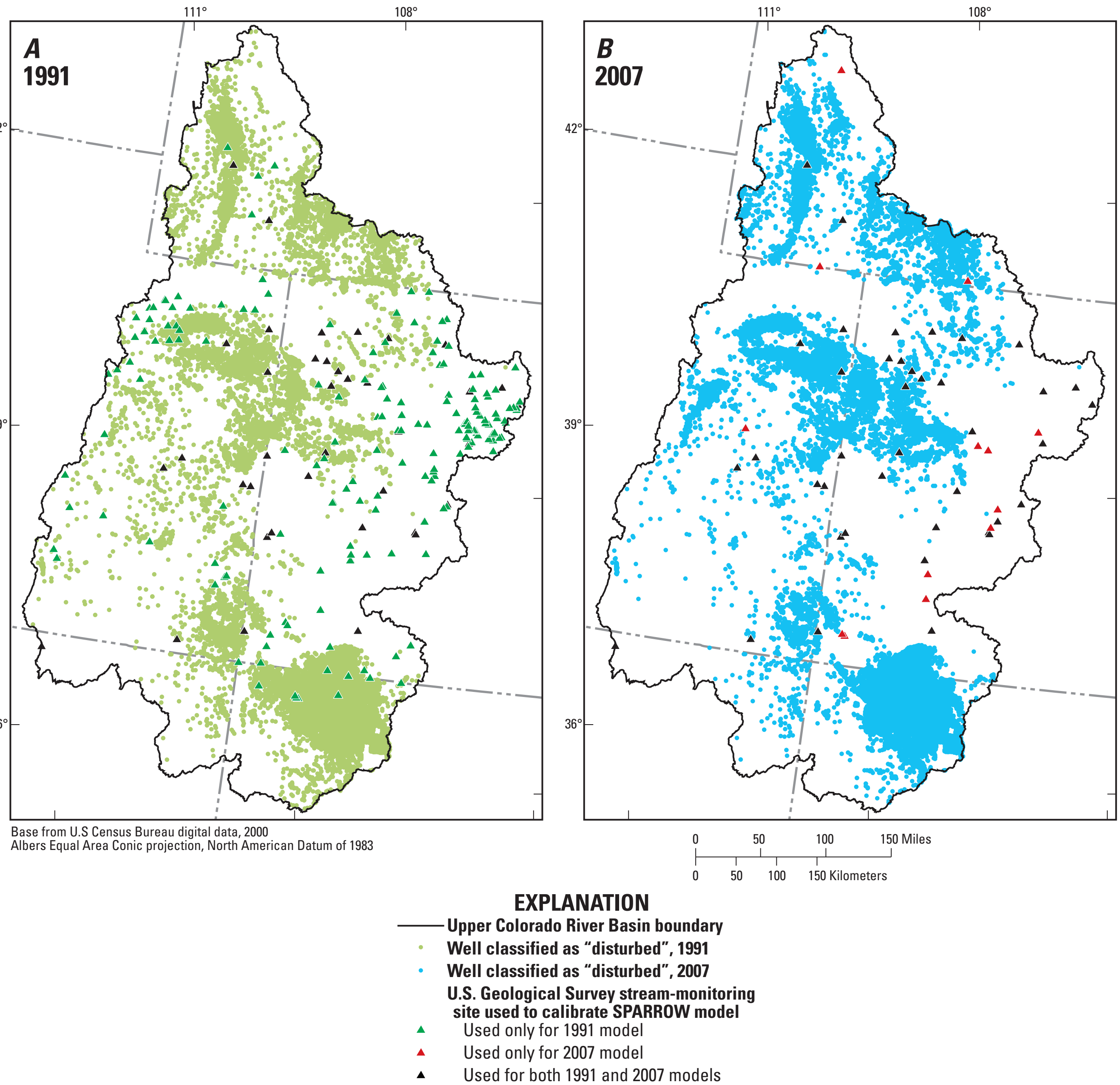

Figure 16. Distribution of U.S. Geological Survey stream-monitoring sites used to calibrate the *A*, 1991 Upper Colorado River Basin (UCRB) dissolved-solids SPARROW model and the *B*, 2007 exploratory UCRB dissolved-solids SPARROW model and the wells classified as "disturbed" in the UCRB oil and gas well dataset in 1991 and 2007.

total area of land disturbed by oil and gas resource development up to 2007 in the UCRB. Additional information about anticipated oil and gas development in the UCRB was used to project disturbance estimates to 2025. The disturbance estimate indicates that there was approximately 120,400 acres of land disturbance from drill pads in 2007. An additional 58,950 acres of disturbance associated with 13,500 miles of resource roads were estimated for 2007. Projected disturbance for 2025 nearly doubles the total pad disturbance to 222,800 acres. Road disturbance projected for 2025 could be more than 96,500 acres for as much as 22,500 miles of new resource roads.

The U.S. Geological Survey, in cooperation with the Bureau of Reclamation and the BLM, developed a dissolved-solids SPARROW model specific to the UCRB (Kenney and others, 2009). The UCRB dissolved-solids SPARROW model was calibrated using 1991 dissolved-solids loads from 218 stream-monitoring sites. Estimated land disturbance data from

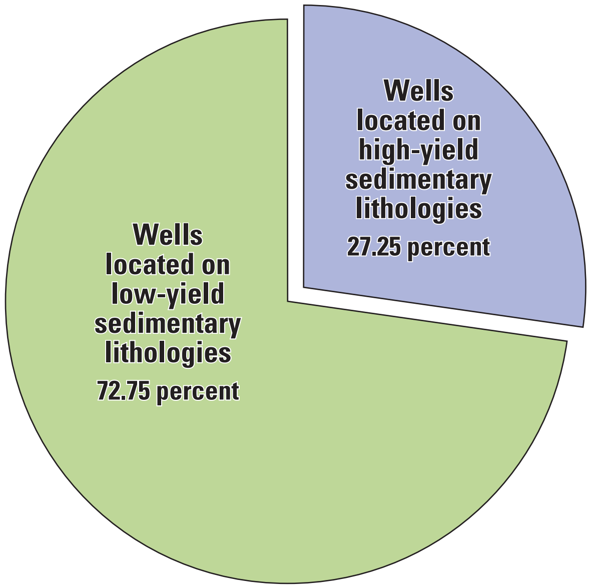

Figure 17. Percentage of oil and gas wells classified as "disturbed" in the 2007 Upper Colorado River Basin (UCRB) oil and gas dataset located on UCRB dissolved-solids SPARROW model geologic source groups.

1991 and 2007 were input to the UCRB SPARROW model to assess the significance of energy-related land disturbance on contributing dissolved solids to basin streams. The statistical analysis was an observational study that used existing data to assess the relation between land disturbance from oil and gas resource development and dissolved-solids load in the UCRB. In each of the model years, the source coefficient estimated for the lands disturbed by oil and gas development was zero. The coefficient indicated that the estimated area of lands disturbed by oil and gas development was not statistically significant as a contributor of dissolved solids in UCRB streams.

The lack of significance of disturbed lands in the SPARROW modeling framework may be due to the amount of available monitoring data, the spatial distribution of monitoring sites with respect to land disturbance, and the overall quantity of disturbed lands associated with oil and gas development basin wide and within calibration reaches. Finally, dissolved-solids loads from natural landscapes may be similar to loads derived from lands disturbed by resource extraction activity. The most significant contributor to dissolved solids in the UCRB is irrigated agriculture, which covers an area substantially larger than the estimated area of disturbed lands by oil and gas development and is subjected to large amounts of artificially applied water.

References Cited

Anning, D.W., Bauch, N.J., Gerner, S.J., Flynn, M.E., Hamlin, S.N., Moore, S.J., Schaefer, D.H., Anderholm, S.K., and Spangler L.E., 2007, Dissolved solids in basin-fill aquifers and streams in the southwestern United States: U.S. Geological Survey Scientific Investigations Report 2006-5315, 168 p., available at http://pubs.usgs.gov/sir/2006/5315/.

Chidsey, T.C., Wakefield, S., Hill, B.G., and Hebertson, M., 2004, Oil and gas fields map of Utah: Utah Geological Survey Map 203DM, CD-ROM.

Colorado Oil and Gas Conservation Commission, 2007, Colorado Oil and Gas Information System (COGIS), accessed May 2007 at http://www.oil-gas.state.co.us/.

Colorado Oil and Gas Conservation Commission, 2009, Well permitting and location approval manual, accessed March 2009 at http://cogcc.state.co.us/ link to "RULES."

Council on Environmental Quality, Executive Office of the President, 2007, A citizens guide to the NEPA—Having your voice heard, accessed February 2009 at http://ceq.hss.doe.gov/nepa/Citizens_Guide_Dec07.pdf.

De Bruin, R.H., 2002, Oil and gas map of the greater Green River Basin and overthrust belt, Wyoming: Wyoming Geological Survey Digital Map MS-52, CD-ROM.

Environmental Systems Research Institute, Inc., 2008, ArcGIS 9.2 Desktop help—Path distance: adding more cost complexity: release 9.2, accessed May 2008 at http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Path_Distance:_adding_more_cost_complexity.

Environmental Systems Research Institute, Inc., 2009a, ESRI support center: GIS Dictionary, accessed August 2009 at http://support.esri.com/index.cfm?fa=knowledgebase.gisDictionary.gateway.

Environmental Systems Research Institute, Inc., 2009b, ArcGIS 9.2 Desktop help—An overview of the create random points tool: release 9.2, accessed August 2009 at http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=An%20overview%20of%20the%20Create%20Random%20Points%20tool.

Huffman, A.C., Jr., 1995, Paradox Basin Province: U.S. Geological Survey 1995 National oil and gas assessments, accessed April 2009 at http://certmapper.cr.usgs.gov/data/noga95/prov21/text/prov21.pdf.

Iorns, W.V., Hembree, C.H, and Oakland, G.L., 1965, Water resources of the Upper Colorado River Basin—Technical report: U.S. Geological Survey Professional Paper 441, 370 p., available at http://pubs.er.usgs.gov/usgspubs/pp/pp441.

Kenney, T.A., Gerner, S.J., Buto, S.G., and Spangler, L.E., 2009, Spatially referenced statistical assessment of dissolved-solids load sources and transport in streams of the Upper Colorado River Basin: U.S. Geological Survey Scientific Investigations Report 2009-5007, 50 p., available at http://pubs.usgs.gov/sir/2009/5007/.

Liebermann, T.D., Mueller, D.K., Kircher, J.E., and Choquette, A.F., 1989, Characteristics and trends of streamflow and dissolved solids in the Upper Colorado River Basin, Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey Water-Supply Paper 2358, 64 p., available at http://pubs.er.usgs.gov/usgspubs/wsp/wsp2358.

Multi-Resolution Land Characteristics Consortium, 2001, National Landcover Database 2001, accessed March 2009 at http://www.mrlc.gov/pdf/nlcd_fact_sheet_2001.pdf.

National Atlas of the United States, 2006a, Federal Lands of the United States: Reston, Virginia, National Atlas of the United States, accessed March 2009 at http://www.nationalatlas.gov/metadata/fedlanp020.html.

National Atlas of the United States, 2006b, Indian Lands of the United States: Reston, Virginia, National Atlas of the United States, accessed March 2009 at http://www.nationalatlas.gov/metadata/indlanp020.html.

New Mexico Institute of Mining and Technology Petroleum Recovery Research Center, 2007, New Mexico state oil and gas production database, accessed May 2007 at http://octane.nmt.edu/gotech/Petroleum_Data/allwells.aspx.

PRISM Group, Oregon State University, 2007, PRISM climate group [Digital climate data]: Corvallis, Oregon, Oregon Climate Service, accessed May 2007 at http://www.prism.oregonstate.edu/.

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques and Methods, book 4, chap. A5, 69 p.

Schlumberger Limited, 2009, The oilfield glossary: Where the oil field meets the dictionary: Schlumberger Limited, accessed February 2009 at http://www.glossary.oilfield.slb.com/.

Schwarz, G.E., Hoos, A.B., Alexander, R.B., and Smith, R.A., 2006, The SPARROW surface water-quality model: Theory, application and user documentation: U.S. Geological Survey Techniques and Methods, book 6, chap. B3, 248 p., available at http://pubs.usgs.gov/tm/2006/tm6b3/contents.htm.

Smith, R.A., Schwarz, G.E., and Alexander, R.B., 1997, Regional interpretation of water-quality monitoring data: Water Resources Research, v. 33, no. 12, p. 2781–2798.

TIBCO Software, Inc, 2008, TIBCO Spotfire S+ 8.1 for Windows Users Guide.

U.S. Bureau of Land Management, 1985, BLM manual handbook 9113 – Roads (release 9-247): U.S. Department of the Interior handbook.

U.S. Bureau of Land Management, 2002, Resourceful management of our natural resources, accessed April 2009 at http://www.blm.gov/pgdata/etc/medialib/blm/wo/Communications_Directorate/general_publications/mgmt.Par.6587.File.dat/handout_02.pdf.

U.S. Bureau of Land Management, 2006, Scientific inventory of onshore Federal lands' oil and gas resources and the extent and nature of restrictions or impediments to their development: Energy policy and conservation act phase II inventory, accessed October 2007 at http://www.blm.gov/epca/.

U.S. Bureau of Land Management, 2007, Surface operating standards and guidelines for oil and gas exploration and development (4th ed.): U.S. Bureau of Land Management publication P-417, [The Gold Book], 76 p.

U.S. Bureau of Land Management, 2008, Oil and gas statistics, accessed February 2009 at http://www.blm.gov/wo/st/en/info/newsroom/Energy_Facts_07/statistics.html.

U.S. Bureau of Land Management, 2009a, Restoration in progress, Bishop Field Office, accessed February 2009 at http://www.blm.gov/ca/st/en/fo/bishop/restoration.html.

U.S. Bureau of Land Management, 2009b, San Juan Public Lands Center, accessed June 2009 at http://www.blm.gov/co/st/en/fo/sjplc.html.

U.S. Bureau of Land Management and U.S. Forest Service, 2008a, National Integrated Land System: Township Geocoder, accessed July 2008 at http://www.geocommunicator.gov/GeoComm/lsis_home/townshipdecoder/index.shtm.

U.S. Bureau of Land Management and U.S. Forest Service, 2008b, National Integrated Land System public land survey system (PLSS) digital data, accessed November 2008 at http://www.geocommunicator.gov/GeoComm/lsis_home/home/index.shtm.

U.S. Census Bureau, 2000, Cartographic boundary files—2000 incorporated places/census designated places: U.S. Census Bureau, Geography Division, accessed March 2009 at http://www.census.gov/geo/www/cob/pl_metadata.html#meta.

U.S. Census Bureau, 2008, INCITS 38:200x, Codes for the identification of the States, the District of Columbia, Puerto Rico, and the insular areas of the United States: U.S. Census Bureau, Geography Division, accessed June 2009 at http://www.census.gov/geo/www/ansi/statetables.html.

U.S. Department of Agriculture, 2006, National Agricultural Imagery Program (NAIP) Information Sheet, accessed February 2009 at http://165.221.201.14/white%20papers/NAIP_final_2006_update.pdf [as of November 13, 2009, available at http://www.fsa.usda.gov/Internet/FSA_File/naip_final_2006_updatep.pdf].

U.S. Department of the Interior, 2003, Quality of water—Colorado River Basin, Progress Report no. 21, 90 p., accessed February 2009 at http://www.usbr.gov/uc/progact/salinity/pdfs/PR21.pdf.

U.S. Forest Service and U.S. Bureau of Land Management, 2007, Onshore oil and gas operations; Federal and Indian oil and gas leases; Approval of operations—Onshore oil and gas order number 1: Federal Register, v. 72, no. 44, accessed August 2009, at http://www.blm.gov/pgdata/etc/medialib/blm/wo/MINERALS__REALTY__AND_RESOURCE_PROTECTION_/energy/onshore_order_videos.Par.62610.File.dat/Onshore_Order_No_1_The_Order.pdf.

U.S. Geological Survey, 1996a, U.S. GeoData Digital Line Graphs: U.S. Geological Survey Fact Sheet 078-96, accessed April 2006 at http://egsc.usgs.gov/isb/pubs/factsheets/fs07896t.pdf.

U.S. Geological Survey, 1996b, 1995 National oil and gas assessment plays, accessed March 2009 at http://energy.cr.usgs.gov/oilgas/noga/data.html.

U.S. Geological Survey, 1999a, National Elevation Dataset, accessed June 2005 at http://ned.usgs.gov/.

U.S. Geological Survey, 1999b, National Hydrography Dataset: U.S. Geological Survey Fact Sheet 106-99, accessed March 2007 at http://erg.usgs.gov/isb/pubs/factsheets/fs10699.html.

U.S. Geological Survey, 2002a, Assessment of undiscovered oil and gas resources of the Uinta-Piceance Province of Colorado and Utah, 2002: U.S. Geological Survey Fact Sheet 026-02, accessed April 2009 at http://pubs.usgs.gov/fs/fs-0026-02/fs-0026-02.pdf.

U.S. Geological Survey, 2002b, Assessment of undiscovered oil and gas resources of the San Juan Basin Province of New Mexico and Colorado, 2002: U.S. Geological Survey Fact Sheet 147-02, accessed April 2009 at http://pubs.usgs.gov/fs/fs-147-02/FS-147-02.pdf.

U.S. Geological Survey, 2002c, Assessment of undiscovered oil and gas resources of the Southwestern Wyoming Province, 2002: U.S. Geological Survey Fact Sheet 145-02, accessed April 2009 at http://pubs.usgs.gov/fs/fs-145-02/FS-145-02.pdf.

U.S. Geological Survey, 2006, Digital orthophoto quadrangles: U.S. Geological Survey Fact Sheet 057-01 (May 2001), accessed May 2009 at http://egsc.usgs.gov/isb/pubs/factsheets/fs05701.html.

U.S. Geological Survey, 2007, The national map seamless server, Earth Resources Observation and Science (EROS): Bureau of Transportation Statistics (BTS) Roads FAQ, accessed March 2009 at http://seamless.usgs.gov/faq/bts_faq.php.

U.S. Geological Survey, 2009, National oil and gas assessment, accessed March 2009 at http://energy.cr.usgs.gov/oilgas/noga/index.html.

Utah Division of Oil, Gas, and Mining, 2004, Preparing an Application for Permit to Drill (APD): Utah Division of Oil, Gas, and Mining guidance document, accessed March 2009 at https://fs.ogm.utah.gov/PUB/Oil&Gas/Publications/Handbooks/guideAPD2.pdf.

Utah Division of Oil, Gas, and Mining, 2007, Utah oil and gas, accessed June 2007 at http://oilgas.ogm.utah.gov/Data_Center/DataCenter.cfm.

Wilshire, H.G., Howard, K.A., Wentworth, C.M., and Gibbons, H., 1996, Geologic processes at the land surface: U.S. Geological Survey Bulletin 2149, 41 p., available at http://pubs.er.usgs.gov/usgspubs/b/b2149.

Wray, L.L., Apeland, A.D., Hemborg, H.T., Brchan, C.A., Morgan, M.L., and Young, G.B.C, 2005, Shapefiles for the 2002 oil and gas fields map of Colorado: Colorado Geological Survey Open File Report 05-09, CD-ROM.

Wyoming Oil and Gas Conservation Commission, 2007, Oil and gas database, accessed June 2007 at http://wogcc.state.wy.us/.

Wyoming Oil and Gas Conservation Commission, 2008, Operational rules, drilling rules: chap. 3, accessed March 2009 at http://soswy.state.wy.us/RULES/rules/6913.pdf.

Appendixes 1 to 5

Appendix 1A. Summary of National Environmental Policy Act documents reviewed to identify common oil and gas drill pad and resource road dimensions for the Upper Colorado River Basin, Utah.

[EIS, Environmental Impact Statement; ft, foot; LOP, life of project; NR, not reported; ROW, right of way]

EIS Number	UT-080-06-240	UT-080-06-329	UT-080-05-322	UT-080-06-253	UT-080-07-671	UT-080-06-076	UT-080-03-0300V	UT-080-06-099
EIS Name	Kerr-McGee Bonanza	Gasco Wilkin Ridge unit	Gasco Riverbend unit	Kerr-McGee Love unit	Enduring Resources Saddletree draw leasing and Rock house development proposal [1]	Enduring Resources West Bonanza area natural gas development	Resource Development Group - Uinta Basin natural gas project	EOG Resources North Alger natural gas expansion
Number of wells	95	54	49	125	60	131	423	44
Number of pads	95	54	49	125	24	131	423	44
Road length (miles)	43.6	21.4	11	43	8.4	33.7	125	13.7
Pipeline length (miles)	77	33	15	82	NR	60	125	13.7
Number of compressor stations	2	0	0	1	NR	4	1	NR
Pads								
Initial pad size (acres)	2.5	3.7	3.7	2.5	2	2	1.19	2.5
LOP pad size (acres) [2]	1	NR	NR	1	NR	NR	NR	2.2
Roads								
Average new ROW (ft)	50	30	30	30	30	30	30	30
Average LOP ROW (ft)	30	NR	NR	15	18	NR	NR	NR
Website [3]								
	http://www.blm.gov/utah/vernal/bonanzaea.htm	http://www.blm.gov/utah/vernal/wilkinridgea.htm	http://www.blm.gov/utah/vernal/gascorev.html	http://www.blm.gov/utah/vernal/loveea.html	http://www.blm.gov/utah/vernal/rockhouse671.htm	http://www.blm.gov/utah/vernal/nepa.html	http://www.blm.gov/utah/vernal/rdgfinal.htm	http://www.blm.gov/utah/vernal/northalger.html

[1] The proposed alternative includes wells that will be drilled from existing pads or multiple wells drilled from a single pad.

[2] If the well becomes a producing well, drill pads are reclaimed to a smaller size after drilling operations are complete.

[3] Documents that are no longer available online can be obtained upon request to the Bureau of Land Management.

Appendix 1B. Summary of National Environmental Policy Act documents reviewed to identify common oil and gas drill pad and resource road dimensions for the Upper Colorado River Basin, Colorado.

[EIS, Environmental Impact Statement; GAP, Geographic Area Plan; LOP, life of project; NR, not reported; ROW, right of way; ft, foot]

EIS Number	CO-140-2005-134	CO-140-2005-113	CO-140-2006-045	CO-140-2007-115	CO-140-05-009	CO-140-05-047	CO-140-2004-081	CO-140-2006-050
EIS Name	Grant Gulch GAP environmental assessment - EnCana Oil and Gas [1]	Orchard Unit GAP - EnCana Oil and Gas [1]	Rulison GAP - EnCana Oil and Gas [1]	Pete and Bill Creek GAP - Noble Energy [1]	Castle Springs GAP - Windsor Energy LLC [1]	Wheeler to Webster GAP - Williams Production Natural Gas [1]	Grass Mesa GAP - EnCana Oil and Gas [1]	South Parachute GAP - EnCana Oil and Gas [1]
Number of wells	97	65	68	42	98	213	100	139
Number of pads	17	7	12	4	18	59	16	26
Road length (miles)	8.27	5.8	6	3	7	NR	NR	NR
Pipeline length (miles)	8.27	5.9	6.4	3	7	NR	NR	NR
Number of compressor stations	0	0	0	0	1	NR	NR	NR
Pads								
Initial pad size (acres)	6.70	6.5	4.6	6	3.26	2.5	6	4.15
LOP pad size (acres) [2]	1	1	1.5	2	1.5	0.5	1	1.5
Roads								
Average new ROW (ft)	60	60	75	75	Variable	30	38	75
Average LOP ROW (ft)	30	30	25	25	18	NR	30	25
Website [3]								
	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html	http://www.blm.gov/co/st/en/fo/gsfo/GSFO_MasterPlansOfDevelopment.html

[1] The proposed alternative includes wells that will be drilled from existing pads or multiple wells drilled from a single pad.

[2] If the well becomes a producing well, drill pads are reclaimed to a smaller size after drilling operations are complete.

[3] Documents that are no longer available online can be obtained upon request to the Bureau of Land Management.

Appendix 1C. Summary of National Environmental Policy Act documents reviewed to identify common oil and gas drill pad and resource road dimensions for the Upper Colorado River Basin, Wyoming.

[EIS, Environmental Impact Statement; ft, foot; LOP, life of project; NA, not available; NR, not reported; ROW, right of way]

EIS Number	WY-040-EA00-094	WY-040-EA03-187	WY-040-EA03-186	WY-040-EADESFT04	WY-040-EA04-008	WY-040-EA04-007
EIS Name	Vermillion Basin natural gas exploration and development	Copper Ridge shallow gas exploration and development	Little Monument natural gas	Desolation Flats natural gas field development [1]	Pacific Rim shallow oil and gas exploration	Bitter Creek shallow oil and gas exploration
Number of wells	56	89	31	385	120	61
Number of pads	56	89	31	361	120	61
Road length (miles)	28	22.25	NR	542	35.64	NR
Pipeline length (miles)	28	66.75	NR	361	50.64	NR
Number of compressor stations	NR	1	NR	4	5	NR
Pads						
Initial pad size (acres)	3.8	2	1.8	4	1.1	3
LOP pad size (acres) [2]	1	1	1	1.5	0.2	1
Roads						
Average new ROW (ft)	55	60	55	50	30	NR
Average LOP ROW (ft)	32	30	NR	50	14	NR
Website [3]						
	http://www.blm.gov/wy/st/en/info/NEPA/rsfodocs/vermbasin.html	http://www.blm.gov/wy/st/en/info/NEPA/rsfodocs/copperridge.html	http://www.blm.gov/wy/st/en/info/NEPA/rsfodocs/littlemonument.html	http://www.blm.gov/wy/st/en/info/NEPA/rfodocs/desflats.html	http://www.blm.gov/wy/st/en/info/NEPA/rsfodocs/pacificrim.html	http://www.blm.gov/wy/st/en/info/NEPA/rsfodocs/bittercreek.html

[1] The proposed alternative includes wells that will be drilled from existing pads or multiple wells drilled from a single pad.

[2] If the well becomes a producing well, drill pads are reclaimed to a smaller size after drilling operations are complete.

[3] Documents that are no longer available online can be obtained upon request to the Bureau of Land Management.

Appendix 1C. Summary of National Environmental Policy Act documents reviewed to identify common oil and gas drill pad and resource road dimensions for the Upper Colorado River Basin, Wyoming.—Continued

[EIS, Environmental Impact Statement; ft, foot; LOP, Life of project; NA, not available; NR , not reported; ROW, right of way]

EIS Number	**WY-040-EA05-161**	**WY-040-EA03-211**	**WY-040-CDWIIROD**	**WY-JIDPEIS-06**	**WY-EIS00-018**	**NA**
EIS Name	**Monell enhanced oil recovery project**	**Lower Bush Creek coalbed methane exploration** [1]	**Continental Divide-Wamsutter II natural gas project**	**Jonah infill drilling project**	**Pinedale Anticline oil and gas exploration and development project**	**Pinedale Anticline oil and gas exploration supplemental EIS** [1]
Number of wells	126	22	2,130	3,100	900	4,399
Number of pads	126	20	2,130	3,100	900	250
Road length (miles)	32	10.14	1,065	485	366	NR
Pipeline length (miles)	132	NR	1,065	465	120	NR
Number of compressor stations	1	NR	3	NR	4	NR
Pads						
Initial pad size (acres)	2	1.39	2.6	3.8	3.7	20
LOP pad size (acres) [2]	1	0.7	0.8	0.9	1.4	7.5
Roads						
Average new ROW (ft)	60	30	50	73	55	See original EIS
Average LOP ROW (ft)	30	12	27	29	NR	NR
Website [3]						
	http://www.blm.gov/wy/st/en/info/NEPA/rsfodocs/monell.html	http://www.blm.gov/wy/st/en/info/NEPA/rsfodocs/lowerbush.html	http://www.blm.gov/wy/st/en/info/NEPA/rfodocs/cd_wamsutter.html	http://www.blm.gov/wy/st/en/info/NEPA/pfodocs/jonah.html	http://www.blm.gov/wy/st/en/info/NEPA/pfodocs/anticline.html	http://www.blm.gov/wy/st/en/info/NEPA/pfodocs/anticline/seis.htm

[1] The proposed alternative includes wells that will be drilled from existing pads or multiple wells drilled from a single pad.

[2] If the well becomes a producing well, drill pads are reclaimed to a smaller size after drilling operations are complete.

[3] Documents that are no longer available online can be obtained upon request to the Bureau of Land Management.

Appendix 2. Summary of Bureau of Land Management Resource Management Plans reviewed to identify reasonably foreseeable development scenarios for the Upper Colorado River Basin.

[BLM, Bureau of Land Management; EIS, Environmental Impact Statement; FO, Field Office; RMP, Resource Management Plan]

State	Area	Date of RMP	Date accessed	Status when accessed	Website[1]
Colorado	BLM Little Snake FO	January 2007	January 16, 2009	Approved	http://www.blm.gov/co/st/en/fo/lsfo/plans/rmp_revision/rmp_docs.html
Colorado	BLM White River FO	November 2007	January 16, 2009	Final	http://www.blm.gov/co/st/en/BLM_Programs/land_use_planning/rmp/white_river/documents.html
Colorado	BLM Glenwood Springs FO	October 2007	January 16, 2009	Final	http://www.blm.gov/pgdata/etc/medialib/blm/co/programs/land_use_planning/rmp/kfo-gsfo/documents.Par.8480.File.dat/GSFO_AMS-Final_103107.pdf
Colorado	Glenwood Springs FO, Roan Plateau geographic area	August 2006	January 16, 2009	Final	http://www.blm.gov/co/st/en/BLM_Programs/land_use_planning/rmp/roan_plateau/documents/final_rmpa_eis.html
Colorado	San Juan public lands geographic area	December 2006	January 16, 2009	Draft EIS	http://ocs.fortlewis.edu/forestPlan/reports.asp
Colorado	BLM Grand Junction FO	November 1985	January 16, 2009	Final	http://www.blm.gov/co/st/en/BLM_Programs/land_use_planning/rmp/archived/grand_junction.html
New Mexico	BLM Farmington FO - San Juan Basin, New Mexico	July 2001	January 16, 2010	Final	http://www.blm.gov/pgdata/etc/medialib/blm/nm/field_offices/farmington/farmington_planning/ffo_rmp_docs.Par.59812.File.dat/RFD.pdf
Utah	BLM Vernal FO	October 2008	January 13, 2009	Approved	http://www.blm.gov/ut/st/en/fo/vernal/planning/rmp/rod_approved_rmp.html
Utah	BLM Monticello FO	November 2008	January 15, 2009	Approved	http://www.blm.gov/ut/st/en/fo/monticello/planning/Monticello_Resource_Management_Plan.html
Utah	BLM Price FO	August 2002	January 15, 2009	Draft EIS	http://www.blm.gov/ut/st/en/fo/price/planning/Resource_Management_Plan/Draft_EIS.html
Utah	BLM Moab FO	August 2005	January 16, 2009	Complete	http://www.blm.gov/pgdata/etc/medialib/blm/ut/moab_fo/rmp/background_documents.Par.44906.File.dat/MoabFinalRFDwithMaps.pdf
Utah	BLM Kanab FO	July 2008	January 16, 2009	Approved	http://www.blm.gov/ut/st/en/fo/kanab/planning/proposed_rmp_feis.html
Utah	BLM Richfield FO	August 2008	January 16, 2009	Proposed RMP/ Final EIS	http://www.blm.gov/pgdata/etc/medialib/blm/ut/richfield_fo/planning/rmp/August_8__2008.Par.20741.File.dat/Vol-III_Appendix-12_Richfield-FEIS_RFD.pdf
Wyoming	BLM Pinedale FO	November 2008	January 13, 2009	Approved	http://www.blm.gov/rmp/wy/pinedale/documents_RFD.html
Wyoming	BLM Kemmerer FO	August 2008	January 13, 2009	Draft EIS	http://www.blm.gov/rmp/kemmerer/feis.htm
Wyoming	BLM Rawlins FO	December 2008	January 13, 2009	Approved	http://www.blm.gov/rmp/wy/rawlins/documents.html
Wyoming	BLM Rock Springs FO - Green River Resource Area	August 1997	January 13, 2009	Approved	http://www.blm.gov/pgdata/etc/medialib/blm/wy/programs/planning/rmps.Par.20275.File.dat/greenriver-rmp.pdf

[1] Documents that are no longer available online can be obtained upon request to the originating agency

Appendix 3. Descriptions and water year 2007 dissolved-solids load estimates for selected sites in the Upper Colorado River Basin.

[Dissolved-solids load estimates determined using a multiple linear regression model included in the computer model LOADEST (Runkel and others, 2004). Horizontal datum is North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; NAVD 88, North American Vertical Datum of 1988; AZ, Arizona; CO, Colorado; SEP, standard error of prediction; UT, Utah; WY, Wyoming; —, no data]

Site identification number	Site name	Decimal latitude	Decimal longitude	Altitude of gage/land surface (feet above datum)	Altitude datum	Hydrologic Unit Code	Drainage area, in square miles	Estimates of dissolved-solids load during water year 2007, in tons				
								Mean daily load	95-percent confidence interval for mean daily load		SEP of mean daily load	Annual load
									Lower bound	Upper bound		
09032000	Ranch Creek near Fraser, CO	39.9500	-105.7656	8,660	NGVD 29	14010001	19.9	0.69	0.61	0.79	0.05	253
09034250	Colorado River at Windy Gap, near Granby, CO	40.1083	-106.0042	7,790	NGVD 29	14010001	789	29.9	27.5	32.4	1.26	10,900
09058000	Colorado River near Kremmling, CO	40.0367	-106.4400	7,320	NGVD 29	14010001	2,380	330	307	354	11.9	121,000
09063000	Eagle River at Red Cliff, CO	39.5083	-106.3667	8,654	NGVD 29	14010003	70.0	10.6	10.4	10.9	0.13	3,890
09066510	Gore Creek at mouth near Minturn, CO	39.6094	-106.4478	7,730	NGVD 29	14010003	102	25.2	23.3	27.2	0.98	9,200
09081000	Roaring Fork River near Emma, CO	39.3733	-107.0839	6,470	NGVD 29	14010004	853	291	281	301	5.14	106,000
09083800	Crystal River below Carbondale, CO	39.4080	-107.2303	6,120	NAVD 88	14010004	350	185	180	189	2.42	67,400
09085000	Roaring Fork River at Glenwood Springs, CO	39.5436	-107.3295	5,721	NGVD 29	14010004	1,450	766	745	788	11.2	280,000
09095500	Colorado River near Cameo, CO	39.2391	-108.2662	4,814	NGVD 29	14010005	8,050	3,620	3,520	3,720	49.1	1,320,000
09107000	Taylor River at Taylor Park, CO	38.8603	-106.5667	9,340	NGVD 29	14020001	128	16.1	15.5	16.7	0.30	5,870
09112200	East River below Cement Creek near Crested Butte, CO	38.7842	-106.8709	8,440	NGVD 29	14020001	238	85.0	80.8	89.5	2.23	31,000
09112500	East River at Almont, CO	38.6644	-106.8481	8,006	NGVD 29	14020001	289	101	97.9	104	1.52	36,800
09113980	Ohio Creek above mouth near Gunnison, CO	38.5878	-106.9314	7,770	NGVD 29	14020002	161	16.6	14.4	19.0	1.17	6,040
09114500	Gunnison River near Gunnison, CO	38.5419	-106.9498	7,655	NGVD 29	14020002	1,010	186	176	196	5.20	67,800
09119000	Tomichi Creek at Gunnison, CO	38.5217	-106.9409	7,629	NGVD 29	14020003	1,060	69.4	64.6	74.4	2.49	25,300
09128000	Gunnison River below Gunnison Tunnel, CO	38.5292	-107.6489	6,526	NGVD 29	14020002	3,970	293	275	313	9.71	107,000
09132500	North Fork Gunnison River near Somerset, CO	38.9258	-107.4342	6,280	NGVD 29	14020004	526	93.8	80.7	108	7.06	34,200
09146020	Uncompahgre River near Ouray, CO	38.0433	-107.6831	7,600	NGVD 29	14020006	77.0	76.0	73.8	78.2	1.13	27,700
09146200	Uncompahgre River near Ridgway, CO	38.1839	-107.7459	6,878	NGVD 29	14020006	149	141	133	149	4.04	51,500
09152500	Gunnison River near Grand Junction, CO	38.9833	-108.4506	4,628	NGVD 29	14020005	7,930	2,950	2,770	3,140	95.2	1,080,000

Appendix 3. Descriptions and water year 2007 dissolved-solids load estimates for selected sites in the Upper Colorado River Basin.—Continued

[Dissolved-solids load estimates determined using a multiple linear regression model included in the computer model LOADEST (Runkel and others, 2004). Horizontal datum is North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; NAVD 88, North American Vertical Datum of 1988; AZ, Arizona; CO, Colorado; SEP, standard error of prediction; UT, Utah; WY, Wyoming; —, no data]

Site identification number	Site name	Decimal latitude	Decimal longitude	Altitude of gage/land surface (feet above datum)	Altitude datum	Hydrologic Unit Code	Drainage area, in square miles	Estimates of dissolved-solids load during water year 2007, in tons				
								Mean daily load	95-percent confidence interval for mean daily load		SEP of mean daily load	Annual load
									Lower bound	Upper bound		
09163500	Colorado River near Colorado-Utah State Line	39.1328	-109.0271	4,325	NGVD 29	14010005	17,800	7,320	7,060	7,580	132	2,670,000
09169500	Dolores River at Bedrock, CO	38.3103	-108.8854	4,940	NGVD 29	14030002	2,020	154	121	193	18.5	56,100
09171100	Dolores River near Bedrock, CO	38.3569	-108.8334	4,910	NGVD 29	14030002	2,150	314	254	383	33.0	114,000
09180000	Dolores River near Cisco, UT	38.7972	-109.1951	4,165	NGVD 29	14030004	4,580	711	609	825	55.0	260,000
09180500	Colorado River near Cisco, UT	38.8105	-109.2934	4,090	NGVD 29	14030005	24,100	7,660	7,220	8,130	232	2,800,000
09196500	Pine Creek above Fremont Lake, WY	43.0305	-109.7702	7,450	NGVD 29	14040102	75.8	3.35	3.22	3.48	0.06	1,220
09211200	Green River below Fontenelle Reservoir, WY	42.0210	-110.0498	6,378	NGVD 29	14040103	4,280	512	493	533	10.2	187,000
09217000	Green River near Green River, WY	41.5164	-109.4490	6,060	NGVD 29	14040106	14,000	688	661	716	13.9	251,000
09229500	Henrys Fork near Manila, UT	41.0125	-109.6729	6,060	NGVD 29	14040106	520	117	69.9	183	29.0	42,500
09239500	Yampa River at Steamboat Springs, CO	40.4830	-106.8324	6,695	NGVD 29	14050001	568	66.7	48.2	90.1	10.7	24,400
09247600	Yampa River below Craig, CO	40.4808	-107.6142	6,100	NGVD 29	14050001	1,750	466	300	691	100	170,000
09251000	Yampa River near Maybell, CO	40.5027	-108.0334	5,900	NGVD 29	14050002	3,410	610	517	716	50.8	223,000
09258980	Muddy Creek below Young Draw, near Baggs, WY	41.0682	-107.6316	6,270	NGVD 29	14050004	—	12.1	7.53	18.4	2.79	4,410
09260050	Yampa River at Deerlodge Park, CO	40.4516	-108.5251	5,600	NGVD 29	14050002	7,660	768	656	893	60.6	280,000
09261000	Green River near Jensen, UT	40.4094	-109.2354	4,758	NGVD 29	14060001	29,700	2,960	2,370	3,650	327	1,080,000
09302000	Duchesne River near Randlett, UT	40.2103	-109.7814	4,756	NGVD 29	14060003	3,790	348	323	374	12.95	127,000
09304200	White River above Coal Creek, near Meeker, CO	40.0050	-107.8253	6,400	NGVD 29	14050005	648	177	166	189	5.80	64,600
09304800	White River below Meeker, CO	40.0133	-108.0931	5,928	NGVD 29	14050005	1,020	406	382	430	12.4	148,000
09306200	Piceance Creek below Ryan Gulch, near Rio Blanco, CO	39.9211	-108.2976	6,070	NGVD 29	14050006	506	42.3	40.5	44.2	0.96	15,400
09306222	Piceance Creek at White River, CO	40.0780	-108.2365	5,730	NGVD 29	14050006	652	67.2	64.4	70.1	1.45	24,500
09306255	Yellow Creek near White River, CO	40.1686	-108.4012	5,535	NGVD 29	14050006	262	8.68	8.18	9.19	0.26	3,170

Appendix 3. Descriptions and water year 2007 dissolved-solids load estimates for selected sites in the Upper Colorado River Basin.—Continued

[Dissolved-solids load estimates determined using a multiple linear regression model included in the computer model LOADEST (Runkel and others, 2004). Horizontal datum is North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; NAVD 88, North American Vertical Datum of 1988; AZ, Arizona; CO, Colorado; SEP, standard error of prediction; UT, Utah; WY, Wyoming; —, no data]

Site identification number	Site name	Decimal latitude	Decimal longitude	Altitude of gage/land surface (feet above datum)	Altitude datum	Hydrologic Unit Code	Drainage area, in square miles	Estimates of dissolved-solids load during water year 2007, in tons				
								Mean daily load	95-percent confidence interval for mean daily load		SEP of mean daily load	Annual load
									Lower bound	Upper bound		
09306290	White River below Boise Creek, near Rangely, CO	40.1797	-108.5654	5,395	NGVD 29	14050007	2,530	503	479	527	12.4	183,000
09306500	White River near Watson, UT	39.9789	-109.1787	4,947	NGVD 29	14050007	4,020	569	516	626	28.1	208,000
09314500	Price River at Woodside, UT	39.2639	-110.3465	4,600	NGVD 29	14060007	1,540	220	188	256	17.4	80,400
09315000	Green River at Green River, UT	38.9861	-110.1512	4,040	NGVD 29	14060008	44,900	3,590	3,230	3,980	194	1,310,000
09328500	San Rafael River near Green River, UT	38.8583	-110.3701	4,190	NGVD 29	14060009	1,630	291	—	—	—	106,000
09352900	Vallecito Creek near Bayfield, CO	37.4775	-107.5437	7,906	NGVD 29	14080101	72.5	16.2	15.3	17.1	0.46	5,920
09359020	Animas River below Silverton, CO	37.7903	-107.6676	9,200	NGVD 29	14080104	146	140	138	143	1.34	51,200
09371492	Mud Creek at State Highway 32, near Cortez, CO	37.3128	-108.6612	5,765	NGVD 29	14080202	33.6	36.1	34.0	38.3	1.10	13,200
09371520	McElmo Creek above Trail Canyon near Cortez, CO	37.3267	-108.7007	5,690	NGVD 29	14080202	234	202	187	218	7.98	73,700
09372000	McElmo Creek near Colorado-Utah State Line	37.3242	-109.0157	4,890	NGVD 29	14080202	346	209	202	216	3.50	76,300
09379500	San Juan River near Bluff, UT	37.1469	-109.8648	4,048	NGVD 29	14080205	23,000	1,590	1,390	1,810	108	580,000
09380000	Colorado River at Lees Ferry, AZ	36.8647	-111.5882	3,106	NGVD 29	14070006	112,000	15,100	14,900	15,400	141	5,520,000

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09010500	53.8	0	0	0	52.7	0	0.173	0.920	0	0	0	0.00
09024000	27.6	0	0	0	27.6	0	0	0	0	0	0	0.00
09025000	28.2	0	0	0	28.2	0	0	0	0	0	0.078	0.00
09025400	7.25	0.034	0	0.081	7.11	0	0.139	0	0	0	0	0.00
09026500	32.9	0	0	0	32.2	0	0	0	0.787	0	0.001	0.00
09032000	20.0	0	0	0	19.8	0	0.222	0	0	0	0	0.00
09032100	6.28	0	0	0	6.28	0	0	0	0	0	0	0.00
09034250	614	14.8	2.64	5.42	332	147	85.5	24.9	8.90	0	15.9	0.005
09034500	36.0	0.934	0.011	0.043	0.737	32.6	2.44	0.146	0	0	0.097	0.00
09034900	6.12	0	0	0	6.12	0	0	0	0	0	0	0.00
09035500	10.3	0	0	0	10.3	0	0	0	0	0	0	0.00
09035700	18.9	0	0	0	18.9	0	0	0	0	0	0	0.00
09035800	8.86	0	0	0	8.86	0	0	0	0	0	0	0.00
09035900	27.7	0	0	0	27.7	0	0	0	0	0	0	0.00
09036000	17.8	0	0	0.106	17.8	0	0	0	0	0	0	0.00
09037500	94.3	0.876	0.272	0.988	75.7	2.99	10.3	0	3.76	0	1.54	0.00
09038500	9.02	0.191	0	0	1.23	1.65	6.14	0	0	0	0	0.00
09039000	44.7	0	0	0.004	39.8	4.45	0.530	0	0	0	0	0.00
09041090	148	0.207	6.11	0.257	22.9	11.1	19.5	54.9	37.8	0	2.02	0.00
09041500	146	0.875	6.10	2.01	36.1	5.07	26.3	39.3	35.5	0.658	3.45	0.00
09046490	42.5	0	0	0	24.3	0	0	0.461	1.93	15.8	0	0.00
09046600	80.9	0	0	0	54.3	0	0	11.0	9.98	3.57	2.03	0.00
09047500	58.1	0	0	0	57.1	0	0	1.04	0	0	0	0.00
09047700	9.39	0	0	0	9.39	0	0	0	0	0	0	0.00
09050100	86.6	0	0	0	56.7	0.407	0	0	0	29.6	0	0.00
09050700	51.3	0	0	0	33.9	5.54	0	7.59	3.66	0	0.602	0.00

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09051050	19.3	0	0	0	18.3	0	0	0.985	0.028	0	0	0.00
09052000	16.0	0	0.014	0	15.3	0	0	0.005	0.756	0	0	0.00
09052400	8.66	0	0	0	8.54	0	0	0	0.124	0	0	0.00
09052800	14.5	0	0	0	12.4	0	1.91	0.191	0.058	0	0	0.00
09054000	15.3	0	0	0	14.5	0.123	0.669	0	0	0	0	0.00
09055300	12.0	0	0	0	10.6	0.275	0.546	0	0.573	0	0	0.00
09057500	163	1.75	2.93	2.85	77.5	3.00	9.66	50.4	18.5	0	3.81	0.00
09057520	61.6	0	1.95	0	16.2	0	0.945	10.5	32.7	1.19	0	0.00
09058000	379	21.7	5.25	4.92	80.5	134	105	16.6	32.9	0.090	9.60	0.00
09058500	12.8	0	0	0	10.8	0	0	0	0	2.05	0	0.00
09058610	3.56	0	0	0	0.148	0	0.100	0	0.008	3.31	0	0.00
09058700	3.58	0	0	0	0.620	0	0.188	0	0	2.77	0	0.00
09058800	3.60	0	0	0	3.25	0	0	0	0.038	0.312	0	0.00
09059500	70.5	0.146	0	0.269	10.7	0	7.63	4.14	19.9	28.1	0	0.00
09060550	72.9	0	0	0	56.4	0	1.58	0	8.42	6.52	0	0.00
09060770	128	1.19	9.35	1.05	22.9	0	10.6	0	78.1	16.6	0	0.014
09063000	76.0	0	0	0	28.0	0.055	0	0	0	45.4	2.50	0.00
09063200	9.69	0	0	0	0.585	0	0.828	0	0	8.27	0	0.00
09063400	14.1	0	0	0	0.937	0	0.487	0	0	12.7	0	0.00
09063900	6.48	0	0	0	6.48	0	0	0	0	0	0	0.00
09064500	51.9	0	0	0	51.0	0.433	0	0	0	0.390	0	0.00
09064600	34.4	0	0	0	21.4	0	0	0	0	13.0	0	0.00
09065100	34.8	0	0	0.008	33.5	0	0	0	0	1.30	0	0.00
09065500	14.6	0	0	0.003	14.3	0	0.006	0	0	0.307	0	0.00
09066000	12.5	0	0	0	3.55	0	0.842	0	0	8.09	0	0.00
09066100	5.65	0	0	0.050	5.63	0	0	0	0	0.026	0	0.00

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09066150	6.19	0	0	0.059	4.83	0	0	0	0	1.13	0.237	0.00
09066200	6.12	0	0	0.021	4.07	0	0	0	0	1.99	0.061	0.00
09066300	6.01	0	0	0.019	1.79	0	0	0	0	4.18	0.043	0.00
09066310	26.0	0	0	0.956	1.90	0	4.39	0	0	18.5	1.15	0.00
09066400	8.49	0	0	0	4.05	0	0	0	0	4.44	0	0.00
09067000	14.8	0	0	0	8.68	0	0	0	0	6.16	0	0.00
09067005	73.7	0.082	0	0.843	7.32	0	5.50	0	0	58.8	2.09	0.00
09070000	549	0.057	1.45	14.8	91.4	0	24.6	35.9	77.0	296	24.6	0.00
09070500	773	1.81	10.5	4.31	209	0.183	89.8	35.5	191	247	0.615	0.00
09071300	6.83	0	0	0	0.320	0	0	0	0	6.51	0	0.00
09071750	137	0	0	0.147	17.0	0	5.89	0	0.096	114	0	0.00
09073300	76.3	0	0	0.029	76.3	0	0	0	0	0	0	0.00
09073400	29.8	0	0	0.158	27.2	0	0	0	0	2.64	0	0.00
09074000	41.7	0	0	0.04	39.8	0	0	0	0	1.93	0	0.00
09074800	32.3	0	0	0	18.1	0	0	0	0	14.2	0	0.00
09075700	35.8	0	0	0	7.92	0	0	0	0	27.9	0	0.00
09080400	223	0.062	0	0.211	146	2.85	2.40	0	0	72.5	0	0.00
09081600	169	0.004	0.132	0.118	33.7	0	6.56	21.2	57.2	50.0	0	0.00
09085000	833	3.93	16.1	32.6	197	0.207	109	19.9	172	296	39.2	0.049
09085100	24.4	0.016	0	0.077	5.25	0	0.277	0	0	18.9	0	0.00
09086000	9.53	0	0.002	0.011	0	0	0	0	1.07	8.46	0	0.00
09086470	91.3	0	0	0.022	1.13	0	0	0	0	90.2	0	0.00
09089500	64.5	0.217	0	0	0.123	0	59.5	4.91	0	0	0	0.004
09093700	1,180	47.1	7.97	16.6	16.6	144	630	49.7	101	194	49.0	2.30
09095500	623	10.2	0	3.18	0	285	307	16.7	6.75	0	7.38	0.535
09105000	592	22.1	3.80	23.0	184	77.3	286	10.7	14.6	0	19.5	0.712

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09106150	172	1.19	0.559	0.236	4.86	1.04	34.8	124	5.54	0	0.916	0.151
09107000	129	0	0	0.239	118	0.045	0	0	0	6.81	3.60	0.00
09107500	44.5	0	0	0	42.9	0.110	0	0	0	0.279	1.19	0.00
09109000	81.9	0	0	0.360	62.8	2.66	0	0	0	9.52	6.91	0.00
09110000	223	0	0.232	0.709	155	0	0	0	8.53	59.3	0.794	0.00
09112500	290	2.14	4.57	10.4	68.1	0	17.3	21.9	108	67.1	6.87	0.00
09114500	245	15.9	9.35	5.87	96.6	0	73.4	28.7	39.6	0	6.74	0.004
09118450	334	5.93	0	9.27	298	0	24.4	0	6.41	0	5.28	0.00
09119000	727	15.4	4.90	8.72	505	0.044	48.9	0	135	38.5	0	0.00
09124500	340	0.649	0	1.65	310	0.592	24.9	0	0	0	4.47	0.00
09126000	67.2	0	0	0	53.8	0	13.5	0	0	0	0	0.00
09128000	1,490	8.87	4.53	8.17	1,220	22.4	141	2.00	98.3	0	4.34	0.00
09128500	43.6	0.001	0.232	0	20.9	0	5.60	0	17.1	0	0	0.00
09132500	525	11.1	0.344	1.44	104	3.27	299	98.0	16.1	0	5.28	0.079
09134000	41.8	0	0.142	0	8.28	0	5.67	15.7	12.1	0	0	0.00
09135900	66.9	0.069	2.38	2.17	15.8	2.86	13.4	9.58	18.5	0	6.78	0.00
09143000	27.7	0	0	0	19.0	1.17	7.36	0.002	0	0	0.114	0.004
09143500	14.9	0	0.156	1.25	5.89	0.736	0.717	1.99	0.163	0	5.39	0.005
09144250	951	13.9	73.4	39.0	91.3	9.71	156	103	518	0	73.1	0.008
09146200	149	0.274	3.29	4.25	87.6	0	12.0	0	29.8	10.1	9.81	0.00
09147000	97.6	2.30	4.55	0.161	23.7	0	20.1	0	53.7	0	0.001	0.00
09147025	18.1	0.096	1.40	0.0475	0.208	0	1.91	0	16.0	0	0	0.00
09147500	183	1.44	3.63	1.30	55.7	0	50.2	0	72.6	1.14	3.26	0.00
09149500	667	33.0	39.0	30.9	1.49	0.290	128	1.86	489	0	47.1	0.015
09152500	1,170	3.89	14.0	13.9	51.1	2.91	50.5	139	899	6.78	20.1	0.041
09153290	17.7	0	9.67	0	0	0	0	0	17.7	0	0	0.022

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09163500	1,170	11.4	53.5	35.5	20.6	51.2	119	346	575	0	60.0	1.59
09165000	105	0	0	0	13.7	0	5.01	6.72	41.8	37.7	0.529	0.00
09166500	399	0	2.76	0.540	16.1	0.520	0	64.1	286	32.2	0	0.005
09166950	69.3	0	0.241	0	0.166	0.263	0	0	68.8	0	0	0.00
09169500	1,450	2.88	6.91	0.027	4.53	0	41.5	140	1,240	17.3	10.6	0.204
09171100	122	4.34	0.086	0.427	0	0	37.0	23.9	44.1	8.06	8.81	0.00
09172500	309	0.196	5.51	1.06	80.8	0.111	20.1	13.1	182	12.4	0	0.00
09177000	1,190	0	43.4	0	16.7	0.482	15.1	24.7	1,130	5.18	0.042	0.081
09180000	928	2.60	1.35	0.635	71.3	0.116	37.2	252	489	7.51	71.3	0.016
09180500	1,530	2.44	2.74	0.998	36.4	235	94.9	407	758	0.029	0	5.88
09184000	74.5	0	0.496	0	3.46	0	1.68	0	65.0	0	4.31	0.006
09186500	30.8	0	0	0	4.97	0	7.42	0	18.4	0	0	0.00
09209400	3,830	365	0.274	13.4	610	149	2,190	0.413	341	154	392	9.00
09211200	370	7.50	0.716	0	0	118	111	14.8	111	9.22	5.43	0.675
09215550	1,130	21.0	0	0.288	83.6	456	550	0.891	0.198	0	44.5	0.274
09216050	600	13.0	0	0	0	492	107	0	0	0	0	0.141
09217000	3,800	0.215	0	0	0	1,470	1,360	702	269	0	0	8.14
09224700	2,980	144	3.94	0.350	0	209	2,020	149	384	21.6	206	3.76
09234500	2,400	37.4	8.38	4.24	0.418	619	1,150	13.2	157	56.5	402	0.858
09235600	24.7	0	0	0	0	0	11.4	0	1.84	0.066	11.4	0.00
09237450	207	5.01	14.9	3.05	26.0	0.492	83.0	0.346	93.7	0	3.67	0.00
09237500	20.5	0.255	0	0	2.86	0	16.5	0	1.08	0	0	0.00
09238900	26.0	0	0	0	26.0	0.066	0	0	0	0	0	0.00
09239500	313	5.40	0.810	4.32	186	0.623	87.1	8.78	24.9	0	6.20	0.016
09240900	123	0	0.026	0.210	112	0	0.271	0	8.67	0	2.67	0.00
09241000	93.3	1.12	0.018	0.206	37.6	0	40.6	0	14.1	0	1.07	0.00

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09242500	243	6.25	6.66	1.59	103	0	45.5	15.1	74.8	0	5.21	0.00
09243700	24.7	0	0.238	0	0	0	0	21.9	2.86	0	0	0.007
09243900	17.7	0	0.058	0	0	0	0	17.7	0	0	0	0.00
09245000	67.8	0	0.094	0	0.986	0	14.7	24.3	27.8	0	0	0.012
09246920	40.3	1.10	0	0	0.116	0	40.1	0	0	0	0	0.011
09247600	952	19.0	12.0	0.015	38.6	78.4	260	379	195	0	1.24	0.534
09249750	458	0.207	10.7	0	23.9	0	53.4	161	220	0	0	0.166
09250507	20.1	0	0.193	0	0	0	0	19.2	0.910	0	0	0.078
09251000	776	6.28	8.72	0.031	0.149	31.6	269	288	180	5.67	0.991	0.246
09253000	252	1.86	0.561	0.710	124	0	96.0	14.2	14.6	0	2.53	0.006
09255000	151	2.19	1.94	0	7.78	14.5	106	7.45	15.4	0	0	0.00
09260000	3,630	39.2	3.61	0.133	89.5	668	2,350	370	109	5.43	38.6	4.12
09260050	517	6.98	0.099	0	0	30.8	369	20.7	60.0	26.5	9.68	0.045
09261000	2,430	4.41	0.244	0.425	13.2	428	944	39.2	167	401	435	1.54
09261700	87.5	0	0.108	0	0	0	30.8	7.53	7.86	30.0	11.3	0.00
09266500	101	0	0	0	0	0	42.0	0	0.382	11.6	47.3	0.00
09275500	63.0	0	0.013	0	0	0	23.5	11.1	28.4	0	0	0.004
09276600	26.9	0	0.134	0	0	0	5.17	2.90	0.490	14.8	3.57	0.00
09277500	268	9.06	0.417	0.677	0	0	64.3	22.3	51.0	45.5	85.1	0.014
09277800	101	0	0	0	0	0	0.143	0	0.327	0	100	0.00
09278000	16.3	0	0	0	0	0	0.093	0	0.261	5.20	10.7	0.00
09279000	35.8	0.075	0	0	0	0	7.02	1.85	0.294	12.0	14.7	0.00
09279100	83.2	0.160	0	0	0	0	47.8	3.64	18.2	7.11	6.44	0.029
09279150	30.3	1.88	0	0	0	0	30.3	0	0.020	0	0	0.117
09285000	214	0	0	0	0	10.9	149	9.98	31.5	11.1	0.918	0.03
09285900	159	0.144	0	0	0	25.3	134	0	0	0	0	0.018

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09286100	31.4	0	0	0	0	0	8.00	13.3	10.1	0	0	0.00
09286700	47.1	0	0	0	0	0	12.5	16.7	17.9	0	0	0.005
09288000	119	2.61	0	0	0	0	112	6.64	0.989	0	0	0.016
09288180	350	3.21	0.948	0	0	115	214	0.087	20.9	0	0	0.106
09288400	140	0.045	0.002	0	0	0	118	0	21.9	0	0	0.634
09289500	77.8	0	0	0	0	0	0	0	0	0	77.8	0.00
09292500	139	0.189	0	0	0	0	22.3	0	0.297	4.85	112	0.004
09295000	763	33.2	14.8	10.6	0	41.5	547	0.747	75.7	7.78	90.3	1.83
09299500	124	0.167	0	0.058	0	0	16.0	0	0.610	3.55	104	0.005
09302000	1,010	87.8	30.8	29.9	0	0	544	8.97	118	13.4	322	2.70
09303000	259	0.010	0	1.29	93.0	0.601	69.7	0	37.6	52.7	5.57	0.00
09303300	52.6	0	0	0	30.0	0.114	0.208	0	0	22.2	0	0.00
09303400	75.8	0	0	0	22.6	0	0.211	0	0	53.0	0	0.00
09304000	51.7	0.060	0	1.87	8.91	0	16.0	0	0	22.5	4.34	0.00
09304200	208	0.588	0.458	1.83	3.21	0.863	11.2	0	34.0	158	0.704	0.00
09304500	113	1.88	5.91	0	0	0	6.38	18.6	83.5	4.54	0	0.026
09304800	264	6.88	5.75	0	0	31.5	78.7	85.2	51.7	16.6	0	0.086
09306007	177	1.23	0.093	0	0	28.8	119	21.1	7.46	0.984	0	0.088
09306200	328	3.57	0	0	0	7.27	321	0	0	0	0	0.299
09306222	146	1.37	0	0	0	11.0	135	0	0	0	0	0.116
09306242	31.7	0	0	0	0	14.3	17.4	0	0	0	0	0.03
09306255	231	0.285	0	0	0	34.8	196	0	0	0	0	0.021
09306290	593	4.04	0.301	0.284	0	151	190	79.4	125	43.1	4.39	0.303
09306500	1,370	2.11	1.25	0	0	382	219	607	137	20.8	0	8.50
09310000	17.0	0	0	0	0	13.0	1.72	2.30	0	0	0	0.00
09310500	47.3	0	0	0	0	24.7	0	22.3	0.309	0	0	0.007

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09312600	93.7	0	0	0	0	84.2	8.24	1.28	0	0	0	0.004
09313000	302	0	0.678	0	0	175	0	123	4.33	0	0	0.111
09315000	6,800	61.3	62.9	0.03	0	2,790	1,850	474	1,530	69.6	76.6	15.0
09326500	141	0	0	0	0	90.2	0.684	34.4	2.84	0	13.1	0.00
09328500	1,520	20.5	26.4	0	0	199	121	360	773	8.73	59.2	0.631
09329050	24.7	0	0	0	11.4	0.249	9.93	0	0.006	0	3.10	0.00
09330000	739	12.5	10.7	2.56	444	1.44	206	4.92	66.8	0	15.9	0.017
09330230	447	2.90	1.56	0.643	33.7	0	72.9	86.1	225	9.79	19.5	0.019
09333500	2,950	12.0	2.54	0	30.3	73.9	229	394	2,190	0.095	30.5	0.554
09337000	67.8	0	0	0	37.4	0	19.3	0	10.5	0	0.610	0.011
09337500	258	1.35	0.480	0	15.8	18.4	96.5	8.25	118	0	0.622	0.085
09339900	65.8	0.135	0.291	0.064	54.0	0	3.31	2.08	5.07	0	1.37	0.00
09342500	215	1.78	4.68	0.416	139	0	30.7	38.2	7.89	0	0	0.009
09346000	176	1.24	2.21	0.042	66.3	0	46.7	38.0	25.3	0	0	0.104
09346400	797	2.98	10.8	0	80.5	0	102	276	338	0	0	0.296
09349800	654	1.23	9.27	2.25	132	0	59.4	70.3	348	36.7	7.06	0.04
09352900	80.3	0	0	0	51.8	0	0.036	0	0	5.40	23.1	0.00
09354500	439	18.0	24.1	5.06	105	4.82	72.9	20.5	173	48.4	14.0	2.09
09355000	58.6	1.60	14.8	0.159	0	0	21.3	0	36.7	0	0.609	0.567
09355500	748	12.3	0.664	0	0	9.66	719	0	18.9	0	0	7.47
09361500	701	0.003	0.473	8.20	271	1.43	5.05	25.0	42.9	311	44.9	0.00
09363500	401	14.6	25.8	7.62	34.3	43.7	67.0	63.3	134	45.5	13.3	2.88
09364500	269	10.1	0.017	0	0	161	105	0	2.30	0	0	7.57
09365000	2,590	41.8	0.039	0	0	880	1,700	0	8.48	0	0	53.5
09367500	586	6.89	15.5	19.1	8.05	89.9	41.9	285	104	9.29	47.8	4.63
09368000	5,070	19.2	42.9	0	4.32	583	262	2,510	1,720	1.63	0	12.8

Appendix 4. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for 1991 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Land disturbance associated with oil and gas development
09371000	528	0	14.3	4.49	4.31	0.231	0	337	176	0.746	9.38	0.140
09371002	25.5	3.93	0.102	0	1.51	0	9.19	2.86	11.9	0	0	0.00
09371010	1,130	1.38	3.41	0	22.2	17.4	21.2	218	847	0	3.08	3.20
09371500	230	8.09	46.2	0	0.589	0.052	16.6	9.90	203	0	0	0.029
09372000	116	0	3.03	0	4.99	0	2.10	4.53	105	0	0	0.05
09378170	8.46	0	0	0	2.33	0	0.055	0	6.07	0	0	0.00
09378200	19.3	0	0	0	2.70	0	0.454	0	16.2	0	0	0.00
09378630	4.52	0	0	0	0.756	0	0	0	3.77	0	0	0.00
09379500	8,110	1.81	67.4	0	49.3	169	187	1,530	5,410	88.1	681	11.2
09380000	14,200	2.36	6.91	0.03	102	46.2	546	1,660	9,850	285	1,750	3.30

Appendix 5. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for exploratory 2007 Upper Colorado River Basin SPARROW model.

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Disturbed lands associated with oil and gas development
09032000	20	0	0	0	19.8	0	0.222	0	0	0	0	0
09034250	770	14.9	2.64	5.5	486	147	85.8	25.9	9.68	0	16	0.005
09058000	1,590	26.6	22.6	11.2	756	201	184	193	178	50.8	23.2	0
09063000	76	0	0	0	28	0.055	0	0	0	45.4	2.5	0
09066510	102	0.082	0	1.37	40.6	0	6.29	0	0	53	2.02	0
09081000	856	0.796	9.29	13.7	394	3.06	19.6	0.113	106	308	24.3	0
09083800	349	0.185	3.24	2.85	67	0	60.2	36.9	87.4	94.5	3.13	0.054
09085000	236	3.02	3.69	16.7	84.3	0	38.4	4.19	35.3	62	11.8	0
09095500	3,980	60.7	29.2	41	575	430	1,140	147	483	1,120	83.2	11.9
09107000	129	0	0	0.239	118	0.045	0	0	0	6.81	3.6	0
09112200	242	0.122	3.35	7.99	60.3	0	9.49	21.2	80.2	66.3	4.25	0
09112500	47.9	2.02	1.22	2.39	7.74	0	7.84	0.68	28.3	0.76	2.62	0
09113980	162	9.72	8.73	3.17	46.6	0	63.6	28.7	19.6	0	3.7	0.004
09114500	433	6.22	0.856	3.77	310	2.77	9.82	0	28.6	69.1	11.9	0
09119000	1,060	21.3	4.89	18	803	0.044	73.3	0	141	38.5	5.28	0
09128000	1,900	9.52	4.53	9.82	1,590	23	180	2	98.3	0	8.81	0
09132500	525	11.1	0.344	1.44	104	3.27	299	98	16.1	0	5.28	0.209
09146020	82.4	0	0.02	0	69.6	0	0	0	3.79	6.27	2.76	0
09146200	66.9	0.274	3.27	4.25	18	0	12	0	26	3.8	7.05	0
09152500	3,280	54.8	139	88.8	293	17.7	439	271	2,100	7.91	156	0.299
09163500	1,950	34.7	67.5	58.7	209	130	440	481	613	0	80.4	4.02
09169500	2,020	2.88	9.91	0.567	34.5	0.783	46.5	211	1,630	87.2	11.1	0.36
09171100	122	4.34	0.086	0.427	0	0	37	23.9	44.1	8.06	8.81	0.01
09180000	2,430	2.8	50.2	1.7	169	0.709	72.4	290	1,800	25.1	71.3	0.564
09180500	1,530	2.44	2.74	0.998	36.4	235	94.9	407	758	0.029	0	5.12
09196500	75.9	0	0	0	74.2	0	0	0	0	0	1.65	0
09211200	4,130	372	0.99	13.4	535	267	2,300	15.3	452	164	396	18.8

Appendix 5. Sources of dissolved solids in Upper Colorado River Basin streams by bounded calibration reach excluding point-source import source group as defined for exploratory 2007 Upper Colorado River Basin SPARROW model.—Continued

[All measurements are in square miles]

Calibration reach labeled by downstream monitoring site number	Drainage area of calibration reach	Irrigated sedimentary-clastic Tertiary lands	Irrigated sedimentary-clastic Mesozoic lands	Irrigated lands of other lithologies	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	Disturbed lands associated with oil and gas development
09217000	5,540	34.2	0	0.288	83.6	2,420	2,020	703	269	0	44.5	16.5
09229500	528	33	2.08	3.73	0	15	280	2.1	40.3	18.9	171	0.241
09239500	567	10.7	15.7	7.37	240	1.18	187	9.13	120	0	9.87	0.026
09247600	1,560	27.5	19.1	2.02	292	78.4	401	458	323	0	10.2	1.05
09251000	1,250	6.49	19.6	0.031	24	31.6	322	469	401	5.67	0.991	1.14
09258980	1,010	2.13	0.285	0	0	272	429	246	59.8	0.771	0	8.04
09260050	3,550	48.1	5.92	0.844	222	441	2,500	166	140	31.2	50.8	4.9
09261000	7,300	153	10.5	1.28	13.6	1,240	3,840	199	670	460	883	12.2
09302000	3,800	139	47.1	41.2	0	193	2,060	98.1	396	125	928	7.49
09304200	647	0.658	0.458	4.98	158	1.58	97.3	0	71.6	308	10.6	0
09304800	377	8.76	11.7	0	0	31.5	85.1	104	135	21.2	0	0.263
09306200	506	4.8	0.093	0	0	36.1	440	21.1	7.46	0.984	0	1.48
09306222	146	1.37	0	0	0	11	135	0	0	0	0	0.302
09306255	262	0.285	0	0	0	49.1	213	0	0	0	0	0.443
09306290	593	4.04	0.301	0.284	0	151	190	79.4	125	43.1	4.39	1.05
09306500	1,370	2.11	1.25	0	0	382	219	607	137	20.8	0	12.9
09314500	1,730	14.9	25.9	0	0	414	121	286	911	0	0	5.15
09315000	5,720	46.4	37.8	0.03	0	2,670	1,810	345	636	111	135	37
09328500	1,660	20.5	26.4	0	0	290	122	394	776	8.73	72.3	1.64
09352900	80.3	0	0	0	51.8	0	0.036	0	0	5.4	23.1	0
09359020	164	0	0	0	146	0	0	0	3.56	10.5	3.99	0
09371492	33.2	4.65	1.81	0	0.589	0	9.67	2.59	20.4	0	0	0
09371520	205	3.44	44.9	0	0	0.052	6.93	7.32	191	0	0	0.032
09372000	108	0	2.57	0	4.99	0	2.1	4.53	96.9	0	0	0.055
09379500	22,400	139	237	47.4	832	1,960	3,460	5,410	9,420	531	819	124
09380000	18,800	31.1	22.7	3.23	683	140	1,190	2,150	12,500	295	1,820	2.38

Buto, Kenney, and Gerner—**Land Disturbance Associated with Oil and Gas Development and Effects of Development-Related Land Disturbance on Dissolved-Solids Loads in Streams in the Upper Colorado River Basin, 1991, 2007, and 2025**—Scientific Investigations Report 2010–5064