GROUNDWATER SYSTEMS IN DELTA COUNTY, COLORADO: SURFACE CREEK VALLEY AREA

GIS-Based Hydrological and Environmental Systems Analysis and Formulation of Conceptual Site Models

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Front Page: Surface Creek Valley at Cedaredge (March 2014).

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1 INTRODUCTION

Under an agreement with Delta County, Colorado, Hydrologic Systems Analysis LLC (HSA) of Golden, Colorado, in conjunction with Heath Hydrology, Inc. (HHI) of Boulder, Colorado, was tasked to perform a study of the groundwater resources of the valley and surrounding area of Surface Creek in Delta County, Colorado between Leroux Creek to the East, Dirty George Creek to the West, US Forest Service lands to the North, and the Gunnison River to the South (Figure 1). The delineation of the study area is based on the nature and extent of the major hydrogeological systems present, the hydrology of the area, and water resources related land use considerations. The study area is located in the North Fork and Lower Gunnison watersheds and roughly covered by Delta County water planning areas 1b, 1c, 1f, 2b, 4d, 6 and a small part of sections 3c and 4b, located to the north of the Gunnison River between Delta and Hotchkiss (Figures 1 and 2). The study area is to the west and adjacent to the previously conducted Oak Mesa and North Fork Valley groundwater studies (*Kolm and van der Heijde, 2012, 2013*; Figure 3), but does not include Rogers Mesa as its groundwater system has already been studied by the US Geological Survey (*Watts, 2008*). It should be noted that for display purposes in this report a rectangular area is used, referred to as *Clipping or Display Area*, which include the entire Surface Creek Valley study area (Figures 1 and 3). However, all analyses regarding the groundwater systems in this report are focused on the irregular shaped *Surface Creek Valley (SCV) Study Area*.

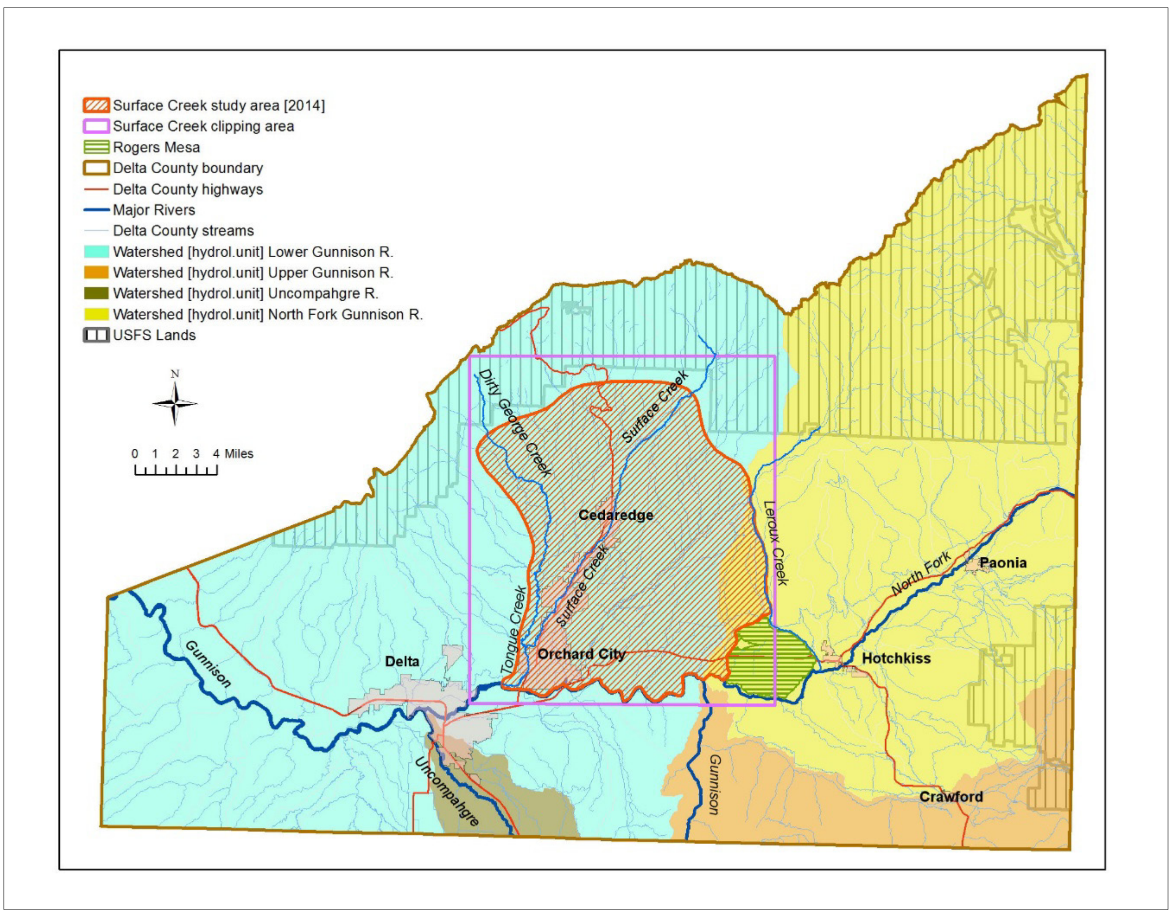

Figure 1. Location of the Surface Creek Valley Study Area and the Major Regional Watersheds.

This study includes a Hydrologic and Environmental System Analysis (HESA) of the groundwater system in the study area and the development of GIS databases and maps of hydrogeologic and hydrologic characteristics of this groundwater system. The HESA is documented in this report, which also contains a description of the development and use of the GIS databases and maps. The report and GIS databases provide support for planning, zoning and other decision-making tasks of county staff, including those related to protection of groundwater resources for use as public or communal water supplies.

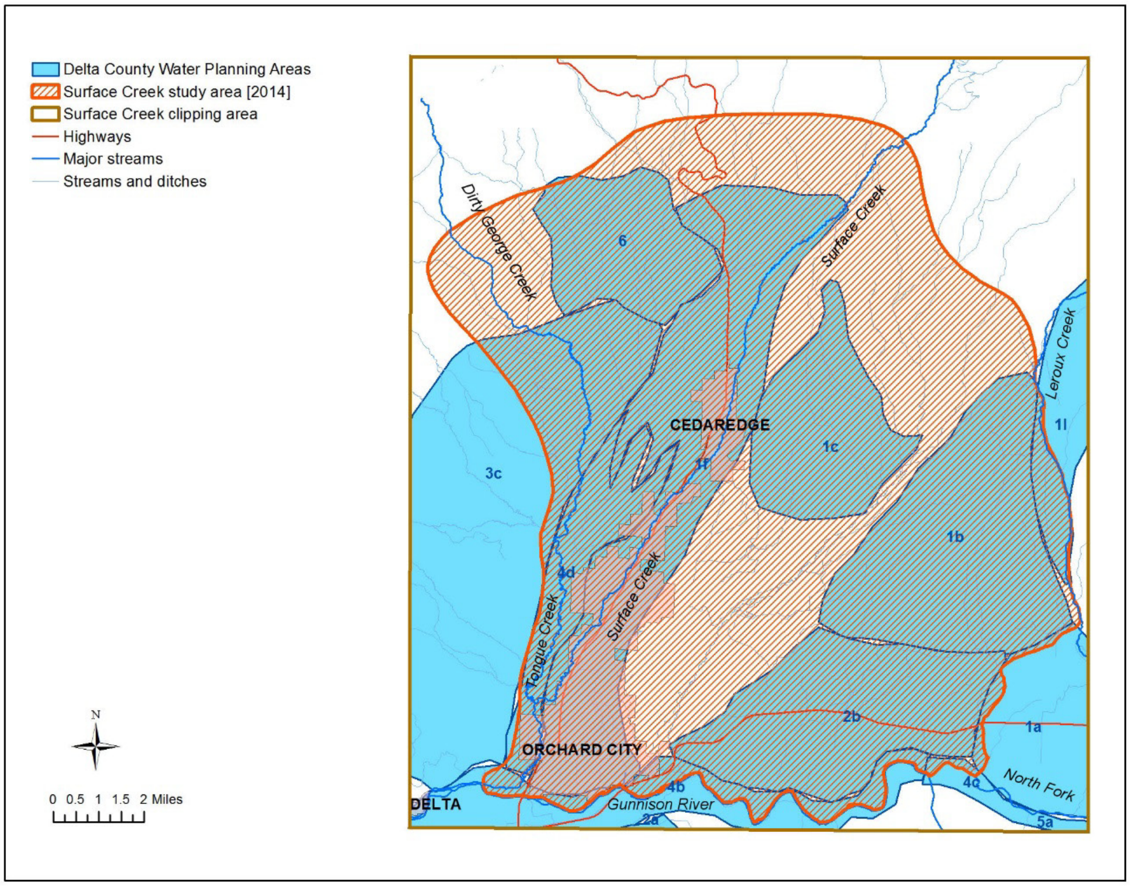

Figure 2. Surface Creek Valley Display Area, Showing the Water Planning Areas and the Study Area's Major Streams.

The GIS maps have been created, in part, from previously published, or otherwise available public information, as well as the results of the HESA. Additional data layers and evaluation were needed to construct the GIS database – particularly with respect to the hydrogeologic layers. The HESA included a few scoping site visits to the study area; no additional fieldwork has been conducted. The maps (and underlying databases) have been produced using the ARCGIS/ARCMAP GIS software system.

The Surface Creek Valley groundwater study included the following tasks:

1. Conduct a comprehensive HESA and formulate relevant conceptual hydrologic site models to provide the physical framework for the availability, sustainability and vulnerability assessments;
2. Refine and, if necessary, extend the hydrogeologic nomenclature developed in previous studies;
3. Digitize existing geologic maps – to the extent and detail necessary for the project – and converting them to hydrogeologic system layers in the GIS, including layers showing hydrogeologic units and characteristic stacks of such units, and hydrostructures; and
4. Adapt additional hydrological and other GIS maps and databases needed to evaluate the groundwater resources in the county; these databases will contain data from various public domain sources.

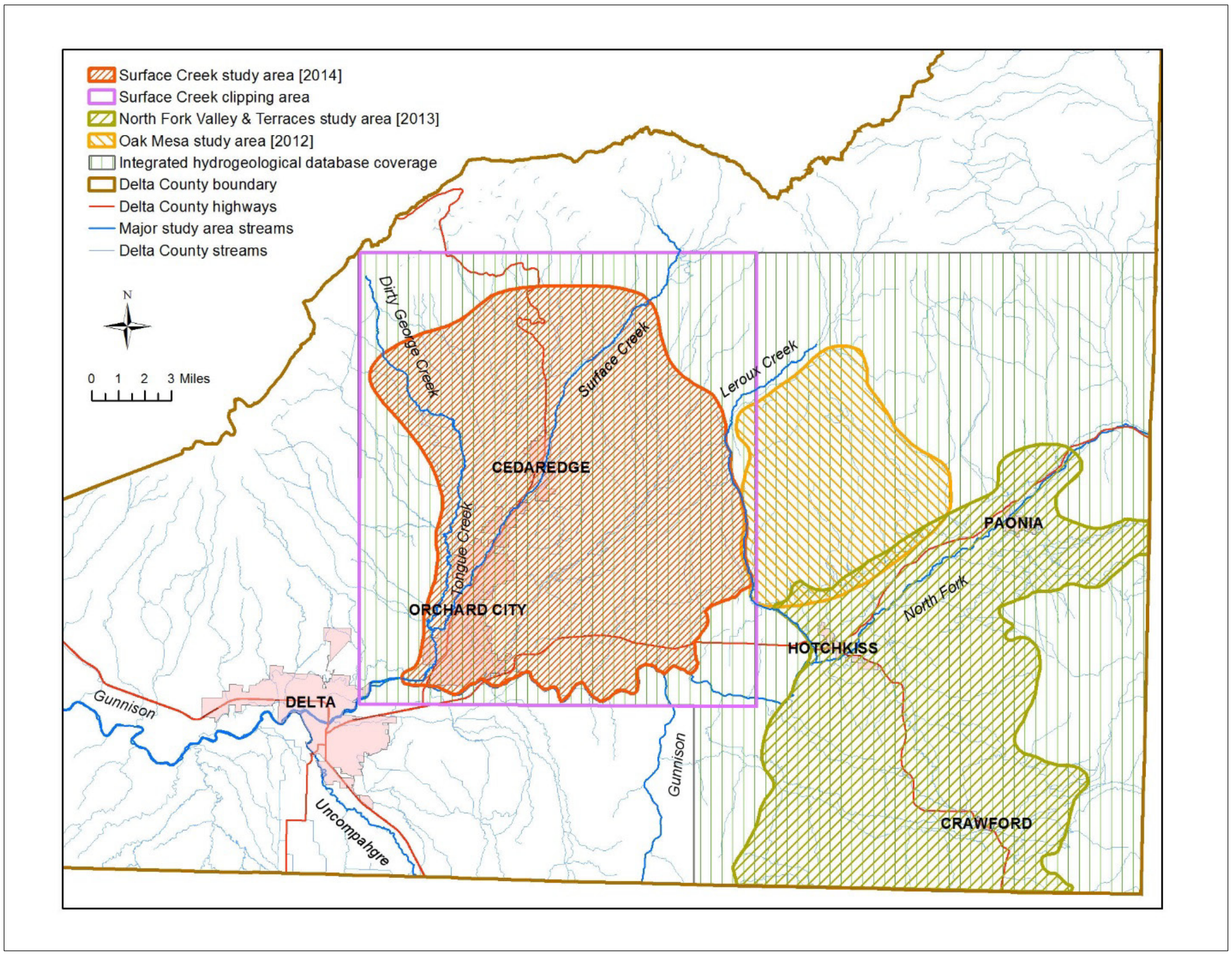

Figure 3. Surface Creek Valley Study and Display Areas in Relationship to the Areas Covered by the Previous Studies. Also Shown Is the Area Covered by the Integrated Hydrogeological Databases Generated in this and Previous Studies.

The hydrogeological databases for the SCV study area are a continuation and extension of the hydrogeological databases prepared during the earlier studies and include the results of the earlier studies. They provide coverages for the area shown in Figure 3 (see chapter 3 for details).

It should be noted that that these maps and databases will not obviate the need for additional hydrogeologic analysis on a site-specific/parcel-specific basis by developers and/or the County, or in any water right, geotechnical, or environmental study requiring due diligence. These maps and the associated groundwater evaluation procedure are intended to be used as indicators only, as part of a multi-step land use decision-making process, and to provide a starting point for further study of the County's groundwater resources.

2 DEVELOPMENT OF CONCEPTUAL SITE MODELS OF THE SURFACE CREEK VALLEY (SCV) STUDY AREA

HESA is an approach used to conceptualize and characterize relevant features of hydrologic and environmental systems, integrating relevant considerations of climate, topography, geomorphology, groundwater and surface water hydrology, geology, ecosystem structure and function, and the human activities associated with these systems into a holistic, three-dimensional dynamic conceptual site model (CSM). This watershed-based, hierarchical approach is described by Kolm and others (*1996*) and codified in ASTM D5979 Standard Guide for Conceptualization and Characterization of Ground Water Systems *(ASTM 1996(2008))*. The CSM of the SCV study area covers elements of climate, topography, soils and geomorphology, surface water characteristics, hydrogeologic framework, hydrology, and anthropogenic activity as related to the shallow groundwater systems in the study area.

Based on field surveys and a preliminary HESA, a number of hydrogeologic subsystems were identified within the SCV study area. Each of these subsystems has a unique hydrogeologic setting and groundwater flow system and is described in detail in forthcoming sections of the report. Furthermore, current anthropogenic modifications of the natural hydrologic features in these subsystems were identified, including groundwater recharge from large scale irrigation ditches and reservoirs, groundwater recharge from irrigated acreage subsurface return flow, and increased or decreased groundwater discharge from existing or newly created springs and seeps. A brief discussion of potential modification of natural flow patterns and impacts on water budgets from proposed oil and gas activities is included.

2.1 Climate

The climate in the study area has both local and regional components and includes effects of elevation and slope aspect (*i.e.*, steepness and orientation with respect to the prevailing winds and sun exposure). The presence of Grand Mesa further influences the climate at the lower elevations by orographic precipitation effects, causing enhanced precipitation on the windward side and local and regional rain shadows on the leeward sides. From the relevant weather stations of the National Weather Service (NWS) Cooperative Network (COOP) near the study area Cedaredge (COOP 051440), located near the town of Cedaredge, and Delta (COOP 052192), located in the town of Delta, have been selected as representative for the study area (Figure 4). Table 1 shows monthly and annual long-term averages for temperature, precipitation, snowfall and snow depth (*WRCC, 2013*); Figure 5 summarizes the average total monthly precipitation (*i.e.*, rain and snowfall SWE - Snow Water Equivalent), snowfall (*i.e.*, thickness of freshly fallen snow), and snow depth (*i.e.*, snow pack) for the two stations. These two stations are located well to represent the climatic differences and, therefore, climatic and hydrologic gradation from the core of the five subsystems of the SCV study area to be discussed, and their down-gradient boundary regions.

The NWS data were used by the Natural Resources Conservation Service (NRCS) to prepare a map of spatially distributed precipitation corrected for elevation (see Figure 6). As these data sources show, there is a significant precipitation gradient in the area from about 30 inches annually at the far northern boundary of the study area on the southern slopes of Grand Mesa to about 8 inches near the Gunnison River in the southwest corner of the study area.

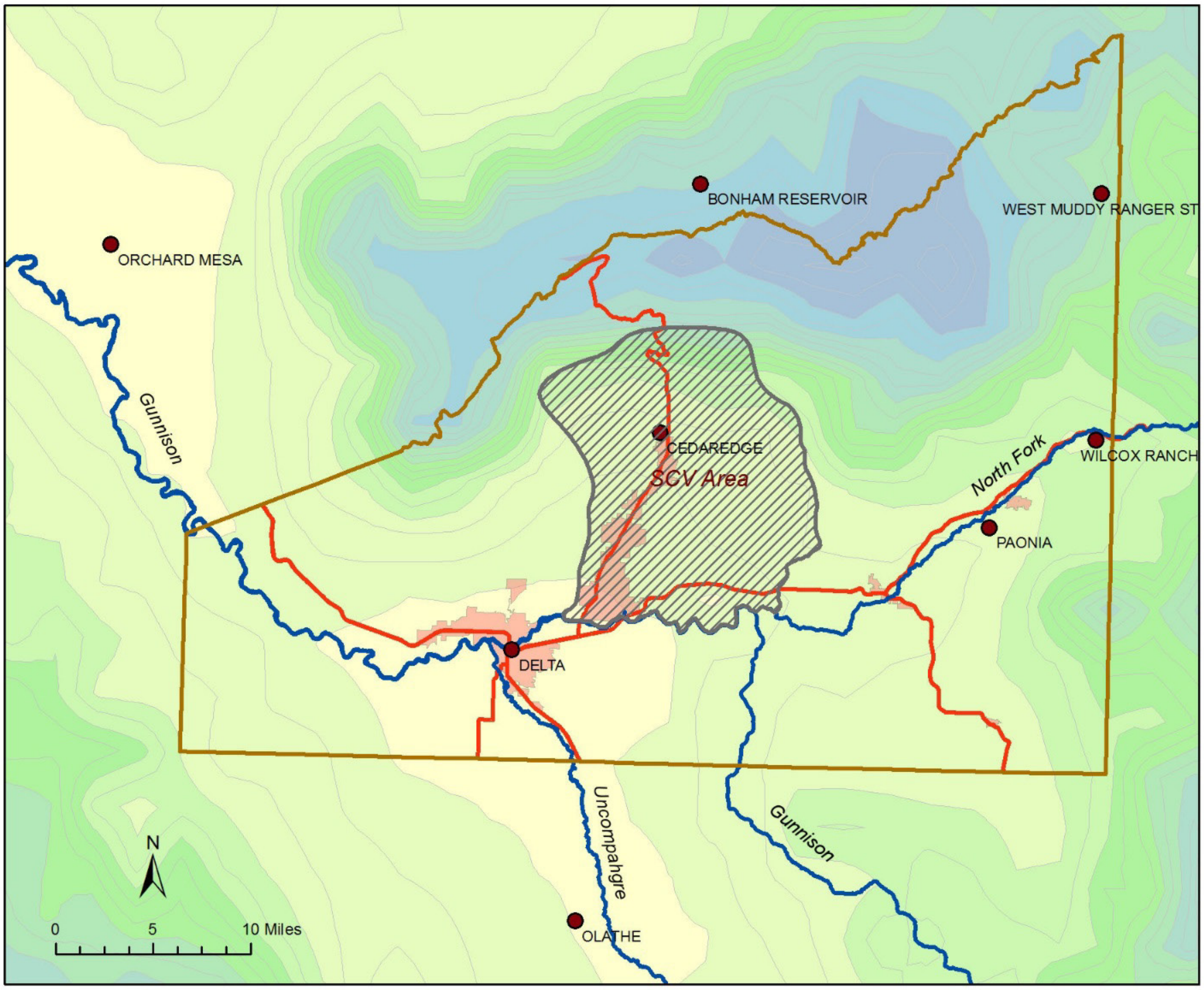

Figure 4. Location of NWS/COOP Weather Stations in and near Delta County and the SCV Study Area.

Precipitation type (rainfall versus snowfall), amount, and temporal and spatial distribution are important for determining the amount of recharge that a groundwater system may receive, particularly as infiltration from precipitation to the shallow bedrock groundwater systems. Average annual precipitation determines the climate of the project area, and in the case of the Surface Creek Valley, the topographically higher terrains near Grand Mesa are humid-to-subhumid and cool and have excellent groundwater recharge potential, both from rainfall in the spring, summer, and autumn months, and from the melting of snowpack throughout the winter and early spring, especially where covered by gravels and slope deposits. By comparison, the lower parts of the hydrologic system, including the terraces and stream valleys between Cedaredge and the Gunnison River, are mostly semi-arid-to-arid and have a small natural recharge potential, mostly from rain and some snow throughout the winter and spring. The summer months are characterized by high evaporation rates and are too desiccated for significant groundwater infiltration and recharge. Thus, most of the natural groundwater recharge in the near-surface aquifers occurs during a very short period of time in the winter and early spring (December to March). It should be noted that the entire study area has groundwater recharge potential, with even the driest areas probably receiving about 1- 2 inches of recharge annually. This is important when considering the ultimate groundwater system flow directions and areas of groundwater recharge.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	38.8	44.2	52.2	62.2	72.0	82.1	87.9	85.5	77.9	66.0	50.7	40.2	63.3
Average Min. Temperature (F)	14.5	19.8	26.0	33.2	40.9	48.7	55.3	53.3	45.6	35.5	24.8	16.7	34.5
Average (Mean) Temperature (F)	26.6	32.0	39.1	47.7	56.4	65.4	71.6	69.4	61.8	50.8	37.7	28.4	48.9
Average Total Precipitation (in.)	0.90	0.89	1.11	1.04	1.11	0.70	0.89	1.20	1.18	1.32	0.86	0.87	12.07
Average Total Snow Fall (in.)	11.3	8.4	6.8	2.5	0.5	0.0	0.0	0.0	0.0	0.9	4.0	8.9	43.4
Average Snow Depth (in.)	3	2	0	0	0	0	0	0	0	0	0	2	1

Table 1a. Average Maximum, Minimum and Mean Monthly and Annual Temperature, and Average Monthly and Annual Precipitation, Snow Fall and Snow Depth for Cedaredge (051440) for period 1/1/1898 to 5/31/1994. (Source: Western Regional Climate Center (WRCC), Desert Research Institute, Reno, Nevada).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	38.7	47.0	57.4	67.6	77.5	87.9	93.1	90.1	82.4	69.9	53.4	40.6	67.1
Average Min. Temperature (F)	12.2	19.0	26.1	33.8	41.9	48.5	54.8	53.1	44.1	33.4	22.8	14.6	33.7
Average (Mean) Temperature (F)	25.5	33.0	41.8	50.7	59.7	68.3	73.9	71.6	63.2	51.6	38.1	27.6	50.4
Average Total Precipitation (in.)	0.48	0.43	0.56	0.61	0.75	0.48	0.72	1.12	0.94	0.93	0.53	0.44	8.01
Average Total Snow Fall (in.)	4.6	2.7	2.0	0.5	0.0	0.0	0.0	0.0	0.0	0.2	1.5	3.7	15.2
Average Snow Depth (in.)	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 1b. Average Maximum, Minimum and Mean Monthly and Annual Temperature, and Average Monthly and Annual Precipitation, Snow Fall and Snow Depth for Delta (052192) for period 1/1/1893 to 12/31/1999. (Source: Western Regional Climate Center (WRCC), Desert Research Institute, Reno, Nevada).

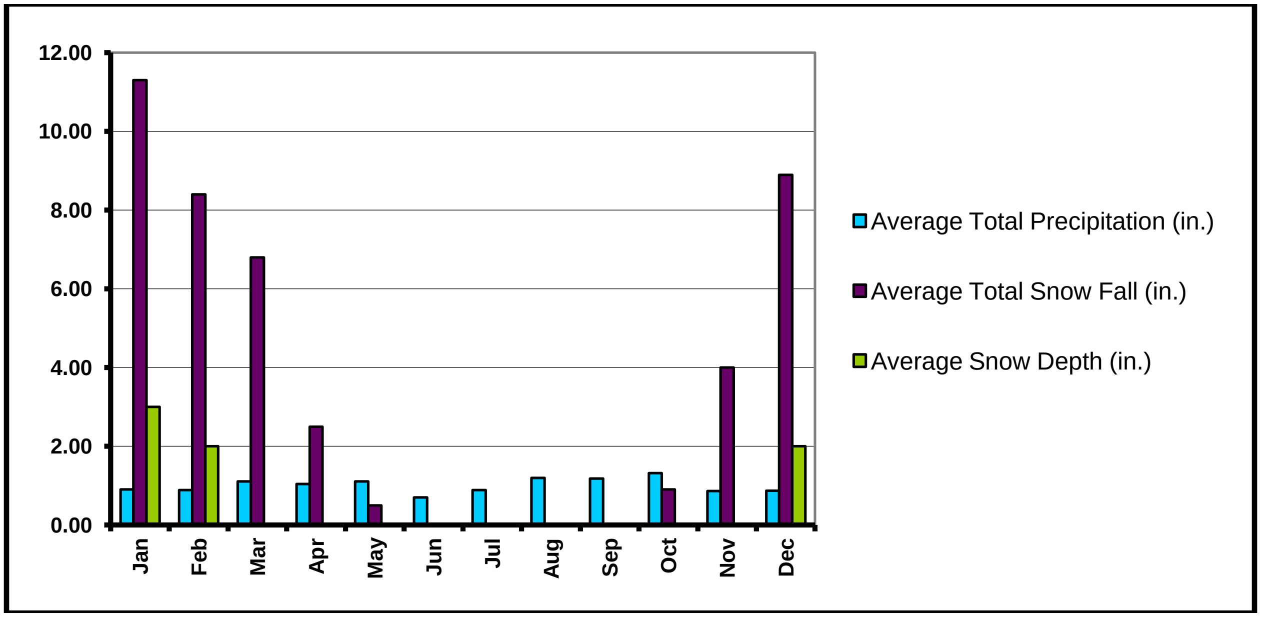

Figure 5a. Average Monthly Precipitation, Snow Fall and Snow Depth for Cedaredge (051440) for period 1/1/1898 to 5/31/1994. (Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

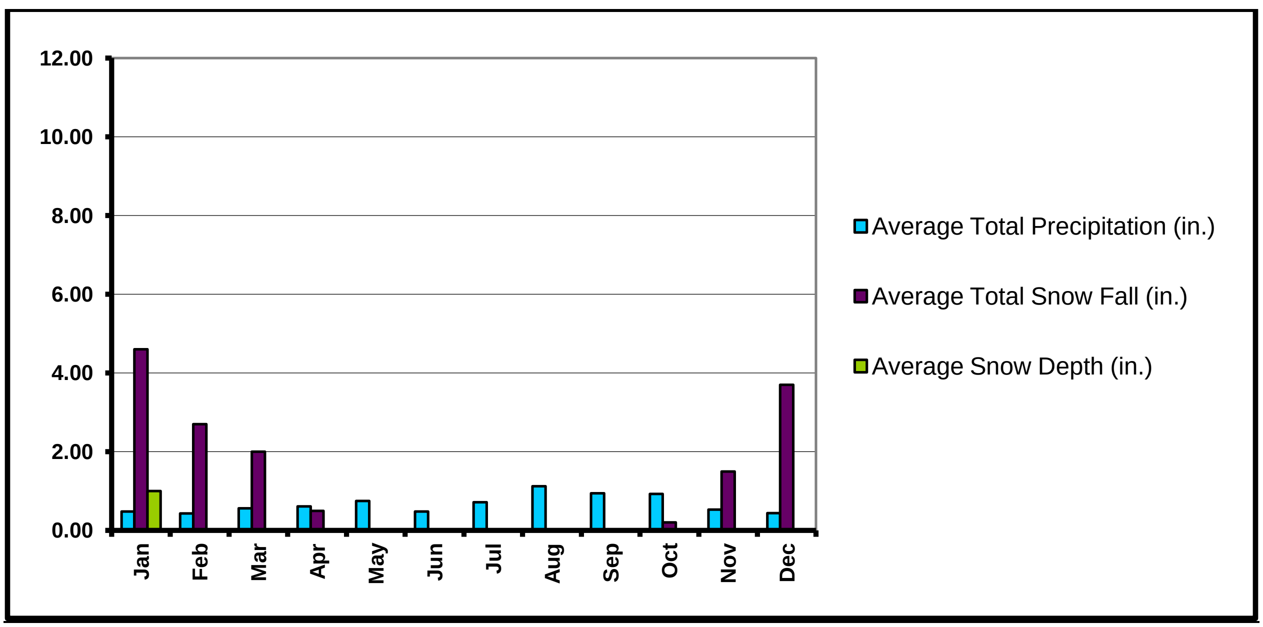

Figure 5b. Average Monthly Precipitation, Snow Fall and Snow for Delta (052192) for period 1/1/1893 to 12/31/1999. (Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

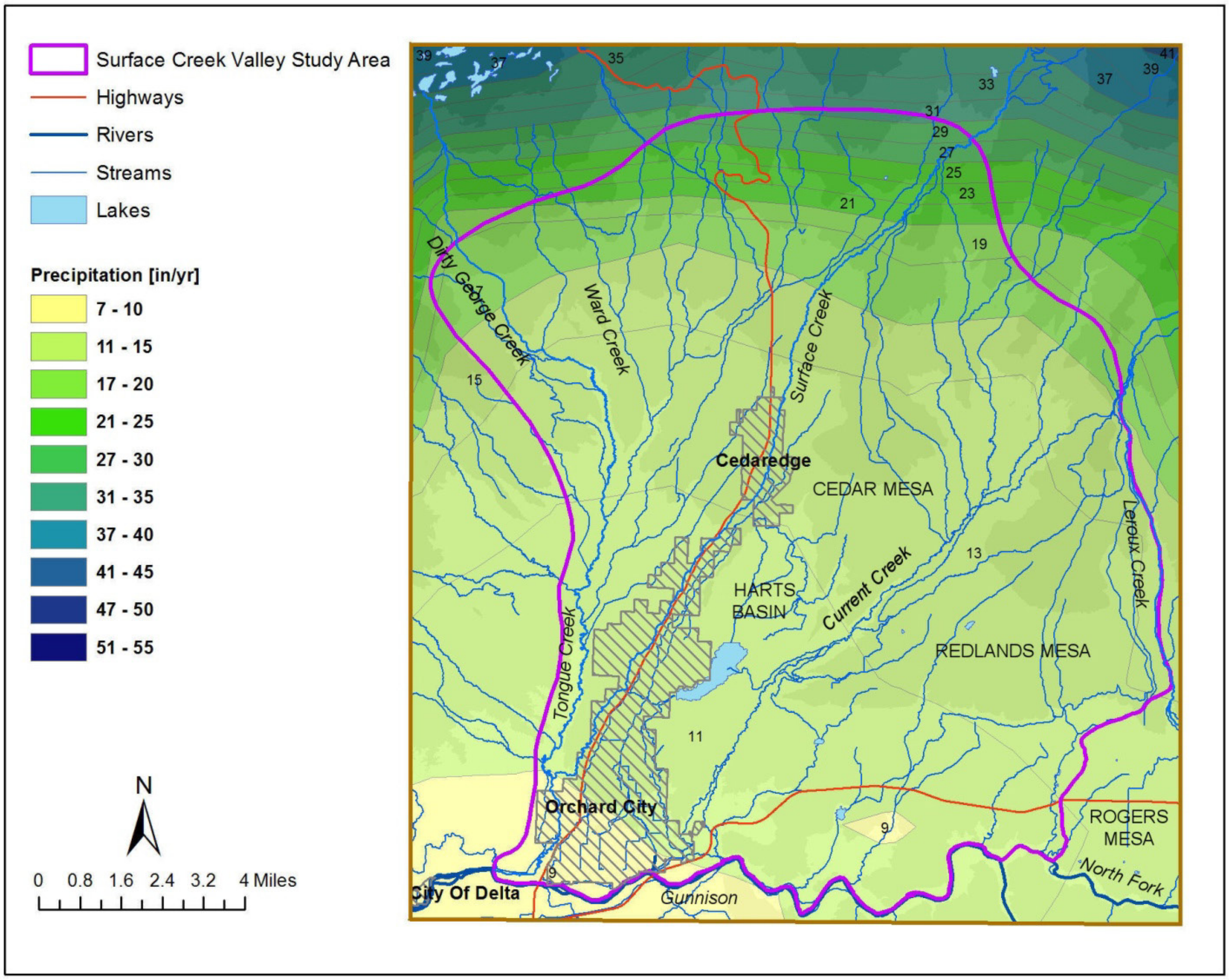

Figure 6. Spatial Distribution of the Average Annual Precipitation in the SCV Area, Delta County, Colorado (Source: Natural Resources Conservation Service 2011).

2.2 Topography and Geomorphology

The surface elevation in the SCV study area ranges from about 1,525 m (≈5,000 ft) in the North Fork valley near Delta to about 2,750 m (≈9,000 ft) on the terraces, fans, and bedrock above the town of Cedaredge (Figure 7). The topography of the study area has three distinct terrains: 1) steeply sloping to gently rolling, gullied bedrock uplands; 2) poorly to moderately dissected, connected and disconnected, continuous and discontinuous hillslope fans and mass wasting features, and alluvial terraces; and 3) continuous alluvial valley bottoms.

In the core of the SCV study area--including Redlands Mesa, Cedar Mesa/Fruitgrowers Reservoir/Harts Basin, Currant Creek Valley, Surface Creek Valley, and Tongue Creek Valley--the fans, mass wasting features, and alluvial terraces are separated topographically by fault- and fracture-controlled drainages derived from Grand Mesa. Each of these topographic regions functions as a separate hydrologic system and is not connected across the drainages to nearby systems. The effects of the stream and valley dissection on the groundwater systems will be discussed in the Groundwater System Conceptual Site Models sections.

The deeper bedrock groundwater systems, if not topographically dissected by the surficial processes, will be continuous and regional in nature. Examples of these regional systems are observed in sedimentary bedrock underlying the northern part of the SCV-study area, and these deeper bedrock systems can be a source of regional groundwater. These systems are recharged by, or are discharging into, the shallow groundwater systems depending on the geomorphic geometry. Most of the alluvial terraces, fans, and river bottoms in the study area are isolated topographically, which results in discrete and localized groundwater systems and can result in discrete and localized springs.

The topographic gradients in the SCV area can be divided into two types: 1) steep gradient bedrock slopes (greater than 2% slope); and 2) low gradient (less than 2% slope) fan and terrace levels and alluvial valley bottoms. The topographic gradient is useful in estimating the surface of the water table and for estimating the amounts of infiltration versus overland flow and interflow.

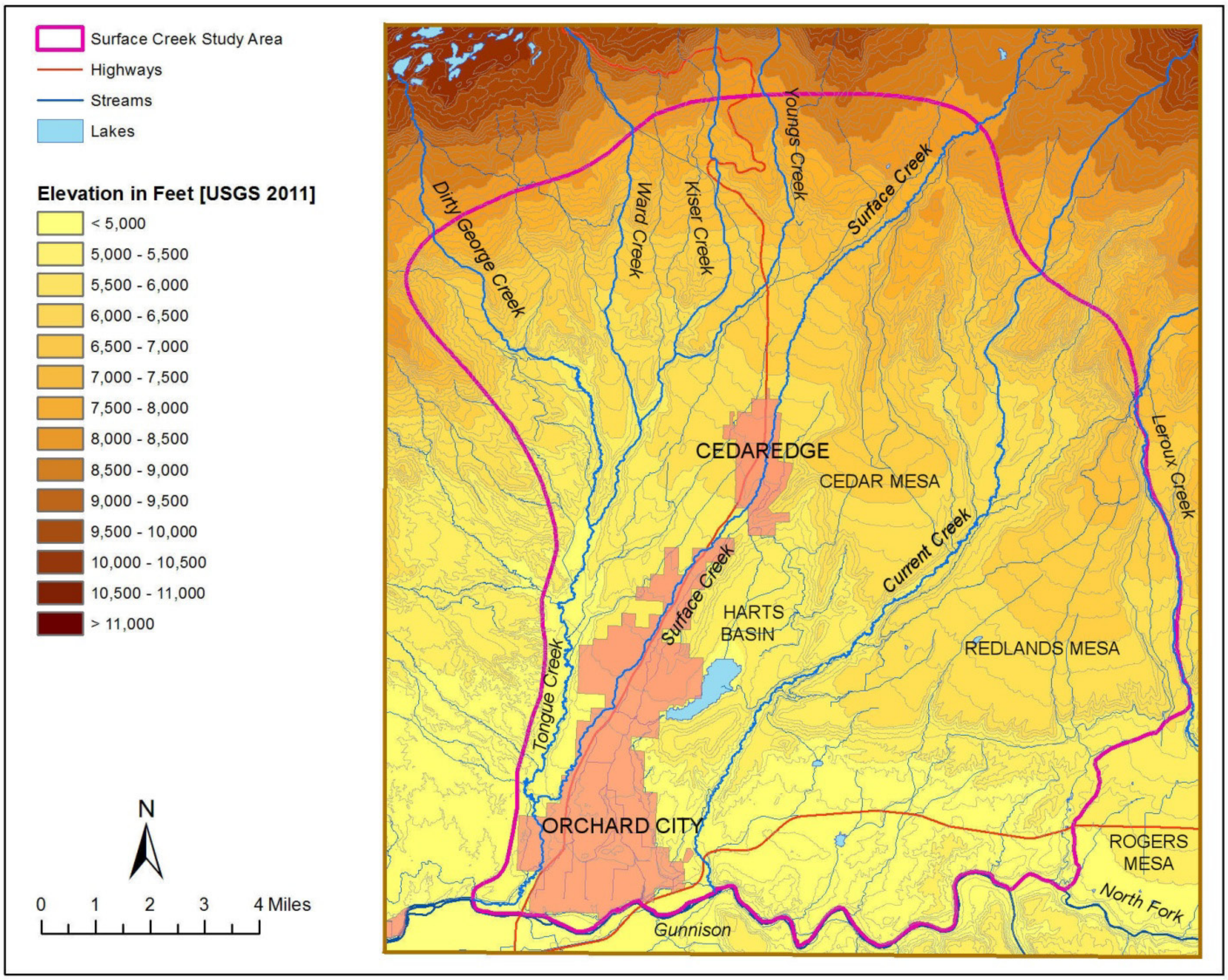

Figure 7. Topography in the SCV Area.
(Sources: Natural Resources Conservation Service 2011; Delta County 2011).

2.3 Surface Water Characteristics and Springs

The SCV study area contains parts of four local watersheds draining to the Gunnison River: Leroux Creek, Currant Creek, Surface Creek, and the Tongue Creek system, including Dirty George Creek, Ward Creek, Kiser Creek and Youngs Creek (Figure 8). Streams can be gaining flow (from groundwater) or losing flow (to groundwater), dependent on local hydrology and time of year. For example, Surface Creek, Currant Creek, and the Tongue Creek main stem and tributaries may be gaining streams in their upper reaches where groundwater discharges from the Quaternary slope deposits (Qs). In the central reaches of these streams above the irrigated regions, surface water most likely enters (recharges) the Quaternary younger valley gravels (Qgy) and Quaternary alluvium (Qal) along the river and may recharge underlying bedrock, resulting in loosing stretches of these streams. The gaining and losing dynamics of these streams is seasonal, with bank full conditions occurring during the spring runoff, and during monsoon rains resulting in losing conditions, and low water conditions occurring during the rest of the year resulting in gaining conditions. In the middle and lower reaches of these streams near and below the irrigated regions of Cedaredge and in Orchard City and near the confluence with the Gunnison River, the streams would be primarily gaining as groundwater would be discharging from the Quaternary younger valley gravels (Qgy) and Quaternary alluvium (Qal) aquifers back into the stream. There would be a net steam flow loss due to well use and irrigation evapotranspiration, but a larger net stream gain from return irrigation groundwater flow.

The Gunnison River is generally a gaining river along the southern boundary of the SCV study area due to the added ground water and surface water from the Currant Creek, Surface Creek, and Tongue Creek hydrologic systems, and from the lower Surface Creek and Cedar Mesa/Fruitgrowers Reservoir/Harts Basin groundwater systems. Groundwater flow back to the Gunnison River is driven by groundwater recharge in nearby alluvium (Qal) and younger valley gravels (Qgy) from infiltration of precipitation, leaky irrigation ditches, and flood irrigation water, and loosing stretches of tributaries along the edges of the modern alluvial valley. The Gunnison River may be locally gaining or losing due to local irrigation dynamics, and seasonality of river stage (spring flooding and monsoon storm runoff verses autumn low stream flow).

The larger mesas as well as the surface Creek valley contain local natural drainages, incising into the mesa and valley gravels mainly in southern and southwestern direction (Big Gulch, Cedar Gulch, Singley Gulch, Lawhead Gulch and Madison Gulch on Redland Mesa; Poison Gulch on Cedar Mesa; Happy Hollow Gulch in the Surface Creek Valley) (Figure 8). These local drainages provide discharge zones for the adjacent groundwater systems. Their natural eroding capacity may have been enhanced by increased runoff due to irrigation return flow.

The SCV area has Fruitgrowers Reservoir and some smaller reservoirs, as well as many ponds (primarily related to farmland modifications and sub-urban development requirements), and an extensive network of irrigation and water diversion ditches (Figure 8; see also Section 2.7). Fruitgrowers Reservoir is located between and fed by diversions from both Currant and Surface Creeks, and affects the surrounding groundwater system as a hydrologic system head boundary (constant head in annual assessments, variable head with season in monthly assessments). Most of the smaller reservoirs and ponds, by comparison, are affiliated with local landowners, and affect only the local surrounding groundwater system. These ponds are filled with groundwater by direct discharge, or by wells or springs supplying local groundwater – most of which is sustained by irrigation, leaky ditches, or to a lesser extent, direct precipitation. These ponds leak into the local aquifer system depending upon location, and tend to concentrate nutrients.

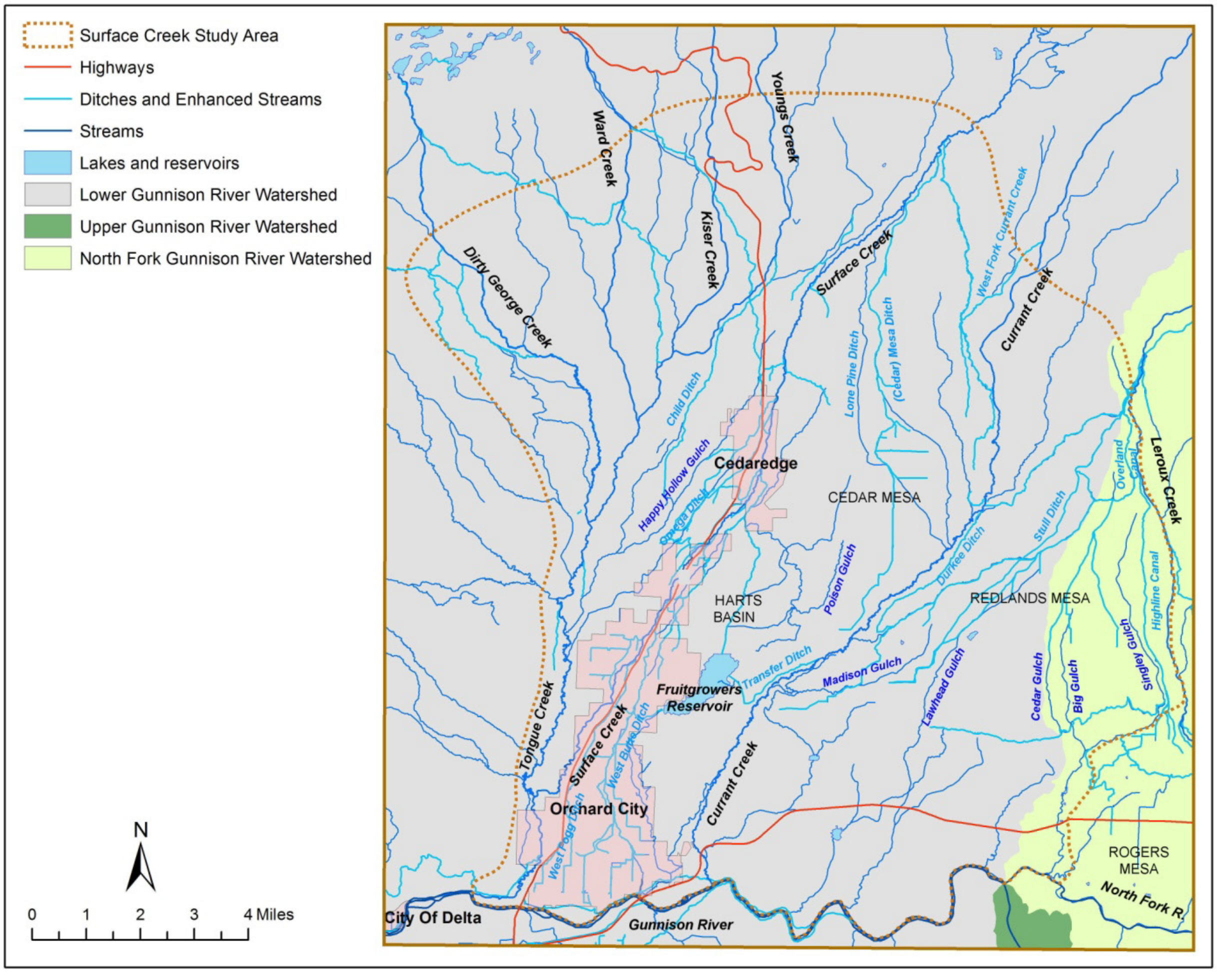

Figure 8. Major Watersheds, Streams, Reservoirs and Ditches in the SCV Area. (Sources: NRCS 2011; Delta County 2011).

The extensive network of ditches has been inventoried by Delta County (Figure 8; see Section 3 for details). Generally, some ditches flow more or less continuously, at least during part of the year, others are only used when fields are being irrigated. Some ditch alignments coincide with stream sections, resulting in so-called "enhanced streamflows" or "enhanced streams." Other ditch alignments contour throughout the landscape, and affect the various streams and mesas that are traversed. Most ditches are unlined, and leak water into the subsurface. More modern practices of piping have minimized this water loss. Wetlands and phreatophyte vegetation are indicators of groundwater discharge to the land surface. The irrigation ditches located on the fans and terraces and along stream valleys often have wetlands, phreatophytes and seeps, indicative of leaky, unlined ditch perimeters, which can be a source of significant groundwater recharge to a hydrogeologic unit that may naturally be dry in normal conditions, but may be an aquifer due to long time ditch leakance into the hydrologic system. Given this situation, there may be an effect of increased surface water flow in springs and drainages due to reservoir and ditch releases that ultimately can affect groundwater recharge to shallow and bedrock systems in various areas. These diversions and anthropogenic changes to the surface water system must be accounted for in the water balance calculations, including springs, for the overall hydrologic system of the SCV area.

Each hydrologic subsystem in the SCV area has ditches that primarily deliver water from the nearby parent stream to the irrigated lands located topographically down gradient from the highpoint of the ditch entry into the subsystem. These ditches typically are responsible for two forms of groundwater recharge to the hydrologic subsystem: 1) If unlined, as linear groundwater recharge sources underneath and beside the ditch in areas indicated by the light blue lines showing ditch location (Figure 8); and 2) Where water is dispersed onto the crop field area, as areal groundwater recharge sources due to irrigation return flow in areas indicated by the green irrigated fields (Figure 9).

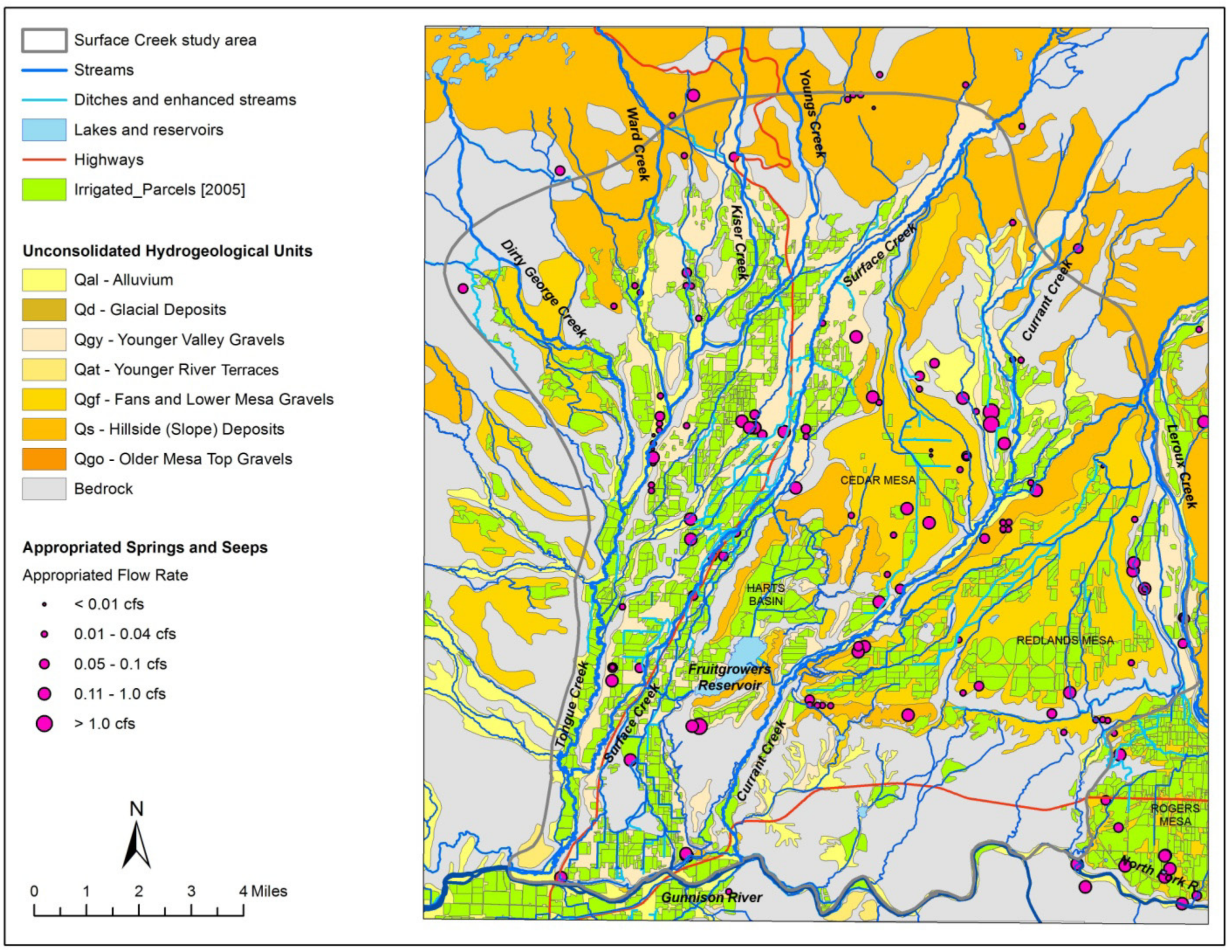

Figure 9. Springs and Seeps in Relationship to Irrigated Areas and Hydrogeology in the SCV Area. (Sources: CDSS 2014, NRCS 2011).

There are three major ditch groups affiliated with the Redlands Mesa area: 1) The Highline Ditch on the east side; 2) the ditches affiliated with Cedar Gulch in the center of the mesa, including the Overland Canal, and 3) the Stull Ditch group on the west side (Figure 8). These ditches, which originate primarily from Leroux Creek, traverse the lower mesa fan gravels (Qgf) and would significantly affect springs located along the southern and western borders of the lower mesa fan gravels (Qgf) and slope deposits (Qs) (Figure 9).

There are three major ditches affiliated with the Currant Creek area: 1) Durkee Ditch on the east side of Currant Creek; 2) the West Fork of Currant Creek ditch group, which connects ditches fed from Surface Creek with those originating in Currant Creek; and 3) Transfer Ditch. The first two ditches traverse the alluvial sediments (Qal) of upper Currant Creek, and would significantly affect the springs located along the southwestern area of the alluvial fan (Qal) (Figure 9). Transfer Ditch transports water from Currant Creek to Fruitgrowers Reservoir.

There are 2 major ditches affiliated with the Cedar Mesa area: 1) (Cedar) Mesa Ditch; and 2) Lone Pine Ditch (Figure 8). These ditches, which originate primarily from Surface Creek, traverse the axis of the lower mesa fan gravels (Qgf) and would significantly affect the streams and Fruitgrowers Reservoir located in the southern and southwestern area of the subsystem (Figure 9).

There are various ditches affiliated with the Surface Creek area, including: 1) Child Ditch, Gipe Ditch, and Omega Ditch between Tongue Creek and Surface Creek, originating from Surface Creek and the Tongue Creek system; and 2) West/East Fogg Ditch and West/East Butte Ditch located east of Surface Creek in the Orchard City area and originating from Surface Creek. These ditches traverse the axis of the younger valley gravels (Qgy) subparallel to Surface Creek, and would significantly affect the surface water flow of Surface Creek from the irrigated lands above the town of Cedaredge for the entire length of the stream below Orchard City (Figure 9).

Finally, there are ditches affiliated with the Tongue Creek system, which originate from the various tributaries of Tongue Creek, traverse the younger valley gravels (Qgy) and alluvium (Qal), and would significantly affect the springs and surface water flow in to the central Tongue Creek system west of Cedaredge (Figures 8 and 9).

As is indicated by wetlands, phreatophytes, and springs/seeps, these unlined ditches leak water into the groundwater systems of the upland lower mesa fan gravels and alluvial fans (Qgf) and slope deposits (Qs), younger valley gravels (Qgy) and some alluvial tributaries (Qal) that are crossed by the ditches, which serve as aquifers used for irrigation and drinking water for landowners located topographically downgradient from the ditch (see sections 2.5 and 2.6).

Springs and seeps indicate places where water flows naturally from a rock or the soil onto the land surface or into a body of surface water. They represent the contact between (saturated) groundwater and the land surface at that location. Springs usually emerge from a single point and result in a visible and measurable flow of water, or contribute measurably to the flow of a stream or the volume of a reservoir or pond. Seeps tend to be smaller than springs, with a more distributed character, and often no visible runoff, especially in the (semi) arid West where, in many cases, the water emerging in seeps is lost to evapotranspiration. Springs may be an expression of discharge of shallow groundwater from an unconfined aquifer, or of discharge from deeper aquifers at the contact between (more) permeable and (near) impermeable formations at or near the land surface, in fracture zones, or through karst conduits.

The SCV study area contains a number of springs and seeps as identified in the Water Rights data base of the State of Colorado [CDWR 2014]. Plotting the location of springs and seeps is very helpful in analyzing the characteristics of localized groundwater systems, and in determining where regional groundwater systems may interact with shallow groundwater systems and streams (Figure 9). Of particular interest is the relationship found between (leaking) irrigation ditches and irrigated areas and spring discharges from shallow groundwater in the SCV area. A detailed discussion of springs and seeps in the SCV area and their relationship with the local groundwater systems is presented in section 2.5.

2.4 Hydrogeologic Framework

Bedrock and unconsolidated materials have traditionally been classified as either aquifers or aquitards based upon being able to provide sufficient water for irrigation and industrial and municipal consumption, In this context, an *aquifer* is a permeable body of rock that is saturated with water and is capable of yielding economically significant quantities of water to wells (human and agricultural use) and springs (human and ecological use). A low-permeability formation overlying an aquifer is often called an *aquitard* or *confining unit*. As the terms “aquifer” and “aquitard” are rather ambiguous (*e.g., what are economically significant quantities?* or *how confining is a low-permeability unit with respect to the transport of contaminants?*), the use of these terms is replaced by that of the term *hydrostratigraphic unit* or *hydrogeologic unit*, in combination with terms qualifying the permeability and/or saturation of the unit (*e.g.*, saturated, high-permeable hydrogeologic unit). A *hydrogeologic unit* is a geologic formation, part of a formation, or a group of formations with similar hydrologic characteristics (*e.g.*, similar permeability characteristics and storage capacity). It should be noted that hydrogeologic units may not equate to geological units such as *formations*, *formation members*, and *formation groups* due to the frequently encountered variability of the flow characteristics of such geologic units. The term *aquifer* in this report is used to indicate a significant source of water supply from hydrogeologic units, and may include the qualifier *potential* (*i.e.*, potential aquifer) when parameter uncertainty exists, especially with respect to average saturated thickness and water table fluctuations.

From a groundwater flow and water supply perspective, the most important property of rocks is the incorporated pore space and related permeability. The pore space, which defines the amount of water storage within a hydrogeologic unit, may be contemporaneous with the rock formation (primary or matrix porosity), or due to secondary geological processes, such as fracturing, faulting, chemical solution, and weathering (secondary porosity, fracture/karst porosity). The degree of connectivity and the size of the pore openings define the permeability of the rock, that is, the ease with which fluid can move through the rock. As with porosity, permeability may be primarily matrix based (matrix permeability), fracture and/or karst based (fracture/karst permeability), or may be a combination of both (*Davis and DeWiest, 1966*).

Unconsolidated sediments and clastic materials, as found in the Surface Creek Valley study area, and observed draping down the south and southwest sides of Grand Mesa, are geologically very young and consist primarily of silts, sands, and gravels. They are generally very porous and permeable, but can be quite variable in their thickness, continuity, and hydraulic properties. For example, field observations revealed that the thickness of the unconsolidated sediments in the SCV study area ranges from less than 1 ft to greater than 100 ft. Estimates of hydraulic conductivity (K) range from 0.1 to 500 ft per day (*Watts, 2008*). These hydrogeologic units most likely contain the greatest amount of groundwater.

Consolidated sedimentary rock and extrusive volcanic rock, by comparison, are often quite porous, but variable in permeability. Most fine-grained detrital rocks like shale, claystone, and siltstone may have relatively high matrix porosities, but very low permeabilities (*Davis and DeWiest, 1966*). These fine-grained bedrock hydrogeologic units are the dominant confining layers of sedimentary groundwater systems, with small hydraulic conductivity values typically less than 0.01 ft per day. Coarser-grained sedimentary rock, such as sandstone, and volcanic basalt, can pair relatively high matrix porosity with significant permeability, and may contain significant amounts of groundwater.

The hydraulic properties of sedimentary and extrusive igneous rock may be largely enhanced when fractures and faults are present (*Davis and DeWiest, 1966*). As a case in point, most of the sandstones and crystalline extrusive volcanic rocks in and near the SCV study area have enhanced permeability due to fracture and fault density and connectivity. Significant secondary porosity and permeability are developed through faulting, fracturing, and weathering of the sedimentary and extrusive igneous rock, especially in association with active faults, fracture zones, and near-surface stress-release.

2.4.1 Regional Hydrogeologic Units

From a regional perspective, the county-wide geology is part of the southern edge of the Piceance Basin (Figure 10), the northern edge of the Black Canyon of the Gunnison uplift, and the western edge of the Uncompaghre uplift. As a result, the sedimentary bedrock stratum ranges from younger rock to the north and east, to older rock in the south and west, and the stratum shows a regional dipping trend to the north and east (see Figures 11 and 12). The youngest bedrock units in the county are the Tertiary intrusive (quartz monzonite) and extrusive (basalt) units of the West Elk Mountains and Grand Mesa volcanic field. These units form mountains and high plateaus in the northern and eastern part of the county. It is in these sedimentary and volcanic units that regional groundwater flow systems are known to occur (*Freethey and Cordy, 1991; Geldon, 2003*).

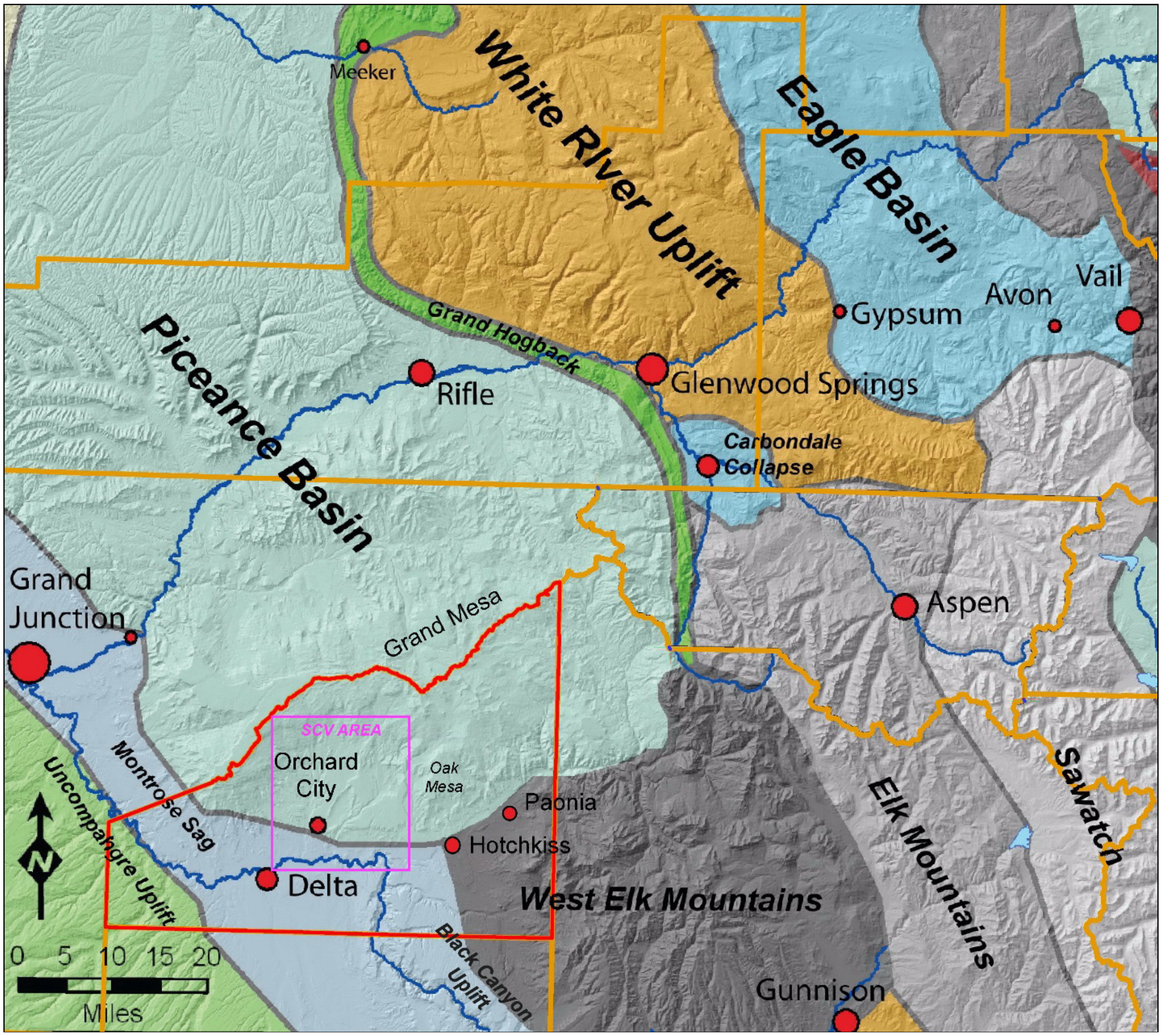

Figure 10. Generalized Map Showing Regional Geographic and Geological Features (*After Topper and others, 2003; Tweto and others, 1978*).

Given the regional geology of the SCV area, the hydrogeologic framework present in the Currant Creek, Surface Creek and Tongue Creek watersheds is complex similar to the Oak Mesa region studied previously (Kolm and van der Heijde, 2012). Upon reviewing various groundwater reports (*Ackerman and Brooks, 1986; Brooks, 1983; Brooks and Ackerman, 1985;* and *Cordilleran Compliance Services, Inc., 2002,* among others) and (hydro-)geologic maps (*Ellis and others, 1987; Hail, 1972a, 1972b; Noe and Zawaski,2013; Tweto and others, 1976, 1978; Williams, 1976*), the SCV study area hydrological systems consist of multiple distinct hydrogeologic and hydrostructural units, including unconsolidated units consisting of various Quaternary-aged, highly permeable deposits, multiple water-bearing and confining bedrock units, and highly transmissive fault and fracture zones. The major hydrogeologic unconsolidated and bedrock units are presented in Figures 13 and 14 and described in Tables 2a and 2b; the major hydrostructural units are presented in Figure 15.

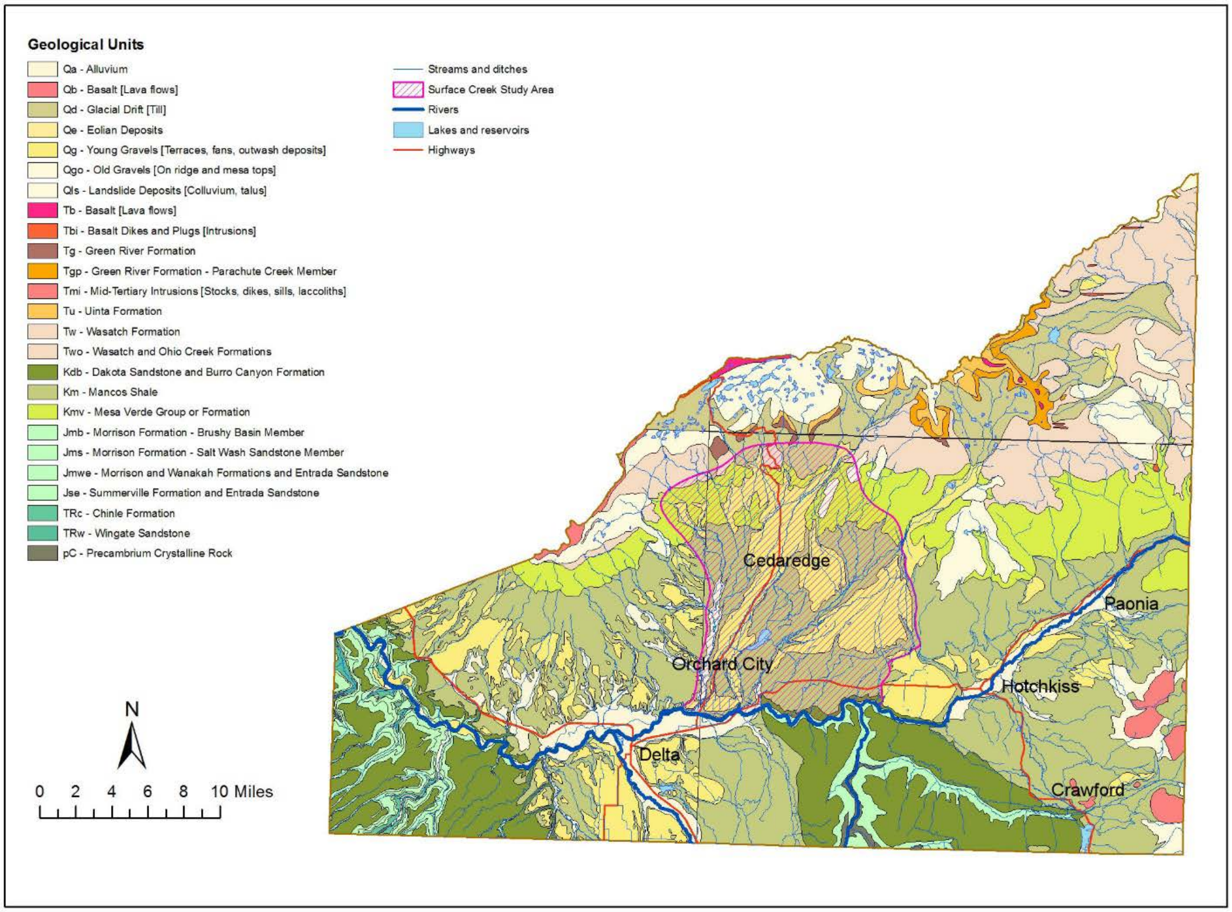

Figure 11. Composite Large Scale Map of the Geology of Delta County
(*Based on Tweto and others, 1976; Tweto and others, 1978; Whitney, 1981; Williams, 1976)*.

2.4.2 Hydrogeologic Units of the SCV Area

There are two significant groups of hydrogeologic units in the SCV study area: 1) Quaternary unconsolidated clastic materials (Figure 13; Table 2a), which are predominantly glacial-fluvial outwash plains and terrace gravels (older mesa top gravels and glacial drift), hillside (slope) deposits, alluvial fans and bajadas (coalescing fans) and lower mesa gravels, younger valley gravels and river terraces, and alluvial valley bottom deposits; overlying 2) Tertiary and Cretaceous bedrock units (Figure 14; Table 2b), including the following potentially water-bearing units: Tertiary Wasatch Formation including the Ohio Creek Formation (Two); Cretaceous Mesaverde Formation (Kmv), including the Barren, and Upper and Lower Coal Bearing members (Kmv), as well as the Rollins Sandstone member (Kmvr); and the Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb). The Mesaverde hydrogeologic units have porosity values ranging from 0.7 – 12%, a matrix transmissivity of less than 50 ft^2/day and a fracture transmissivity of up to 100 times matrix transmissivity (*Robson and Banta, 1995*).

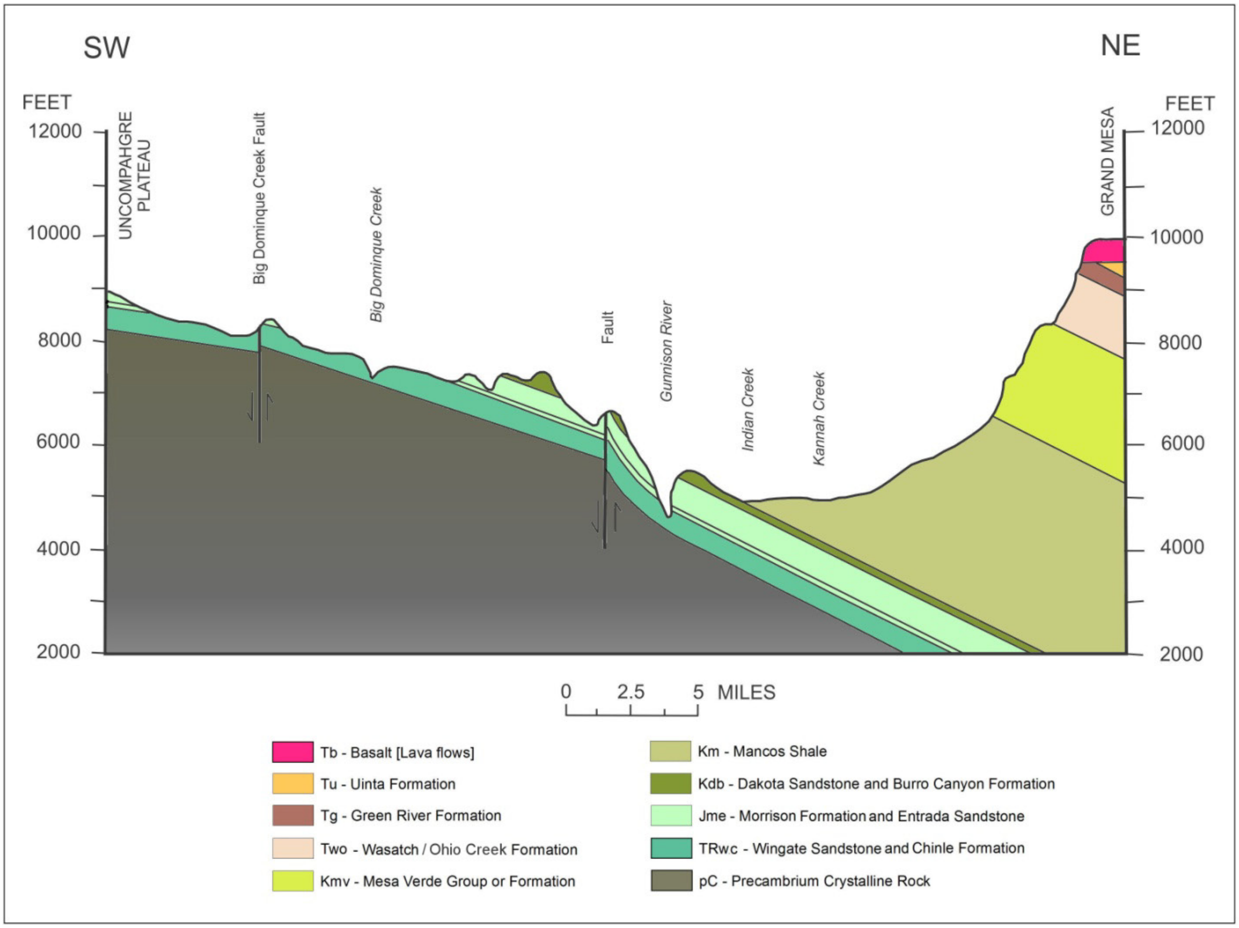

Figure 12. Generalized Northeast-Southwest Geological Cross Section Representative for Delta County. *(Modified from Brooks and Ackerman, 1985)*.

The Upper and Lower Coal Bed members of the Mesaverde Formation have good transmissivities ranging from 1.5 – 16.7 ft^2/day (*Brooks, 1983*).The Dakota/Burro Canyon hydrogeologic units have porosity values ranging from 0.7 – 12% and transmissivities in the range 10-100ft^2/day (*Robson and Banta, 1995*). By comparison, the Mancos Shale unit (Km) may act as a thick, poorly transmissive confining layer *(Robson and Banta, 1995*).

From a water supply perspective, the unconsolidated clastic sediments, specifically when composed of larger size particles (>2.5 mm or 0.1 in) and observed to have sufficient saturated thickness and horizontal continuity, may provide a significant and accessible water supply. The water supply function of bedrock units is largely dependent on rock type, large-scale structure and degree of fracturing, layer geometry and orientation, and the spatially variable hydrologic inputs and outputs, and may vary significantly dependent on location. The focus of this project was on both the shallow groundwater flow systems in the Quaternary unconsolidated clastic materials, which is a source of drinking and irrigation water for several municipalities and households, and the Cretaceous Mancos Shale bedrock confining unit that may protect the integrity and water quality of the shallow drinking water systems, particularly from nearby energy development activities. In addition, the Tertiary Wasatch Formation., the Cretaceous Mesa Verde Group, and the Cretaceous Dakota-Burro Canyon hydrogeologic units are considered as a source for water supply.

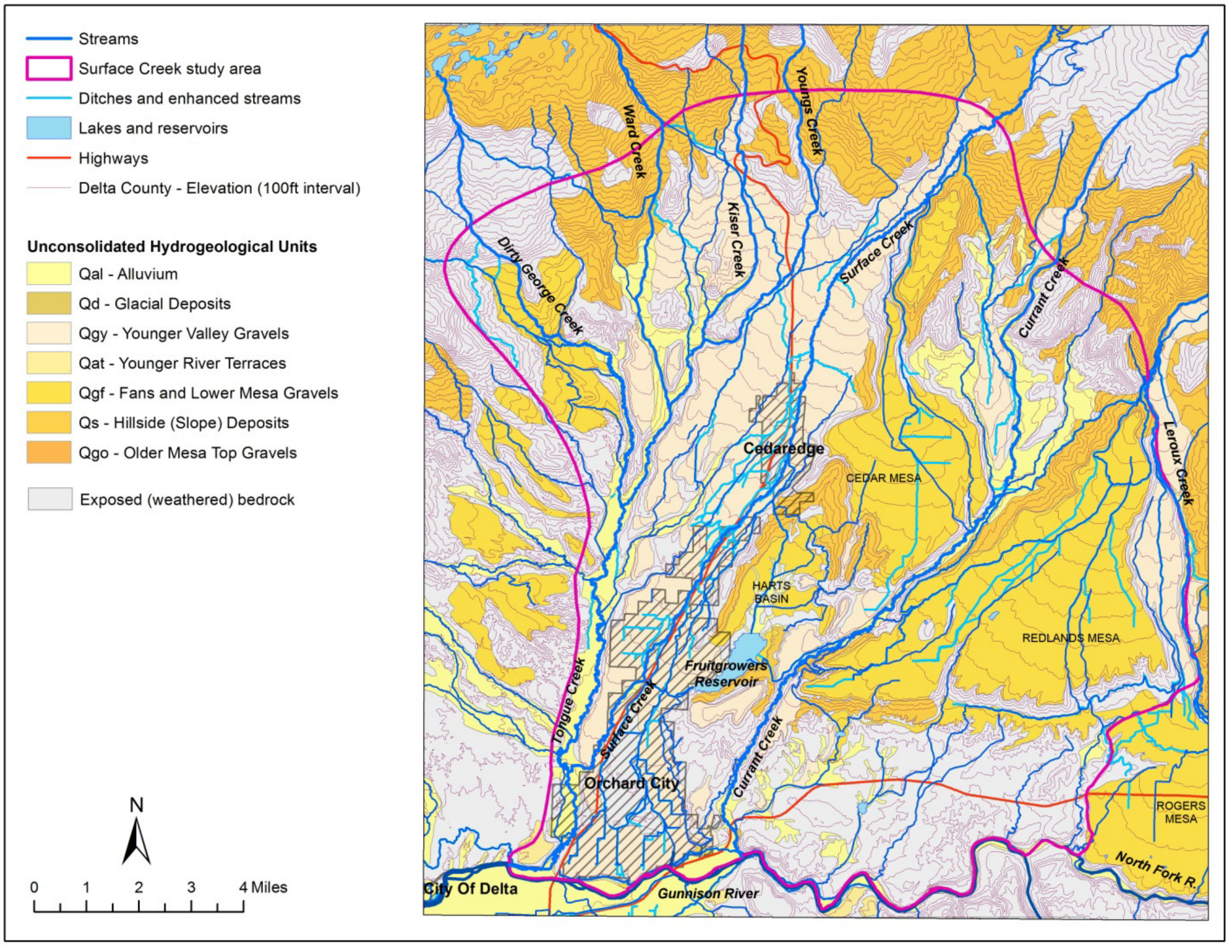

Figure 13. Map Showing the Shallow Unconsolidated Hydrogeologic Units in the SCV Area.

The Quaternary unconsolidated clastic units (Qal, Qgy, Qat, Qs, Qd, Qgf, and Qgo in Table 2a and Figure 13) are locally heterogeneous, with predominantly a mix of coarser and finer materials in the older alluvial deposits, and finer materials in the younger deposits. These deposits, which are moderately to highly permeable, are recharged by infiltration from precipitation that is non-uniformly distributed due to the slope steepness, slope aspect, and to position in the landscape, and by the incidental leaky irrigation ditch and irrigation return flow. The unconsolidated units are variably to fully saturated based on spatial location and seasonal precipitation events. There may be lateral and vertical groundwater flow connection between the unconsolidated materials and the Tertiary and Cretaceous sedimentary units in the underlying bedrock formations.

Of special hydrological interest is the possible occurrence of a weathered zone on the surface of the Mancos Shale (Km). This occurs near the topographic surface of exposed or shallow Mancos Shale bedrock Km(w) on the top of and along the hills surrounding Redlands Mesa, Cedar Mesa, Harts Basin, Surface Creek, or the Tongue Creek (and tributaries) areas. This weathered surface is due to natural rebound of the land surface combined with the physical and chemical weathering processes. As a result, this weathered zone may transmit water of variable water quality along the topographic gradient of occurrence, and as a result, Qgf and Qgy deposits can be connected to the Hillslope deposits (Qs) as one system. Indeed, the weathered Mancos Shale will tend to fail in slump failures and mudflows to become the Hillslope (Qs) aquifer. This will become apparent in the discussions of the Redlands Mesa and Cedar Mesa (Qgf-Km(w)-Qs) hydrologic connectivity, and the Tongue Creek Subsystem (Qgy-Km(w)-Qs-Qal) hydrologic connectivity.

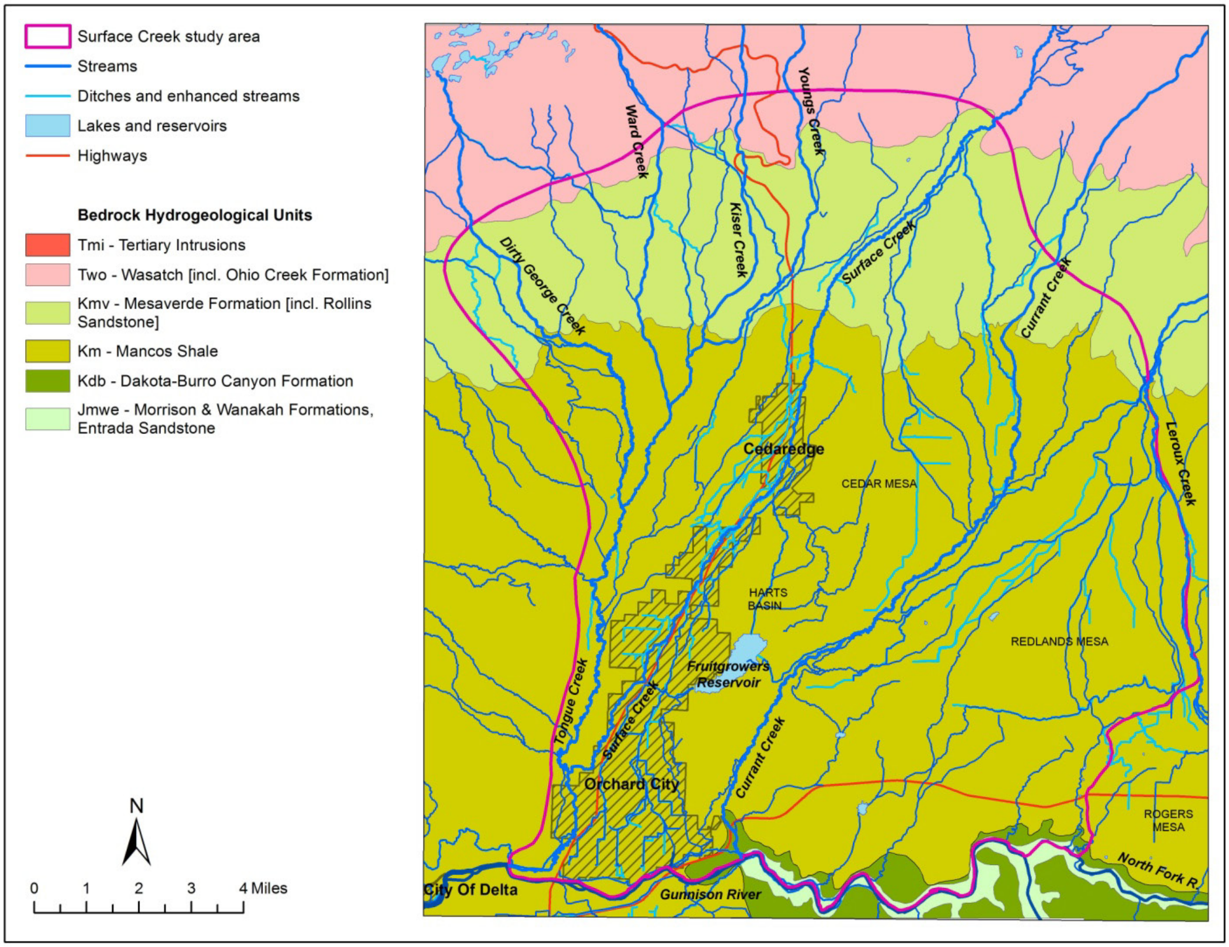

Figure 14. Map Showing Top of Bedrock Hydrogeologic Units in SCV Area.

2.4.3 Hydrostructural Units of the SCV Area

Hydrostructures, which are defined by faults and fracture zones, control the location of most of the main drainages and exist subregionally and regionally (Figure 15). These fault and fracture zones have influenced the location of the main surface water drainages in the SCV study area by providing zones of weakness whereby the streams have downcut through the unconsolidated deposits into the underlying Mancos Shale bedrock. As a result, the SCV study area is dissected into five distinct and unconnected hydrologic systems: Redlands Mesa; Currant Creek; Cedar Mesa (including Harts Basin); Surface Creek Valley, and the Tongue Creek drainage system with associated tributaries.

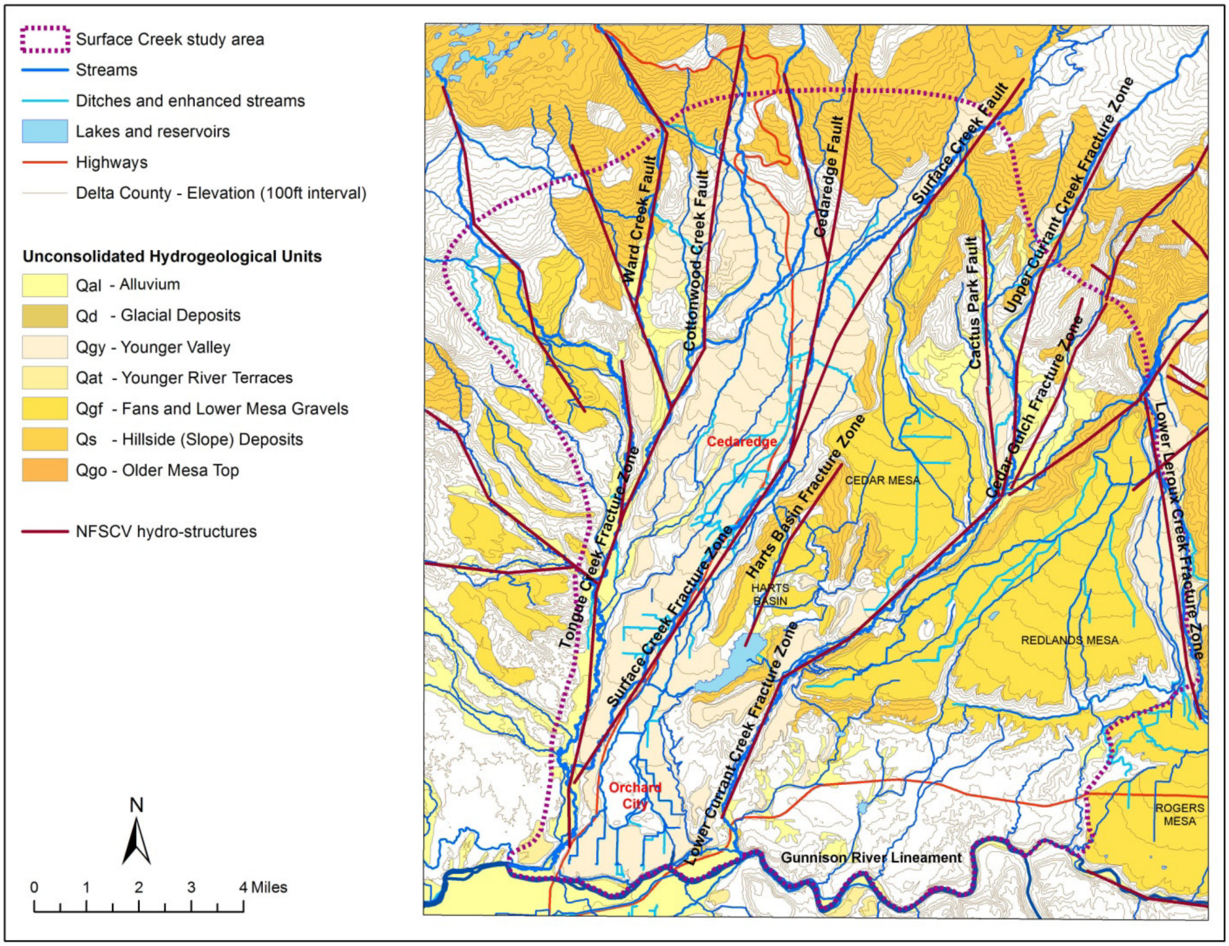

Figure 15. Map Showing Major Hydrostructures (Faults and Fracture Zones) in the SCV Area.

The faults and fracture zones may influence the hydrogeology and hydrologic systems of Currant Creek, Surface creek, and the Tongue Creek main stem and tributaries and the main Gunnison River as hydrostructures (Figure 15). These hydrostructures underlie these drainages in the bedrock systems (Mancos Shale primarily) and are most likely associated with preferential groundwater flow along fault and fracture zones that are observed or hypothesized to transmit groundwater either vertically or laterally along the fault or fracture planes or zones. These structures may serve as distinct hydrogeologic units, may enhance the permeability of sections of bedrock hydrogeologic units, may connect multiple hydrogeologic units together, or may restrict the thickness and flow of overlying unconsolidated deposits resulting in springs and groundwater discharge areas. These hydrostructures, if "open", may also result in connectivity between deeper groundwater systems and the streams, which may be a concern if oil and gas activity is progressing at depth (fracking, horizontal drilling).

Each fault and fracture zone should be evaluated for the following characteristics: 1) fault and fracture plane geometry, including the vertical or horizontal nature of the fault/fracture plane and the relations of rock types and geometry on both sides of the structure; and 2) the transmissive nature of the fault/fracture plane or fault/fracture zone, including the nature of fault gouge, if any (clay, gravel) and tectonic setting of fault/fracture plane or zone (extension or compression). The fault/fracture plane geometry is important to evaluate if groundwater can move horizontally across the zone from one transmissive unit to another, or whether the groundwater is forced to move vertically upward to the surface, in many cases, or downward into a different hydrogeologic unit, or laterally parallel to the fault and fracture zone like a geotechnical French drain. The tectonic setting helps determine whether the fault/fracture plane is “open”—able to easily move water (extension), or “closed”—not able to easily move water (compression).

Three broad hydrostructure sets occur in the SCV area: 1) the northeast-trending faults and fractures that parallel the Currant and Surface Creek fault zones and associated en-echelon faults and fracture zones to the east (for example, Upper Leroux Creek fault zone and the North Fork Valley lineament); 2) the north-south-trending Tongue Creek fracture zone and Cottonwood Creek and Ward Creek faults, which parallel the Lower Leroux Creek fault zone; and 3) the east-west trending Gunnison River lineament (Figure 15).

The northeast-trending faults and fractures are relatively young, as the geomorphic systems of Currant Creek and Surface Creek are responding with considerable downcutting, allowing for partial to full penetration of the unconsolidated hydrogeologic unit aquifers. It is hypothesized that the northeast fracture zones are “open” and function like French drains. Groundwater moves laterally down valley and vertically downward along the northeast-trending fault and fracture zone planes, and may move vertically up along the fault and fractures plane near the lower reaches of the various drainages (this would be evidenced by gaining reaches in streams or increased groundwater head with depth in local wells).

The north-south-trending Tongue Creek fracture zone and associated en-echelon fault and fracture zones, are also hypothesized to be “open” and function like French drains. Groundwater moves laterally down valley and vertically downward along the north-south-trending fault and fracture zone planes, and may move vertically up along the fault and fractures plane near the lower reaches of the various drainages (this would be evidenced by gaining reaches in streams or increased groundwater head with depth in local wells).

In the east-west trending Gunnison River lineament/fracture zone, groundwater in alluvium and the underlying bedrock systems moves horizontally along the fault plane from east to west, and vertically upward from bedrock systems into unconsolidated materials in the lower reaches below Orchard City, where it discharges into the lower Gunnison River. Therefore, the effects of anthropogenic activities, such as irrigation or oil and gas activity, may propagate to the land surface along the Gunnison River (Figure 15).

Geological Unit	Geological Subunit	Hydrogeological Unit	Hydro-geological Unit Symbol	Composition	Hydrogeological Characteristics	Permeability/Storativity	Depth to Water (small/ moderate/ large/ highly fluctuating)	Extent (local/ sub-regional/ regional)	Recharge Type (natural/ anthropogenic)
Alluvium (Qa); alluvium and eolian deposits (Qae)		Alluvium	Qal	Poorly sorted riverine gravel, sand and silt deposited mainly in stream channels and floodplains in major stream valley bottoms; moderately to well bedded deposits	Generally good local phreatic aquifer with matrix based permeability; limited variations in groundwater levels; often sustained by local and sub-regional discharge to adjacent stream or recharge directly from stream. Seasonal and storm variations of water table with stream variations	high matrix-permeability; high storativity	small	local	natural and anthropogenic
Younger gravel (Qg, Qgy)		Younger valley gravels	Qgy	Poorly sorted sands and gravels; pebbles and cobbles in sand to silt matrix	Potentially good, spatially continuous phreatic aquifer with high matrix based permeability; may be supported by underlying bedrock.	high matrix-permeability; high storativity	highly fluctuating	local	natural and anthropogenic
Glacial drift, till, moraine (Qd, Qm, Qpt)		Quaternary glacial deposits	Qd	Heterogeneous, poorly sorted deposits of boulders, gravel, sand, silt and clay	Potentially good local phreatic aquifer with variable matrix based permeability and high water table gradients.	high matrix-permeability; high storativity	highly fluctuating	local	natural and anthropogenic
Landslide deposits, colluvium, mudflow deposits, talus (Ql, Qcl, Qs, Qls, Qta); unconsolidated deposits derived from the Wasatch Formation and Basalt cap on Grand Mesa (Quw)		Hillside (slope) deposits	Qs	Loose gravels and rock debris with mixed matrix composition (sand-clay) on valley sides, valley floors and hillslopes; deposited by gravitational processes	Potentially good, highly localized phreatic aquifer with high matrix based permeability and high water table gradients.	high matrix-permeability; high storativity	highly fluctuating	local	natural and anthropogenic
Old/older gravels (Qgo, Qgd)		Older mesa top gravels	Qgo	Poorly sorted sands and gravels; pebbles and cobbles in sand to silt matrix	Potentially good, spatially continuous phreatic aquifer with high matrix based permeability; may be prone to significant (seasonal) water table fluctuations; tends to recharge bedrock systems	high matrix-permeability; high storativity	moderate	local	natural and anthropogenic
Middle gravel (Qgm) and fans (Qf)		Fans and lower mesa gravels	Qgf	Poorly sorted sands and gravels; pebbles and cobbles in sand to silt matrix	Having high matrix based permeability, presence of groundwater depends on location in topography and on landuse. In the NFVT area this unit only contains significant groundwater where leaking ditches are present; in the SCV area and on Rogers Mesa it is a major groundwater unit due to irrigation return flow..	high matrix-permeability; high storativity	highly fluctuating	local	natural and anthropogenic
High level alluvium (Qat); younger terraces (Qad); alluvial gravels (Qga)		Younger river terraces	Qat	Poorly sorted sands and gravels; pebbles and cobbles in sand to silt matrix; forms terraces above current North Fork level	Potentially good, spatially continuous phreatic aquifer with high matrix based permeability.	high matrix-permeability; high storativity	highly fluctuating	local	natural and anthropogenic

Table 2a. Correlation of Geological and Hydrogeologic Units in the SCV Study Area: Unconsolidated Sediments.

Geological Unit	***Geological Subunit***	***Hydrogeo-logical Unit***	***Hydro-Unit Symbol***	***Composition***	***Hydrogeological Characteristics***	***Permeability/Storativity***	***Depth to Water*** (small/ moderate/ large/ highly fluctuating)	***Extent*** (local/ sub-regional/ regional)	***Recharge Type*** (natural/ anthropogenic)
Tertiary Intrusive Rocks		Tertiary Intrusive Rocks	Tmi	Granodiorite and quartz monzonite; may occur as dikes and sills	Fractured crystalline system with very low matrix permeability; not a (sub-)regionale aquifer; may produce locally water in fracture zones and support adjacent unconsolidated aquifers. These characteristics may extend into adjacent rocks,methamorphosed during the Tertiary intrusion.	mostly low permeability, localized zones with moderate fracture permeability; low storativity	large	local	natural
Wasatch Formation (Tw) - including Ohio Creek Member		Wasatch Formation	Two	Channel sandstones and overbank siltstones and shales; conglomerate; carbonaceous shales and lignite near base	Overbank sandstones form a good aquifer system with moderate to good matrix and fracture based permeability; may be a locally good water producer; siltstones and shales are confining layers; outcrops are recharge areas for a regional flow.	layers with very low permeability and layers with moderate matrix and fracture permeability; low to moderate storativity	large	regional	natural
Mesa Verde Group (Kmv)	Undivided Barren Member Upper Coal-bearing Layer Lower Coal-bearing Layer Rollins Sandstone Member	Mesa Verde Group (undivided)	Kmv	Interbedded sandstones and siltstones, shales and carbonaceous shales and coals.	Good regional bedrock aquifer system; sandstones and coals have both moderate matrix and fracture based permeability; may locally be a good water producer; shales are confining layers; outcrops are recharge areas for regional flow.	layers with very low permeability and layers with moderate matrix and fracture permeability; low to moderate storativity	large	regional	natural
Mancos Shale (Km)	Undivided Upper and Lower Sandstone Members of Mancos Shale (Kms, Kmsl) Fort Hays Limestone Member of Mancos Shale (Kmf) Lower Mancos Shale, including Frontier Sandstone and Mowry Shale members (Kml)	Mancos Shale (undivided)	Km	Silty to sandy shale with bentonites with minor limestone- and sandstone beds; when undivided, lower section includes Ft Hays limestone	Mostly aquitard with very low permeability serving as a confining layer for underlying or embedded aquifers; however, locally moderate aquifer conditions when highly fractured or in areas with sand lenses and sandy beds.	very low permeability rock with some moderately permeable beds; low storativity	highly fluctuating	n.a.	natural
Dakota Sandstone and Burro Canyon Formation (Kdb)		Dakota Sandstone and Burro Canyon Formation	Kdb	Well indurated, medium to coarse grained quartzose sandstones in well-cemented thick beds and conglomerate with occasional siltstones and carbonaceous shale	Good regional bedrock aquifer system; sandstones have both moderate matrix and fracture based permeability; sub-regionally aquifer with recharge in outcrop areas.	moderate matrix and fracture permeability; moderate storativity	large	regional	natural
Morrison Formation (Jm, Jmb, Jms); Morrison, Wanakah and Entrada Formations undivided (Jmwe)		Morrison and Entrada Formations	Jmwe	Morrison Form. (Jm): Siltstones and claystones throughout with sandstones becoming more common in lower sections, and limestone near base; Entrada Form. (Je): fine-grained, well-sorted sandstones; Je is overlain by Jm	Entrada is a very good, regionally sustainable aquifer with moderate to good matrix and fracture based permeability. Morrison shales are confining layers while the lower Morrison sandstones and limestone may serve as local to sub-regional aquifers.	layers with very low permeability and layers with moderate matrix and fracture permeability; low to moderate storativity	large	regional	natural

Table 2b. Correlation of Geological and Hydrogeologic Units in the SCV Study Area: Bedrock Units.

2.5 Groundwater Flow Systems

Groundwater flow is the movement of water from the earth's surface into the subsurface (groundwater infiltration and recharge), through the subsurface materials (groundwater flow and storage), and from the subsurface back to the Earth's surface (groundwater discharge), expressed in terms of flow directions, patterns and velocities. The driving force for groundwater flow is a difference in (piezometric) "head" or groundwater levels, as expressed, for example, by the slope of the water table. The general CSM of the groundwater flow system consists of 1) water inputs (recharge); 2) storage in and movement through subsurface hydrogeologic units (groundwater flow); and 3) outputs (discharge). Natural recharge is based on climate and soils resulting in infiltration of precipitation and snowmelt. Groundwater interaction with streams, vegetation (evapotranspiration), and human activity (irrigation, urbanization, wells and individual sewage disposal systems, reservoirs and ponds, oil and gas activity, mining, dewatering) will affect groundwater movement to varying degrees. The CSM also incorporates topography (steepness, slope aspect, degree of landscape dissection), geomorphology, and soil and rock properties. Because of the time-space variance of these inputs and outputs, a groundwater system often shows significant variations in water levels, water storage, flow velocities, and flow patterns. Some of the variations are seasonal; others may be related to multi-year periods of above-average or below-average precipitation. This results in variations in the availability of water from these hydrogeologic units.

Based on the HESA approach (*Kolm and others, 1996*), and previously collected supporting data, the subregional and local scale (typically less than 100 square miles) shallow groundwater flow systems are delineated. The broad hydrologic system inputs include infiltration of precipitation as rain and snowmelt, areas of losing streams and rivers (upper Currant Creek, upper Surface Creek, upper Tongue Creek, sections of the Gunnison River below Hotchkiss) in some locations, infiltration and runoff from water bodies (cattle and house ponds, Fruitgrowers Reservoir), upland irrigation areas (leaking ditches, irrigation return flow), and inter-aquifer transfer of groundwater between unconsolidated materials and bedrock systems. Mesa Top and Hillslope subsystems consist of the hydrologic processes of surface runoff (overland flow) and rapid near-surface runoff (interflow or shallow through-flow); saturated groundwater flow in parts of the bedrock units, landslides, terraces, and valley bottoms; and discharge to springs and seeps, graining streams, by plants as evapotranspiration, and by pumping wells. In general, shallow groundwater flow in these systems is towards the valley bottoms, perpendicular to the major streams. Where permeable bedrock units intersect mesa tops, hillslopes, and valley bottoms, recharge by groundwater moving from unconsolidated hydrogeologic units into the bedrock hyhdrogeologic units may force the groundwater into a more regional pattern determined by geological structure, independent from local topography and hydrography, as is observed in the northern part of the study area near the higher slopes of Grand Mesa. The SCV groundwater systems are a complex mix of predominantly the shallow aquifer systems underlain by a more confining hydrogeologic unit: the Cretaceous Mancos shale. Locally and subregionally, various hydrostructures may influence interconnectivities of the shallow units with deeper bedrock systems.

The Mesa Top (Redlands Mesa; Cedar Mesa/Harts Basin) subsystems, located in close proximity to the Valley Bottom subsystems, have a unique, sometimes complex groundwater story, often resulting from human interference. Under natural conditions, these subsystems have hydrologic system inputs and outputs, similar to Hillslope subsystems. However, natural and anthropogenic influences have frequently attached these subsystems hydrologically to adjacent Valley Bottom subsystems.

The Valley Bottom subsystems, where stream-aquifer-wetland interactions occur, are areas of both groundwater recharge and discharge, and groundwater flow can have a rather diffuse character and often flows towards or aligns more or less with the streams and rivers. These subsystems depend primarily on interactions with their main streams such as Currant Creek, Surface Creek, and Tongue Creek (with tributaries), and the Gunnison River; and the management of subregional ditches and subsurface return flow from irrigation lands and corresponding spring storage.

The wetlands associated with the local hydrogeologic subsystems in the Gunnison River, and in Currant, Surface, and Tongue Creeks are a mix of slope-type and riverine-type classifications given the groundwater support of various ditches and irrigation schemes, unconsolidated hydrogeologic unit groundwater systems, and hydrostructures.

As springs are discharge points of groundwater flow systems, their presence in the SCV study area provide clues about these groundwater flow systems, including the role of the hydrogeological units, and the effects of natural and anthropogenic recharge on flow and water quality. To identify the location and discharge rates of springs and seeps in the SCV area the State water rights database was searched in May 2014 (*CDWR 2014*).

There are two general categories of springs, based on spring location with respect to hydrogeologic location, that are identified on topographic maps and in the State water rights records for Delta County (Figure 9): 1) Unconsolidated Unit/Cretaceous Mancos Shale interface springs; and 2) Unconsolidated Unit or non-interface springs controlled by topography and geomorphology. The interface springs are located at the Qa/Km interfaces along drainages or at the Qgf/Qs/Km interfaces along the edges of mesas where the fans and lower mesa gravels (Qgf) and mass wasting slope materials (Qs), which are the potential unconsolidated aquifers, abut against the Cretaceous Mancos Shale (Km), which is a confining unit, forcing groundwater to the surface. The non-interface springs are located in the modern alluvium (Qal) and younger valley gravels (Qgy).

Springs can also be categorized with respect to recharge dynamics: 1) Springs recharged primarily by natural precipitation and infiltration; 2) Springs recharged primarily by leaky irrigation ditches, with secondary recharge by return flow from irrigation and infiltration of natural precipitation; and 3) Springs recharged primarily by return flow from irrigation, and secondary recharge by precipitation and/or leaky irrigation ditches. Springs recharged primarily by natural precipitation and infiltration are observed in Qs in the uppermost (northern) regions of the SCV study area (for example in the Ward Creek and Currant Creek area). Springs recharged primarily from leaky irrigation ditches, with secondary recharge by return flow from irrigation and infiltration of natural precipitation are observed in the upper parts of the Cedar Mesa and Redlands Mesa, where the irrigation ditches initially connect with the Qgf units and the effects of irrigation return flow are not present. The springs recharged primarily from return flow from irrigation, and secondary recharge by precipitation and/or leaky irrigation ditches, are observed in the lower discharge areas in the Qgf units on Cedar and Redlands Mesas, the Qs deposits associated with the Cedar and Redlands Mesas, and the Qgy springs in the Surface Creek Valley near Cedaredge.

Finally, springs can also be categorized with respect to age based on information from the State water rights data base for springs/seeps and ditches (*CDWR 2014*): 1) Pre-irrigation springs that most likely were the result of infiltration of natural precipitation; and 2) Post-irrigation springs that most likely were the result of either irrigation return flow to the groundwater or infiltration of water due to leaky irrigation ditches. This latter category of springs and nearby wells is most vulnerable to changes in water use and water rights decisions. Most of the springs in the SCV area and affiliated water rights will be associated with the effects of the various leaky irrigation ditches and the return flow of irrigated water.

2.6 Groundwater System Conceptual Site Models by Subsystem

Based on the presence and orientation of various hydrogeologic and hydrostructural units, hydrography and topography, three CSMs will be discussed in the SCV study area:

1. Mesa Top and Hillslope Shallow Aquifer Subsystems, which include the Redlands Mesa and Cedar Mesa\Harts Basin Subsystems;
2. Valley Bottom Shallow Aquifer Subsystems, which include the Currant Creek, Surface Creek, and Tongue Creek Subsystems; and
3. Regional Bedrock Aquifer Subsystems.

In addition, a brief discussion of the interface of the Valley Bottom Shallow Aquifer Subsystems with the Gunnison River Subsystem will be presented.

The conceptual models are discussed in forthcoming sections and illustrated by cross-sectional and plan view figures, and by Google Earth screen shots. The locations of representative cross-sections are shown in Figure 16. A landscape view of the area is shown in Figure 17. Note that Redlands Mesa, Cedar Mesa, and Antelope Hill are topographic islands.

2.6.1 Mesa Top and Hillslope Shallow Aquifer Subsystems

As stated in Section 2.4.2, there are two significant hydrogeologic groups in the Mesa Top and Hillslope Shallow Aquifer Subsystems, which include the Redlands Mesa Subsystem, and the Cedar Mesa\Harts Basin Subsystem:

1. Quaternary unconsolidated clastic units (Qs and Qgf in Table 2a and Figure 13), which are predominantly hillside (slope) deposits and lower mesa gravels and fans; and
2. Cretaceous bedrock unit of the Mancos Shale (Km) (Table 2b and Figure 14).

The shallow Quaternary unconsolidated materials in these two subsystems are ubiquitous, and include glacial-alluvial, mass wasting, and paleo-alluvial (terrace) deposits (Figure 13 and Table 2a). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in all of the deposits. These deposits are underlain by a paleotopographic surface carved out by paleofluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated.

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the shallow groundwater on Redlands Mesa is dominated by the Quaternary unconsolidated materials (Qgf and Qs), which receive natural recharge by infiltration of precipitation (snow and rain; Rp), and major recharge from leaky irrigation ditches originating from Leroux Creek (Rd) and reservoirs locally, and return flow from area irrigation locally(Ri) (Figures 18, 19, and 20). The unlined ditches are "line" sources of groundwater recharge (Rd) leading to and at the top of the irrigated field areas; the return flow from irrigation is considered an "area" source of groundwater recharge (Ri). Water leaking from the unlined ditches and irrigated areas enter into the (connected) gravels underneath and flows downgradient towards the discharge zones (streams, springs and seeps, and wetlands) (Figures 18, 19, and 20).

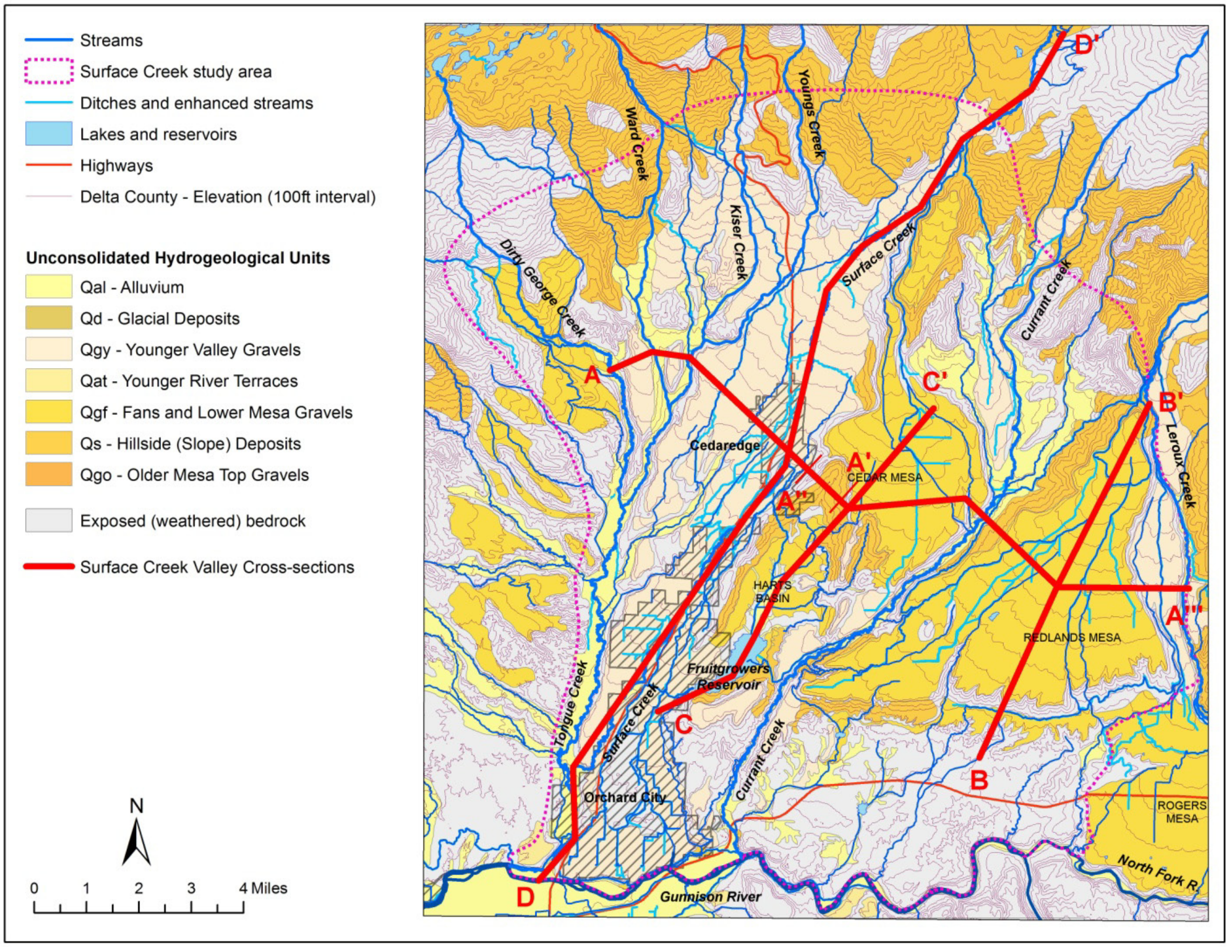

Figure 16. Map Showing the Locations of the Cross-sections Representative for the Conceptual Site Models in the SCV Area on Top of the Hydrogeologic Units.

Groundwater flow on top of the gravel-capped Redlands Mesa then moves with topography or subsurface paleo-topography to discharge into springs at the gravel/Mancos Shale interface along the incised drainages that bound the mesas (Dsp), discharge directly out the front of the mesa as seeps or springs (Dsp) at the gravel/Mancos Shale interface, or discharge into the hillslope slope and mudslide deposits (Qs) causing further mass wasting activity (Figures 18, 19, 20, and 26). Given the "new" water that has recharged the aquifer, springs may have been developed after the initiation of irrigation on the mesa and claimed as being "new" springs. There is also groundwater discharge from the gravels locally by groundwater wells (Dw) and by phreatophytes (Dp). The shallow groundwater subsystems in this Mesa Top and Hillslope area have little connection to the local bedrock or the regional groundwater systems, or to nearby alluvial systems, such as Leroux or Currant Creeks. Google Earth can be used to visualize these relationships (for example, Figures 21a and b).

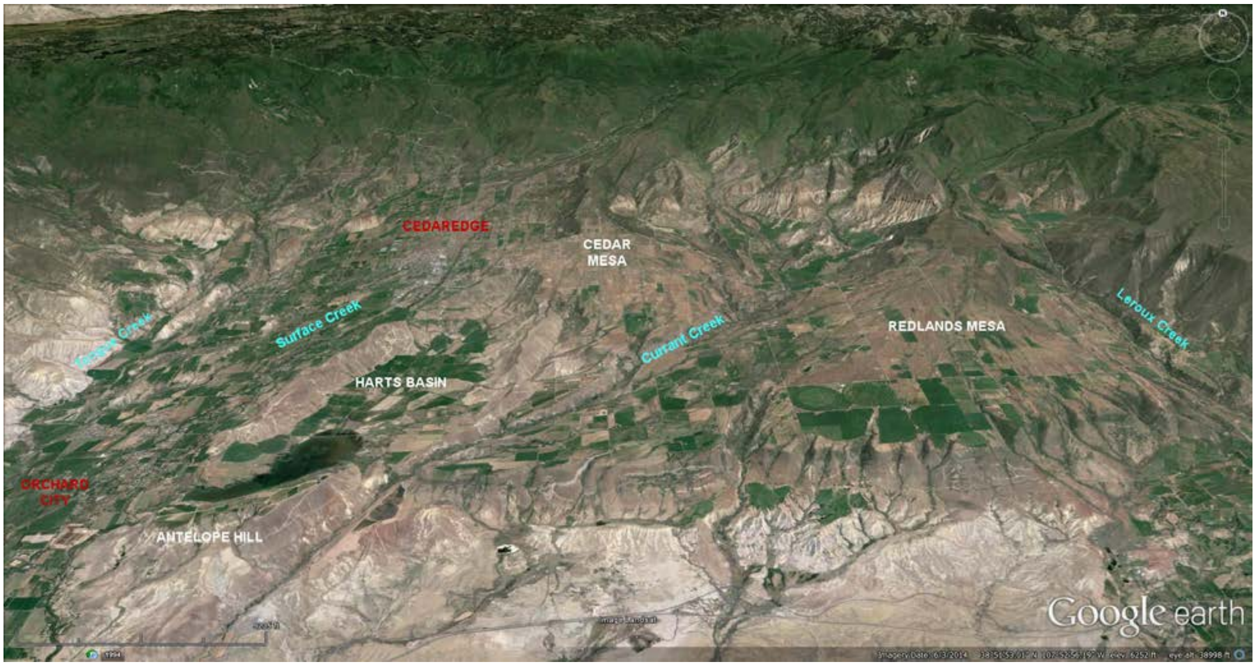

Figure 17. Google Earth View of the Study Area Looking North.

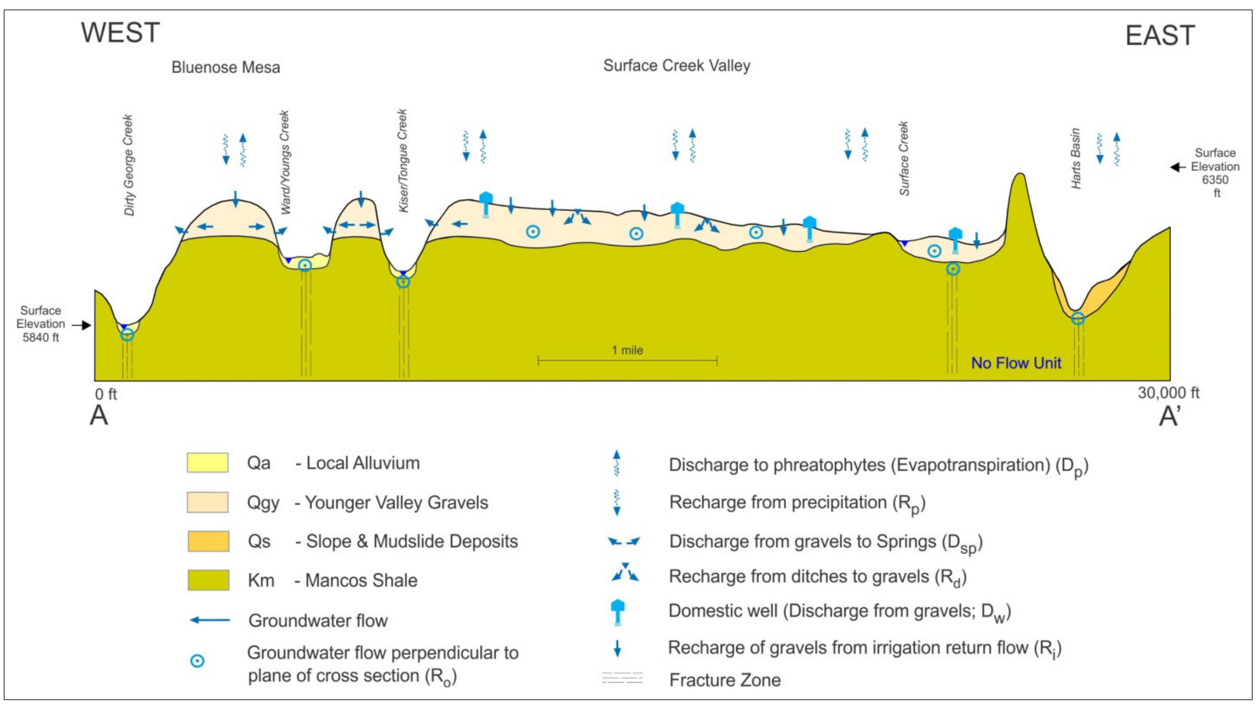

Figure 18a. East-west Cross-sectional View of the Conceptual Site Models of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystems in the SCV Study Area (Western section; A-A' in Figure 16).

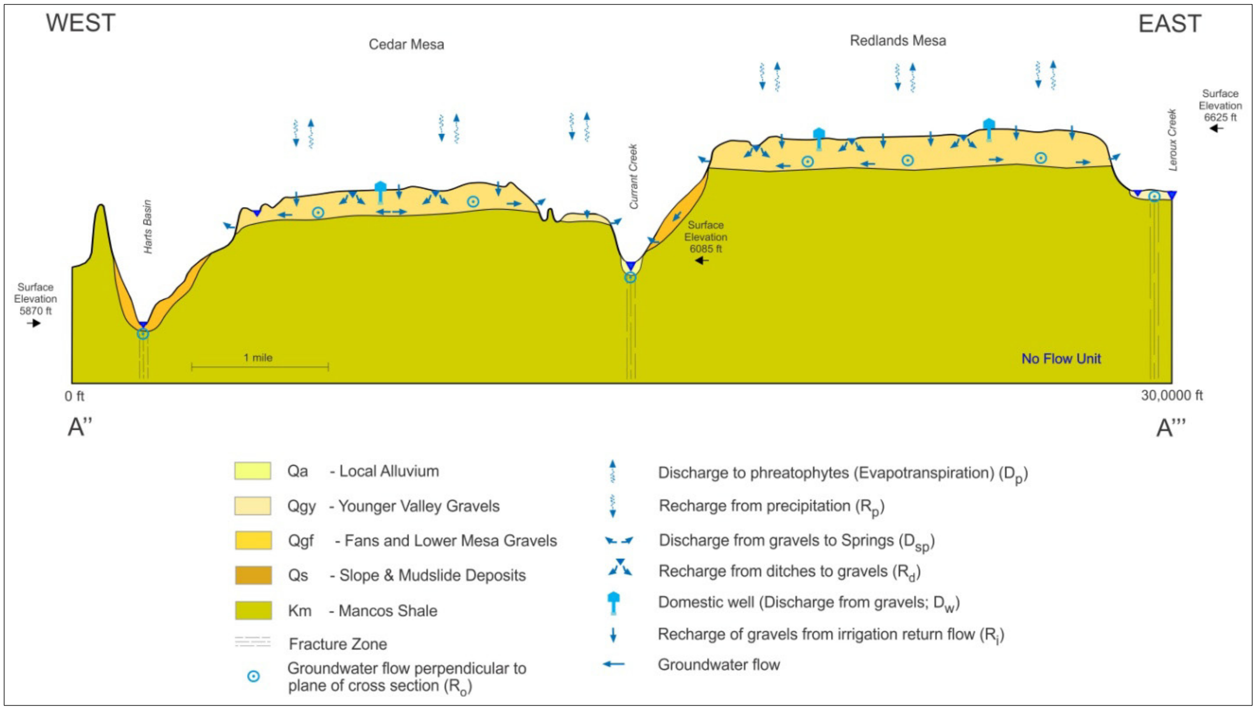

Figure 18b. East-west Cross-sectional View of the Conceptual Site Models of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystems in the SCV Study Area (Eastern section; A''-A''' in Figure 16).

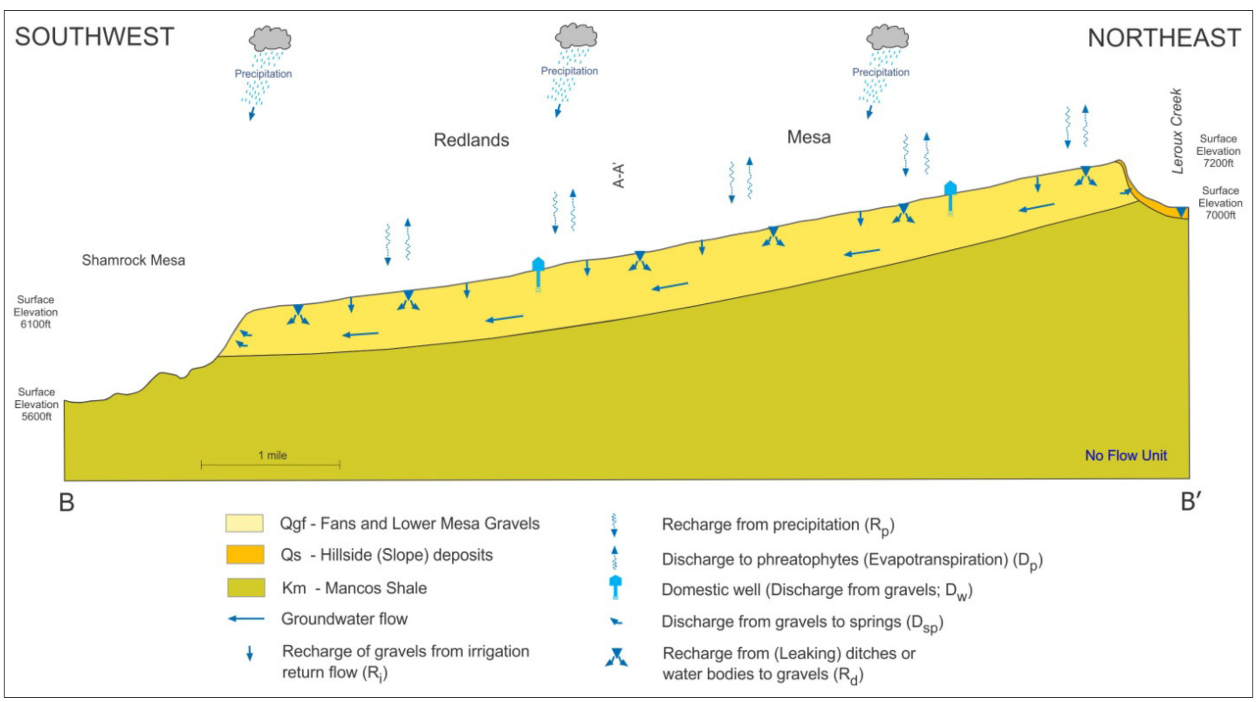

Figure 19. North-south Cross-sectional View of the Conceptual Site Models of the Mesa Top and Hillslope Subsystem in the Redlands Mesa area (B-B'' in Figure 16).

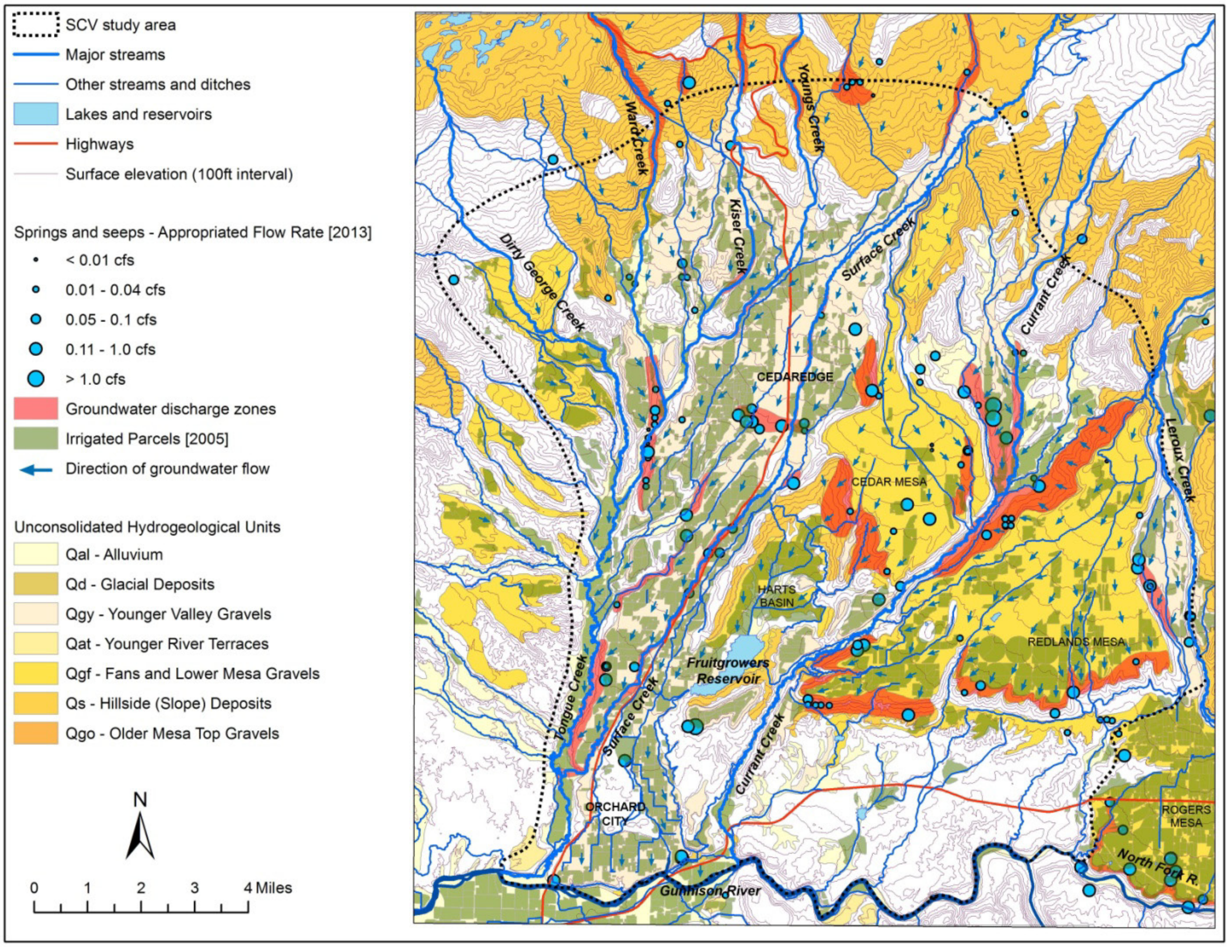

Figure 20. Plan View of the Conceptual Site Model of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystems with Discharge Zones and Groundwater Flow Direction.

A similar hydrologic system exists on Cedar Mesa, a subsystem that extends from Cedar Mesa through Harts Basin to Surface Creek (Figures 18, 20, and 22). The Cedar Mesa\Harts Basin Subsystem is dominated by the Quaternary unconsolidated materials (Qgf), which receive natural recharge by infiltration of precipitation (snow and rain; Rp), and major recharge from leaky irrigation ditches originating from upper and middle Surface Creek (Rd) and reservoirs locally, and return flow from flood irrigation locally(Ri) (Figures 18, 20, and 22). Water leaking from the unlined ditches and irrigated areas enter into the (connected) gravels underneath and flows downgradient towards the discharge zones (streams, springs and seeps, and wetlands). (Figures 18, 20, and 22).

Groundwater flow on top of the gravel-capped Cedar Mesa aquifer (Qgf) then moves with topography or subsurface paleo-topography to discharge into springs at the gravel/Mancos Shale interface along the incised drainages that bound the mesas (Dsp), discharge directly out the front of the mesa as seeps or springs (Dsp) at the gravel/Mancos Shale interface, discharge into partially incised drainages as gaining streams (Dgs), discharge as surface springs due to underlying topography (Dss), or discharge into the hillside slope and mudslide deposits (Qs) causing further mass wasting activity (Figures 18, 20, 22 and 26). Given the "new" water that has recharged the aquifer from irrrigation related sources, springs may have been developed and claimed as being "new" springs. There is also groundwater discharge from the gravels locally by groundwater wells (Dw) and by phreatophytes (Dp). The shallow groundwater subsystems in this Mesa Top and Hillslope area have little connection to the local bedrock or the regional groundwater systems, or to nearby alluvial systems, such as Surface or Currant Creeks. Google Earth can be used to visualize these relationships (for example, Figure 23).

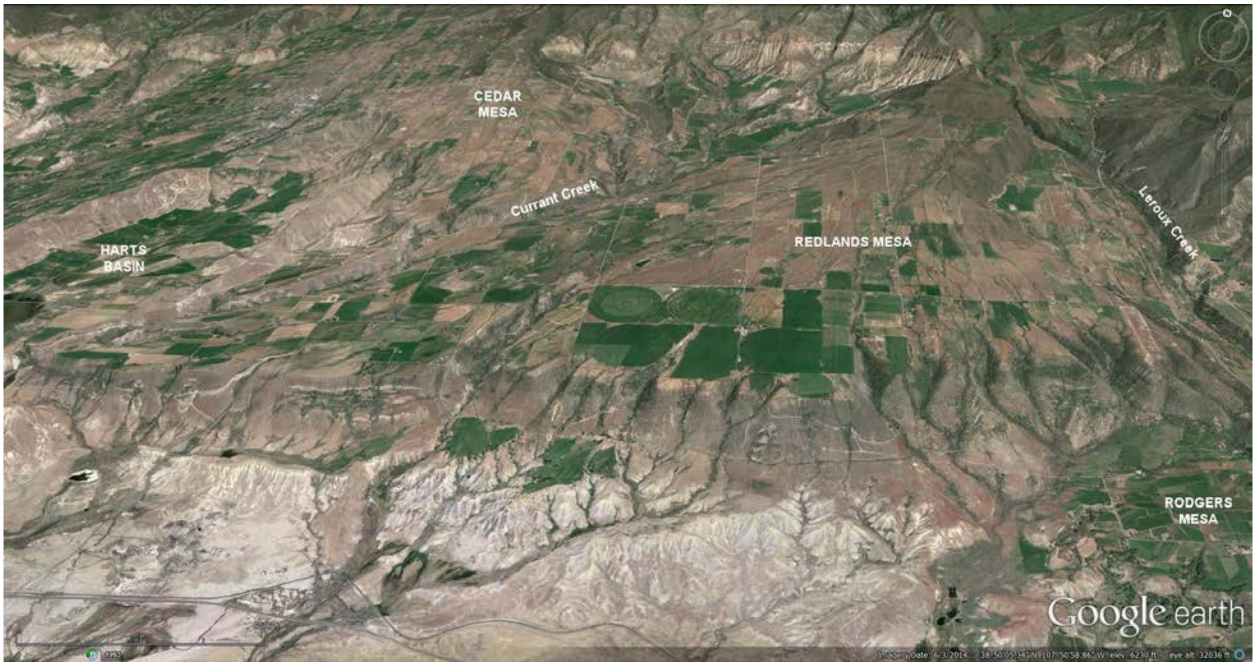

Figure 21a. Google Earth View of the Mesa Top and Hillslope Subsystem at Redlands Mesa, Looking North. Note Groundwater Discharge in the Gullies at the Southern Slopes of Redlands Mesa and the Line of Seepage from a Ditch Halfway Down the Slopes (dark green areas).

Figure 21b. Google Earth View of the Mesa Top and Hillslope Subsystem at Redlands Mesa, Looking Northeast. Note Groundwater Discharge Areas in Discontinuous Hillslope Deposits on Northwestern Side of Redlands Mesa. In Some Areas Hillslope Deposits Connect Gravels on Top of Mesa with Currant Creek Alluvium.

Groundwater discharge from the Cedar Mesa subsystem enters the surface water system in ditches and gaining streams, and contributes to the surface water flow into the north side of Fruitgrowers Reservoir (Figures 20 and 22).

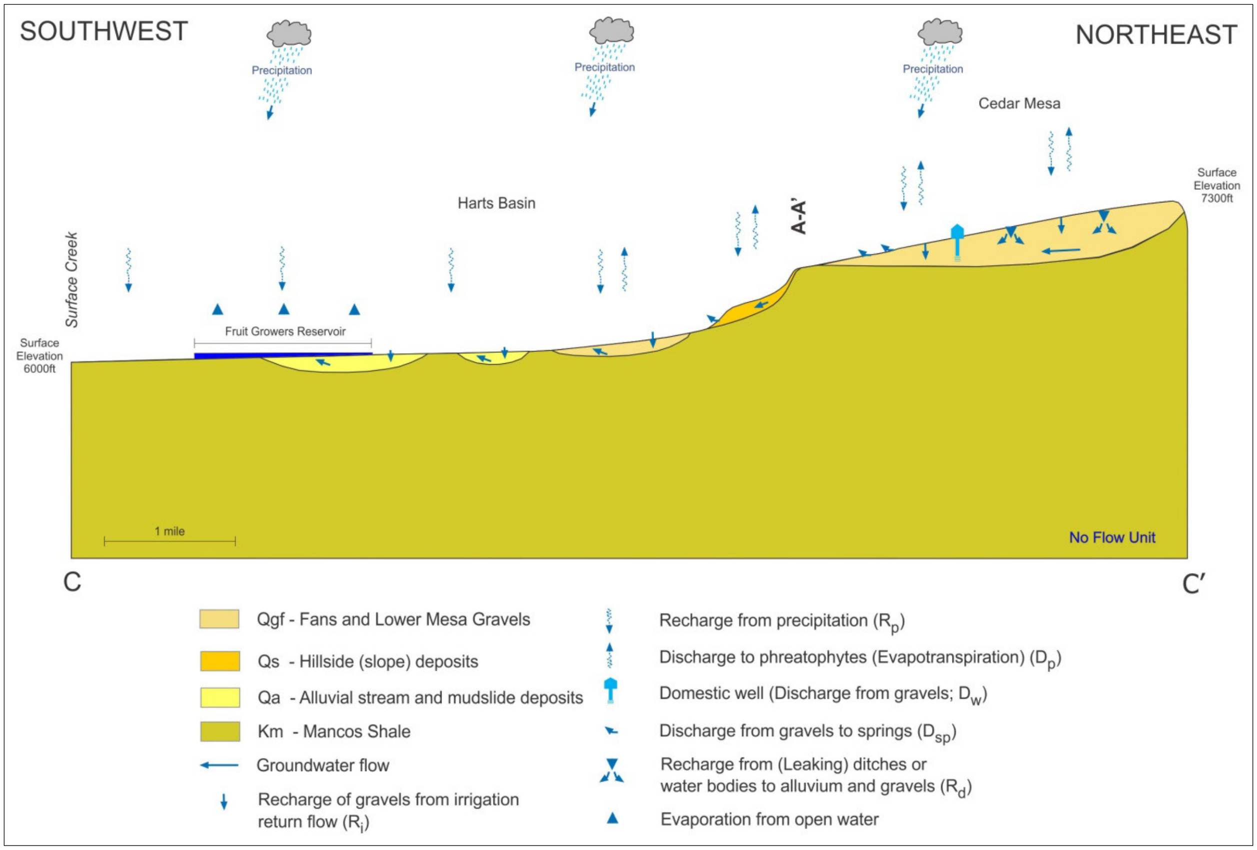

Figure 22. North-south Cross-sectional View of the Conceptual Site Models of the Mesa Top and Hillslope Subsystem in the Cedar Mesa Area (C-C' in Figure 16).

2.6.2 Valley Bottom Shallow Aquifer Subsystems

As stated in Section 2.4.2, there are three significant hydrogeologic groups in the Valley Bottom Shallow Aquifer Subsystems, which include the Currant Creek Subsystem, the Surface Creek Subsystem, and the Tongue Creek (and affiliated tributaries) Subsystem:

1. Quaternary unconsolidated clastic materials (Qal and Qgy) in Table 2a and Figure 13), which are predominantly alluvial valley bottom and terrace deposits;
2. Bedrock units, including the Tertiary Wasatch Formation (including the Ohio Creek Member; Two in Table 2b and Figure 14); Cretaceous Mesa Verde Group (Kmv in Table 2b and Figure 14); Cretaceous Mancos Shale bedrock unit (Km in Table 2b and Figure 14); and Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb in Table 2b and Figure 14); and
3. Northeast-trending and north-south trending fault/fracture zone/lineament hydrostructures (Figure 15).

Figure 23a. Google Earth View of the Mesa Top and Hillslope Subsystem at Cedar Mesa, Looking North. Note Groundwater Discharge at the Southeastern Slopes along Currant Creek and towards Harts Basin on the Southwestern Slopes (dark green areas).

Figure 23b. Google Earth View of the Mesa Top and Hillslope Subsystem at Harts Basin, Looking Northeast. Note Groundwater Discharge from Harts Basin Is Towards Fruitgrowers Reservoir; Groundwater Discharge from Antelope Hill Is Primarily Through Springs and Seeps (dark green areas).

The shallow Quaternary unconsolidated materials in these subsystems are ubiquitous, and include modern alluvium (Qal) and younger valley gravels (Qgy) (Figure 13 and Table 2a). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in the alluvial deposits (usually coarser sediments on the bottom grading to finer sediments on top). These deposits are underlain by a paleo-topographic surface carved out by paleo-fluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated.

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the shallow groundwater in the Currant Creek subsystem is dominated by the Quaternary alluvium (Qal), which receives natural recharge by infiltration of precipitation (snow and rain; Rp) and losing streams (Rs); input from hillside (slope) deposits derived from the glacial gravels (Rsd); and additional recharge from leaky irrigation ditches originating from both Leroux Creek and Currant Creek (Rd); and return flow from irrigation locally (Ri) (Figures 18b and 24). Water leaking from the unlined ditches and irrigated areas enter into the (connected) gravels underneath and flows downgradient towards the discharge zones (streams, springs and seeps, and wetlands) (Figures 18b and 24).

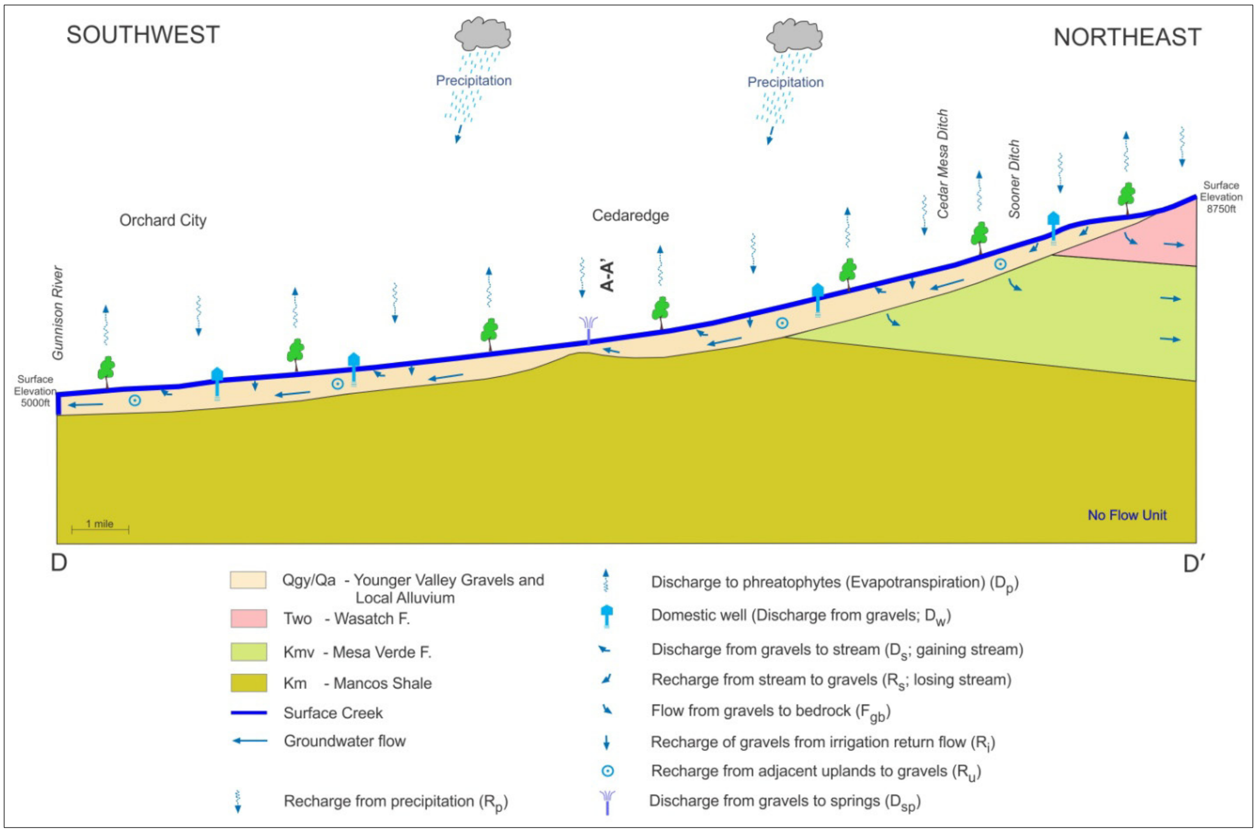

Figure 24. North-south Cross-sectional View of the Conceptual Site Models of the Valley Bottom Shallow Aquifer Subsystem in the Surface Creek Valley (D-D' in Figure 16).

Groundwater flow in the Currant Creek alluvium moves in the same direction as the stream with various stream reaches being gaining (Ds) or losing (Rs) depending on subsurface topography, saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events. Springs are observed at the Qal/Mancos Shale (Km) interface along the stream bed (Figures 18b and 20). There is also groundwater discharge from the alluvium locally by groundwater wells (Dw) and by phreatophytes (Dp). The shallow groundwater in the Currant Creek subsystem would normally have little connection to the local bedrock or the regional groundwater systems, given the Mancos Shale bedrock. However, underlying the Currant Creek alluvium is the Lower Currant Creek Lineament – Fracture Zone, the Cedar Gulch lineament, the Upper Currant Creek Lineament, and the Cactus Park Fault Zone (Figure 15). These areas of hydrostructures are hypothesized to be open conduits, where the faulted and fractured bedrock may combine with the alluvium (Qal) to form a French Drain affect resulting in increased groundwater flow and storage, and connectivity to deeper hydrologic systems (Figure 18b). This could result in decreased water quality either naturally (Mancos Shale water has higher TDS, metals) or due to human activities, such as fracking or waste disposal activities. A Google Earth view of the Valley Bottom subsystem in the Currant Creek drainage is shown in Figure 25a.

Figure 25a. Google Earth View of the Valley Bottom Subsystem in the Currant Creek Drainage, Looking Southwest.

A second valley bottom hydrologic system exists along Surface Creek, a subsystem that extends from the top of Grand Mesa and west of Cedar Mesa through the towns of Cedaredge and Orchard City ending at the Gunnison River (Figures 20 and 24). The Surface Creek subsystem is dominated by the Quaternary unconsolidated younger gravels (Qgy), which receive natural recharge by infiltration of precipitation (snow and rain; Rp) system-wide, by input from adjacent uplands to gravels (Ru) and by hillside (slope) deposits derived from the glacial gravels (Rsd) in the upper reaches of the subsystem, and major recharge from leaky irrigation ditches originating from upper and middle Surface Creek and upper Ward Creek (Rd); and return flow from irrigation throughout the middle and lower part of the subsystem (Ri) (Figures 20 and 24). Water leaking from the unlined ditches and irrigated areas enter into the (connected) gravels underneath and flows downgradient towards the discharge zones (streams, springs and seeps, and wetlands) (Figures 20 and 24).

Groundwater flow in the Surface Creek younger valley gravels (Qgy) moves in the same direction as Surface Creek with various stream reaches being gaining (Ds) or losing (Rs) depending on subsurface topography, saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events (Figure 20 and 24). Generally, the upper part of Surface Creek is gaining when flowing through the hillside (slope) gravels (Qs) as these gravels are discharging groundwater into the stream (Ds). However, at depth, the Surface Creek hillside (slope) gravels and younger valley gravels (Qgy) are recharging the Wasatch (Two) and Mesa Verde (Kmv) bedrock aquifers (Rgb) (Figures 20 and 24).

As Surface Creek crosses into the younger valley gravels (Qgy) underlain by the Mancos Shale (Km), the surface flow decreases as groundwater recharge occurs to the gravels (Rs). This function is reversed above Cedaredge and Surface Creek becomes a gaining stream due to an increase in groundwater discharge derived from leaky irrigation ditches and return flow from irrigation. Springs are observed near Cedaredge due to the thinning of the Qgy at the Qgy/Mancos Shale (Km) interface beneath the stream bed (Figure 20 and 24). There is also groundwater discharge from the gravels locally by groundwater wells (Dw) and by phreatophytes (Dp).

The shallow groundwater in the Surface Creek subsystem would normally have little connection to the local bedrock or the regional groundwater systems in the central and southern part of the subsystem, given the Mancos Shale bedrock. However, underlying the Surface Creek gravels is the Surface Creek Lineament – Fracture Zone (Figure 15). This hydrostructure is hypothesized to be an open conduit, where the faulted and fractured bedrock may combine with the younger valley gravels (Qgy) to form a French Drain affect resulting in increased groundwater flow and storage, and connectivity to deeper hydrologic systems. This could result in decreased water quality either naturally (Mancos Shale water has higher TDS, metals) or due to human activities, such as fracking or waste disposal activities.

A Google Earth view of the Valley Bottom subsystem in the Surface Creek drainage is shown in Figure 25b (upper part of valley) and Figure 25c (lower part of valley).

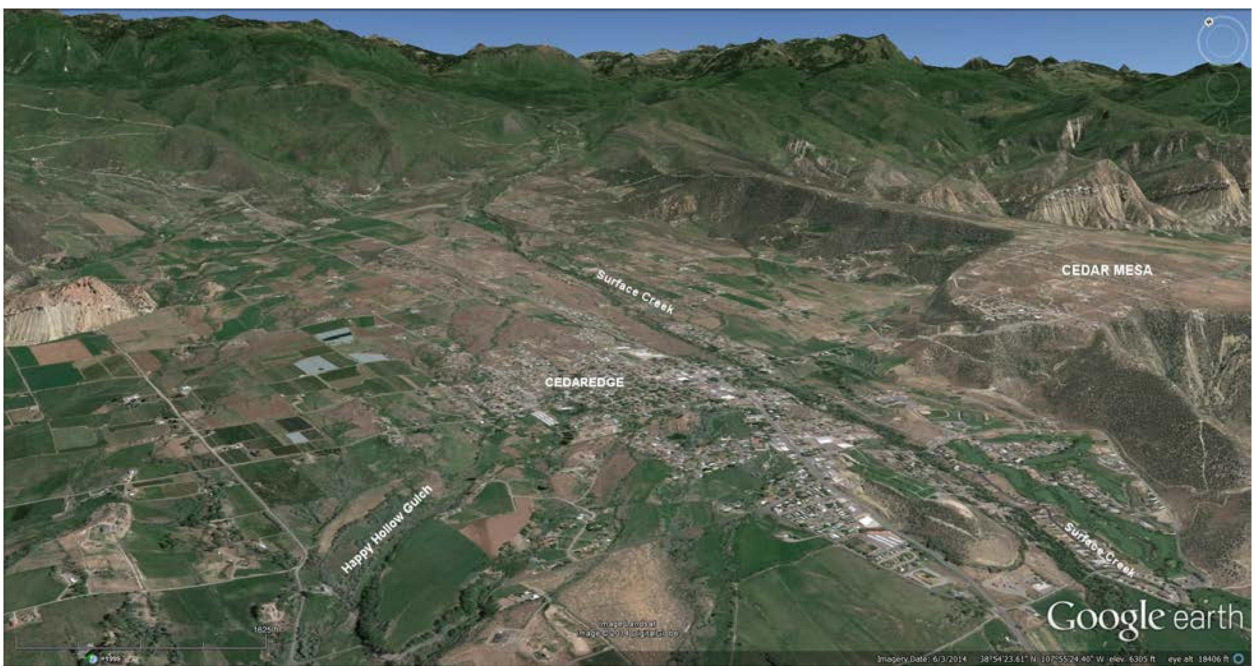

Figure 25b. Google Earth View of the Upper Section of the Valley Bottom Subsystem at Surface Creek, Looking Northeast. Note the Shale Outcroppings in the Lower Left and Right Indicative of Local Near-surface Bedrock.

The Tongue Creek Subsystem (and tributaries including Oak Creek, Dirty George Creek, Ward Creek, and Cottonwood Creek, is a third Valley Bottom subsystem (Figures 20 and 25). The shallow groundwater in the Tongue Creek Subsystem is dominated by the Quaternary alluvium (Qal), which receives natural recharge by infiltration of precipitation (snow and rain; Rp) and losing streams (Rs); input from hillside (slope) deposits derived from the glacial gravels (Rsd) in the upper reaches of the tributaries and from younger valley gravels (Qgy) on the drainage divides in the middle and lower reaches of the drainage; and additional recharge from return flow from irrigation along most of the alluvial sections of the stream (Ri) (Figures 20 and 24). The return flow from irrigation (Ri) discharges locally to nearby streams (Figure 20).

Figure 25c. Google Earth View of the Lower Part of the Valley Bottom Subsystems at Surface and Tongue Creeks and Tributaries, Looking North. Note Groundwater Discharge Zones at Southern Slopes of Surface Creek Valley System (dark green areas directly below terrace) and Effects of Leaking Ditch Along Bottom of Southern Slopes.

Groundwater flow in the Tongue Creek alluvium moves in the same direction as the stream with various stream reaches being gaining (Ds) or losing (Rs) depending on subsurface topography, saturated thickness of the alluvium, proximity to irrigation areas, or the seasonal variations caused by snowpack runoff or storm events. Springs are observed along several reaches of the stream bed due to the thinning of the Qal at the Qal/Mancos Shale (Km) interface beneath the stream bed, or where mass wasting deposits (landslides) connect the gravels of the drainage divide (Qgy) with the Tongue Creek alluvium (Qal) (Figure 20). There is also groundwater discharge from the gravels locally by groundwater wells (Dw) and by phreatophytes (Dp).

The shallow groundwater in the middle and lower Tongue Creek subsystem would normally have little connection to the local bedrock or the regional groundwater systems, given the Mancos Shale bedrock. However, underlying the Tongue Creek alluvium is the Lower Tongue Creek Lineament – Fracture Zone, the Upper Dirty George Creek Lineament-Fracture Zone, the Oak Creek Lineament – Fracture Zone, the Ward Creek Lineament-Fault Zone, and the Cottonwood Creek Fault Zone (Figure 15). These areas of hydrostructures are hypothesized to be open conduits, where the faulted and fractured bedrock may combine with the alluvium (Qal) to form a French Drain affect resulting in increased groundwater flow and storage, and connectivity to deeper hydrologic systems. This could result in decreased water quality either naturally (Mancos Shale water has higher TDS, metals) or due to human activities, such as fracking or waste disposal activities.

A Google Earth view of the Valley Bottom subsystem in the Tongue Creek drainage is shown in Figure 25c (lower part) and Figure 25d (upper part). Figure 25e shows a detail of the western slope of the Surface Creek Valley terrace and Tongue Creek near the confluence with Surface Creek,

Figure 25d. Google Earth View of the Upper Part of the Valley Bottom Subsystem at Tongue Creek and Tributaries, Looking North.

Figure 25e. Google Earth View of Detail of Central Part of the Valley Bottom Subsystem at Tongue Creek and Tributaries, Looking East. Note Seepage Faces and 'Wet' Landslide Deposits on Terrace Slopes.

2.6.3 Regional Bedrock Aquifer Subsystems

The regional hydrogeologic units in the SCV study area, discussed in Section 2.4, are the Tertiary and Cretaceous bedrock units (Figure 15 and Table 2b), including the following potentially water-bearing units: Tertiary Wasatch Formation including the Ohio Creek Formation (Two); Cretaceous Mesaverde Formation (Kmv), including the Barren, and Upper and Lower Coal Bearing members (Kmv), as well as the Rollins Sandstone member (Kmvr); and the Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb). The general aspects of the bedrock hydrogeology and hydrostructures are discussed in Section 2.5. The bedrock units are variably to fully saturated based on location and proximity to recharge area. Groundwater recharge by infiltration of precipitation (snow and rain) and by losing streams, for example Currant Creek and Surface Creek, occurs through the Hillside (slope) deposits (Qs) and younger valley gravels (Qgy) in the outcrop area (Rgb; Figures 20 and 24), and groundwater flows laterally to the north along the dip of the bedrock, where it becomes incorporated into the regional groundwater flow system. The groundwater flow direction in the regional bedrock systems is from south to north beneath the SCV Study Area and Grand Mesa (Figures 24 and 26). This flow direction is away from human activities and Delta County in general.

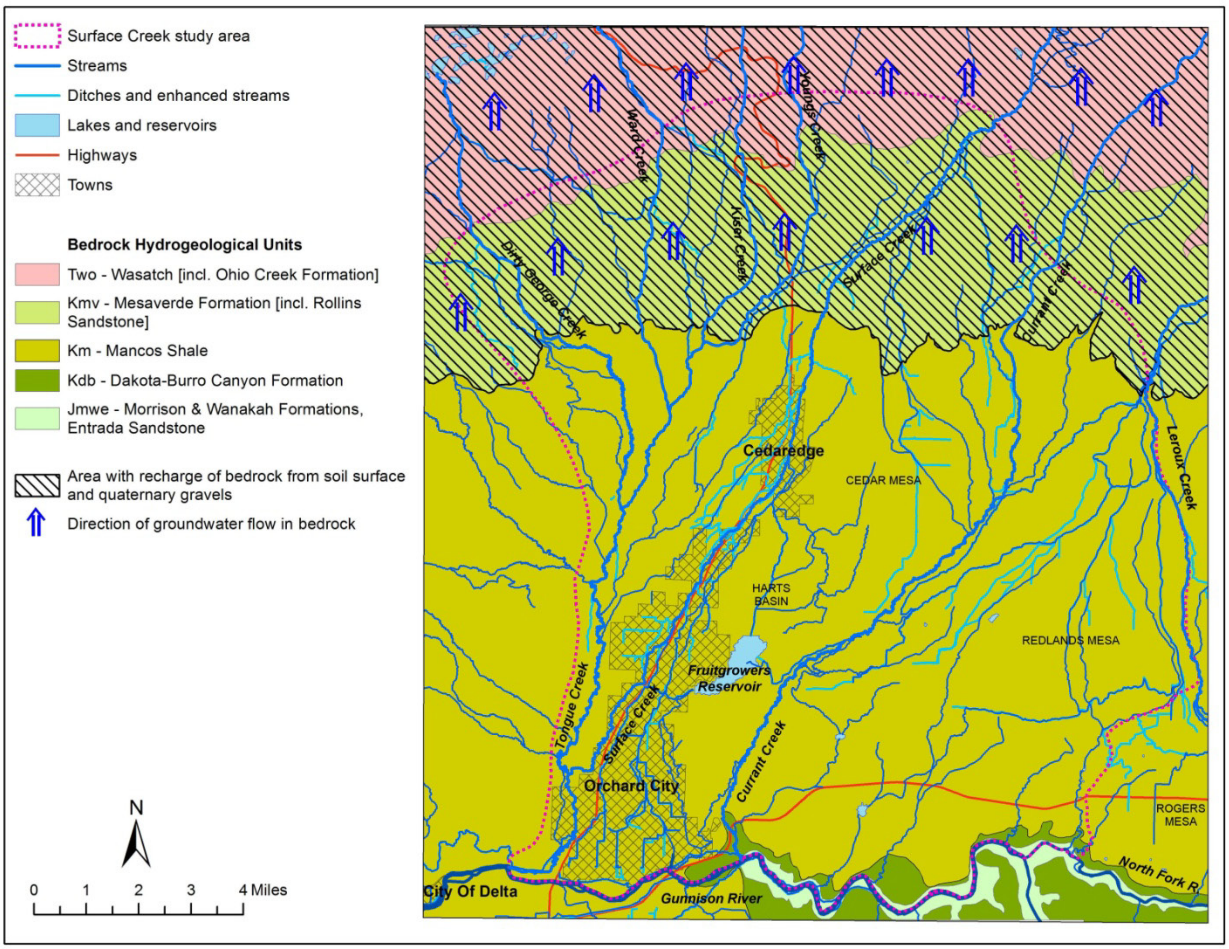

Figure 26. Plan View of the Conceptual Site Model of the Regional Bedrock Subsystems.

2.7 Anthropogenic Influences

Human activity in the SCV study area has affected both the surface and subsurface parts of the hydrologic systems. Past land use and human activity was mostly associated with agricultural production and reservoir construction and operation, and has resulted in removal of native vegetation, introduction of irrigation and high-ET (evapotranspiration) crops, construction of (often leaking) irrigation ditches, and the drilling of primarily domestic wells. This activity has resulted in long-term increase of water levels in local, shallow aquifers of the Quaternary materials (Qgf and Qs) both on top of the Mesa Top and Hillslope subsystems, such as the Redlands Mesa and Cedar Mesa Subsystems, and in the alluvium (Qal) and younger valley gravels (Qgy) of Currant Creek, Surface Creek, and the Tongue Creek (with tributaries) Subsystems.

2.7.1 Effects of Land Use Changes on Groundwater Systems

Traditionally, agricultural activities take place on the bottomlands and terraces of the valleys, while most grazing activities focus in a relative small area on the uplands. Agricultural production is supported by surface water irrigation, often delivered through an extensive conveyance system. The main irrigation method in use is flood irrigation, which tends to provide more water to the fields than can be consumed by vegetation. Excess water from irrigation results in infiltration to the water table and recharge of the groundwater system (*i.e.*, irrigation return flow). At this time, this part of Delta County is experiencing a shift from agricultural to nonagricultural land use, particularly around the towns of Cedaredge and Orchard City and in the Surface Creek Valley. This may lead to decreasing return flow from irrigation and subsequent reduced groundwater recharge, and to changes in groundwater quality due to fertilization practices or urban activities.

The SCV study area consists primarily of mesa top, hillslope, bottomland and terraces, limiting the irrigated areas to the top and lower portions of the subsystems (Figures 27). Here, there are a number of mostly unlined irrigation ditches that are excavated primarily in unconsolidated Quaternary deposits (Figures 8, 13, and 27). When carrying water, the ditches may leak, as evidenced by the phreatophytes often found alongside. The ditch system in the study area contains two types of ditches: 1) primary ditches, which carry water during most of the growing season; and 2) secondary ditches, which carry water only during an actual irrigation cycle. The water leaking from the ditches may be used by vegetation and discharged as evapotranspiration, or may recharge the underlying groundwater system, forming a local groundwater mound or divide. As most of the groundwater systems in the study area are local in nature, ditch leakage may contribute significantly to the local water balance, increase the water table elevation, and influence groundwater flow patterns.

As discussed previously, irrigation return flow and leaky irrigation ditches can be a significant recharge element in the local and regional groundwater balance. Taking irrigated fields out of production and re-allocating ditch-conveyed water reduces recharge of groundwater resulting in lowered water tables, reduced groundwater discharges to wetlands and streams, and decreased water supplies. Note that the change in irrigation acreage between 1993 and 2005 has been minimal (Figure 27).

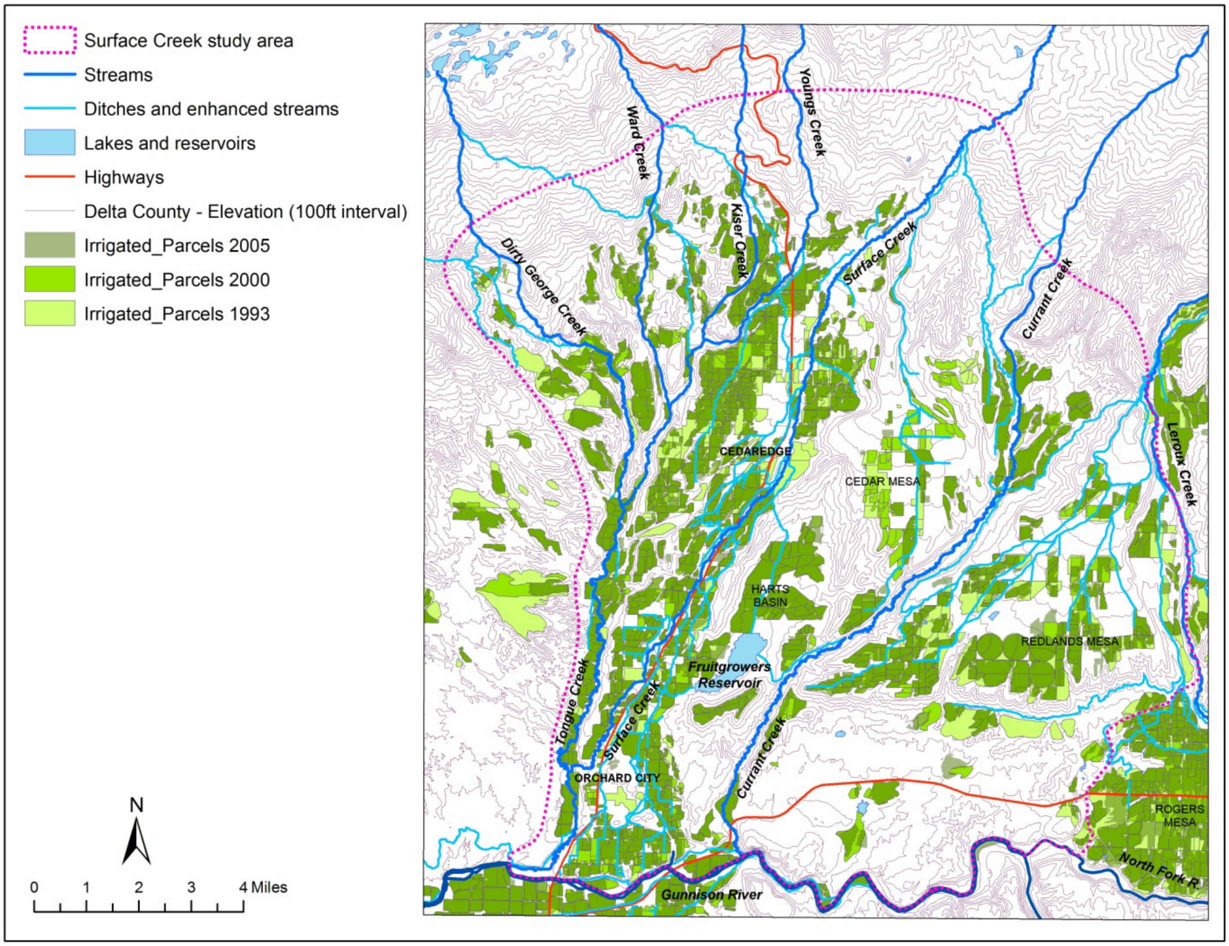

Figure 27. Anthropogenic Influences: Irrigated Areas and Irrigation Ditches in the SCV Area (Source: Delta County GIS, 2010; CDWR GIS, 2011).

Water wells are found throughout the SCV study area, primarily in the unconsolidated Quaternary deposits at the mesa tops and valley bottoms (Figure 28). Most of these wells serve domestic water supply needs, or the needs of municipalities located along Surface Creek (for example Cedaredge), and the effect on the groundwater system locally may be significant. However, if additional water is needed by urban or agricultural development, or water is displaced by oil and gas activities, for example, the compound effect on the groundwater system could be more significant in the future, resulting in a possible lowering of the water table, changes in flow direction, decreasing discharge to streams or increasing stream loss to groundwater, draining of wetlands, or even depletion of local aquifers.

2.7.2 Potential Effects of Oil and Gas on Hydrology

The hydrology of a natural groundwater hydrologic system may be altered by the construction and operation of proposed oil and gas wells. During drilling and fracking, the oil and gas operations may behave like a connection mechanism between the deep and shallow aquifers, mixing water of various chemistries from various bedrock and shallow aquifers. Depending on management strategies for produced water disposal and use, groundwater levels in the shallow unconsolidated systems may be altered with respect to the amount, velocity, storage, and direction of the local groundwater system and related regional groundwater levels and discharges. Changes to the natural groundwater system will likely have ecological, geo-hydrological, and, potentially, legal consequences. The effects of water disposal after fracking and oil and gas well development are not discussed in this report as relevant information on the planned oil and gas development and operations is not available at this time. These management strategies and their effects on the shallow and bedrock aquifer subsystems should be evaluated in more detail. Currently, there are no oil/gas lease parcels present in the SCV area.

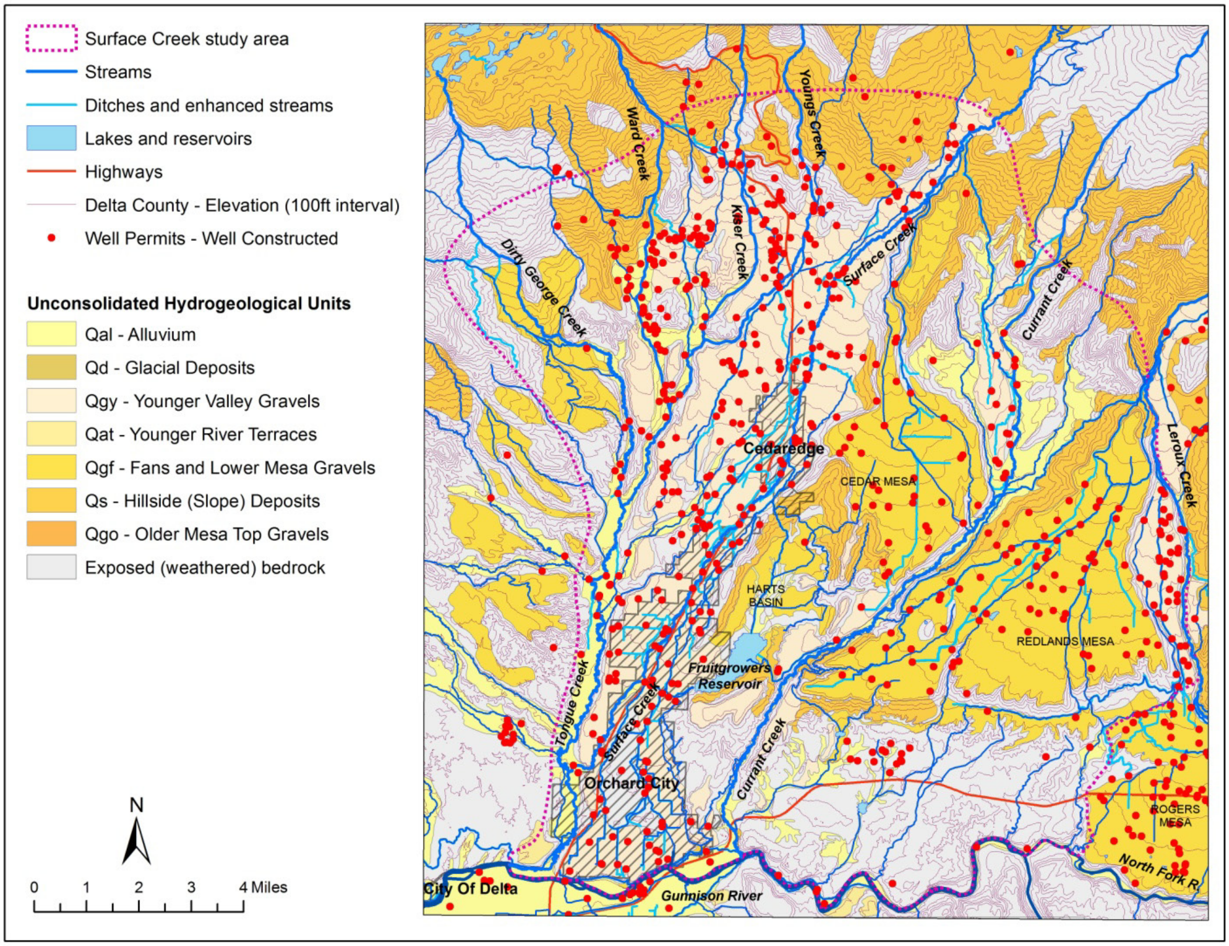

Figure 28. Anthropogenic Influences: Constructed Wells in the SCV Study Area (Source: CDWR GIS, 2014).

The Redlands Mesa and Cedar Mesa Subsystems are least likely to be affected by oil and gas operations because they are located in the recharge area and have a shallow groundwater flow system above the affected bedrock zones and have relatively few hydrostructures that could promote connectivity (Figures 13, 15, 18, and 20). However, the potential for groundwater discharge from the deeper bedrock to the shallow aquifers in the Valley Bottom subsystems, including Currant Creek, Surface Creek, and Tongue Creek, due to hydrostructures, may be affected by fracking or other oil and gas drilling activities (Figures 13, 15, 18, 20 and 24), which could affect the water supply and water quality. In addition, significant amounts of shallow aquifer water quality may be affected by the surface water runoff and groundwater recharge affected by drill site activities and water disposal.

The regional groundwater subsystem may be affected by the oil and gas operations, but these systems are not currently being explored for water supplies. However, the interconnectivity between these deeper systems and the shallow unconsolidated systems is hypothesized, but currently undetermined (Figures 14, 15, and 26).

3 GIS MAPS, LAYERS, DATABASES, AND DATA SOURCES

3.1 GIS and GIS Maps

Geographical information system (GIS)-based maps provide a flexible and efficient way to analyze and display spatial information. The strength of a GIS system is that data from various sources can be collected in local or remotely accessed databases, which can be easily maintained and updated. GIS maps support optimal analysis, specifically in hydrogeologic evaluations at different scales, geographic distribution densities, and different levels of accuracy and information value.

A GIS map consists of a series of layers, each containing a single or multiple topological features. These features can represent a variety of geographic items, such as rivers and lakes, roads, towns and cities, land use, land ownership, wells, etc. Selected features can be further described with associated attribute tables and linked to other types of information by their attribute tables or via their spatial location. At each step of a geographic analysis, individual features can be displayed, analyzed, and combined with other features via layers, and individual features interrogated with respect to their attributes. Switching scales, like enlarging (zooming in to) a particular detail or regionalizing (zooming out) to encompass a larger set of features can be accomplished at any time; the ability to selectively visualize (switch) layers, perform advanced searches, and use select and overlay capabilities, further enhances the utility of a GIS map.

The GIS maps resulting from this study allow for informed planning and management of groundwater resources in the SCV area. The database formats that have been used in this study include ESRI shape files, database tables, georeferenced images, Microsoft Excel files, and ESRI GRID files (for the digital elevation model [DEM], among others). The GIS map and database for the SCV study were prepared using ArcView™ version 8.3 and evaluated using Arc-Desktop™ version 10.2 (ESRI®, Redlands, California).

3.2 Use of GIS in the SCV Area Study

In this study, GIS has been used in support of the HESA described in Chapter 2 and in the preparation of report figures. In addition, the GIS maps and databases will provide a base for further studies of the hydrology and hydrogeology of SCV area, as well as other parts of Delta County. Three multi-layer GIS maps have been prepared for this study: 1) a map with hydrologic and hydrogeologic features of Delta County (Figure 29); 2) a map with hydrologic and hydrogeologic features of the SCV area (Figure 30); and 3) a map with hydrologic and hyrdogeologic features of the combined SCV (Surface Creek Valley), NFVT (North Fork Valley and Terraces, *Kolm and van der Heijde 2013*), and the Oak Mesa (*Kolm and van der Heijde 2012*) study areas referred to as the NFVSC area (Figure 31). The GIS maps consist of a number of layers representing various data types relevant to the assessment of the groundwater resources at user-specified locations. Below is a detailed description of the layers and the related data sources.

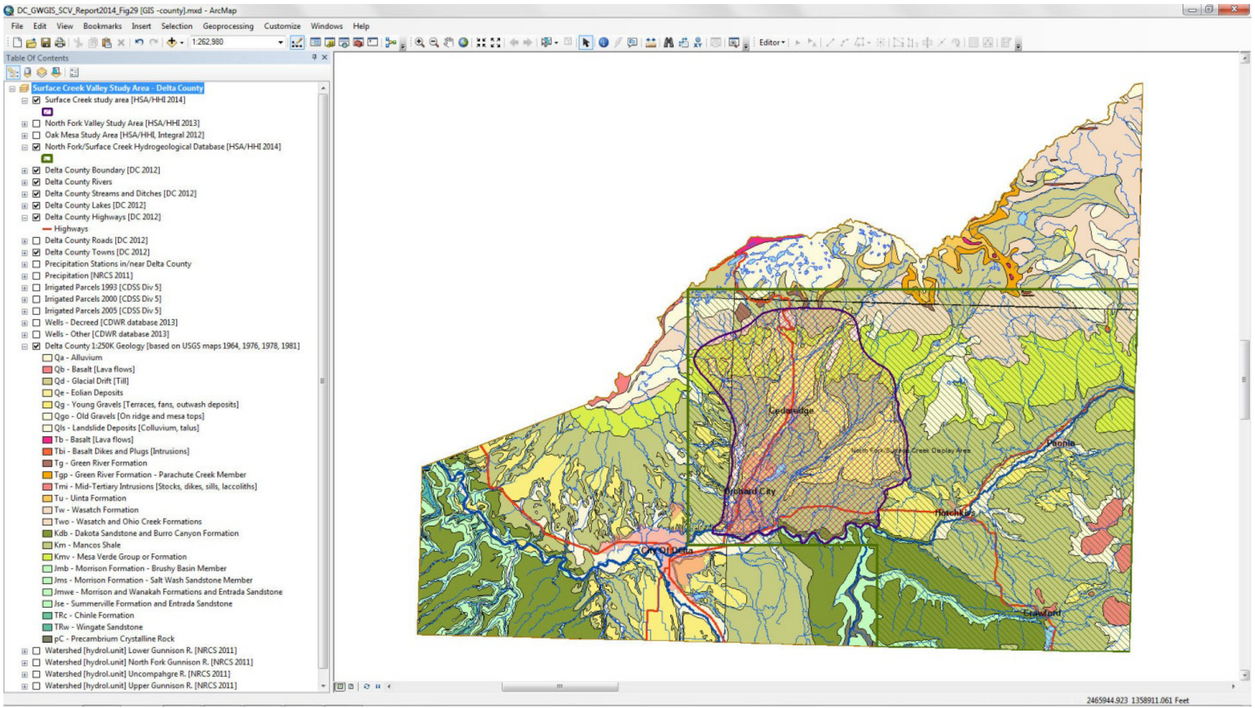

Figure 29. Delta County GIS Map Showing SCV Study Area, Area Covered by Hydrogeological Databases, Streams, Ditches and Roads on Top of County-wide Geology.
(The left display area is the table of contents [TOC] showing all available layers;
the right side of the window is the map display area showing the activated layers.)

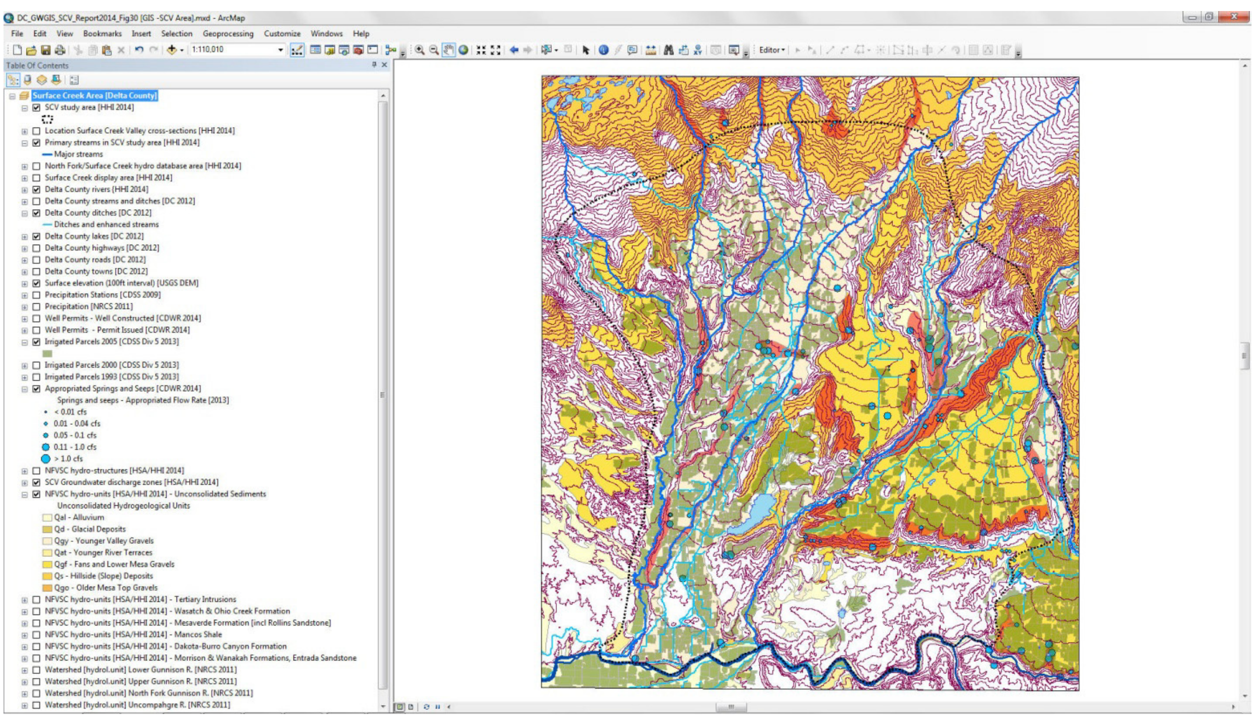

Figure 30. SCV GIS Map Showing Streams, Ditches and Irrigated Areas on Top of Unconsolidated Hydrogeologic Units and Groundwater Discharge Areas.
(The left display area is the TOC showing all available layers;
the right side of the window is the map display area showing the activated layers.)

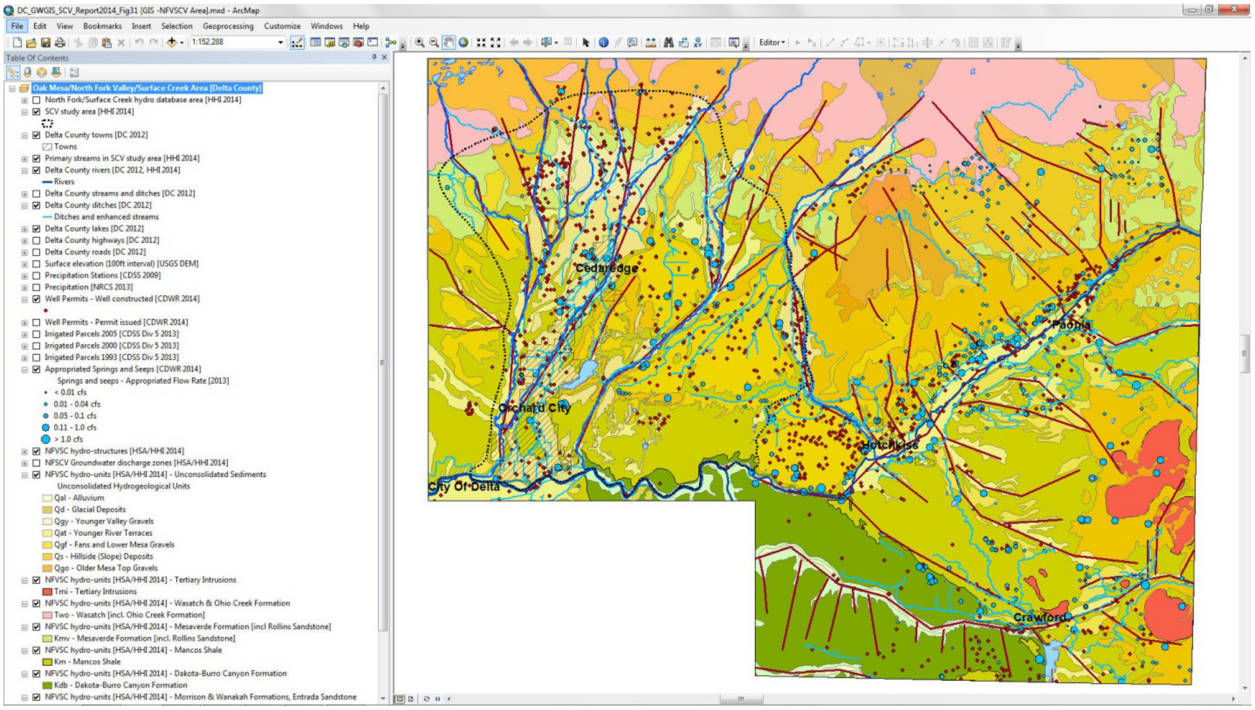

Figure 31. NFVSC GIS Map Showing Streams, Ditches and SCV Study Area on Top of Hydrogeologic Unconsolidated and Bedrock Units and Hydrogeologic Structures.

Enabling the *Table of Contents* (TOC; the left side of the display in Figures 29, 30 and 31) in ArcGIS provides information on the layers displayed in the *Map Display* area (the right side of the display in Figures 29, 30 and 31). The GIS layers of the three GIS maps contain three types of geographic information: 1) general geographic information (county border, roads, towns, DEM-elevations) used primarily for orientation purposes; 2) hydrologic information (including precipitation, watersheds, streams, lakes/ponds, irrigation ditches, and irrigated areas); and 3) hydrogeologic information (including hydrogeologic units, faults and hydro-structures, springs and wells). Most layers have been georeferenced with respect to State Plane, Colorado Central Zone, NAD83 (units of measure in feet), except for some public data obtained from state and federal sources.

3.3 GIS Map, Layers, and File Structure

Each line in the TOC is a GIS layer representing a set of features of the same type, such as streams, parcels, wells, etc. By clicking on a check box in the TOC, elements of the activated layer become visible in the map display area. A layer may consist of point values (*e.g.*, wells), line features (*e.g.*, roads, streams, ditches), and area features (*e.g.*, parcels, lakes, hydrogeologic units). Right-clicking on a layer in the TOC and selecting the *open attribute table* option, provides additional information on the layer, such as the names of particular features (Figure 32). This additional information can be used to label the features in the map display area.

The order of the layers in the GIS maps may be changed, affecting which layer(s) are in the foreground in the map and which layers are in the background. When enabled, a layer is shown on top of the layer listed below it in the TOC. When this layer is opaque, the layer beneath it is not visible. Some layers are (partially) transparent, others are opaque, dependent on the type of information they display and the use in the assessment procedure. Layer transparency/opaqueness can be changed by the user using the layer properties option under the display tab. The order of the layers can be changed by the user by dragging a layer to the desired location in the TOC.

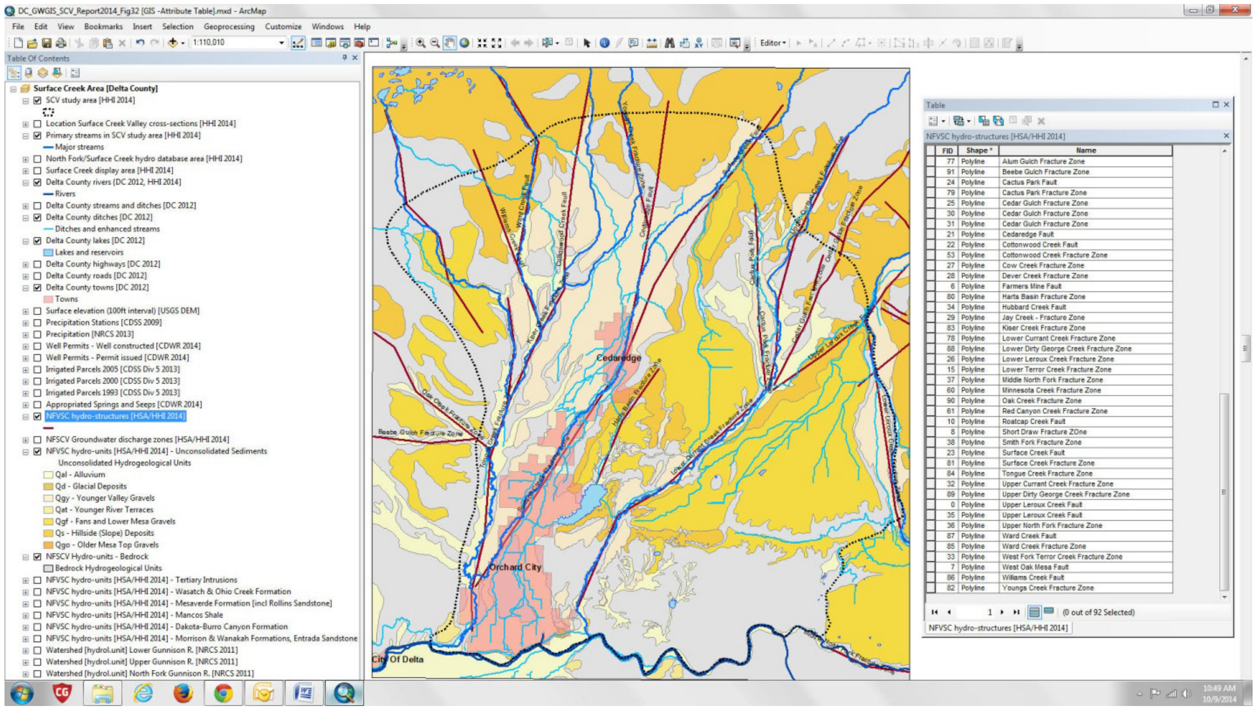

Figure 32. GIS Map Showing the Attribute Table for the Hydrogeologic Structures (Hydrostructures) Layer in the SCV Area *(right side of figure)*.

The map is designed to show relevant labels (text) for most of the layers based on the contents of one of the fields in the attribute table, such as stream name, well number, etc. When zooming in on a particular area of the map, additional information of a selected layer can be displayed by activating the *Label* feature. This can be done by right-clicking the layer and selecting *Label Feature*. The label feature can be set by right-clicking the layer, selecting *Properties*, clicking the *Label* tab, and selecting the appropriate field of the database table. Database information regarding a particular feature on the map can also be obtained by using the (*Identify*) option from the *Tools* toolbar, clicking on the feature of interest, and selecting the appropriate layer in the popup *Identify Results* window.

3.4 Data Sources and Databases

Delta County and study area GIS maps retrieve various files included in five relative-path subdirectories: 1) CDWR_CDSS; 2) Delta_County; 3) HHI; 4) NRCS; and 5) USGS_DEM. The directories reflect the various data sources used for the three GIS maps introduced in the previous section. Selection of the relative-path option in the GIS program provides for straightforward portability between computers. Note that layers that refer to a state-wide data set (such as the NRCS precipitation file), or a multi-county data set (such as the CDSS irrigated areas files), have been clipped on the maps to show only the Delta County, NFVSC, or SCV area coverage.

The *CDWR_CDSS* subdirectory contains seven sets of GIS files and databases downloaded from Colorado Division of Water resources (CDWR) water rights and well permits databases and from the Colorado Decision Support System (CDSS), which is managed by the Colorado Water Conservation Board and the Colorado Division of Water Resources (CDWR). These file sets are 1) irrigated areas in CDWR Division 4 on the Western Slope as of 1993 (*Irrigated_Parcels_1993* files); 2) irrigated areas in CDWR Division 4 on the Western Slope as of 2000 (*Irrigated_Parcels_2000* files); 3) irrigated areas in CDWR Division 4 on the Western Slope as of 2005 (*Irrigated_Parcels_2005* files); 4) permitted wells that have been completed (*WellPermits_WellConstructed* files); 5)permitted wells that have not yet been drilled (*WellPermits_PermitIssued* files); 6) appropriated springs and seeps (*NorthForkSurfaceCr_Springs* files); and 7) precipitation stations in Colorado (*co_precipstations* files). The well, spring and irrigation data have been downloaded in 2013 and 2014. The irrigated areas data sets provide a single year snapshot of the irrigated lands and crop types of the western slope of Colorado. In the GIS maps, the 2000 data layer lies on top of the 1993 data layer, and the 2005 data layer lies on top of the 1993 and 2000 data layers, showing the irrigated acreage taken out between 1993 and 2000 and between 2000 and 2005. The CDSS files can be downloaded from: *http://water.state.co.us/DataMaps/Pages/default.aspx#onlinedata.*The well records can be accessed at: *http://www.dwr.state.co.us/wellpermitsearch/,* and the springs and seeps records at: *http://cdss.state.co.us/onlineTools/Pages/WaterRights.aspx.* More details about the springs and seeps layer can be found in Appendix 1 of Kolm and Van der Heijde (2013).

The *Delta_County* subdirectory contains selected files received from the Delta County GIS department in 2012. Coverages used in this project include county boundary, highways, roads, streams and ditches, lakes, irrigation ditches (and enhanced streams), water planning areas, and towns. The ditch data provided by the county does not distinguish between primary and secondary ditches. Additional field verification is needed to assess the hydrologic importance of individual ditches. It should be noted that the GIS-based aerial photography provided by the county has been used, in conjunction with GIS-based topographic images obtained from the NRCS data portal and Google™ Earth imagery, to remotely assess topography, vegetation and hydrology in preparation of this report.

The *HHI* subdirectory contains the databases produced for this project by Heath Hydrology, Inc. It contains various hydrogeology files, including: *NorthFork_SurfaceCreek_Hydrogeol_xxx*, *NorthFork_SurfaceCreek_Hydrostructures*, and *DeltaCounty_Geology*; and files related to the location of current and previous study areas: *SurfaceCreek_StudyArea*, *NorthForkValley_ StudyArea*, *OakMesa_StudyArea*,and *NorthFork_SurfaceCreek_DisplayArea*). The *SCV_SelectedStreams* files were created to separately show the more important streams in the SCV study area and are based on Delta County's stream layer. The hydrogeology layers resulted from digitizing and evaluating the 1:24.000 scale geological map of the Orchard City quad (*Noe and Zawaski 2013*), 1:48,000 scale geologic maps of the Cedaredge and Hotchkiss areas (*Hail, 1972a, 1972b*), and the 1:100,000 scale geologic map of the Paonia and Gunnison area (*Ellis and Others, 1987*), and combining and editing the GIS versions (*Day and Others, 1999*) of the Leadville, Montrose, Grand Junction and Moab 1^o x 2^o quadrangle geologic maps (scale 1:250,000) (*Tweto and Others, 1976; Tweto and Others, 1978; Whitney, 1981; Williams, 1964)*. The NFVSC hydro-structures layer is in part based on the 1:100,000 scale geologic map of the Paonia and Gunnison area (*Ellis and Others, 1987*), and enhanced through analysis of geomorphic features, including lineaments, by the project team.

There are seven GIS layers and databases for the hydogeologic units in the SCV (and NFVSC) area (*i.e.*, "hydro units" for short) (Figures 13, 14, 30 and 31): 1) a layer showing the Quaternary unconsolidated deposits grouped by their hydrogeological characteristics (*NFVSC hydro-units [HSA/HHI 2014] - Unconsolidated Sediments*); and 2) six layers each showing the extent of an individual bedrock hydrogeologic unit (*NFVSC hydro-units [HSA/HHI 2014] – Tertiary Intrusions, NFVSC hydro-units [HSA/HHI 2014] - Wasatch and Ohio Creek Formation, NFVSC hydro-units [HSA/HHI 2014] - Mesaverde Formation [incl. Rollins Sandstone], NFVSC hydro-units [HSA/HHI 2014] - Mancos Shale, NFVSC hydro-units [HSA/HHI 2014] - Dakota-Burro Canyon,* and *NFVSC hydro-units [HSA/HHI 2014] – Morrison & Wanakah Formations, Entrada Sandstone*). When all six bedrock layers are activated, the GIS map shows top bedrock (see Figure 14).

The *NRCS* subdirectory contains state-wide averaged annual precipitation data for the period 1961–1990 obtained from the NRCS (*precip_a_co* files). These data have been developed from the NWS precipitation data using PRISM (Parameter elevation Regression on Independent Slopes Model), which utilizes a rule-based combination of point measurements and a DEM and includes consideration of topographic facets *(Daly and Johnson, 1999).* The *NRCS* subdirectory also includes files for the watersheds in the county (*wbdhu12_a_14020002 - 06*). The NRCS data can be downloaded from: *http://datagateway.nrcs.usda.gov/GatewayHome.html*.

The *USGS_DEM* subdirectory contains the raster-based DEM and the 100ft elevation contours for Delta County. In the database, surface elevations are stored in meters; however, in the TOC of the GIS maps, the elevations are given in feet for display purposes. The USGS DEM was downloaded from the NRCS Data Gateway portal in May 2012 and is based on the USGS version published in April 2012.

4 SUMMARY AND CONCLUSIONS

A Hydrologic and Environmental Systems Analysis (HESA) of the groundwater system of the Surface Creek Valley area (SCV) in Delta County, Colorado, and the development of supporting GIS databases and maps of hydrogeologic and hydrologic characteristics, have been completed to provide support for planning, zoning, and other decision-making tasks of county staff, including those related to protection of groundwater resources for use as public or communal water supplies. This study consisted of the following tasks: 1) conduct a comprehensive HESA and formulate relevant conceptual hydrologic models to provide the physical framework for assessment of potential impacts of anthropogenic system modifications on groundwater resources and interrelated surface water resources; 2) develop a consistent and practical hydrogeologic nomenclature that can be expanded to county-wide use; 3) digitize existing geologic maps and convert them to hydrogeologic system layers and databases in the GIS, including layers showing hydrogeologic units and characteristic stacks of such units, and hydrostructures; and 4) adapt additional hydrological and other GIS maps and databases needed to evaluate the groundwater resources in the county; these databases will contain data from various public domain sources.

The HESA analysis showed that there are two significant groups of hydrogeologic units in the SCV study area: 1) Quaternary unconsolidated clastic materials, which are predominantly glacial-fluvial outwash plains and terrace gravels (older mesa top gravels and glacial drift), hillside (slope) deposits, alluvial fans and bajadas (coalescing fans) and lower mesa gravels, younger valley gravels and river terraces, and alluvial valley bottom deposits; overlying 2) Tertiary and Cretaceous bedrock, including the following potentially water-bearing units: Tertiary Wasatch Formation including the Ohio Creek Formation (Two); Cretaceous Mesaverde Formation (Kmv), including the Barren, and Upper and Lower Coal Bearing members (Kmv), as well as the Rollins Sandstone member (Kmvr); and the Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb). The Mancos Shale unit (Km) may act as a thick, poorly transmissive confining layer.

The Quaternary unconsolidated clastic units (Qal, Qgy, Qat, Qs, Qd, Qgf, and Qgo) are locally heterogeneous, with predominantly a mix of coarser and finer materials in the older alluvial deposits, and finer materials in the younger deposits. These deposits, which are moderately to highly permeable, are recharged by infiltration from precipitation that is non-uniformly distributed due to the slope steepness, slope aspect, and to position in the landscape, and by the incidental leaky irrigation ditch and irrigation return flow. The unconsolidated units are variably to fully saturated based on spatial location and seasonal precipitation events. There may be lateral and vertical groundwater flow connection between the unconsolidated materials and the Tertiary and Cretaceous sedimentary units in the underlying bedrock formations.

Three broad hydrostructure sets occur in the SCV area: 1) the northeast-trending faults and fractures that parallel the Currant and Surface Creek fault zones and associated en-echelon faults and fracture zones to the east (for example, Upper Leroux Creek fault zone and the North Fork Valley lineament); 2) the north-south-trending Tongue Creek lineament and fault zone, which parallels the Lower Leroux Creek fault zone; and 3) the east-west trending Gunnison River lineament.

The northeast-trending and north-south trending faults and fracture zones are relatively young, as the geomorphic systems of Currant Creek and Surface Creek are responding with considerable downcutting, allowing for partial to full penetration of the unconsolidated hydrogeologic unit aquifers. It is hypothesized that these faults/fracture zones/lineaments are “open” and function like French drains. Groundwater moves laterally down valley and vertically downward along the northeast-trending fault and fracture zone planes, and may move vertically up along the fault and fractures plane near the lower reaches of the various drainages.

Based on the presence and orientation of various hydrogeologic and hydrostructural units, hydrography and topography, three CSMs observed in the SCV study area: 1) Mesa Top and Hillslope Shallow Aquifer Subsystems; 2) Valley Bottom Shallow Aquifer Subsystems; and 3) Regional Bedrock Aquifer Subsystems are discussed. The Mesa Top and Hillslope Subsystems, including the Redlands Mesa Subsystem and the Cedar Mesa\Fruitgrowers Reservoir Subsystem, and Valley Bottom Shallow Aquifer Subsystems, including the Currant Creek, Surface Creek, and Tongue Creek (with associated tributaries) subsystems, in the SCV area are dominated by the Quaternary unconsolidated materials. Specifically, the shallow groundwater on Redlands Mesa and Cedar Mesa is dominated by the Quaternary unconsolidated materials (Qgf and Qs), which receive natural recharge by infiltration of precipitation (snow and rain; Rp), and major recharge from leaky irrigation ditches (Rd) and reservoirs locally, and return flow from flood irrigation locally (Ri). The unlined ditches are “line” groundwater recharge sources (Rd) at the top of the irrigated field areas, and water leaks from the ditches into all of the connected gravels underneath and downgradient. The return flow from flood irrigation are “area” groundwater recharge sources (Ri) located downgradient and along the nearby irrigation ditches.

Groundwater flow on top of the gravel-capped Redlands Mesa and Cedar Mesa then moves with topography or subsurface paleo-topography to discharge into springs at the gravel/Mancos Shale interface along the incised drainages that bound the mesas (Dsp), discharge directly out the front of the mesa as seeps or springs (Dsp) at the gravel/Mancos Shale interface, or discharge into the hillslope slope and mudslide deposits (Qs) causing further mass wasting activity. Given the “new” water that has recharged the aquifer, springs may have been developed and claimed as being “new” springs. There is also groundwater discharge from the gravels locally by groundwater wells (Dw) and by phreatophytes (Dp). The shallow groundwater subsystems in this Mesa Top and Hillslope area have little connection to the local bedrock or the regional groundwater systems, or to nearby alluvial systems, such as Leroux Creek, Currant Creek, or Surface Creek.

The shallow groundwater flow in the Current Creek, Surface Creek, and Tongue Creek Valley Bottom subsystems is dominated by the Quaternary unconsolidated materials, and include modern alluvium (Qal) and younger valley gravels (Qgy). Specifically, the shallow groundwater in the Currant Creek and Tongue Creek subsystems is dominated by the Quaternary alluvium (Qal), which receives natural recharge by infiltration of precipitation (snow and rain; Rp) and losing streams (Rs); input from hillside (slope) deposits derived from the glacial gravels (Rsd); and additional recharge from leaky irrigation ditches (Rd); and return flow from irrigation locally (Ri). Water leaking from the unlined ditches and irrigated areas enter into the (connected) gravels underneath and flows downgradient towards the discharge zones (streams, springs and seeps, and wetlands.

Groundwater flow in the Currant Creek and Tongue Creek alluvium moves in the same direction as the streams with various stream reaches being gaining (Ds) or losing (Rs) depending on subsurface topography, saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events. Springs are observed at the Qal/Mancos Shale (Km) interface along the stream bed or due to the thinning of the Qal/Mancos Shale (Km) interface beneath the stream bed, or where mass wasting deposits (landslides) connect the gravels of the drainage divide (Qgy) with local alluvium (Qal). There is also groundwater discharge from the alluvium locally by groundwater wells (Dw) and by phreatophytes (Dp). The shallow groundwater in the Currant Creek and middle and lower Tongue Creek subsystems would normally have little connection to the local bedrock or the regional groundwater systems, given the Mancos Shale bedrock. However, underlying the Currant Creek and Tongue Creek alluvium is the Lower Currant Creek Lineament – Fracture Zone, the Cedar Gulch lineament, the Upper Currant Creek Lineament, the Cactus Park Fault Zone Lower Tongue Creek Lineament – Fracture Zone, the Upper Dirty George Creek Lineament-Fracture Zone, the Oak Creek Lineament – Fracture Zone, the Ward Creek Lineament-Fault Zone, and the Cottonwood Creek Fault Zone. These areas of hydrostructures are hypothesized to be open conduits, where the faulted and fractured bedrock may combine with the alluvium (Qal) to form a French Drain affect resulting in increased groundwater flow and storage, and connectivity to deeper hydrologic. This could result in decreased water quality either naturally (Mancos Shale water has higher TDS, metals) or due to human activities, such as fracking or waste disposal activities.

By comparison, the Surface Creek Valley Bottom subsystem extends from the top of Grand Mesa and west of Cedar Mesa through the towns of Cedaredge and Orchard City ending at the Gunnison River. The Surface Creek subsystem is dominated by the Quaternary unconsolidated younger gravels (Qgy), which receive natural recharge by infiltration of precipitation (snow and rain; Rp) system-wide, by input from adjacent uplands to gravels (Ru) and by hillside (slope) deposits derived from the glacial gravels (Rsd) in the upper reaches of the subsystem, and major recharge from leaky irrigation ditches originating from upper and middle Surface Creek and upper Ward Creek (Rd); and return flow from irrigation throughout the middle and lower part of the subsystem (Ri). Water leaking from the unlined ditches and irrigated areas enter into the (connected) gravels underneath and flows downgradient towards the discharge zones (streams, springs and seeps, and wetlands).

Groundwater flow in the Surface Creek younger valley gravels (Qgy) moves in the same direction as Surface Creek with various stream reaches being gaining (Ds) or losing (Rs) depending on subsurface topography, saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events. Generally, the upper part of Surface Creek is gaining when flowing through the hillside (slope) gravels (Qs) as these gravels are discharging groundwater into the stream (Ds). However, at depth, the Surface Creek hillside (slope) gravels and younger valley gravels (Qgy) are recharging the Wasatch (Two) and Mesa Verde (Kmv) bedrock aquifers (Rgb).

As Surface Creek crosses into the younger valley gravels (Qgy) underlain by the Mancos Shale (Km), the surface flow decreases as groundwater recharge occurs to the gravels (Rs). This function is reversed above Cedaredge and Surface Creek becomes a gaining stream due to an increase in groundwater discharge derived from leaky irrigation ditches and return flow from irrigation. Springs are observed near Cedaredge due to the thinning of the Qgy at the Qgy/Mancos Shale (Km) interface beneath the stream bed . There is also groundwater discharge from the gravels locally by groundwater wells (Dw) and by phreatophytes (Dp).

The shallow groundwater in the Surface Creek subsystem would normally have little connection to the local bedrock or the regional groundwater systems in the central and southern part of the subsystem, given the Mancos Shale bedrock. However, underlying the Surface Creek gravels is the Surface Creek Lineament – Fracture Zone. This hydrostructure is hypothesized to be an open conduit, where the faulted and fractured bedrock may combine with the younger valley gravels (Qgy) to form a French Drain affect resulting in increased groundwater flow and storage, and connectivity to deeper hydrologic systems. This could result in decreased water quality either naturally (Mancos Shale water has higher TDS, metals) or due to human activities, such as fracking or waste disposal activities.

The regional hydrogeologic units in the SCV study area, discussed in Section 2.4, are the Tertiary and Cretaceous bedrock units, including the following potentially water-bearing units: Tertiary Wasatch Formation including the Ohio Creek Formation (Two); Cretaceous Mesaverde Formation (Kmv), including the Barren, and Upper and Lower Coal Bearing members (Kmv), as well as the Rollins Sandstone member (Kmvr); and the Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb). The general aspects of the bedrock hydrogeology and hydrostructures are discussed in Section 2.5. The bedrock units are variably to fully saturated based on location and proximity to recharge area. Groundwater recharge by infiltration of precipitation (snow and rain) and by losing streams, for example Currant Creek and Surface Creek, occurs through the Hillside (slope) deposits (Qs) and younger valley gravels (Qgy) in the outcrop area (Rgb), and groundwater flows laterally to the north along the dip of the bedrock, where it becomes incorporated into the regional groundwater flow system. The groundwater flow direction in the regional bedrock systems is from south to north beneath the SCV Study Area and Grand Mesa. This flow direction is away from human activities and Delta County in general.

Human activity in the SCV study area has affected both the surface and subsurface parts of the hydrologic systems. Past land use and human activity was mostly associated with agricultural production and reservoir construction and operation, and has resulted in removal of native vegetation, introduction of irrigation and high-ET (evapotranspiration) crops, construction of (often leaking) irrigation ditches, and the drilling of primarily domestic wells. This activity has resulted in long-term increase of water levels in local, shallow aquifers of the Quaternary materials (Qgf and Qs) both on top of the Mesa Top and Hillslope subsystems, such as the Redlands Mesa and Cedar Mesa Subsystems, and in the alluvium (Qal) and younger valley gravels (Qgy) of Currant Creek, Surface Creek, and the Tongue Creek (with tributaries) Subsystems. At this time, this part of Delta County is not experiencing a shift from agricultural to nonagricultural land use at the same rate as many other areas of the western United States.

The hydrology of a natural groundwater hydrologic system may be altered by the construction and operation of proposed oil and gas wells. During drilling and fracking, the oil and gas operations may behave like a connection mechanism between the deep and shallow aquifers, mixing water of various chemistries from various bedrock and shallow aquifers. Depending on management strategies for produced water disposal and use, groundwater levels in the shallow unconsolidated systems may be altered with respect to the amount, velocity, storage, and direction of the local groundwater system and related regional groundwater levels and discharges. These management strategies and their effects on the shallow and bedrock aquifer subsystems should be evaluated in more detail.

The Redlands Mesa and Cedar Mesa Subsystems are least likely to be affected by oil and gas operations because they are located in the recharge area and have a shallow groundwater flow system above the affected bedrock zones and have relatively few hydrostructures that could promote connectivity. However, the potential for groundwater discharge from the deeper bedrock to the shallow aquifers in the Valley Bottom subsystems, including Currant Creek, Surface Creek, and Tongue Creek, due to hydrostructures, may be affected by fracking or other oil and gas drilling activities, which could affect the water supply and water quality. In addition, significant amounts of shallow aquifer water quality may be affected by the surface water runoff and groundwater recharge affected by drill site activities and water disposal.

The GIS maps resulting from this study provide for use in planning and management of groundwater resources in the SCV area. The database formats that have been used in this study include ESRI shape files, database tables, georeferenced images, and ESRI GRID files (for the DEM, among others). The GIS map and database for the NFVT study were prepared using ArcView™ version 8.3 and evaluated using Arc-Desktop™ version 10.2 (ESRI®, Redlands, California).

Three multi-layer GIS maps have been prepared for this study: 1) a map with hydrologic and hydrogeologic features of Delta County; 2) a map with hydrologic and hydrogeologic features of the SCV area; and 3) a map with hydrologic and hyrdogeologic features of the combined SCV (Surface Creek Valley), NFVT (North Fork Valley and Terraces), and the Oak Mesa study areas referred to as the NFVSC area. The GIS maps consist of a number of layers representing various data types relevant to the assessment of groundwater resources at user-specified locations. The GIS layers of the Delta County, SCV and NFVSC maps contain three types of geographic information: 1) general geographic information (county border, roads, towns, imagery) used primarily for orientation purposes; 2) hydrologic information (including precipitation, watersheds, streams, lakes/ponds, irrigation ditches, and irrigated areas); and 3) hydrogeologic information (including hydrogeologic units, faults and hydrostructures, recharge and discharge areas, springs/seeps, and wells. The hydrogeological databases prepared for the SCV area include all data collected and prepared for the previous studies (Oak Mesa and North Fork Valley and Terraces).

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