GROUNDWATER SYSTEMS IN DELTA COUNTY, COLORADO: OAK MESA AREA

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

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Front Page: West Reservoir on Oak Mesa Facing East (June 2012)

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1 INTRODUCTION

Under an agreement with Delta County, Colorado, Integral Consulting Inc. (Integral) of Louisville, Colorado, was tasked to perform a groundwater study of the Oak Mesa area of Delta County, Colorado (Figure 1). This study included 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.

This study consisted of the following tasks:

1. Conduct a comprehensive HESA and formulate relevant conceptual hydrologic models to provide the physical framework for assessments 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.

These tasks were completed in a manner that when future studies of adjacent sections of the county are conducted, there will be a continuous and consistent hydrogeological and hydrological GIS coverage.

It should be noted that that the reported HESA results and the GIS maps and databases will not obviate the need for additional hydrogeologic analysis on a site-specific basis in any project requiring due diligence, such as water right assessments, geotechnical studies, or environmental or water resources impact evaluations.

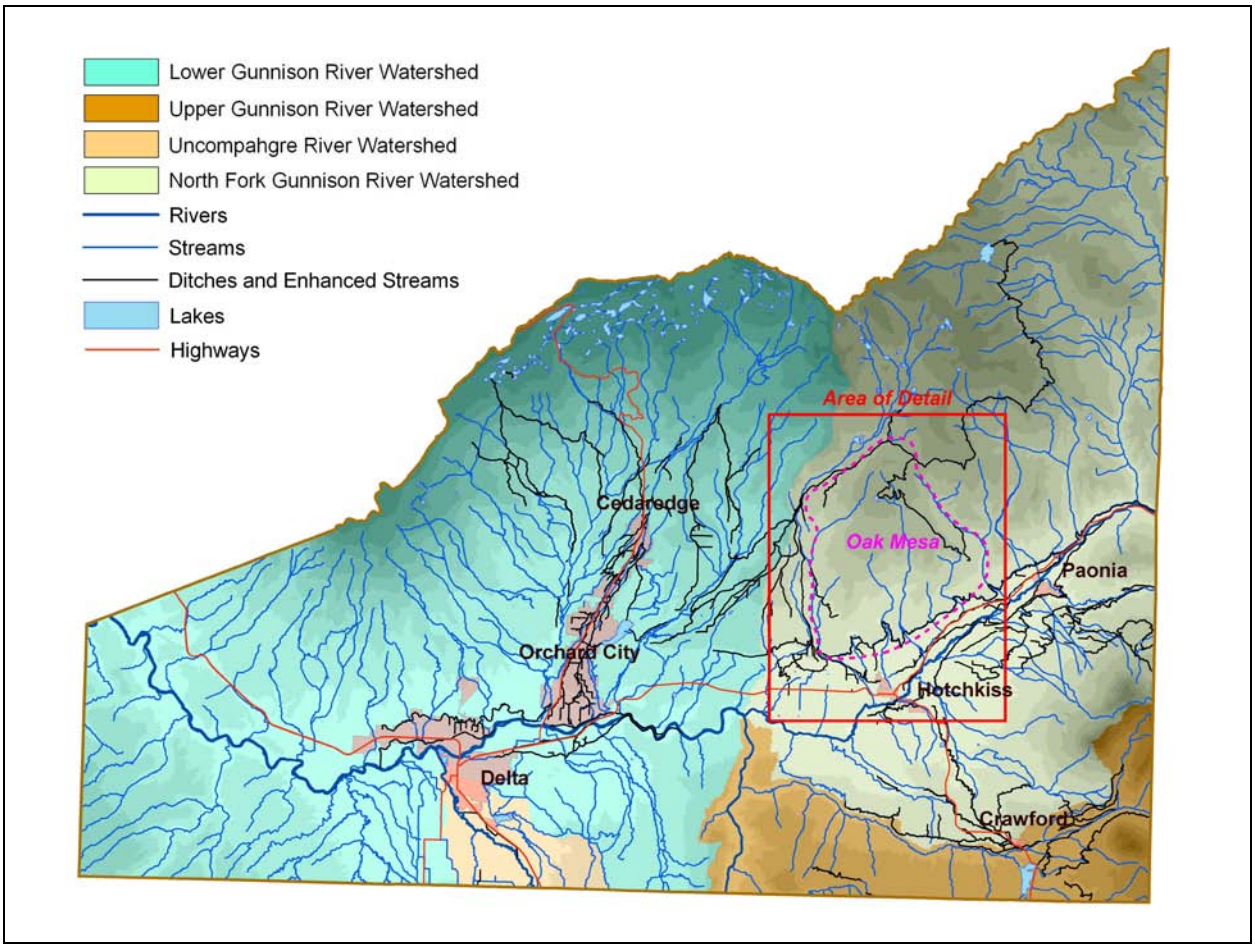

Figure 1. Location of the Oak Mesa Area, Delta County, Colorado.

2 DEVELOPMENT OF CONCEPTUAL SITE MODELS OF THE OAK MESA 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. The CSM of the Oak Mesa 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 Oak Mesa 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. A brief discussion of potential modification of natural flow patterns and impacts on water budgets from dewatering by a proposed underground coal mine 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, causing local and regional rain shadows. From the relevant weather stations of the National Weather Service (NWS) Cooperative Network near the study area, three have been selected as representative: Bonham Reservoir (station 050825) located in Mesa County on northern slope of Grand Mesa near the top; Cedaredge (station 051440) located midway down the south side of Grand Mesa; and Delta (station 052192) located in the Gunnison River Valley. Figures 2, 3, and 4 summarize 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 these stations. Figure 5 shows a comparison between the average total monthly precipitation at the three stations. 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 from about 45 inches annually at the top of Grand Mesa to about 12 inches annually near Hotchkiss. Tables showing monthly long-term averages for temperature, precipitation, snowfall and snow depth are included in Appendix 1.

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 Oak Mesa, the topographically higher terrains are subhumid and cool. This northern part of the hydrologic system, represented by Bonham Reservoir, Colorado, has excellent recharge potential, both from rainfall in the spring, summer, and autumn months, and from the melting of snowpack throughout the winter and early spring. Similarly, the midlevel parts of the hydrologic system, represented by Cedaredge, Colorado, have good, but lower, recharge potential, both from rainfall in the spring, summer, and autumn months, and from the melting of snowpack throughout the winter and spring. By comparison, the lower parts of the hydrologic system, represented by Delta, Colorado, are semi-arid and have minimal recharge potential, mostly from rain and snow throughout the winter and spring. The summer and autumn months are characterized by high evaporation rates and are too desiccated for significant groundwater infiltration and recharge. Thus, most of the recharge in the near-surface aquifers occurs during a very short period of time in the early spring. It should be noted that the entire study area has groundwater recharge potential, with even the driest areas probably receiving about 1 inch of recharge annually. This is important when considering the ultimate groundwater system flow directions and areas of groundwater recharge.

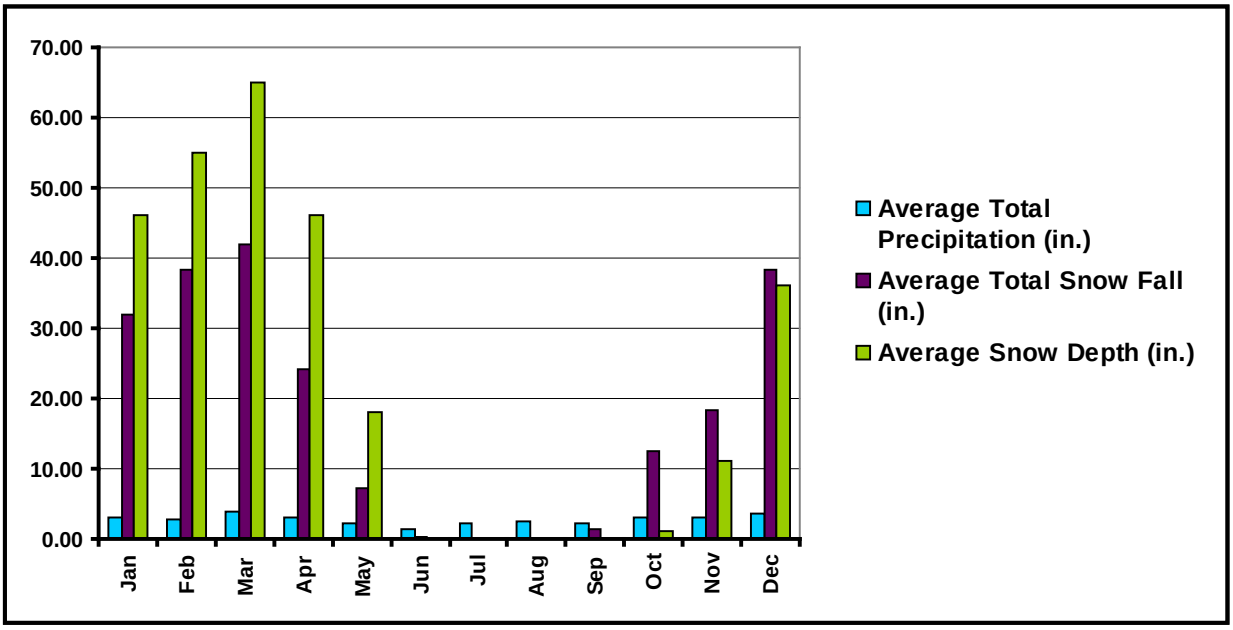

Figure 2. Average Total Monthly Precipitation, Snow Fall and Snow Depth for Bonham Reservoir (station 050825), Colorado for Period 7/1/1963 to 5/31/2012
(Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

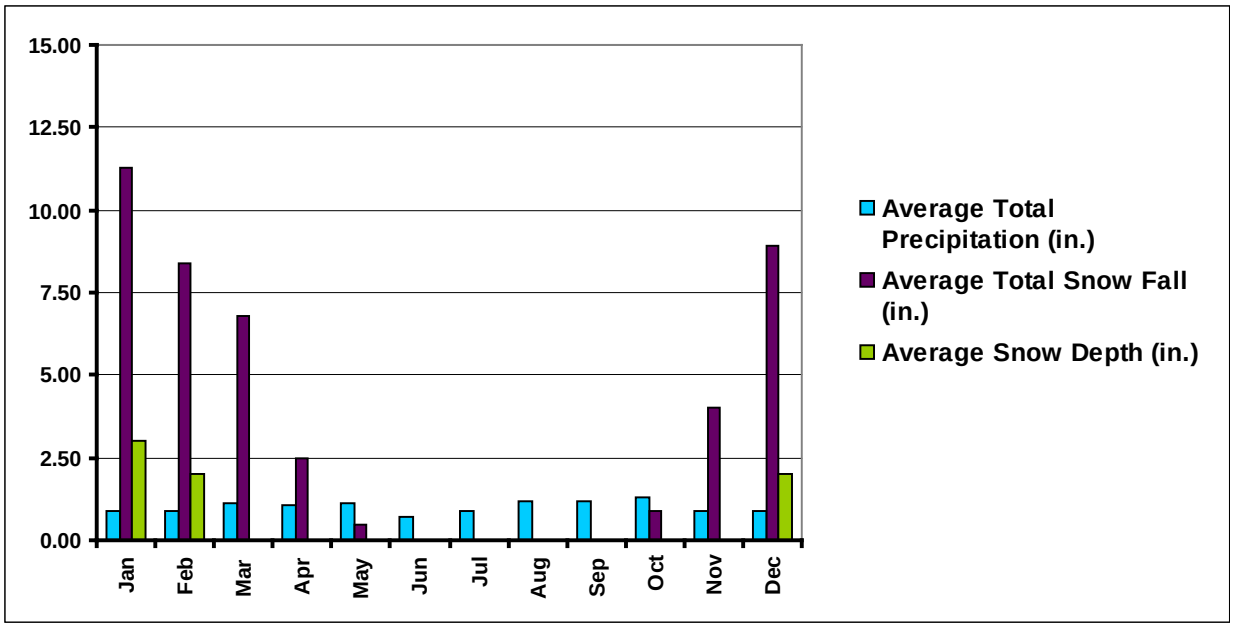

Figure 3. Average Total Monthly Precipitation, Snow Fall and Snow Depth for Cedaredge (station 051440), Colorado for Period 1/1/1898 to 5/31/1994
(Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

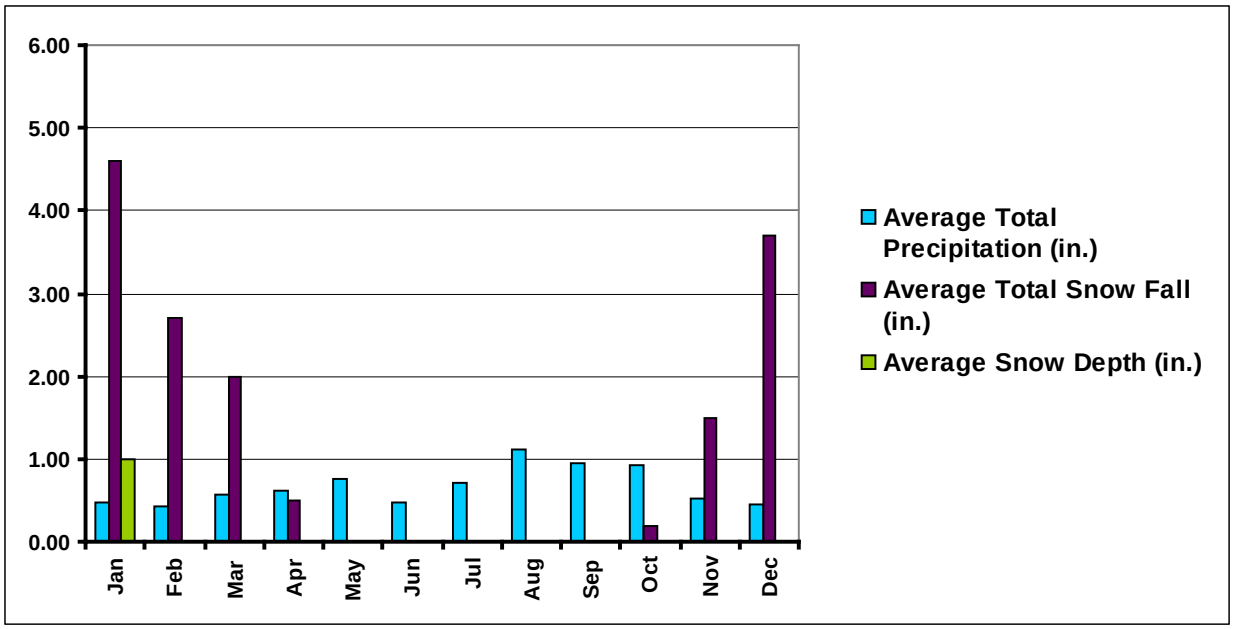

Figure 4. Average Total Monthly Precipitation, Snow Fall and Snow Depth for Delta (station 052192), Colorado for Period 1/1/1893 to 12/31/1999
(Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

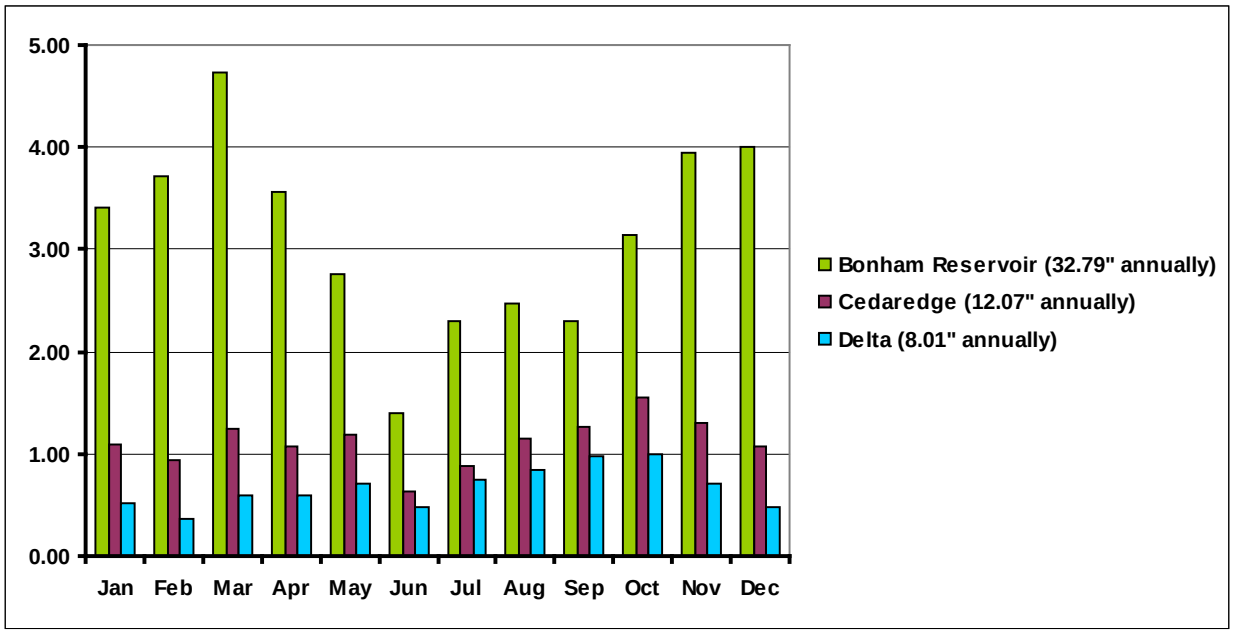

Figure 5. Comparison between the Average Total Monthly Precipitation at the Bonham Reservoir, Cedaredge and Delta Stations for the Period 1/1/1971 – 12/31/2000
(Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

2.2 Topography and Geomorphology

The surface elevation in the Oak Mesa study area ranges from about 1,700 m (≈5,600 ft) north of Hotchkiss to about 2,800 m (≈9,200 ft) 1.5 miles northeast of West Reservoir (Figure 7). The topography of the Oak Mesa area has three distinct terrains: 1) poorly-dissected uplands, terraces and plateaus; 2) connected and disconnected, continuous and discontinuous hillslope fans and mass wasting features; and 3) continuous alluvial valley bottoms. The poorly-dissected uplands indicate that surface water and shallow groundwater systems will be continuous, but localized by topography. However, 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 Oak Mesa, and these deeper bedrock systems can be a source of regional groundwater. These systems are recharged by, or discharging into, the shallow groundwater systems depending on the geomorphic geometry. At the top of Oak Mesa and its northeast, north, and northwest sides, the alluvial terraces, fans, and river bottoms are often isolated topographically, which causes discrete and localized groundwater systems.

The topographic gradients in the Oak Mesa study area can be divided into two types: steep gradient hill slopes (greater than 2% slope) characteristic of the northwest and northeast sides of Oak Mesa; and 2) low gradient, high terrace levels and alluvial valley bottoms characteristic of the top of Oak Mesa and the surrounding river valleys (Leroux Creek, Roatcap Creek) bordering Oak Mesa. 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.

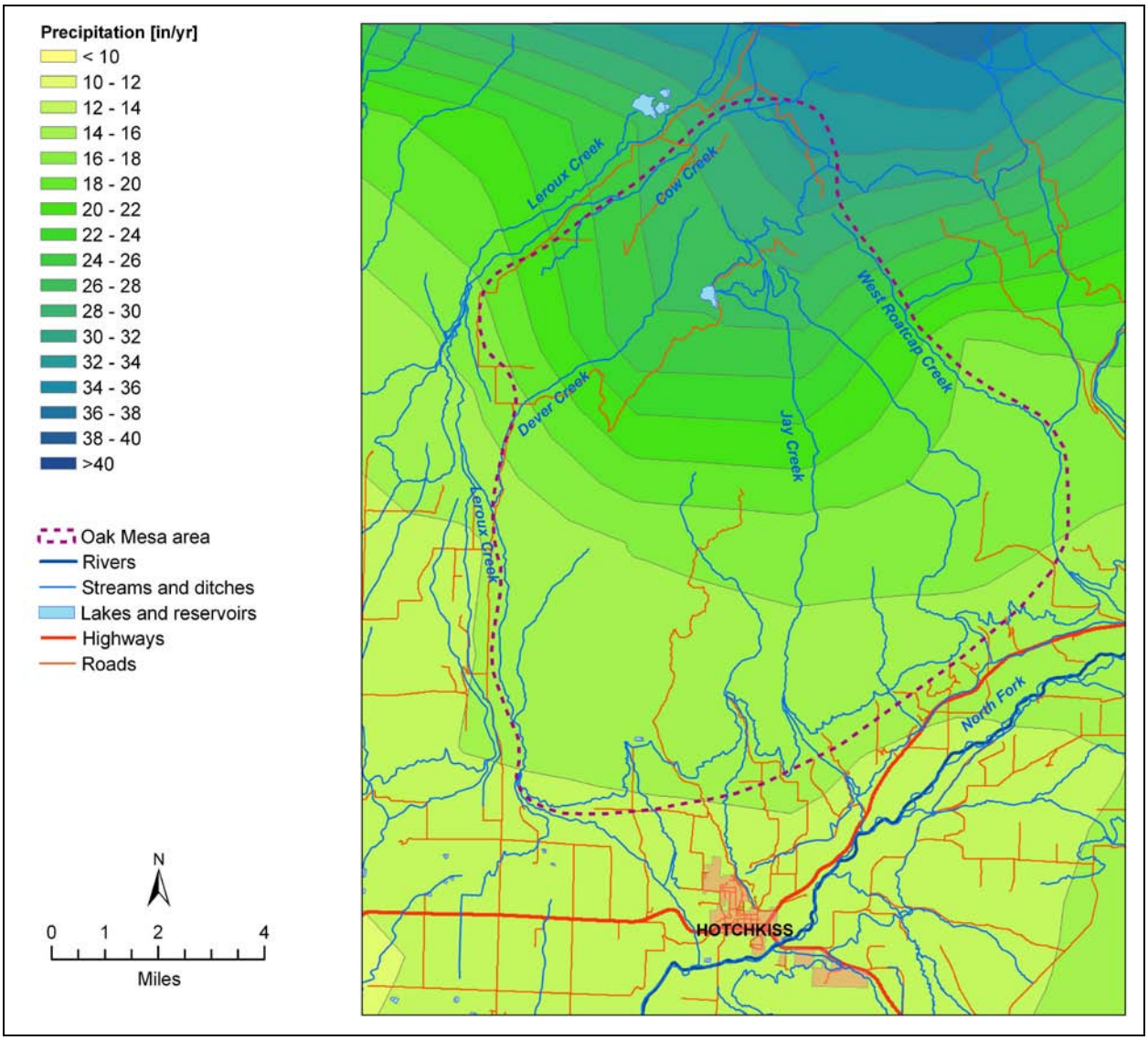

Figure 6. Spatial Distribution of the Average Annual Precipitation in the Oak Mesa Area, Delta County, Colorado (Source: Natural Resources Conservation Service 2011).

2.3 Surface Water Characteristics

The study area contains parts of four distinct watersheds (Figure 7): 1) Leroux Creek main stem and tributaries, covering the western and northwestern part of the study area; 2) Roatcap Creek drainage, bordering the east and northeast side of the study area; 3) Jay Creek, partially penetrating the middle of Oak Mesa from north to south; and 4) North Fork of the Gunnison River to the south. Streams can be gaining (from groundwater) or losing (to groundwater), dependent on local hydrology and time of year. For example, Roatcap Creek is a gaining stream in its upper reaches where springs discharge from the gravels to the surface. In the central reaches of Roatcap Creek, just east of Oak Mesa, surface water decreases and the shallow and bedrock groundwater systems are recharged by surface water. Similarly, the upper

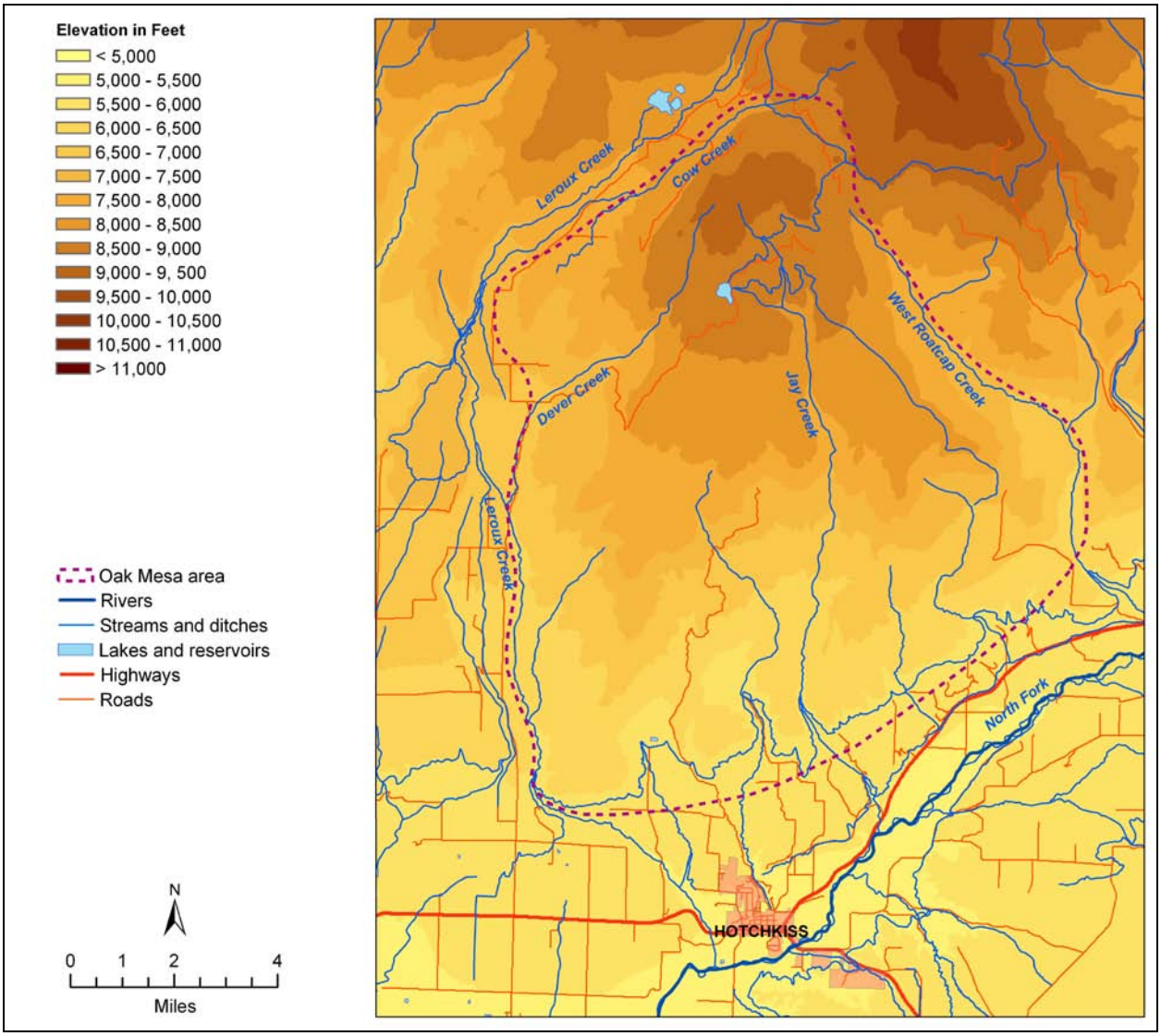

Figure 7. Topography and Surface Water in the Oak Mesa Study Area, Colorado. (Sources: Natural Resources Conservation Service 2011; Delta County 2011).

reaches of Jay Creek are gaining reaches due to surface water supplied by the West Reservoir and the alluvial groundwater system associated with Jay Creek. In the central reaches of Jay Creek, in the center of Oak Mesa, surface water decreases and the shallow and bedrock groundwater systems are recharged. By comparison, most of the reaches of Leroux Creek, located to the west of Oak Mesa, are gaining reaches due to groundwater discharge from surrounding surficial aquifers and nearby releases of reservoir water. The North Fork of the Gunnison has minimal effect on the Oak Mesa groundwater systems.

The Oak Mesa study area also contains a few reservoirs and ponds (primarily related to farmland modifications and [sub-]urban development requirements), and local networks of irrigation and water diversion ditches (Figure 7; see also Section 2.7). 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." This is specifically the case with the lower section of Cow Creek and sections of Leroux Creek in conjunction with the Overland Ditch. Springs, seeps, and most wetlands are indicators of groundwater discharge to the land surface. The irrigation ditches located on the terraces and along stream valleys often have phreatophytes and seeps, indicative of leaky, unlined ditch perimeters. Non-bottomland ditches can transport water over long distances from the diversion points. One of the critical ditches to observe is the extension of the Overland Ditch onto Oak Mesa to fill West Reservoir. This leaky ditch, and the reservoir, recharges the shallow groundwater system in surrounding areas of Oak Mesa. Similarly, the irrigation ditches along Roatcap Creek and Leroux Creek alter the shallow groundwater flow locally in their respective drainages, and contribute additional groundwater recharge to the shallow and bedrock aquifer systems. Finally, there is the effect of increased surface water flow in Jay, Leroux, and Roatcap creeks 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 for the overall hydrologic system of the Oak Mesa area.

2.4 Hydrogeologic Framework

Depending on their capability to provide sufficient water for irrigation and industrial and municipal consumption, bedrock and unconsolidated materials have traditionally been classified as either aquifers or aquitards. Here, 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?*), increasingly 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 stream valleys, and observed on top of and draping down the northwest and northeast side of the Oak Mesa Plateau, 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 Oak Mesa 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, by comparison, is 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, can pair relatively high matrix or vesicle porosity with significant permeability, and may contain significant amounts of groundwater.

The hydraulic properties of sedimentary rock may be largely enhanced when fractures and faults are present (*Davis and DeWiest, 1966*). As a case in point, most of the sandstones in the Oak Mesa 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 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 8), 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 9 and 10). 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*).

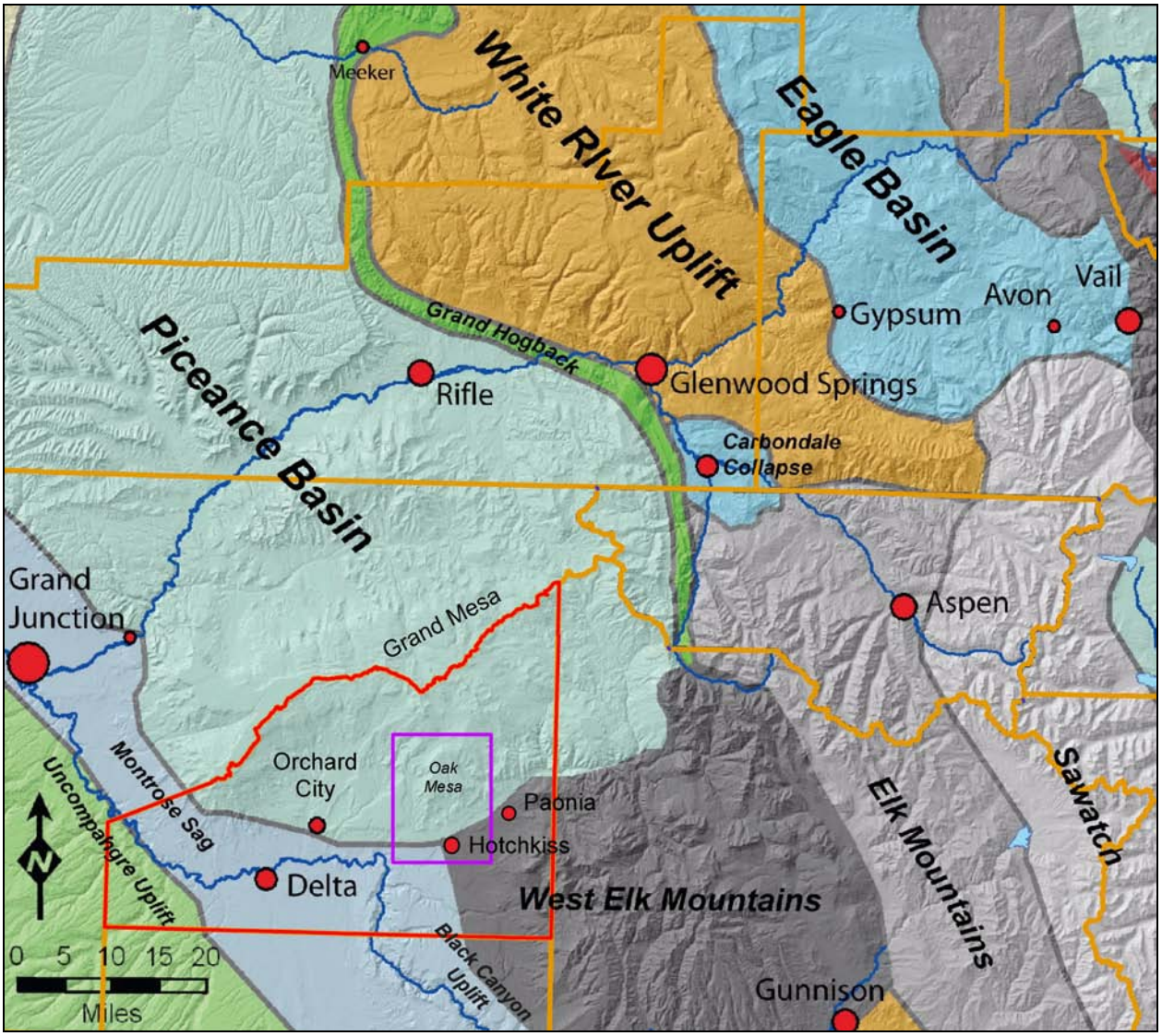

Figure 8. Generalized Map Showing Regional Geographic and Geological Features (*After Topper and others, 2003; Tweto and others, 1978*).

Given the regional geology of the Oak Mesa area, the hydrogeologic framework present in the Oak Mesa watersheds is complex. 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; Tweto and others, 1978*), it appears that the Oak Mesa 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 11 and 12 and described in Tables 1a and 1b; the major hydrostructural units are presented in Figure 13.

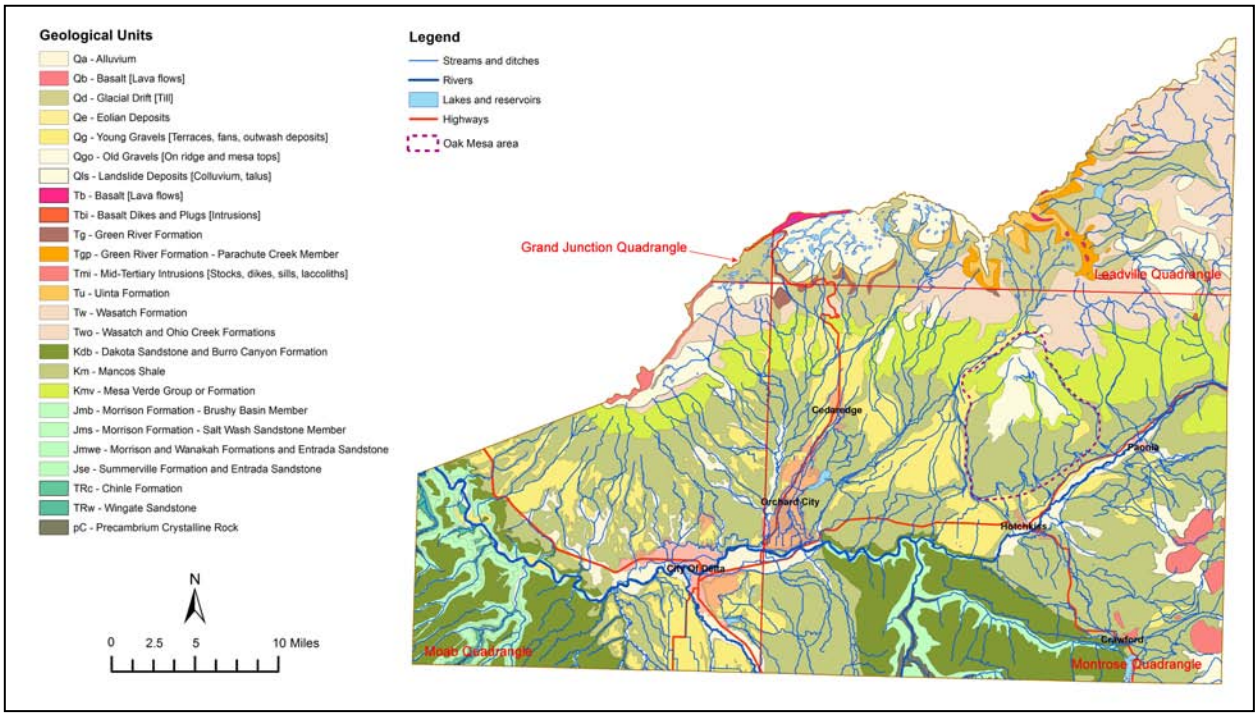

Figure 9. Composite Large Scale Map of the Geology of Delta County
(*Based on Tweto and others, 1976; Tweto and others, 1978; Whitney, 1981; Williams, 1964)*.

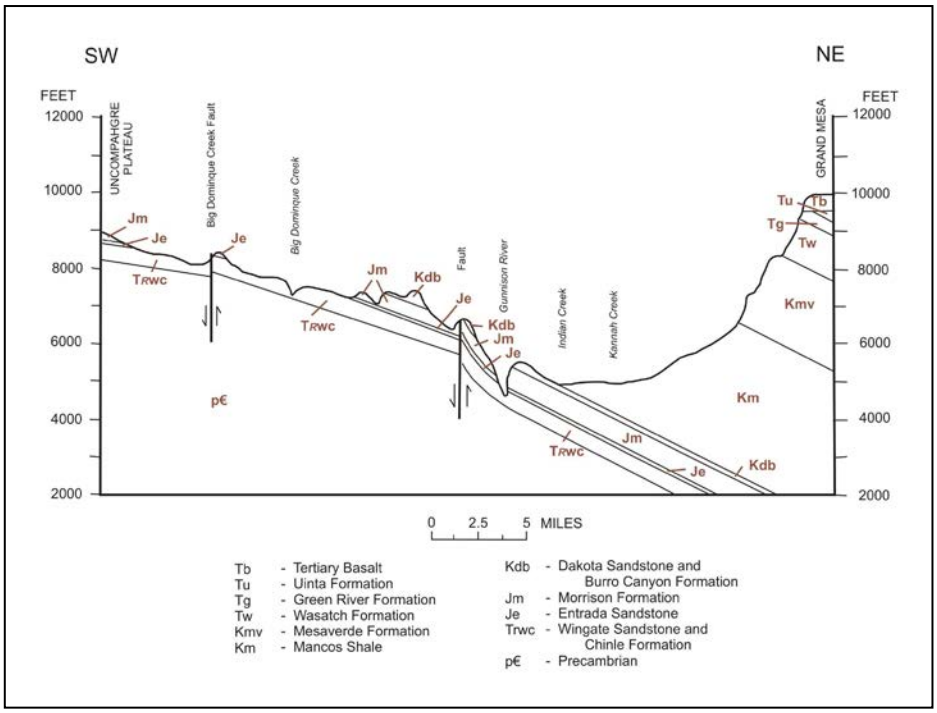

Figure 10. Generalized Northeast-Southwest Geological Cross Section Representative for Delta County
(*From Brooks and Ackerman, 1985)*.

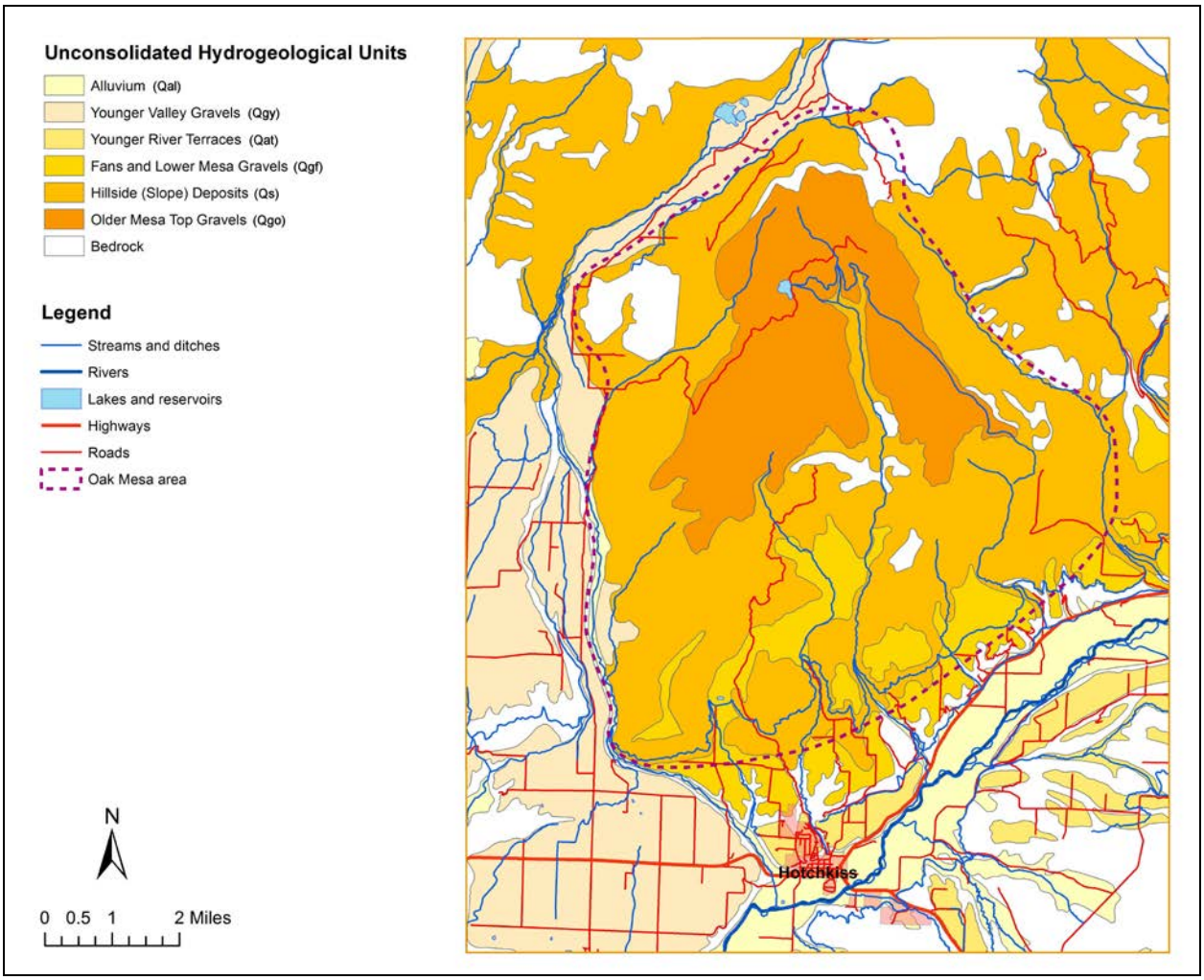

Figure 11. Map Showing the Shallow Unconsolidated Hydrogeologic Units in the Oak Mesa Study Area

2.4.2 Hydrogeologic Units of the Oak Mesa Study Area

There are two significant groups of hydrogeologic units in the Oak Mesa study area: 1) Quaternary unconsolidated clastic materials (Figure 11; Table 1a), 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 12; Table 1b), including the following potentially water-bearing units: Tertiary Wasatch Formation (Tw); Cretaceous Mesaverde Formation (Kmv), including the Ohio Creek, Barren, and Upper and Lower Coal Bearing members (Kmvc), as well as the Rollins Sandstone member (Kmvr). The Mesaverde hydrogeologic units have porosity values ranging from 0.7 – 12% (*Robson and Banta, 1995*); and Upper and Lower Coal Bed members have good transmissivities ranging from 1.5 – 16.7 ft squared per day (*Brooks, 1983*). The Mancos Shale unit (Km) may act as a thick, poorly transmissive confining layer *(Robson and Banta, 1995*). Other units that lie under the Oak Mesa

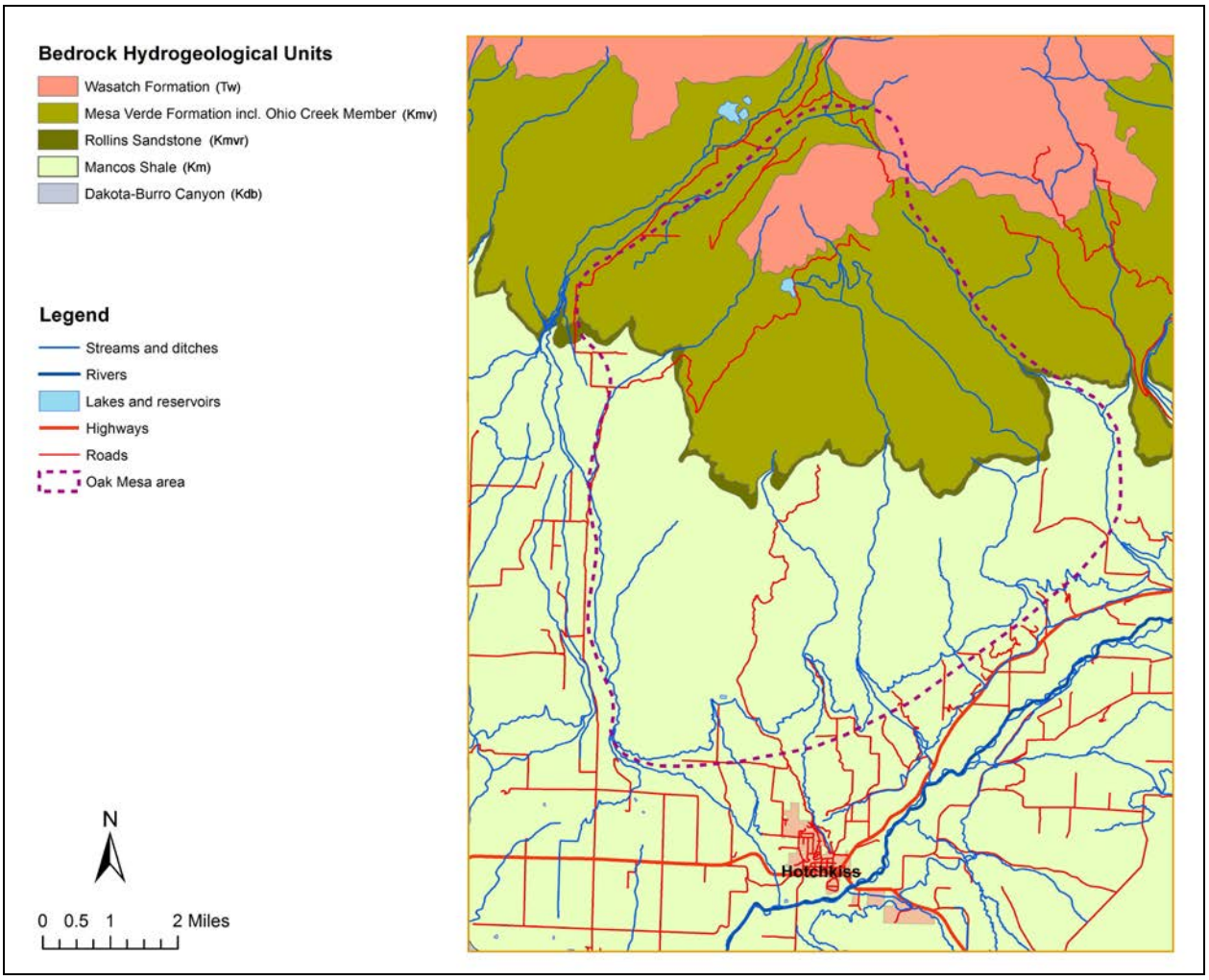

Figure 12. Map Showing Top of Bedrock Hydrogeologic Units in the Oak Mesa Study Area.

area, but are not deemed critical for this part of the study, include the Dakota – Burro Canyon (Kdb) sandstone aquifer; and the Morrison-Entrada Formation (Jme), which may act as both an aquifer and confining layer.

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, by comparison, 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 system in the Quaternary unconsolidated clastic materials, which is a source of drinking water for several municipalities, and the bedrock aquifers that may supply water to the shallow drinking water systems, and may be affected by coal mining activities.

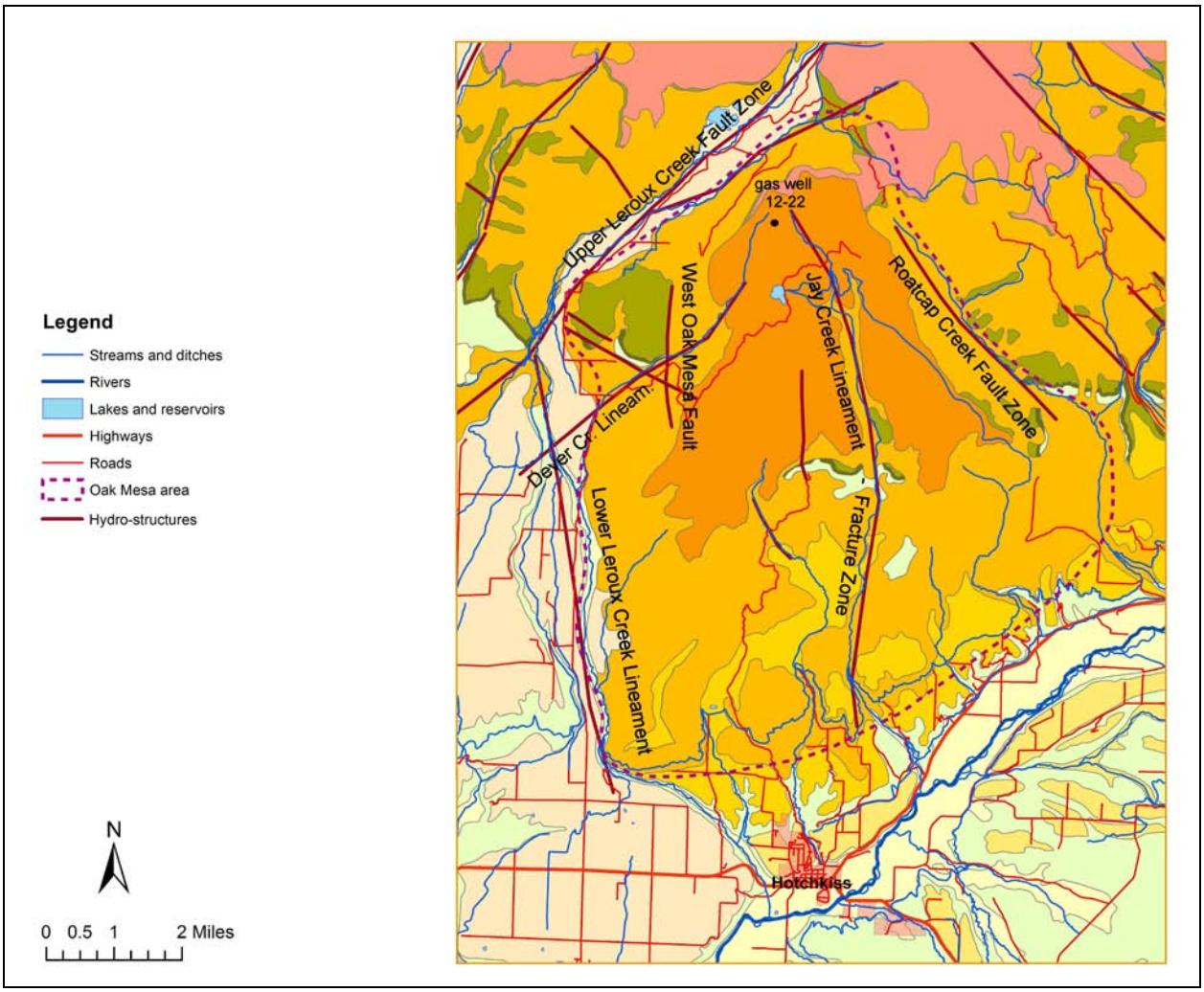

Figure 13. Map Showing Major Hydrostructures (Faults and Fracture Zones) in the Oak Mesa Study Area
(See Figures 11 and 12 for legend of hydrogeologic units; location of gas well from COGCC GIS Database, 2010).

The Quaternary unconsolidated clastic units (Qal, Qgy, Qat, Qs, Qgf, and Qgo in Table 1a and Figure 11) 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.

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 directly by stream.	high matrix-permeability; high storativity	small	local	natural
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	Although having high matrix based permeability, location in topography precludes any significant groundwater presence.	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 1a. Correlation of Geological and Hydrogeologic Units in the Oak Mesa Study Area: Unconsolidated Sediments.

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)
Wasatch formation (Tw) - without Ohio Creek Member		Wasatch Formation	Tw	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) including Ohio Creek Member	Undivided	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
	Ohio Creek Member								
	Barren Member								
	Upper Coal-bearing Layer	Coal-bearing Members	Kmvc	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
	Lower Coal-bearing Layer								
	Rollins Sandstone Member	Rollins Sandstone	Kmvr	Fine grained massive sandstone	Moderate local aquifer where fractured.	Primarily fracture permeability; low storativity	large	local	natural
Mancos Shale (Km)	Undivided	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
	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)								
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	Jme	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 1b. Correlation of Geological and Hydrogeologic Units in the Oak Mesa Study Area: Bedrock Units.

2.4.3 Hydrostructural Units of the Oak Mesa Study Area

Hydrostructures most likely exist subregionally and locally (Figures 8 and 13), and are responsible for various springs and groundwater discharge and recharge areas observed in Roatcap, Jay, and Leroux creeks. Hydrostructures in this study area are 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 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.

Each fault zone should be evaluated for the following characteristics: 1) fault plane geometry, including the vertical or horizontal nature of the fault plane and the relations of rock types and geometry on both sides of the fault; and 2) the transmissive nature of the fault plane or fault zone, including the nature of fault gouge (clay, gravel) and tectonic setting of fault plane or zone (extension or compression). The fault plane geometry is important to evaluate if groundwater can move horizontally across the fault 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. The tectonic setting helps determine whether the fault plane is "open"—able to easily move water (extension), or "closed"—not able to easily move water (compression).

Three broad hydrostructures occur in the Oak Mesa area: 1) the northwest-trending Roatcap Creek fault zone and associated en-echelon faults to the east; 2) the northeast-trending Upper Leroux Creek fault zone and en-echelon lineaments such as the Dever Creek lineament; and 3) the north-south-trending Jay Creek lineament-fracture zone and associated en-echelon lineaments such as Lower Leroux Creek and faults such as the west Oak Mesa fault (Figure 13).

The Roatcap Creek fault zone delineates the edge of the potential upland bedrock and unconsolidated groundwater systems to the east of Oak Mesa. Therefore, the effects of anthropogenic activities such as coal mining located to the west on Oak Mesa may not propagate further to the east of this boundary. The fault zone is relatively young, as the geomorphic system of Roatcap Creek is responding with considerable downcutting, allowing for full penetration of the bedrock aquifers. It is hypothesized that the Roatcap fault zone is "open" and that it behaves like a French drain. Along its trace, groundwater moves horizontally along the fault plane, and vertically up along the fault plane near the headwaters (evidenced by springs). In the middle reaches, groundwater moves downward from unconsolidated materials, where it recharges the regional bedrock systems (indicated by reaches of losing stream flows).

The Leroux Creek fault zone and en-echelon lineaments are also "open." Along the Leroux Creek fault zone, groundwater moves horizontally along the fault plane, and vertically downward from unconsolidated materials, where it recharges the regional bedrock systems in the northeast-trending reaches along the fault. The Leroux Creek fault zone delineates the edge of the potential bedrock and unconsolidated groundwater systems to the northwest of Oak Mesa. Therefore, the effects of anthropogenic activities, such as coal mining located to the east on Oak

Mesa, may not propagate further to the west of this edge. Dever Creek similarly is an "open" lineament/fracture zone that functions as French drain. Along the Dever Creek zone, groundwater moves from the surrounding gravels and bedrock into the upper reaches of the stream near natural gas well 12-22 (Figure 13).

The Jay Creek lineament/fracture zone dissects the Oak Mesa Plateau in a north-south direction. Because of its orientation, the effects of anthropogenic activities, such as coal mining located beneath Oak Mesa, may affect the bedrock groundwater system to the north of this area. The Jay Creek lineament/fracture zone is relatively young, as evidenced by the geomorphic system where considerable downcutting, allowing for full penetration of the bedrock aquifers, has occurred. It is hypothesized that the Jay Creek fracture zone is "open." Groundwater within the fracture zone moves horizontally along the fault plane, and vertically up along the fault plane near the headwaters (evidenced by a gaining stream). In the middle reaches of Jay Creek before it exits Oak Mesa, groundwater moves downward from unconsolidated materials where it recharges the regional bedrock systems (indicated by reaches of losing stream flows). It is hypothesized that underground mining activity will most likely be affected by the hydrological setting of Jay Creek.

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 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) based on climate (infiltration of precipitation and snowmelt). Groundwater interaction with streams, vegetation (evapotranspiration), and human activity (irrigation, urbanization, wells and individual sewage disposal systems [ISDS], reservoirs and ponds, mining) 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 (Roatcap, Jay, and Leroux creeks) in some locations, infiltration and runoff from water bodies (West Reservoir, cattle ponds), upland irrigation areas (leaking ditches, irrigation return flow), and inter-aquifer transfer of groundwater between unconsolidated materials and bedrock systems. 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, local recharge may force the groundwater into a more regional pattern determined by geological structure, independent from local topography and hydrography. The Oak Mesa groundwater systems are a complex mix of all these mechanisms.

The mesa top terrace, fan, and bajada subsystems, located in close proximity to the valley 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 area. Here, groundwater flow can have a rather diffuse character and often flows towards or aligns more or less with the streams. These subsystems depend primarily on interactions with the Roatcap, Jay, and Leroux creeks; and the management of subregional ditches and corresponding reservoir storage.

The wetlands associated with the local hydrogeologic subsystems in the Roatcap, Jay, Leroux, Cow, and Dever creeks are predominantly of the slope-type with some riverine-type classifications given the groundwater support of various bedrock groundwater systems and hydrostructures.

2.6 Groundwater System Conceptual Site Models by Subsystem

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

1. Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems; and
2. Regional Bedrock Subsystems.

The conceptual models are discussed in forthcoming sections and illustrated by cross-sectional and plan view figures (Figures 14, 15, 16, 17, 18, and 19).

2.6.1 Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems

As stated in Section 2.4.2, there are two significant hydrogeologic groups in the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems:

1. Quaternary unconsolidated clastic materials (Qal, Qgy, Qat, Qs, Qgo, and Qgf in Table 1a and Figure 11), which are predominantly terrace gravels, alluvial fans and bajadas, and alluvial valley bottom deposits; and

2. Tertiary and Cretaceous bedrock units (Table 1b and Figure 12), including the following potentially water-bearing units: Tertiary Wasatch Fm (Tw); Cretaceous Mesaverde Formation (Kmv), including the Ohio Creek, Barren, and the Upper and Lower Coal Bearing members, as well as the Rollins Sandstone Member (Kmvr); and the Mancos Shale unit (Km).

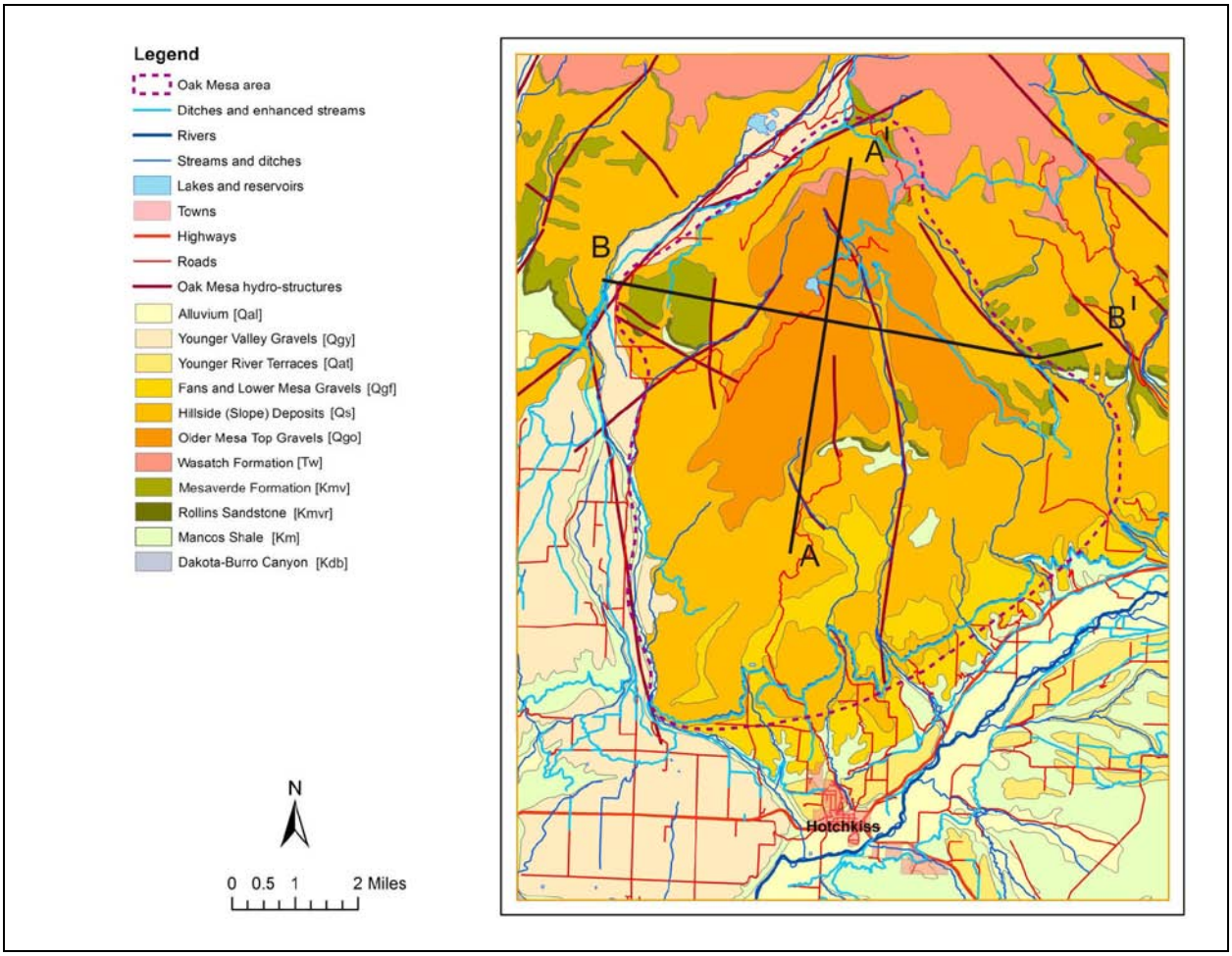

Figure 14. Map Showing the Locations of the Cross-sections Representative for the Conceptual Site Models in the Oak Mesa Study Area.

The shallow Quaternary unconsolidated materials in this subsystem are ubiquitous, and include glacial-alluvial, mass wasting, and modern alluvial deposits (Figure 11 and Table 1). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in the alluvial deposits.

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the shallow groundwater in the Oak Mesa area is dominated by the Quaternary unconsolidated materials, which receive recharge by infiltration of precipitation (snow and rain), leaky irrigation ditches and reservoirs, and losing streams swelled to capacity from reservoir storage (Figures 15 and 16). Recharge by infiltration of precipitation and snowmelt is greatest at the highest elevations in the north part of the study area at the top and

on the north-facing sides of Oak Mesa (Qs, Qgo), and the headwaters of Leroux, Cow, Jay, and Roatcap creeks. The Overland Ditch extension onto Oak Mesa is a "line" groundwater recharge source on the top and northeast side of Oak Mesa, and the headwaters of Roatcap Creek. In addition, the Overland Ditch carries water into upper Leroux Creek and Cow Creek, where these losing streams and leaky irrigation ditches recharge the Qs, Qat, and Qgy materials. West Reservoir, on Oak Mesa, acts as an area of enhanced groundwater recharge into the underlying Quaternary materials. In addition, releases from West Reservoir enhance the surface water flows in upper Dever and Jay creeks, resulting in increased groundwater recharge to alluvium in the upper part of these drainages.

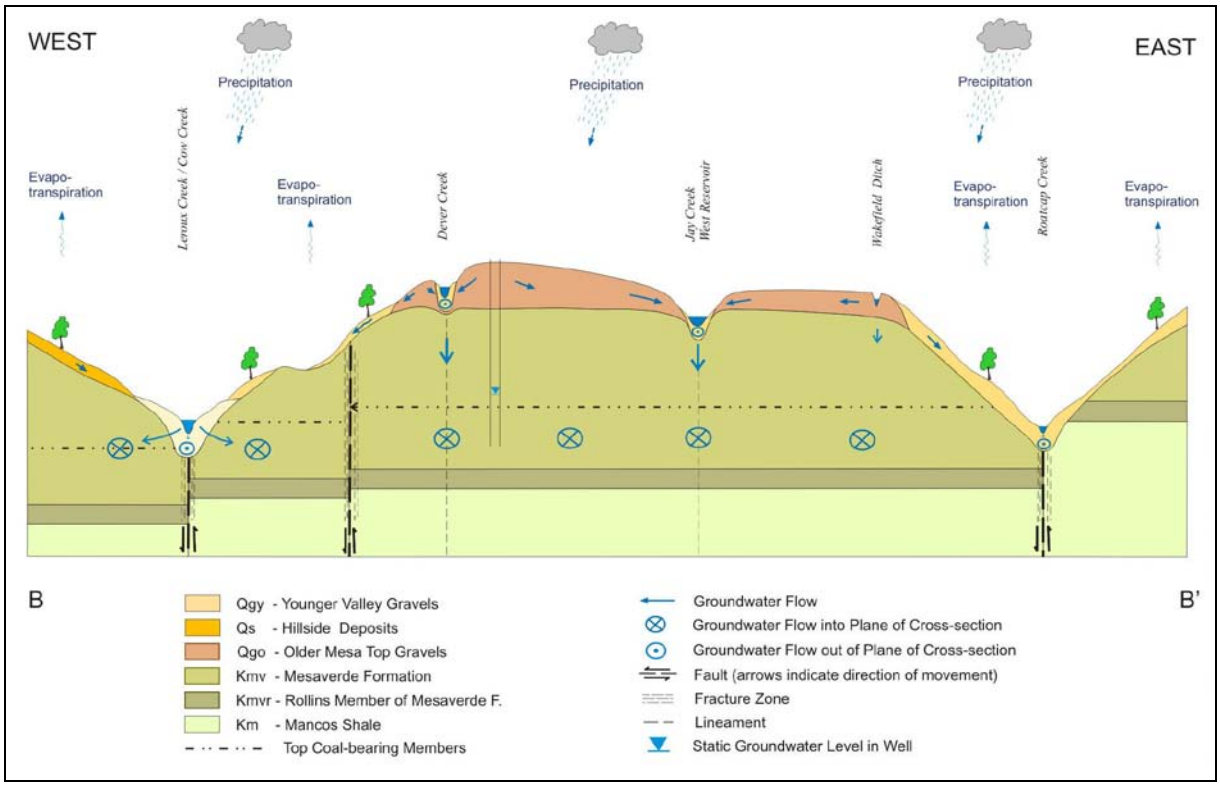

Figure 15. Cross-sectional View of the Conceptual Site Model of the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems (B-B' in Figure 14).

Groundwater flow on top of Oak Mesa then moves with topography into Dever Creek to the west and Jay Creek to the east. In addition, groundwater that flows through the hillslope deposits in the northeast area eventually discharges into Roatcap Creek, and, likewise, groundwater that flows through the hillslope deposits in the northwest area eventually discharges into Cow Creek. The presence of aspen trees serves as an indicator of an active shallow groundwater system in this area (Figures 15, 16, and 17). The absence of phreatophytes and seeps or springs in the southern section of Oak Mesa suggests that no groundwater flows to the south to daylight out in the southern slopes of Oak Mesa. Groundwater levels from wells completed in bedrock provide additional evidence that very little groundwater infiltrates into the underlying bedrock on Oak Mesa proper (*Ackerman and Brooks, 1986*). The shallow groundwater system in this area has little connection to the local bedrock or the regional groundwater systems.

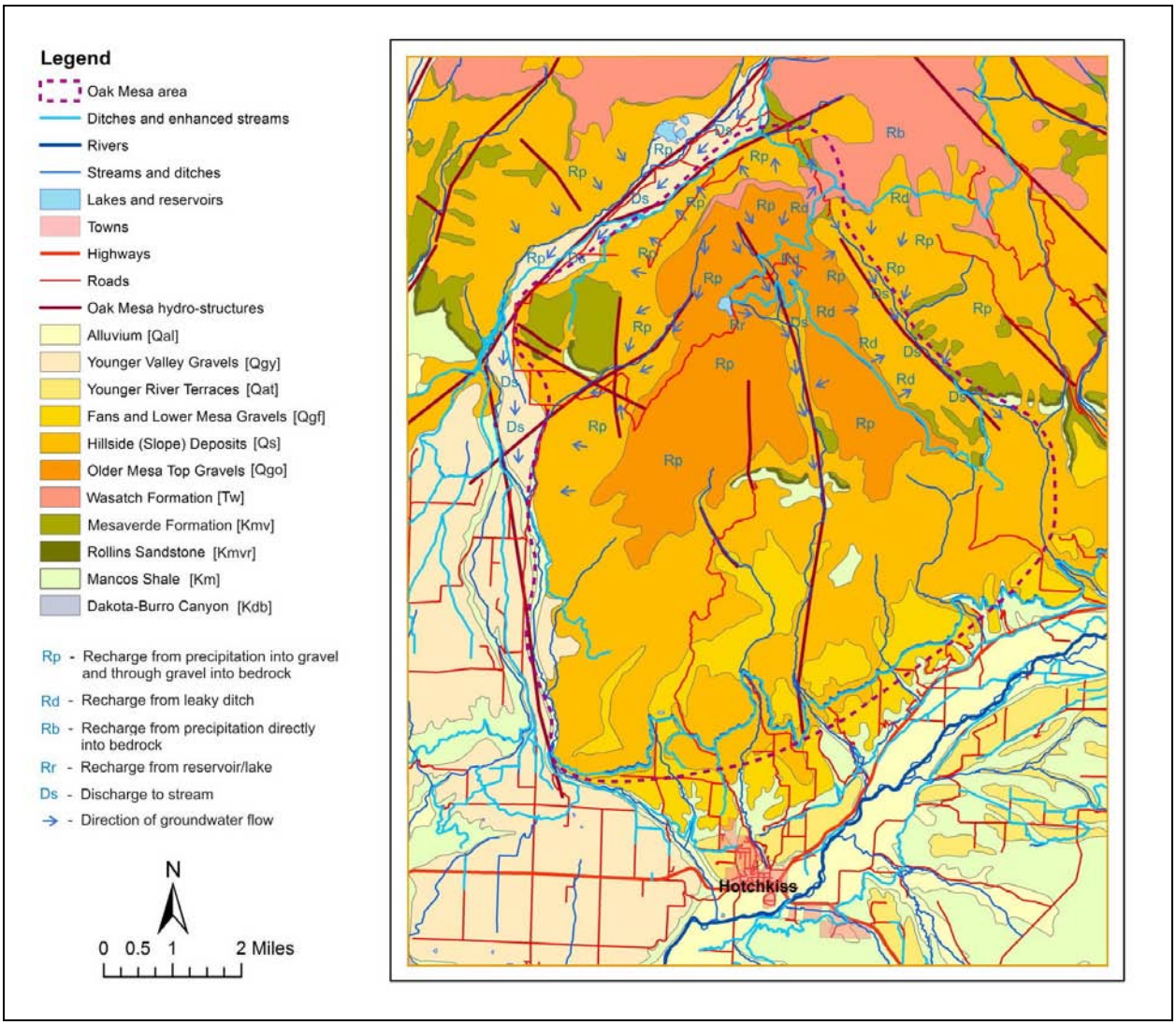

Figure 16. Plan View of the Conceptual Site Model of the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems.

In the valley of Jay Creek, the groundwater system flows parallel to the creek. Jay Creek becomes a losing stream about half way down the Mesa, and the stream and shallow groundwater system recharge the Cretaceous Mesaverde Bedrock system at about the Coal Bearing members unit, which has been confirmed by drilling (*Ackerman and Brooks, 1986*). Likewise, in the valley of Roatcap Creek, the groundwater system flows parallel to the creek. Roatcap Creek becomes a losing stream about halfway down the valley from the headwaters to the North Fork of the Gunnison River. The stream and shallow groundwater system recharge the Cretaceous Mesaverde Bedrock system at about the Coal Bearing members units. Dewatering of the Cretaceous Mesaverde Bedrock system by coal mining may affect the surface water and shallow groundwater flow of the Jay Creek and Roatcap Creek systems (Figures 15, 16, and 17).

The groundwater system flows in the valley of Leroux Creek parallel to the creek. Leroux Creek and the Leroux Creek aquifer receive a great deal more water then most creeks

surrounding Oak Mesa. Leroux Creek and the Leroux Creek aquifer receive large quantities of water from other bedrock and alluvial aquifers on Grand Mesa. Leakage from the Overland Ditch, Cow Creek, and from various reservoirs and irrigation ditches enhances recharge to the Leroux Creek aquifer. Leroux Creek probably is a losing stream along the northeast-trending reach, where regional recharge is lost to the Mesaverde aquifer. The stream should not be losing flow to the bedrock along the north-south trending reach, where the Mancos Shale is present. Numerous phreatophytes along the entire length of this creek, as well as in Cow, Jay, and Roatcap creeks, result in large amounts of evapotranspiration. The dewatering of the Mesaverde unit by coal mining may alter the surface water and shallow groundwater flow of Leroux Creek (Figures 15, 16, and 17); however, the impacts would tend to be muted by the vast groundwater recharge network which is independent of the bedrock system.

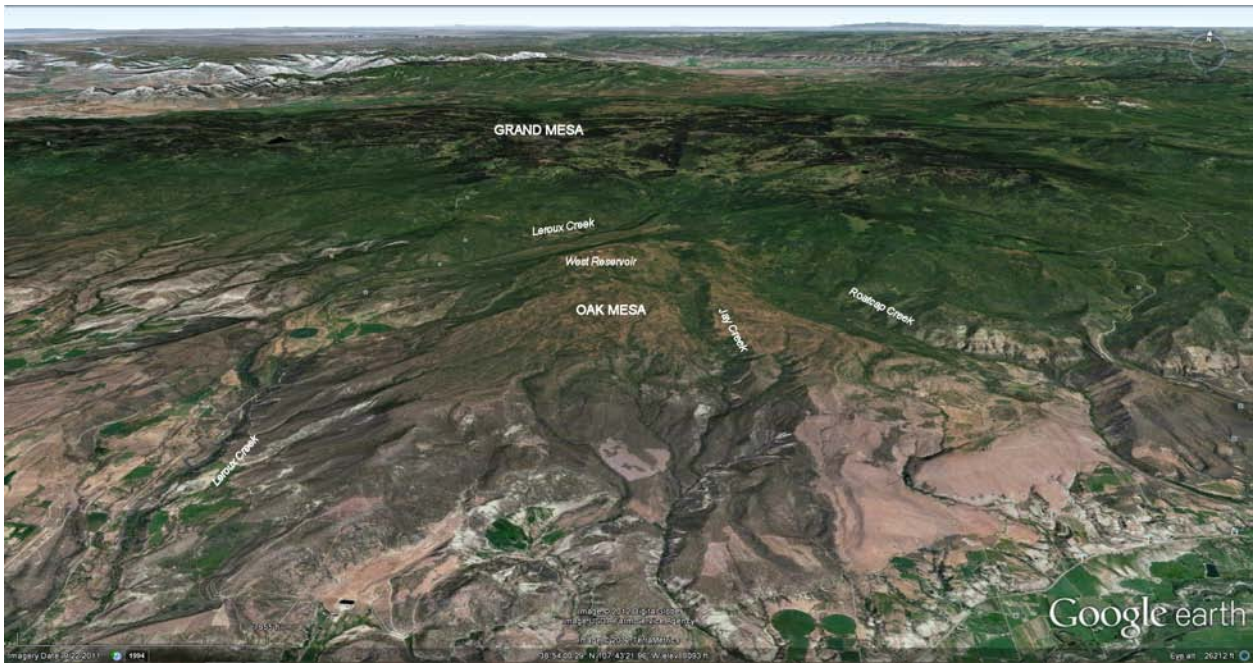

Figure 17. Google Earth View of the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems.

2.6.2 Regional Bedrock Subsystems

The regional hydrogeologic units in the Oak Mesa study area, discussed in Section 2.4, are the Tertiary and Cretaceous bedrock units (Figure 12 and Table 1b), including the following potentially water-bearing units: Tertiary Wasatch Fm (Tw); Cretaceous Mesaverde Formation (Kmv), including Ohio Creek, Barren, and Upper and Lower Coal Bearing members (Kmvc), and the Rollins Sandstone member (Kmvr); and the Mancos Shale unit (Km), that may act as a thick, poorly transmissive confining layer (Figures 12, 15, 18, and 19; Table 1b). The shallow Quaternary unconsolidated materials in this subsystem are ubiquitous, and are the overlying materials providing conditions that allow recharge to the regional bedrock system mostly in stream valley and mesa top areas (Figures 15 and 18).

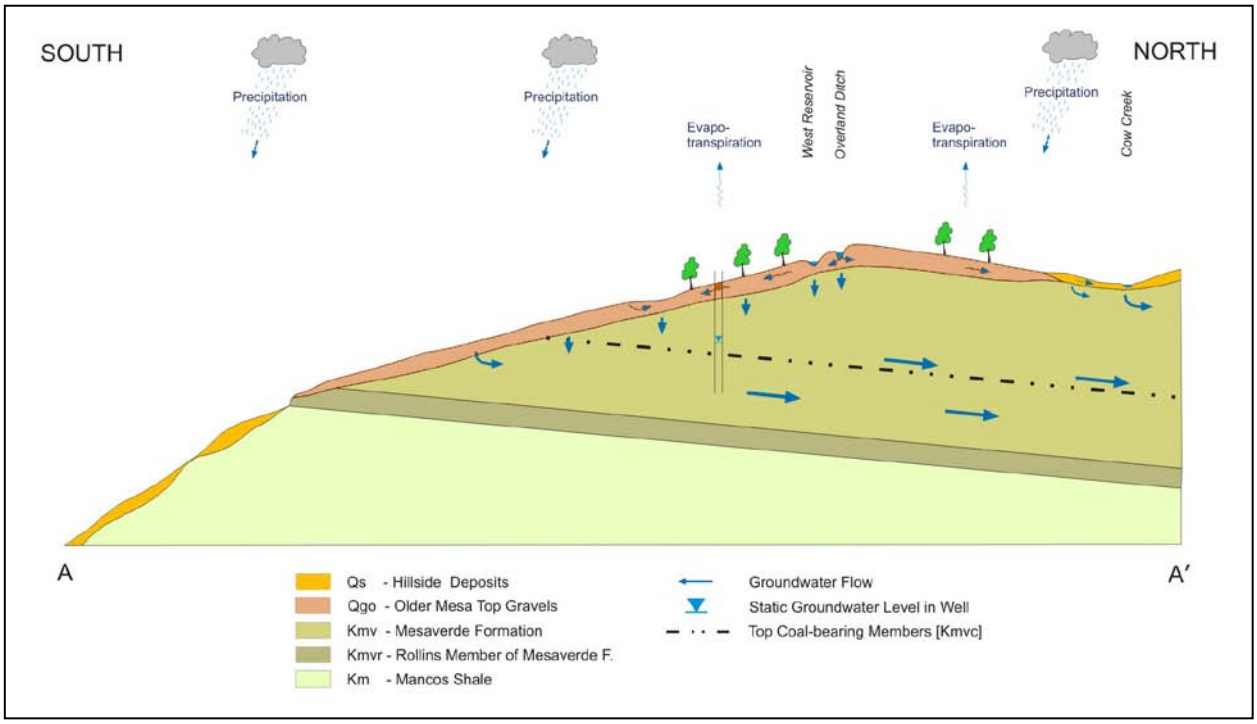

Figure 18. Cross-sectional View of the Conceptual Site Model of the Regional Bedrock Subsystems (A-A' in Figure 14).

The general aspects of shallow groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. The unconsolidated units are variably to fully saturated based on spatial location and seasonal precipitation events, and serve as the conduits for regional recharge along with losing streams, leaky ditches, and reservoir and ditch enhancement of surface water and groundwater systems. The lower reaches of Leroux, Cow, Jay, and Roatcap creeks are losing streams located along French drains, and are areas of regional recharge to the Wasatch and Mesaverde aquifers (Figures 15, 18, and 19).

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. The Mesaverde aquifer is partially saturated in the south and central areas of Oak Mesa, as evidenced by the water levels recorded in well logs (see Figure 15). The water table appears to be above the Upper and Lower Coal Bearing units, which suggests that dewatering will be necessary.

Groundwater flows vertically, then horizontally to the north along hydrostructures, 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 Oak Mesa and Grand Mesa (Figures 18 and 19). This flow direction is away from the coal mining activities, drinking water supplies, and Delta County in general.

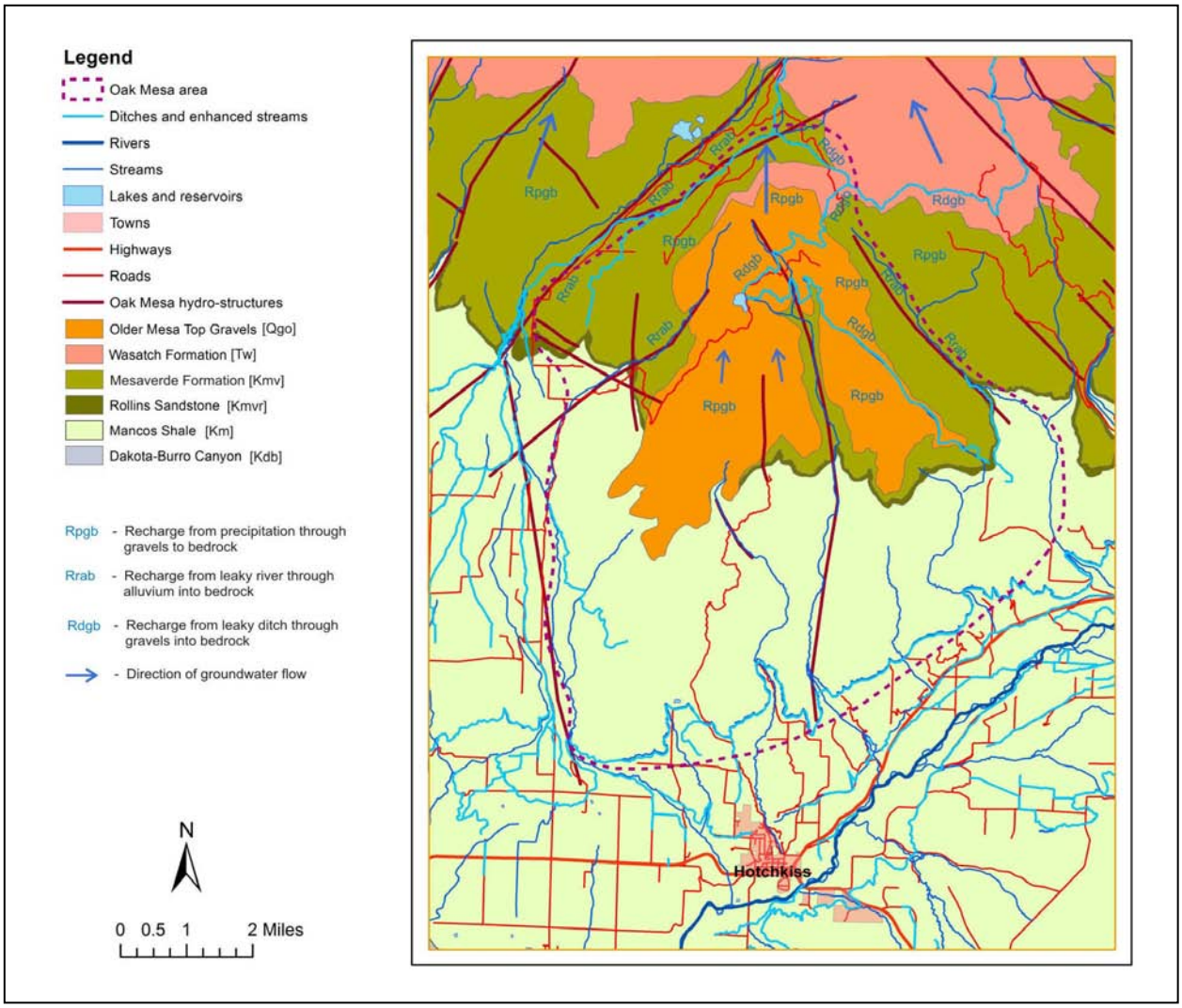

Figure 19. Plan View of the Conceptual Site Model of the Regional Bedrock.

2.7 Anthropogenic Influences

Human activity in the Oak Mesa 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 (Figure 20). This activity has resulted in long-term increase of water levels in local, shallow aquifers of the Quaternary materials both on top of Oak Mesa, and in the high valleys of Roatcap, Jay, Cow, and Leroux creeks. Invariably, regional recharge into the Wasatch and Mesaverde aquifers has occurred, as well.

Figure 20. Google Earth Image of Anthropogenic Influences: Irrigation Ditches and Reservoirs in the Oak Mesa Study Area.

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, the Oak Mesa 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 Oak Mesa study area consists primarily of mesa top, hillslope, bottomland and terraces, limiting the irrigated areas to the top and lower portions of the subsystems. Here, there are a number of mostly unlined irrigation ditches that are excavated primarily in unconsolidated Quaternary deposits (Figure 21). When carrying water, the ditches may leak, as evidenced by the phreatophytes often found alongside them. 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 alter groundwater flow patterns.

As discussed above, 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.

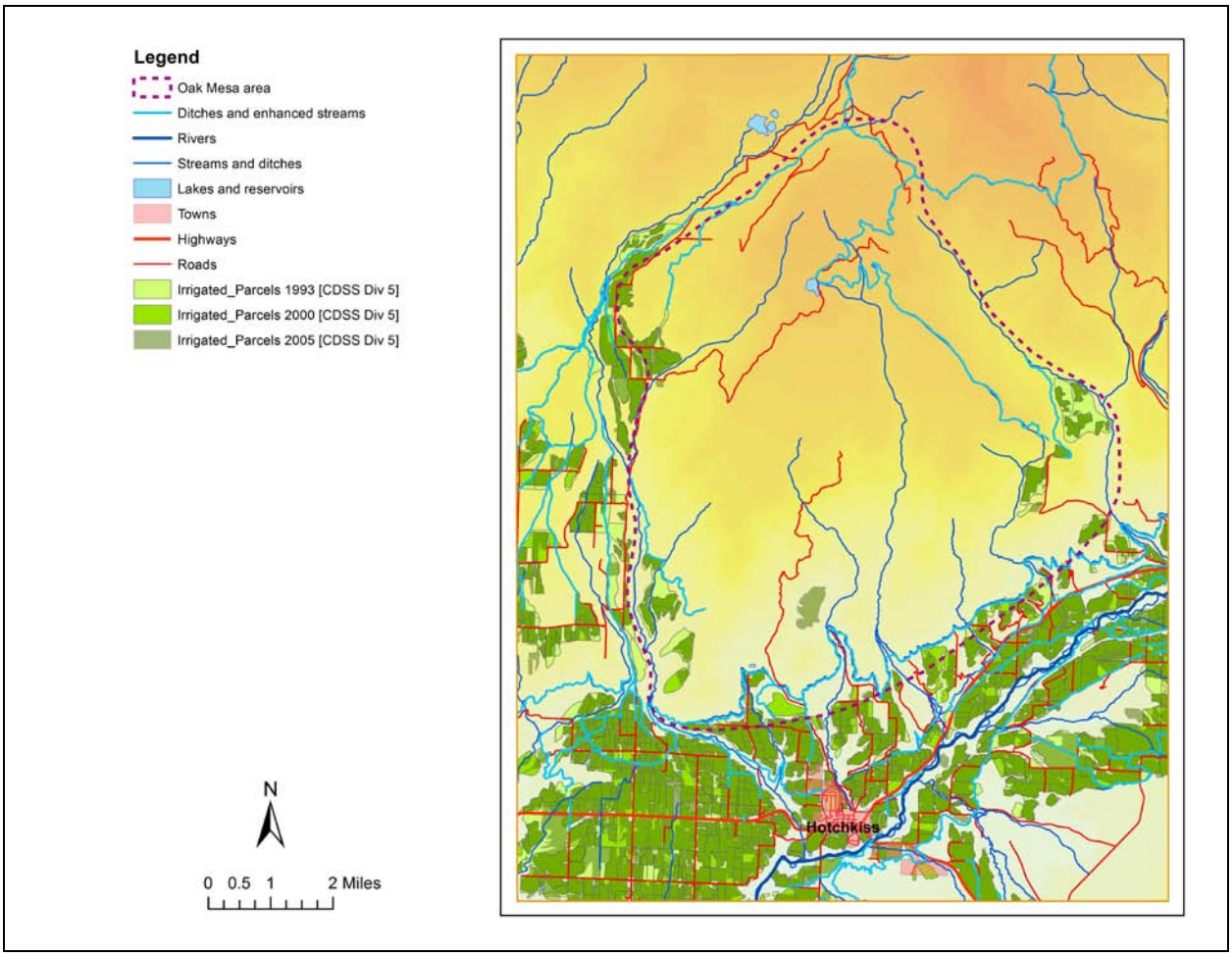

Figure 21. Anthropogenic Influences: Irrigated Areas and Irrigation Ditches in the Oak Mesa Study Area (Source: Delta County GIS, 2010; CDWR GIS, 2011).

The water wells in the Oak Mesa study area are clustered mostly along Leroux, Cow, Jay, and Roatcap creeks and bottomland (Figure 22). Most of these wells serve domestic water supply needs, or the needs of municipalities located along the North Fork of the Gunnison River (Hotchkiss, for example), and the effect on the groundwater system is limited. However, if additional water is needed, or water is displaced by mining activities, for example, the compound effect on the groundwater system could be 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.

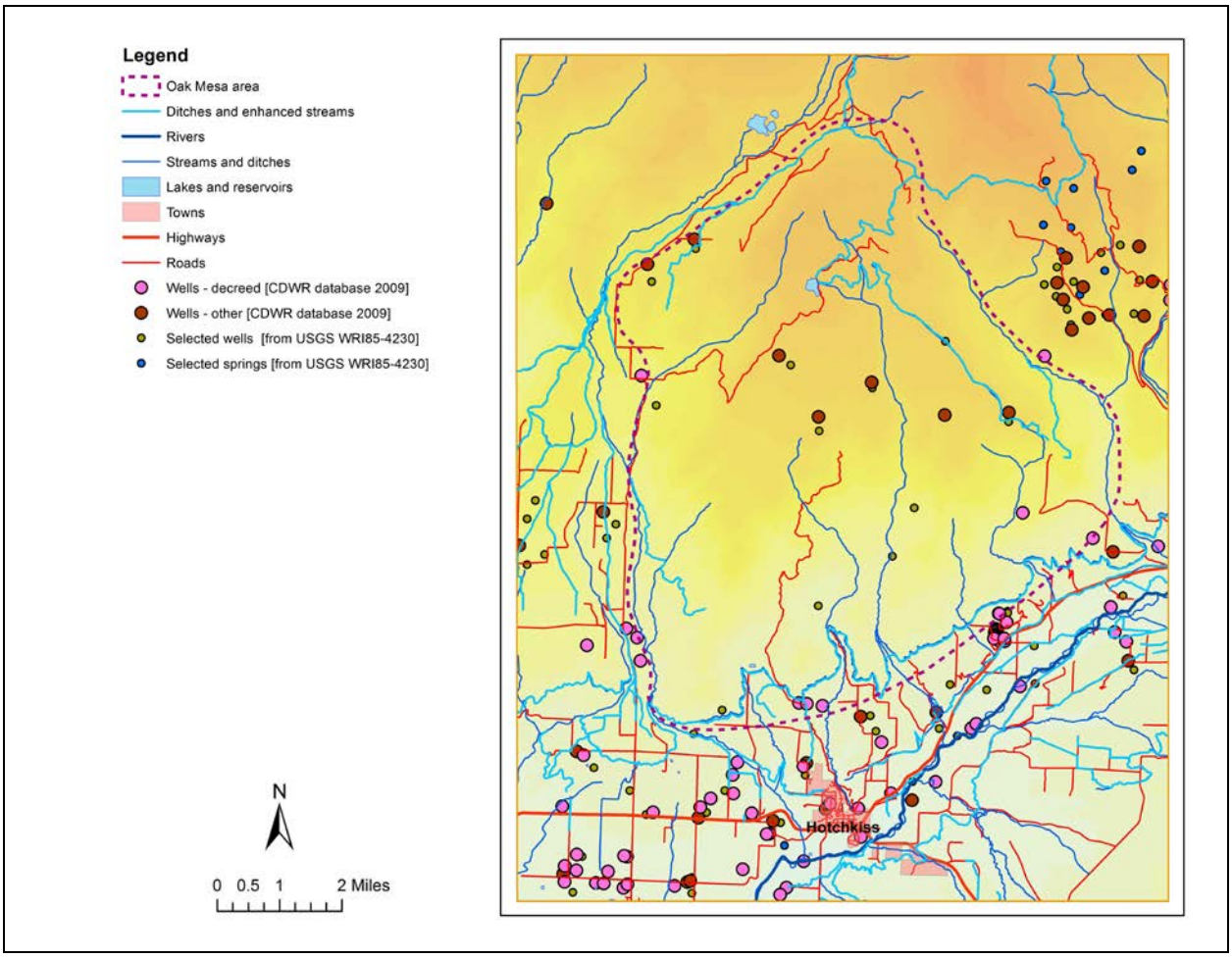

Figure 22. Anthropogenic Influences: Wells in the Oak Mesa Study Area (Source: CDWR GIS, 2011).

2.7.2 Potential Effects of Coal Mine Hydrology

The hydrology of a natural groundwater hydrologic system will be altered by the construction and operation of the proposed underground coal mining operation. During mine dewatering, the coal mine may behave like a very large well, drawing water towards it from locations further away. Depending on management strategies for produced water disposal, groundwater levels may increase at other locations. The groundwater levels in the bedrock systems will also 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.

Assuming that the coal mining activities are underground, and assuming that dewatering is the major activity of the coal mining operations, both the shallow and bedrock aquifer subsystems will potentially be affected. The effects of water disposal after dewatering are not discussed in this report as the mine design plans and operations are not available at this time.

These management strategies and their effects on the shallow and bedrock aquifer subsystems should be evaluated in more detail.

The mesa top and upper hillslope parts of the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystem are least likely to be affected by mining operations because they are located in the recharge area and have a shallow groundwater flow system above the bedrock dewatering zone (Figures 15, 16, 18, and 19). However, the amount of groundwater discharge from the bedrock to the shallow aquifers in the lower hillslope and valley bottom areas in the Leroux Creek drainage may be reduced by dewatering action (Figures 15, 16, 18, 19), which could affect the Hotchkiss water supply. In addition, significant amounts of alluvial water in both Jay and Roatcap creeks may be reduced due to mine dewatering (Figures 15, 16, 18, 19).

The regional groundwater subsystem will be affected by the mining operations as the edge will be effectively removed and the regional recharge area of the regional bedrock system will be dewatered (Figures 18 and 19). However, the effects of the reduced groundwater amounts in the regional system will most likely be insignificant relative to the flows supporting the Colorado River drainage in the areas north of Grand Mesa.

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 Oak Mesa 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 digital elevation model [DEM], among others). The GIS map and database for the Oak Mesa study were prepared using ArcView™ version 8.3 and Arc-Desktop™ version 10.1 (ESRI®, Redlands, California).

3.2 Use of GIS in the Oak Mesa 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 the Oak Mesa area, as well as other parts of Delta County. Two multi-layer GIS maps have been prepared for this study: 1) a map with hydrologic and hydrogeologic features of Delta County (Figure 23); and 2) a map with hydrologic and hydrogeologic features of the Oak Mesa area (Figure 24). 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.

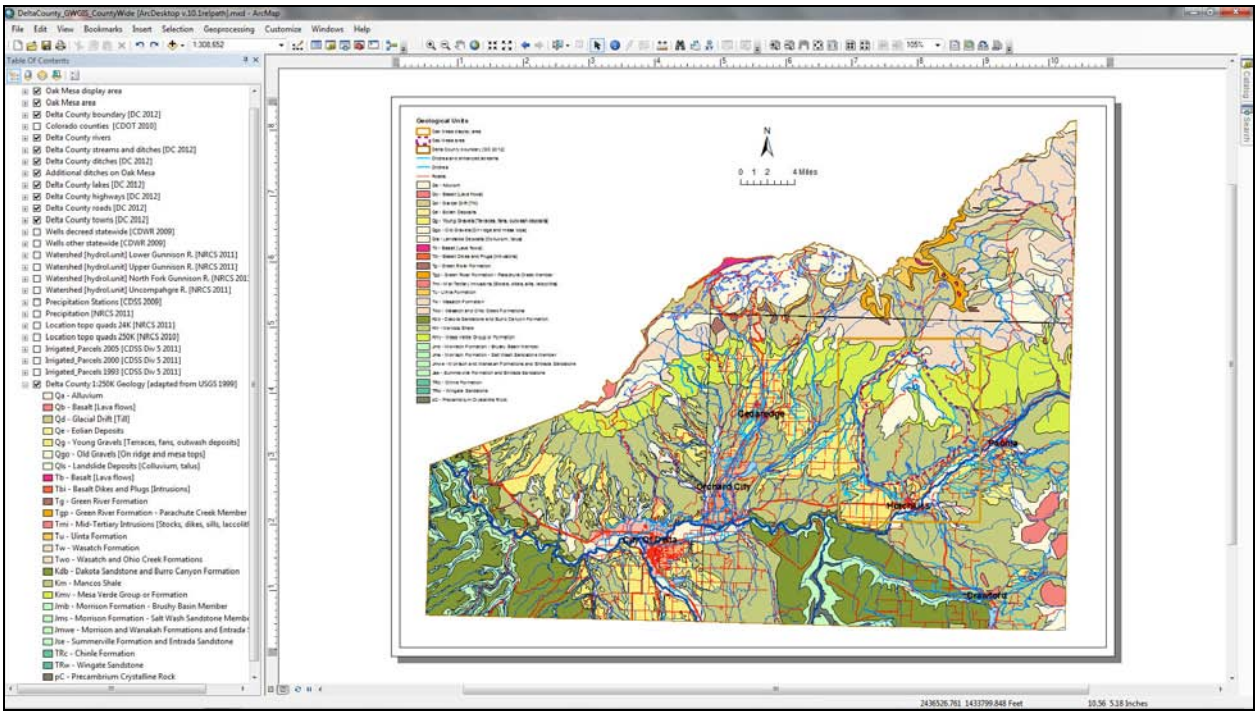

Figure 23. Delta County GIS Map Showing Streams, Ditches and Roads on Top of County-wide Geology.
(The left display area is the table of contents [TOC] showing all available layers;
the right side of the window is the map display area showing the activated layers.)

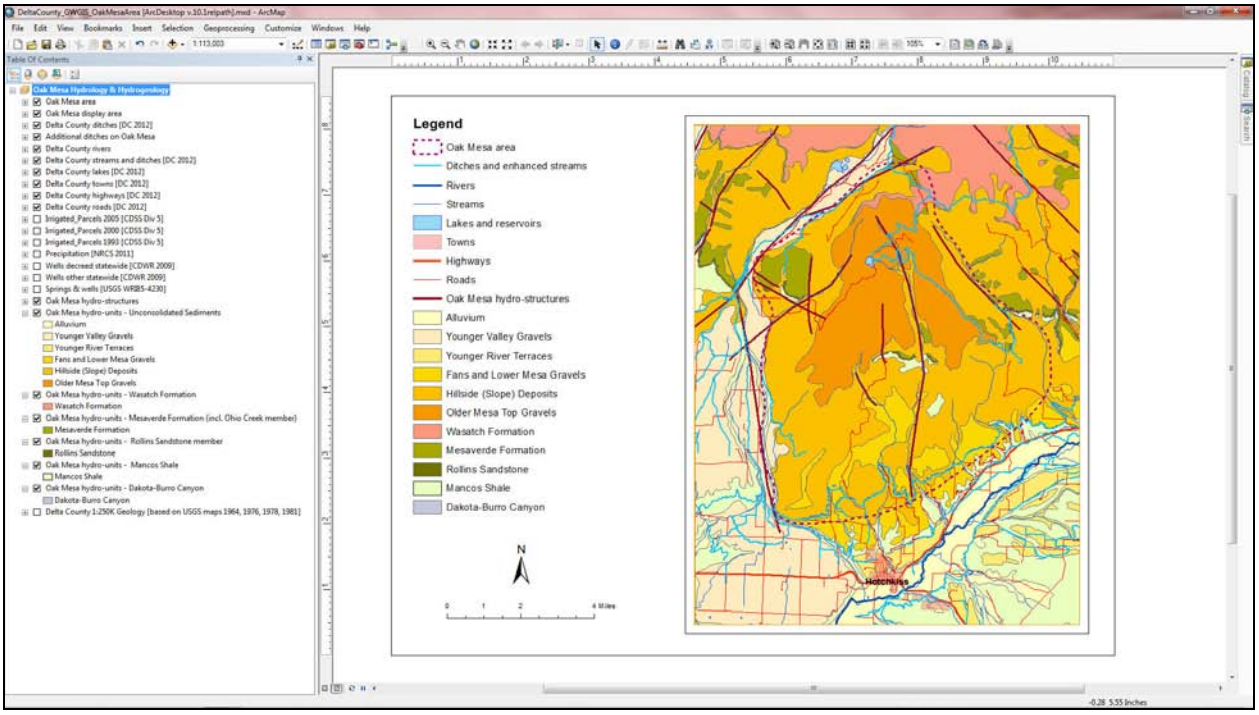

Figure 24. Oak Mesa GIS Map Showing Streams, Ditches and Roads on Top of Hydrogeologic Unconsolidated and Bedrock Units and Hydrogeologic Structures.
(The left display area is the TOC showing all available layers;
the right side of the window is the map display area showing the activated layers.)

Enabling the *Table of Contents* (TOC; the left side of the display in Figures 23 and 24) in ArcGIS provides information on the layers displayed in the *Map Display* area (the right side of the display in Figures 23 and 24). The GIS layers of the Delta County and Oak Mesa 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 25). This additional information can be used to label the features in the map display area.

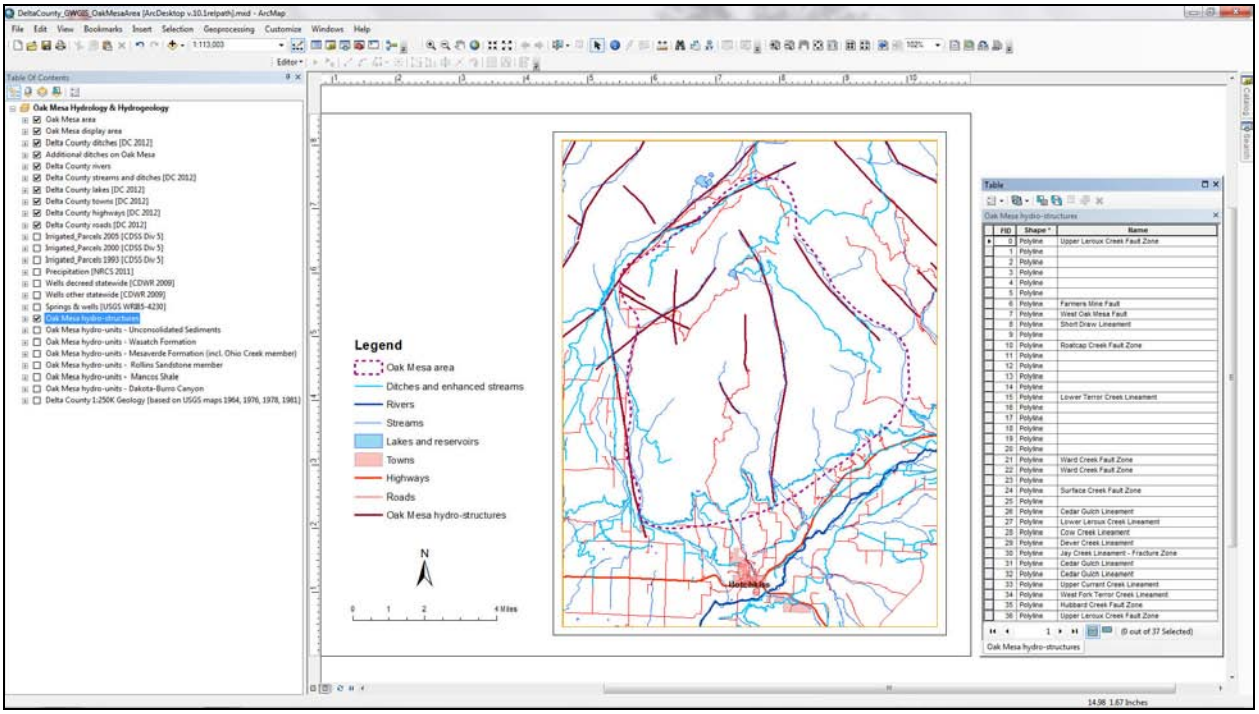

Figure 25. GIS Map Showing the Attribute Table for the Hydro(logic) Structures Layer in the Oak Mesa Area *(right side of figure)*.

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.

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

Delta County and Oak Mesa GIS maps retrieve various files included in six relative-path subdirectories: 1) CDOT; 2) CDSS; 3) Delta_County; 4) Integral; 5) NRCS; and 6) USGS_DEM. The directories reflect the various data sources used for the map. 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 or Oak Mesa area coverage.

The *CDOT* (Colorado Department of Transportation) subdirectory contains the Colorado county boundaries (*counties* files). In this project this layer is primarily used for general orientation purposes. The CDOT GIS data can be downloaded from: *http://apps.coloradodot.info/dataaccess/*.

The *CDSS* subdirectory contains six sets of GIS files and databases downloaded 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 (*Div_4_Irrigated_Lands_1993.mdb*); 2) irrigated areas in CDWR Division 4 on the Western Slope as of 2000 (*Div_4_Irrigated_Lands_2000.mdb*); 3) irrigated areas in CDWR Division 4 on the Western Slope as of 2005 (*Div_4_Irrigated_Lands_2005.mdb*); 4) National Weather Service (NWS) precipitation stations in Colorado (*co_precipstations* files); 5) decreed wells included in the CDWR's Hydrobase (*co_wells_decreed* files); and 6) other wells included in the CDWR's Hydrobase (*co_wells_other* files). The well data reflect the Hydrobase status of July 2009. 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 2005. The CDSS data can be downloaded from: *http://water.state.co.us/DataMaps/Pages/default.aspx#onlinedata.*

The *Delta_County* subdirectory contains selected files received from the Delta County GIS department in June 2012. Coverages used in this project include county boundary, highways, roads, streams and ditches, lakes, irrigation ditches (and enhanced streams), 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. One important ditch for the Oak Mesa study was not included in the county's ditch file: the connection between the Overland Ditch and West Reservoir on Oak Mesa. Our field observations indicated that this ditch can carry significant water and is used to supply West Reservoir from the Overland Ditch. It should be noted that the GIS-based aerial photography (*Ortho* files) 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.

The *Integral* subdirectory contains the databases produced for this project by Integral. It contains various (hydro-)geology files (*OakMesa_Hydrogeol_xxx, OakMesa_hydrostructures, DeltaCounty_Geology, Springs*) and files related to the location of the study area (*OakMesa_DisplayArea, OakMesa_StudyArea*). The *main_streams_dc* files were created to separately show the county's major rivers and are based on Delta County's stream layer. The hydrogeology layers resulted from digitizing and evaluating the 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° x 2° quadrangle geologic maps (scale 1:250,000) (*Tweto and Others, 1976; Tweto and Others, 1978; Whitney, 1981; Williams, 1964)*. The Oak Mesa hydro-structures layer is primarily based on the 1:100,000 scale geologic map of the Paonia and Gunnison area (*Ellis and Others, 1987*).

Selected wells and springs used in a study of the groundwater resources of the North Fork Gunnison River basin have been digitized from a low-quality scanned image of an appendix of the report (*Ackerman and Brooks, 1986*). It should be noted that the location of these wells and springs are approximate and may be inaccurate. During a field reconnaissance in June 2012, a ditch connecting the Overland Ditch with West Reservoir was found to be of importance to the hydrology of Oak Mesa and has been digitized from topographic maps, the Delta County *ortho* files, and Google Earth views (*newditch_OakMesa*).

There are six GIS layers and databases for the hydogeologic units in the Oak Mesa area (*i.e.*, "hydro units" for short) (Figures 11 and 12): 1) a layer showing the Quaternary unconsolidated deposits grouped by their hydrogeological characteristics (*Oak Mesa Hydro Units - Unconsolidated Sediments*; see Figure 24); and 2) five layers each showing the extent of an individual bedrock hydrogeologic unit (*Oak Mesa Geology - Wasatch Formation, Oak Mesa Geology - Mesaverde Formation [incl. Ohio Creek member], Oak Mesa Geology - Rollins Sandstone, Oak Mesa Geology - Mancos Shale, Oak Mesa Geology - Dakota-Burro Canyon*). When all five layers are activated, the GIS map shows top bedrock (see Figure 12).

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 location and name of the 1:24,000 (7.5 minute) quadrangles in Delta County (*quads24k_a_co029*) and the 1:250.000 (2 degree) quadrangles (*quads250k_a_co*), and data 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 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 HESA of the groundwater system of the Oak Mesa area 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 Oak Mesa study area:

1. Quaternary unconsolidated clastic materials, which are predominantly glacial-fluvial outwash plains and terrace gravels (older mesa top gravels and glacial drift) , slope deposits, alluvial fans and bajadas and lower mesa gravels, younger valley gravels and river terraces, and alluvial valley bottom deposits; and
2. Tertiary and Cretaceous bedrock units, including the following potentially water-bearing units: Tertiary Wasatch Formation (Tw); Cretaceous Mesaverde Formation (Kmv), including Ohio Creek, Barren, and Upper and Lower Coal Bearing members (Kmvc), as well as the Rollins Sandstone member (Kmvr); and the Mancos Shale unit (Km), which may act as a thick, poorly transmissive confining layer.

The Quaternary unconsolidated clastic units (Qal, Qgy, Qat, Qs, Qgf, and Qgo), 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. There may be lateral and vertical connection (upward or downward groundwater flow depending on position in the hydrologic system) between the unconsolidated materials and the Tertiary and Cretaceous sedimentary units in the underlying bedrock formations.

Three broad hydrostructures occur in the Oak Mesa area: 1) the northwest-trending Roatcap Creek fault zone and associated en-echelon faults to the east; 2) the northeast-trending Upper Leroux Creek fault zone and en-echelon lineaments such as the Dever Creek lineament; and 3) the north-south-trending Jay Creek lineament-fracture zone and associated en-echelon lineaments such as Lower Leroux Creek and faults such as the west Oak Mesa fault. These hydrostructures function as French drains and are responsible for various springs and groundwater discharge and recharge areas observed in Roatcap, Jay, and Leroux creeks. These hydrostructures move significant quantities of groundwater horizontally and vertically, interconnecting the shallow aquifers with deep bedrock aquifers.

Based on the presence and orientation of various hydrogeologic and hydrostructural units, hydrography and topography, two CSMs in the Oak Mesa study area—Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems; and Regional Bedrock Subsystems—are discussed. Specifically, the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems in the Oak Mesa area are dominated by the Quaternary unconsolidated materials, which receive recharge by infiltration of precipitation (snow and rain in the highest elevations in the north part of Oak Mesa), leaky irrigation ditches (for example, the Overland Ditch), infiltration at reservoir sites (for example, West Reservoir on Oak Mesa), and losing streams, such as the central reaches of Leroux, Cow, Jay, and Roatcap creeks.

Groundwater flow on top of Oak Mesa then moves with topography into Dever Creek to the west, and Jay Creek to the east. In addition, groundwater that flows through the hillslope deposits in the northeast area eventually discharges into Roatcap Creek, which in turn flows through the hillslope deposits in the northwest area, eventually discharging into Cow Creek. In the valley of Jay Creek, the groundwater system flows parallel to the creek. Jay Creek becomes a losing stream about halfway down the mesa, and the stream and shallow groundwater system recharge the Cretaceous Mesaverde Bedrock system at about the Coal Bearing members unit. In the valley of Roatcap Creek, the groundwater system flows parallel to the creek. Roatcap Creek becomes a losing stream about halfway down the valley from the headwaters to the North Fork of the Gunnison River, and the stream and shallow groundwater system recharge the Cretaceous Mesaverde Bedrock system at about the Coal Bearing members units. The groundwater system flows in the valley of Leroux Creek parallel to the creek. Leroux Creek and the Leroux Creek aquifer receive large quantities of water from other bedrock and alluvial aquifers on Grand Mesa, and receive enhanced recharge from the Overland Ditch, Cow Creek, the hillslope materials, high precipitation amounts, and leakage and enhancement from various reservoirs and irrigation ditches. The lower reaches of Leroux, Cow, Jay, and Roatcap creeks are losing streams located along French drains, and are areas of recharge to the regional Wasatch and Mesaverde bedrock aquifers.

The Regional Bedrock Subsystems in the Oak Mesa study area include the following potentially water-bearing units: Tertiary Wasatch Fm (Tw); Cretaceous Mesaverde Formation (Kmv), including Ohio Creek, Barren, and Upper and Lower Coal Bearing members (Kmvc), as well as the Rollins Sandstone member (Kmvr); and the Mancos Shale unit (Km). The bedrock units are variably saturated based on location and proximity to recharge area. The Mesaverde aquifer is partially saturated in the south and central areas of Oak Mesa, as evidenced by the water levels recorded in well logs. The water table appears to be above the Upper and Lower Coal Bearing units, which suggests that dewatering will be necessary. Groundwater flows vertically, then horizontally to the north along hydrostructures that become part of the regional groundwater flow system. The groundwater flow direction in the regional bedrock systems is from south to north beneath Oak Mesa and Grand Mesa, and is away from the coal mining activities, drinking water supplies, and Delta County in general.

The main land use in the Oak Mesa area is agricultural, and includes irrigated land cultivation and cattle grazing. The Oak Mesa study area consists primarily of mesa top, hillslope, bottomland, and terraces, limiting the irrigated areas to the top and lower portions of the

subsystems where there are a number of unlined and leaky irrigation ditches that are excavated in mostly unconsolidated Quaternary deposits. The water leaking from the ditches and the return flow from irrigated lands may recharge the underlying groundwater system, forming a local groundwater mound or divide, and may contribute significantly to the local water balance, increase the water table elevation, and alter groundwater flow patterns.

The hydrology of a natural groundwater hydrologic system will be altered by the construction and operation of the proposed underground coal mining operation. During dewatering, the coal mine may act as a very large well, drawing water in towards it from surrounding areas. Depending on management strategies for water disposal, water levels may increase in other locations. Groundwater levels in the bedrock systems will also be altered in the amount, velocity, storage, and direction of the local groundwater system and related regional groundwater levels and discharges. Changes to the natural groundwater system may have unintended ecological, geo-hydrological, and legal consequences.

The mesa top and upper hillslope parts of the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystem are least likely to be affected by the mining operations, as they are located in the recharge area and shallow groundwater flow system above the bedrock dewatering zone. However, the amount of groundwater discharge from the bedrock to the shallow aquifers in the lower hillslope and valley bottom areas in the Leroux Creek drainage may be reduced by dewatering action, which could affect the Hotchkiss water supply. In addition, significant amounts of alluvial water in both Jay and Roatcap creeks may be reduced due to mine dewatering.

The GIS maps resulting from this study provide for use in planning and management of groundwater resources in the Oak Mesa 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 Oak Mesa study were prepared using ArcView™ version 8.3 and Arc-Desktop™ version 10.1 (ESRI®, Redlands, California).

Two multi-layer GIS maps have been prepared for this study: 1) a map with hydrologic and hydrogeologic features of Delta County; and 2) a map with hydrologic and hydrogeologic features of the Oak Mesa 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 and Oak Mesa maps contain three types of geographic information: 1) general geographic .information (county border, roads, towns) 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, springs, and wells.

5 REFERENCES

Ackerman, D.J., and T. Brooks. 1986. *Reconnaissance of Ground-Water Resources in the North Fork Gunnison River Basin, Southwestern Colorado*. U.S. Geological Survey. Water Resources Investigations 85-4230.

Brooks, T. 1983. *Hydrology and subsidence potential of proposed coal-lease tracts in Delta County, Colorado.* U.S. Geological Survey. Water Resources Investigations 83-4069.

Brooks, T., and D.J. Ackerman. 1985. *Reconnaissance of Ground-Water Resources in the Lower Gunnison River Basin, Southwestern Colorado*. U.S. Geological Survey. Water Resources Investigations 84-4185.

Cordilleran Compliance Services, Inc. 2002. *Hydrogeology of the South Flank of the Grand Mesa in the Vicinity of Cedaredge and Paonia, Delta County, Colorado*. Prepared for Gunnison Energy Corporation.

Daly, C., and G.L. Johnson. 1999. PRISM *Spatial Climate Layers: An Overview of the USDA-NRCS Spatial Climate Mapping Project*. PRISM Guide Book. PRISM Group, Oregon State University in cooperation with USDA-NRCS.

Davis, S.N., and R.J.M. DeWiest. 1966. *Hydrogeology*. John Wiley & Sons, New York.

Day, W.C., G.N. Green, D.H. Knepper, Jr., and R.C. Phillips. 1999. *Mineral Resource Assessment Area, Southwestern Colorado and Digital Data for the Leadville, Montrose, Durango, and Colorado Parts of the Grand Junction, Moab, and Cortez 1° X 2° Geologic Maps*'. U.S. Geological Survey. Open-File Report 99-427.

Ellis, M.S., D.L. Gaskill, and C.R. Dunrud. 1987. *Geologic Map of the Paonia and Gunnison Area, Delta and Gunnison Counties, Colorado*. U.S. Geological Survey. Coal Investigations Map C-109.

Freethey, G.W., and G.E. Cordy. 1991. *Geohydrology of Mesozoic Rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, Excluding the San Juan Basin*. U.S. Geological Survey. Professional Paper 1411-C.

Geldon, A.L. 2003. *Hydrologic Properties and Ground-Water Flow Systems of the Paleozoic Rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, Excluding the San Juan Basin*. U.S. Geological Survey. Professional Paper 1411-B.

Hail, W. J., Jr. 1972a. *Reconnaissance Geologic Map of the Cedaredge Area, Delta County, Colorado*. U.S. Geological Survey. IMAP 697.

Hail, W. J., Jr. 1972b. *Reconnaissance Geologic Map of the Hotchkiss Area, Delta and Montrose Counties*, Colorado. U.S. Geological Survey. IMAP 698.

Kolm, K. E., P.K.M. van der Heijde, J.S. Downey, and E.D. Gutentag. 1996. *Conceptualization and Characterization of Ground-Water Systems*. In: Subsurface Fluid-Flow (Ground Water and Vadose Zone) Modeling, ASTM STP 1288, J. D. Ritchey and J. O. Rumbaugh, eds., American Society for Testing and Materials, West Conshohocken, PA.

Robson, S.G., and E.R. Banta. 1995. Groundwater Atlas of the United States: Colorado Plateau Aquifer. U.S. Geological Survey, HA 730-C.

Topper, R., K.L. Spray, W.H. Bellis, J.L. Hamilton, and P.E. Barkmann, 2003. *Ground Water Atlas of Colorado*. Colorado Geological Survey, Special Publication 53.

Tweto, O., R.H. Moench, and J.C. Reed. 1978. *Geologic Map of the Leadville 1 Degree x 2 Degrees Quadrangle, Northwestern Colorado*. U.S. Geological Survey. Miscellaneous Investigations Series Map I-999, scale 1:250000.

Tweto, O, T.A. Steven, W.J. Hail, and R.H. Moench. 1976. *Preliminary Geologic Map of the Montrose 1 Degree x 2 Degrees Quadrangle, Northwestern Colorado*. U.S. Geological Survey. Miscellaneous Field Studies Map MF-761, scale 1:250000.

Watts, K.R., 2008. *Availability, Sustainability, and Suitability of Ground Water, Rogers Mesa, Delta County, Colorado—Types of Analyses and Data for Use in Subdivision Water-supply Reports*. U.S. Geological Survey. Scientific Investigation Report 2008–5020.

Whitney, J.W. 1981. *Surficial Geologic Map of the Grand Junction 1 Degree x 2 Degrees Quadrangle, Colorado and Utah*. U.S. Geological Survey. Miscellaneous Investigations Series Map I-1289, scale 1:250000.

Williams, P.L. 1964. *Geology, Structure, and Uranium Deposits of the Moab Quadrangle, Colorado and Utah*. U.S. Geological Survey. Miscellaneous Geologic Investigations Map I-360, scale 1:250000.

Appendix 1. Climate Data for the Oak Mesa Area, Delta County

(Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	24.0	24.2	32.4	39.4	50.1	62.1	67.9	64.1	56.4	44.8	33.7	23.5	43.5
Average Min. Temperature (F)	-1.1	-0.5	6.5	14.9	25.3	34.3	40.4	38.6	30.7	22.2	11.0	1.4	18.6
Average (Mean) Temperature (F)	11.4	11.8	19.1	27.2	37.8	48.2	54.2	51.3	43.6	33.5	22.4	12.5	31.1
Average Total Precipitation (in.)	3.02	2.80	3.89	3.03	2.19	1.31	2.26	2.52	2.36	2.98	2.93	3.50	32.79
Average Total Snow Fall (in.)	32.0	38.2	41.9	24.2	7.2	0.4	0.0	0.0	1.4	12.6	18.2	38.4	214.5
Average Snow Depth (in.)	46	55	65	46	18	0	0	0	0	1	11	36	23

Table 1. Monthly Climate Summary for Bonham Reservoir, Colorado [station 050825] for period 7/1/1963 to 5/31/2012.

	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 2. Monthly Climate Summary for Cedaredge, Colorado [station 051440] for period 1/1/1898 to 5/31/1994.

	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 3. Monthly Climate Summary for Delta, Colorado [station 052192] for period 1/1/1893 to 12/31/1999.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bonham Reservoir (32.79" annually)	3.41	3.7	4.74	3.57	2.75	1.40	2.29	2.48	2.29	3.15	3.94	4.01	37.75
Cedaredge (12.07" annually)	1.10	0.93	1.25	1.08	1.18	0.64	0.88	1.14	1.27	1.55	1.30	1.08	13.39
Delta (8.01" annually)	0.51	0.37	0.59	0.59	0.71	0.48	0.74	0.84	0.97	1.00	0.70	0.47	7.97

Table 4. Average Total Precipitation (in.) for period 1/1/1971 to 12/31/2000