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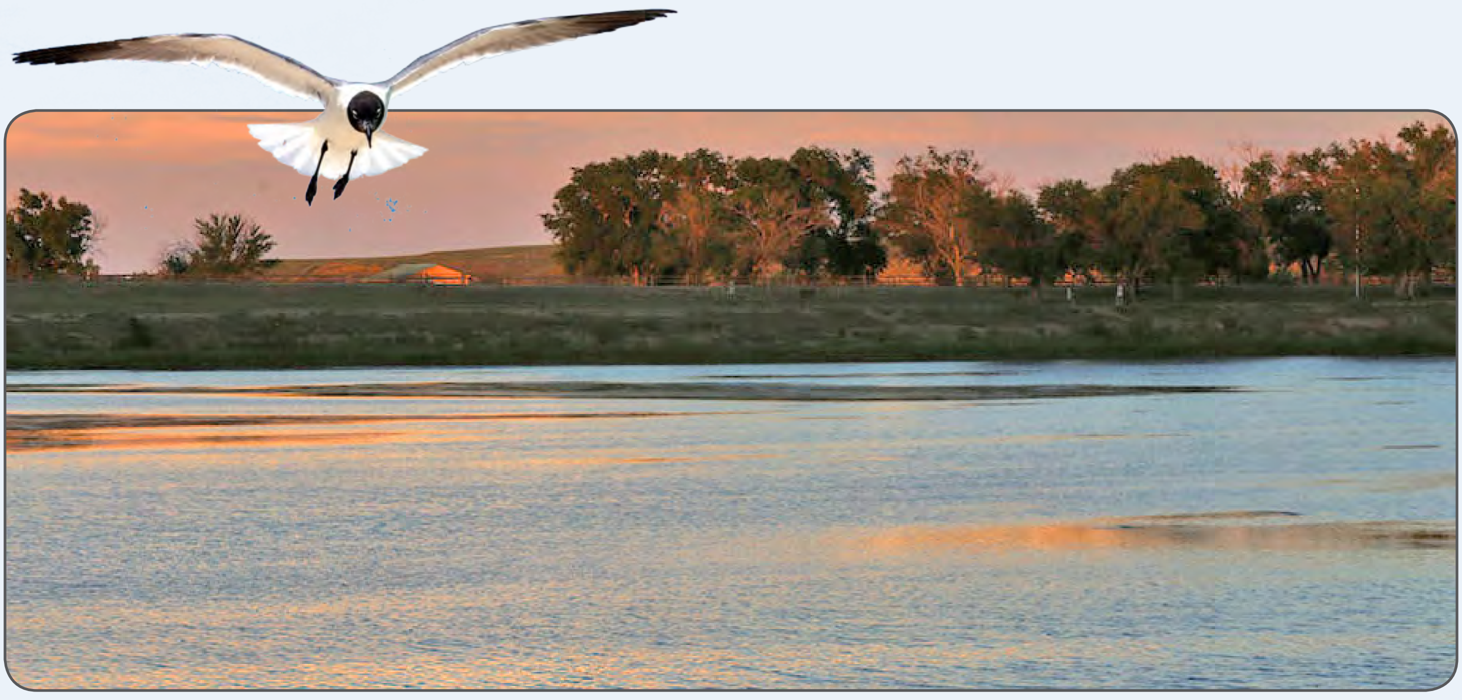
Hydrogeologic Characteristics and Geospatial Analysis of Water-Table Changes in the Alluvium of the Lower Arkansas River Valley, Southeastern Colorado, 2002, 2008, and 2015

Pamphlet to accompany
Scientific Investigations Map 3378

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



Cover. Photographs of John Martin Reservoir (courtesy of Colorado Parks and Wildlife).

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Abbreviations

GIS	Geographic Information System
IDW	inverse distance weighting
LAV	lower Arkansas Valley
USGS	U.S. Geological Survey

Hydrogeologic Characteristics and Geospatial Analysis of Water-Table Changes in the Alluvium of the Lower Arkansas River Valley, Southeastern Colorado, 2002, 2008, and 2015

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Abstract

The U.S. Geological Survey in cooperation with the Lower Arkansas Valley Water Conservancy District measures groundwater levels periodically in about 100 wells completed in the alluvial material of the Arkansas River Valley in Pueblo, Crowley, Otero, Bent, and Prowers Counties in southeastern Colorado, of which 95 are used for the analysis in this report. The purpose of this report is to provide information to water-resource administrators, managers, planners, and users about groundwater characteristics in the alluvium of the lower Arkansas Valley extending roughly 150 miles between Pueblo Reservoir and the Colorado-Kansas State line. This report includes three map sheets showing (1) bedrock altitude at the base of the alluvium of the lower Arkansas Valley; (2) estimated spring-to-spring and fall-to-fall changes in water-table altitude between 2002, 2008, and 2015; and (3) estimated saturated thickness in the alluvium during spring and fall of 2002, 2008, and 2015, and thickness of the alluvium in the lower Arkansas Valley. Water-level changes were analyzed by geospatial interpolation methods.

Available data included all water-level measurements made between January 1, 2001, and December 31, 2015; however, only data from fall and spring of 2002, 2008, and 2015 are mapped in this report. To account for the effect of John Martin Reservoir in Bent County, Colorado, lake levels at the reservoir were assigned to points along the approximate shoreline and were included in the water-level dataset. After combining the water-level measurements and lake levels, inverse distance weighting was used to interpolate between points and calculate the altitude of the water table for fall and spring of each year for comparisons. Saturated thickness was calculated by subtracting the bedrock surface from the water-table surface. Thickness of the alluvium was calculated by subtracting the bedrock surface from land surface using a digital elevation model.

In order to analyze the response of the alluvium to varying environmental and anthropogenic conditions, the percentage of area of the lower Arkansas Valley showing an absolute change of 3 feet or less was calculated for each of the six water-table altitude change maps. For fall water-table altitude change maps, the periods between 2002 and 2008, 2008 and 2015, and 2002 and 2015 showed that 86.5 percent, 85.2 percent, and 66.3 percent of the study area, respectively, showed a net change of 3 feet or less. In the spring water-table altitude change maps these periods showed a net change of 3 feet or less in 94.4 percent, 96.1 percent, and 90.2 percent of the study area, respectively. While the estimated change in water-table altitude was slightly greater and more variable in fall-to-fall comparisons, these high percentages of area with relatively small net changes indicated that, at least in comparisons of the years presented, there was not a large amount of fluctuation in the altitude of the water table.

The saturated thickness in the lower Arkansas Valley was between 25 and 50 feet in 34.4 to 35.9 percent of the study area, depending on the season and year. Between 30.2 and 35.6 percent of the area showed saturated thicknesses between 0 and 25 feet. Less than 1 percent of the area showed a saturated thickness greater than 200 feet in all mapped seasons and years.

Introduction

The Arkansas River is an important agricultural and municipal water supply in southeastern Colorado (sheet 1), and it is the primary supply for about 400,000 acres of irrigated land in southeastern Colorado (Ortiz, 2013). Changes in land use, irrigation practices, and urbanization can potentially cause changes in streamflow characteristics in the Arkansas River and its tributaries, as well as groundwater recharge (Miller and others, 2010). Unconfined alluvial systems, such as the Arkansas River Basin in southeastern Colorado, are characterized by a fluvial valley bounded by bedrock (Larkin and Sharp, 1992). Because the river and aquifer are hydraulically connected, monitoring groundwater levels in the alluvium can provide insight into the stream-aquifer system.

Groundwater levels, when considered in aggregate, provide insight into changes in regional groundwater-flow patterns. Large monitoring networks can help define how water moves through a region's stream-aquifer system and that system's response to external factors such as consumptive use, drought, and flooding. Groundwater monitoring networks are also valuable sources of data relating to water use, climatic conditions, groundwater storage, changes in land use, irrigation practices, and the quantity and timing of streamflow (Taylor and Alley, 2001).

The U.S. Geological Survey (USGS) in cooperation with the Lower Arkansas Valley Water Conservancy District measures groundwater levels periodically in about 100 wells completed in the alluvial material of the Arkansas River Valley in Pueblo, Crowley, Otero, Bent, and Prowers Counties in Southeastern Colorado (sheet 2), of which 95 are used for the analysis in this report. There are, however, few published interpretations of these data (Hurr and Moore, 1972; Nelson and others, 1989a, b, c).

Purpose and Scope

The purpose of this report is to provide information to water-resource administrators, managers, planners, and users about groundwater characteristics in the alluvium of the lower Arkansas Valley (LAV) between Pueblo Reservoir and the Colorado-Kansas State line. This report includes three map sheets showing (1) bedrock altitude at the base of the alluvium of the LAV; (2) estimated spring-to-spring and fall-to-fall changes in water-table altitude between 2002, 2008, and 2015; and (3) estimated saturated thickness in the alluvium during spring and fall of 2002, 2008, and 2015, and thickness of the alluvium in the LAV. Geospatial data and metadata developed for this report are available as a data release at https://doi.org/10.5066/F71G0JF6, and groundwater levels measured in the wells used for this study can be found on the Web at https://nwis.waterdata.usgs.gov/usa/nwis/gwlevels (search by USGS site number given in appendix 1). The data analysis was limited to data collected in the LAV during this period. Hereinafter in this report, "the period" or "this period" refers to the years 2002, 2008, and 2015, and "season" or "seasonal" refers to fall or spring, where "fall" is defined as June 1 through November 30, and "spring" is defined as January 1 through May 31 and December 1 through December 31 of the same year. Most fall measurements were made between September 1 and November 30; and most spring measurements were made between March 1 and May 31. The dataset was divided into "spring" and "fall" in this manner to reflect the general pre- and post-irrigation periods. Groundwater levels were measured before irrigation season started and after irrigation season ended to eliminate any bias in measurements caused by nearby wells being pumped (Taylor and Alley, 2001).

Study Area

The study area consists of a reach of the Arkansas River Valley from Pueblo Reservoir near Pueblo, Colorado, extending roughly 150 miles (mi) east to the Colorado-Kansas state line (sheet 1). The alluvium in this reach is approximately 12 mi across at its widest point near the western tip of John Martin Reservoir and its maximum thickness is approximately 275 feet (ft) (sheet 3). Major tributaries to the Arkansas River in the area include Fountain and Timpas Creeks, and the St. Charles, Huerfano, Apishapa, and Purgatoire Rivers (see fig. 1). Streamflow in this reach of the Arkansas River is regulated by Pueblo Reservoir near Pueblo, Colorado, and John Martin Reservoir near Las Animas, Colorado (sheets 1–3). Both of these reservoirs store water in the winter months as part of the Winter Water Storage Program (Ortiz, 2013; Cain, 1985).

The population of Pueblo, Crowley, Otero, Bent, and Prowers counties combined is approximately 205,000 people. The city of Pueblo, with a population of approximately 109,000 (U.S. Census Bureau, 2015a) is the largest municipal water consumer in the area. Most of the water used in Pueblo County comes from Pueblo Reservoir. Constructed in the 1970s, Pueblo Reservoir is supplied by the Arkansas River headwaters on the eastern slope of the Rocky Mountains and by water from the Fryingpan River and tributaries of the Roaring Fork River on the western slope of the Rocky Mountains as part of the Fryingpan-Arkansas Project (Rogers, 2006). Water is diverted along the river to many ditches and canals (including Fort Lyon Canal, Catlin Canal, and Bessemer Ditch, among others) for agricultural purposes—largely for irrigated hay, wheat, corn, sorghum, melons, and vegetables, as well as for supplying feed lots (fig. 1). The amount of water diverted for irrigation and consumption decreases streamflow in the Arkansas River from upstream to downstream (Cain, 1985).

The climate of the LAV is semi-arid with an average precipitation of approximately 14 inches per year. Average minimum and maximum temperatures range from about 14 degrees Fahrenheit (°F) in the winter to over 90 °F in the summer, respectively (National Oceanic and Atmospheric Administration [NOAA], 2016).

The alluvium underlying the LAV consists of Holocene and Pleistocene clay, sand, silt, and gravel. Below the alluvium is a layer of minimally permeable Upper Cretaceous limestone and shale (Goff and others, 1998). This limestone and shale layer acts as a barrier to flow (an aquitard), limiting water losses from the alluvium to the deeper aquifers and allowing water storage. The saturated alluvium in the LAV is pumped for irrigation (Lin and Garcia, 2012). Some of the seasonal and annual fluctuations in the water-table altitude in the alluvium of the LAV can be attributed to pumping. Ivahnenko and others (2010) describe the estimated withdrawals and use of water in the State of Colorado.

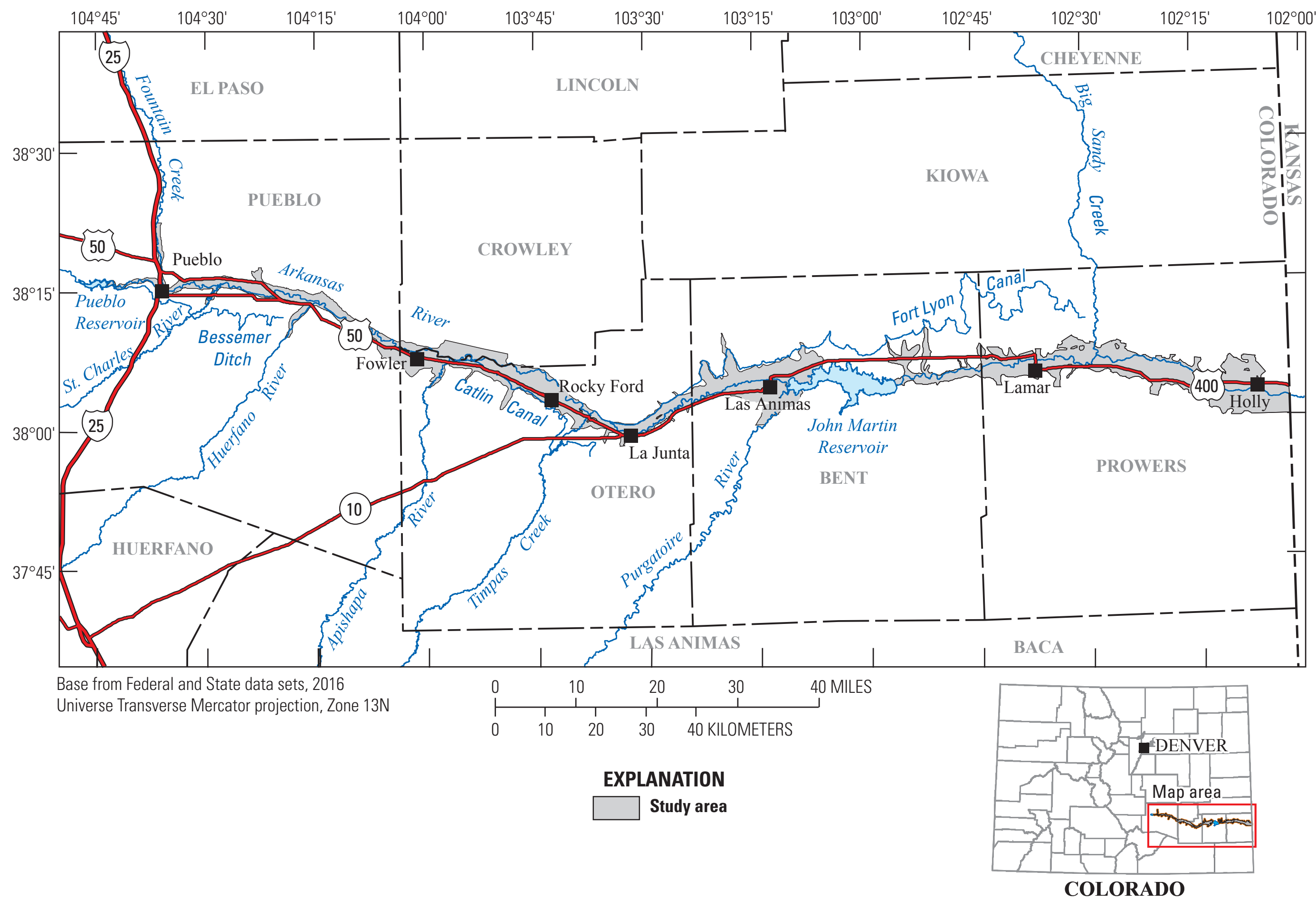

Figure 1. Map of the study area showing major roads, towns, rivers or streams, and selected irrigation canals, lower Arkansas River Valley, Southeastern Colorado.

Methods

A digital elevation model (DEM) (U.S. Geological Survey [USGS], 2016a) was used to define land-surface altitude in the study area. Other geographic information system (GIS) geospatial datasets included stream hydrography (USGS, 2016b) and political features (counties and towns from the U.S. Census Bureau, 2015b; USGS, 1981). The areal extent of the alluvium in the study area was derived from Tweto (1979). Water-level changes and other datasets were analyzed by geospatial interpolation methods. This approach is useful in that it provides an overview of water-level changes; however, it necessarily limits the degree to with hydrology-based insight informs the resulting maps. To produce raster datasets from linear data (elevation contours), esri's ArcGIS Topo to Raster tool was used (esri, 2011). Topo to Raster is a direct linear interpolation between known points, lines, or polygons specifically designed for hydrological applications. For discrete point data (water levels), inverse distance weighting (IDW) was used. The IDW model is a spatial interpolation method based on an assumption that the value of an unknown point is the weighted average of known points within a given area, and the weights are inversely related to the distance between known and unknown points (Lu and Wong, 2008).

Hydrogeologic Characteristics

Changes in estimated altitude of the water-table surface and estimated saturated thickness were examined using geospatial analyses. Water-table change maps and saturated thickness maps were produced using several data sources including existing bedrock-surface maps, land surface DEMs, observed groundwater levels, and observed lake levels in John Martin Reservoir.

Bedrock Surface

Hurr and Moore (1972) and Nelson and others (1989a, b, c) produced a series of maps showing the altitude of the bedrock underlying the LAV, as well as the altitude of the water-table and saturated thickness in the area. However, because of water-table changes resulting from water use by an increasing population and land-use changes, an update was needed. Bedrock contours from Hurr and Moore (1972) and Nelson and others (1989a, b, c) were digitized with their respective altitude values (sheet 1). The boundary of the LAV was also delineated from these maps, and the bedrock contour lines were terminated at the boundary. In the original bedrock maps, the alluvial extent along the tributaries was truncated. Without having bedrock information outside this boundary, all further calculations and geospatial datasets were limited to the extent of the LAV as shown in sheets 1–3.

Estimated Multiannual Change in Water-Table Altitude

Water-level measurements made between January 1, 2001, and December 31, 2015, and approved and published by the USGS (https://nwis.waterdata.usgs.gov/usa/nwis/gwlevels; search by USGS site number) were used to generate water-table maps for the fall and spring of 2002, 2008, and 2015. This selection of years allowed for a basin-wide comparison near the beginning, middle, and end of the study period. The years selected also represented a water-level dataset with good geospatial coverage in both fall and spring, minimizing spatial and seasonal bias.

To calculate the estimated changes in altitude and configuration of the water table the following information was used:

- Water levels measured in wells (for well locations, see sheet 2, figure *G*) in the LAV and,
- Seasonal median altitude of water surface at John Martin Reservoir (median of all daily mean lake levels for each season in each year)

Water levels in the LAV were generally measured twice each year: once in the fall and once in the spring. Measurements were made with an electric tape measure, a steel tape measure, or a pressure transducer, depending on the well construction and measurement conditions. All water-level measurements were tabulated, and in the event that more than one measurement was taken at a well during the same season, an average was used. Measurements were recorded in feet below land surface and referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) (appendix 1; data release, https://doi.org/10.5066/F71G0JF6). Land-surface altitudes at 15 of the wells used were referenced to the North American Vertical Datum of 1988 (NAVD 88). The land-surface altitudes of these wells were converted from NAVD 88 to NGVD 29 using the Vertcon program (NOAA, 2003).

Lake levels at John Martin Reservoir in Bent County, Colorado (referenced to NGVD 29), were collected using a float-activated encoder in a stilling well and were tabulated for each day of the year (data from 2001 through 2007 are from the U.S. Army Corps of Engineers; written commun., 2016 [data are provided in appendixes 1 and 2]; data from 2008 through 2015 can be found at http://waterdata.usgs.gov/co/nwis/uv?site_no=07130000). The seasonal median altitudes of the water surface for the fall and spring were assigned to a series of points along the approximate shoreline of the reservoir in the water-level geospatial datasets within the GIS. The seasonal median altitude of the water surface at John Martin Reservoir is given in appendix 1, and a hydrograph showing continuous lake level data at John Martin Reservoir is in appendix 2.

After combining the water-level measurements and lake levels, IDW was used to interpolate between points and calculate the estimated altitude of the water table above NGVD 29 for fall and spring of each year. Fall-to-fall and spring-to-spring changes from 2002–2008, 2008–2015, and 2002–2015 were calculated using IDW to create raster datasets for each season of each year. A raster is a matrix of cells organized in a grid pattern, with each cell containing a value representing information. Rasters representing water-table change for the years shown were obtained by subtraction. For example; the water-table surface for the spring of 2002 was subtracted from the water-table surface for the spring of 2008 to generate the water-table change between spring 2002 and spring 2008. The resulting change maps were limited to the extent of the alluvium bounded by the study area (sheet 2).

Some of the bullseye patterns present in the maps in sheet 2 can be attributed to a sparsity of data coverage. These bullseye patterns occur around data points (wells) and are an artifact of the interpolation method in areas where there are large differences in water-level change values and data are not available to define a gradation between points with large differences. Five wells near the western tip of John Martin Reservoir are among those that show bullseye patterns around them. The small changes in water-table altitude in the wells relative to the water-surface altitude changes in the reservoir (especially when comparing fall of 2002 or 2008 to fall of 2015 due to an unusually wet summer in 2015; see sheet 2, figures *E* and *F*) contribute to the appearance of these bullseye patterns.

Estimated Saturated Thickness and Alluvium Thickness

Saturated thickness is defined as the distance between the water-table surface and the base of the aquifer. Saturated thickness was calculated by subtracting the bedrock surface from the water-level surface. Bedrock contours were interpolated into a raster dataset using esri's ArcGIS Topo to Raster tool for use in saturated thickness calculations.

The terminal points of the bedrock contours obtained from Hurr and Moore (1972) and Nelson and others (1989a, b, c) do not extend beyond the boundary discussed in the "Bedrock Surface" section; this limitation may have resulted in errors in the interpolated bedrock surface near the boundary. Additional sources of error may include uncertainties in the DEM and water-level measurements, as well as the accumulation of any undocumented errors resulting from other data collection methods. These errors propagate in some areas as large negative saturated thicknesses (base of alluvium interpolated as being above the water table). These errors were as large as -120 ft after subtracting the bedrock from the water-table surfaces. To remove these erroneous values, the extents of the saturated thickness maps were truncated to only those areas where the saturated thickness was zero or greater (sheet 3), and the rest of the study area was assumed to have a saturated thickness between 0 and 25 ft.

To create the map showing thickness of the alluvium in the LAV (sheet 3), the bedrock surface was subtracted from land surface using a DEM. In order for the DEM (USGS, 2016a) to be used, the altitude values first needed to be converted from NAVD 88 to NGVD 29. To accomplish this, a grid consisting of 500- by 500-meter (m) cells with a point in the center of each cell was superimposed over the study area. The latitudes and longitudes (referenced to the North American Datum of 1983) of these points were entered into the Vertcon program (NOAA, 2003), which produced a shift value representing the difference between the two vertical datums at each point. These shift values, which ranged from 1.38 to 3.51 feet, were then assigned to the points in the grid, and IDW was used to calculate a “shift raster.” This raster was then subtracted from the original DEM, yielding a new land-surface altitude dataset referenced to NGVD 29. The resultant alluvial thickness raster was then clipped to the extent of the study area.

Geospatial Analysis of Water-Table Change

In order to analyze the response of water levels in the alluvium to varying environmental and anthropogenic conditions, the percentage of area of the LAV showing an absolute change of 3 ft or less was calculated for each of the six water-table change maps on sheet 2. Each cell in the resulting surface rasters represented a 120- by 120-m area of the LAV. For fall water-table altitude change maps, the periods between 2002 and 2008, 2008 and 2015, and 2002 and 2015 showed that 86.5 percent, 85.2 percent, and 66.3 percent of the study area, respectively, showed a net change of 3 ft or less. In the spring water-table altitude change maps these periods showed a net change of 3 ft or less in 94.4 percent, 96.1 percent, and 90.2 percent, respectively. While the estimated change in water-table altitude was slightly greater and more variable in fall-to-fall comparisons, these high percentages of area with relatively small net changes indicate that, at least in comparisons of the years presented, there was not a large amount of fluctuation in the altitude of the water table. A complete list of water-table change ranges and their respective percentages of the study area are shown in table 1.

Maximum estimated saturated thicknesses in the LAV during fall and spring of 2002, 2008, and 2015 ranged from 219 to 228 ft. The greatest saturated thickness occurred near the eastern end of the study area due to the low bedrock altitude in portions of eastern Prowers County, as shown in the bedrock contour maps in sheet 1, figure *D*. The saturated thickness in the LAV was between 25 and 50 ft in 34.4 to 39.5 percent of the study area, depending on the season and year. Between 30.2 and 35.6 percent of the area had saturated thicknesses between 0 and 25 ft. Less than 1 percent of the area had a saturated thickness greater than 200 ft in all mapped seasons and years. A complete list of saturated thickness ranges and their percentages are shown in table 2.

Table 1. Ranges of estimated water-level change and their respective percentages of the study area, lower Arkansas River Valley, Southeast Colorado, 2002, 2008, and 2015.

[ft, foot; %, percent; --, no data]

Water level change, ft	Period					
	Spring[1] 2002 to Spring 2008 (%)	Fall[2] 2002 to Fall 2008 (%)	Spring 2008 to Spring 2015 (%)	Fall 2008 to Fall 2015 (%)	Spring 2002 to Spring 2015 (%)	Fall 2002 to Fall 2015 (%)
–7.9 to –7.0	--	--	0.33	0.02	0.56	--
–6.9 to –5.0	0.62	--	1.51	0.10	2.95	0.05
–4.9 to –3.0	4.59	--	2.05	4.45	6.25	0.07
–2.9 to –1.0	18.77	1.25	19.42	20.28	53.92	0.73
–0.9 to 1.0	69.89	37.09	76.41	49.18	35.45	23.74
1.1 to 3.0	5.77	48.13	0.29	15.75	0.86	41.77
3.1 to 5.0	0.36	8.62	--	2.40	--	11.20
5.1 to 7.0	--	3.35	--	0.79	--	7.12
7.1 to 10.0	--	1.55	--	0.81	--	2.65
10.1 to 15.0	--	--	--	1.72	--	1.51
15.1 to 20.0	--	--	--	1.82	--	0.76
20.1 to 30.0	--	--	--	2.31	--	9.02
30.1 to 40.0	--	--	--	0.37	--	1.38

[1]Spring defined as January 1–May 31 and December 1–31.

[2]Fall defined as June 1–November 30.

Table 2. Ranges of saturated thickness values and their respective percentages of the study area, lower Arkansas River Valley, southeast Colorado, 2002, 2008, and 2015.

[ft, foot; %, percent; >, greater than; --, no data]

Saturated thickness, ft	Period					
	Spring[1] 2002 (%)	Fall[2] 2002 (%)	Spring 2008 (%)	Fall 2008 (%)	Spring 2015 (%)	Fall 2015 (%)
0 to 25	33.44	35.60	34.69	32.97	30.75	30.15
25.1 to 50	36.79	36.17	37.54	39.45	34.37	36.42
50.1 to 75	16.20	14.99	15.71	18.49	20.68	13.68
75.1 to 100	7.41	7.02	6.05	4.55	7.84	9.27
100.1 to 125	2.14	2.14	2.08	1.39	2.98	5.72
125.1 to 150	1.38	1.41	1.35	0.93	1.04	2.52
150.1 to 175	0.90	0.91	0.88	0.86	0.96	0.82
175.1 to 200	0.96	0.97	0.92	0.94	1.01	0.93
200.1 to 225	0.74	0.75	0.74	0.44	0.38	0.48
Greater than 225	0.03	0.03	0.02	--	--	--

[1]Spring defined as January 1–May 31 and December 1–31.

[2]Fall defined as June–November 30.

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Appendix 1. Well Information and Measured Water Levels in the Lower Arkansas Valley, Southeast Colorado, 2001–2015

Click here to access Appendix 1.

Appendix 2. Hydrographs Showing Water-Table Altitude in Select Monitoring Wells in the Lower Arkansas Valley and Water-Surface Altitude in John Martin Reservoir, Southeast Colorado, 2001–2015

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