GROUNDWATER SYSTEMS IN DELTA COUNTY, COLORADO: NORTH FORK VALLEY AND TERRACES AREA

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

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Front Page: Orchards on the terraces of the North Fork Valley near Paonia. (June 2012).

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1 INTRODUCTION

Under an agreement with Delta County, Colorado, Hydrologic Systems Analysis LLC (HSA) of Golden, Colorado, in conjunction with Heath Hydrology, Inc. (HHI) of Boulder, Colorado, was tasked to perform a study of the groundwater resources of the valley and terraces of the Upper North Fork River area from Hotchkiss to northeast of Paonia in Delta County, Colorado (Figure 1). The delineation of the study area is based on the nature and extent of the major hydrogeological systems present and some water resources related land use considerations (Figure 2). The study area is located in the North Fork and Upper Gunnison watersheds and roughly coincide with the Delta County water planning areas 1h, 1g, 1i, 1j, 1k, 3a, 3b, 3d, and 4c, located in the North Fork watershed (Figure 1 and 2). The study area is to the southeast and adjacent to the previously conducted Oak Mesa groundwater study (*Kolm and van der Heijde, 2012*) (Figure 1 and 3). It should be noted that for display purposes in this report a rectangular area is used, referred to as *Display Area*, which includes both the North Fork study area and the Oak Mesa study area (Figure 3). However, all analyses regarding the groundwater systems in this report are focused on the irregular shaped *North Fork Valley and Terraces (NFVT) Study Area*.

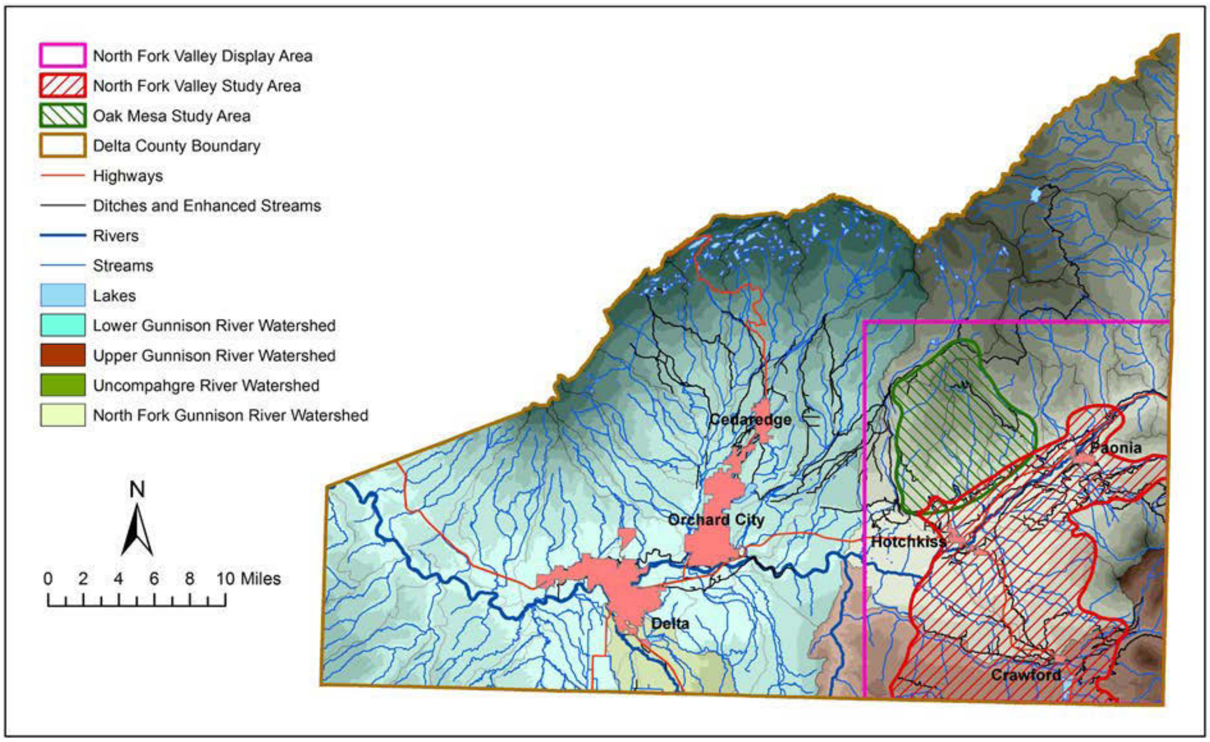

Figure 1. Location of the North Fork Valley and Terraces and the Oak Mesa Study Areas in Relationship to the Major Watersheds, Delta County, Colorado.

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

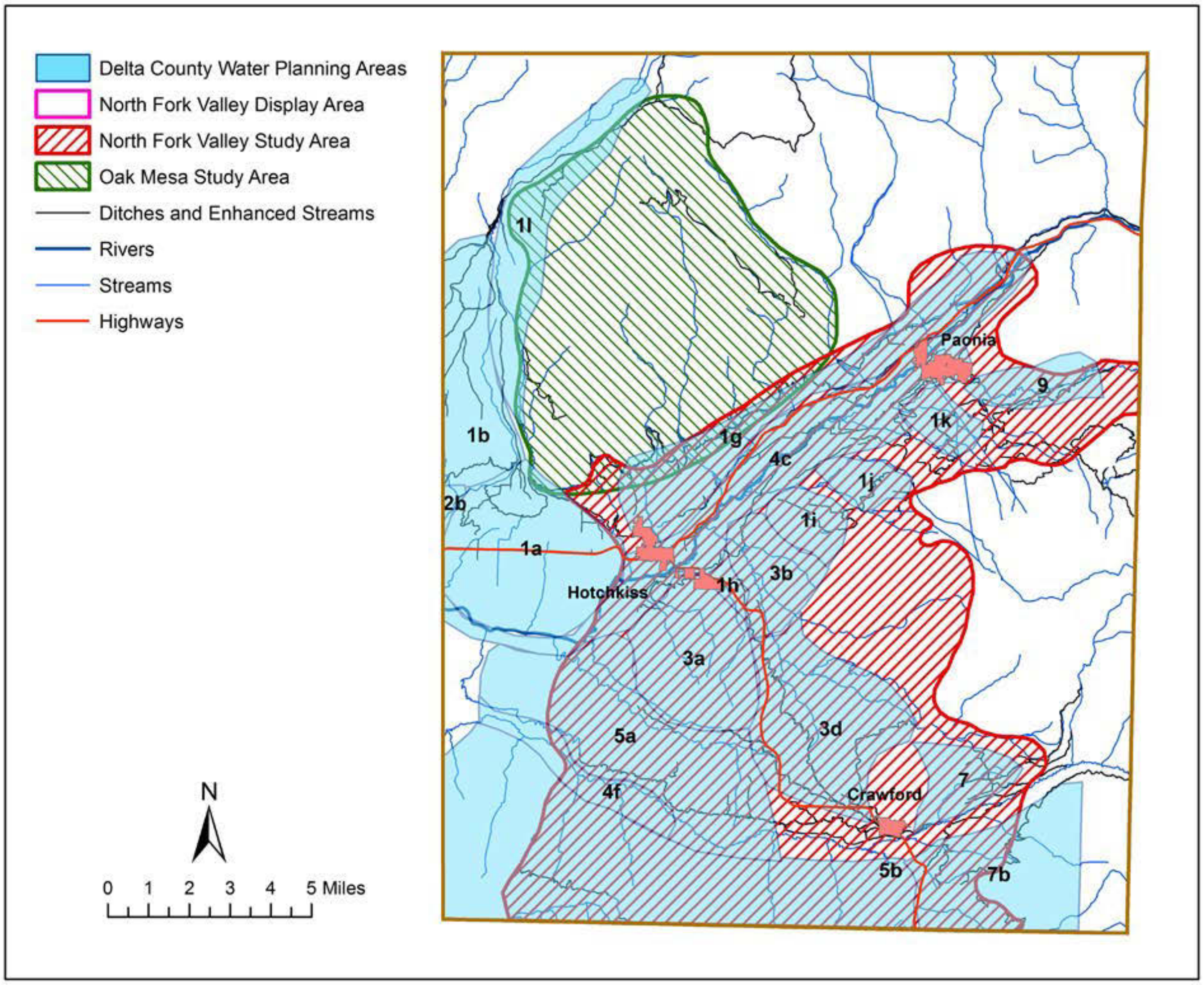

Figure 2. North Fork Valley Display Area, Showing the Water Planning Areas and the Oak Mesa and the North Fork Valley and Terraces Study Areas.

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

The North Fork Valley and Terraces groundwater study included the following tasks:

1. Conduct a comprehensive HESA and formulate relevant conceptual hydrologic site models to provide the physical framework for the availability, sustainability and vulnerability assessments;
2. Refine the hydrogeologic nomenclature developed in the previous study;

3. Digitize existing geologic maps – to the extent and detail necessary for the project – and converting them to hydrogeologic system layers in the GIS, including layers showing hydrogeologic units and characteristic stacks of such units, and hydrostructures; and
4. Adapt additional hydrological and other GIS maps and databases needed to evaluate the groundwater resources in the county; these databases will contain data from various public domain sources.

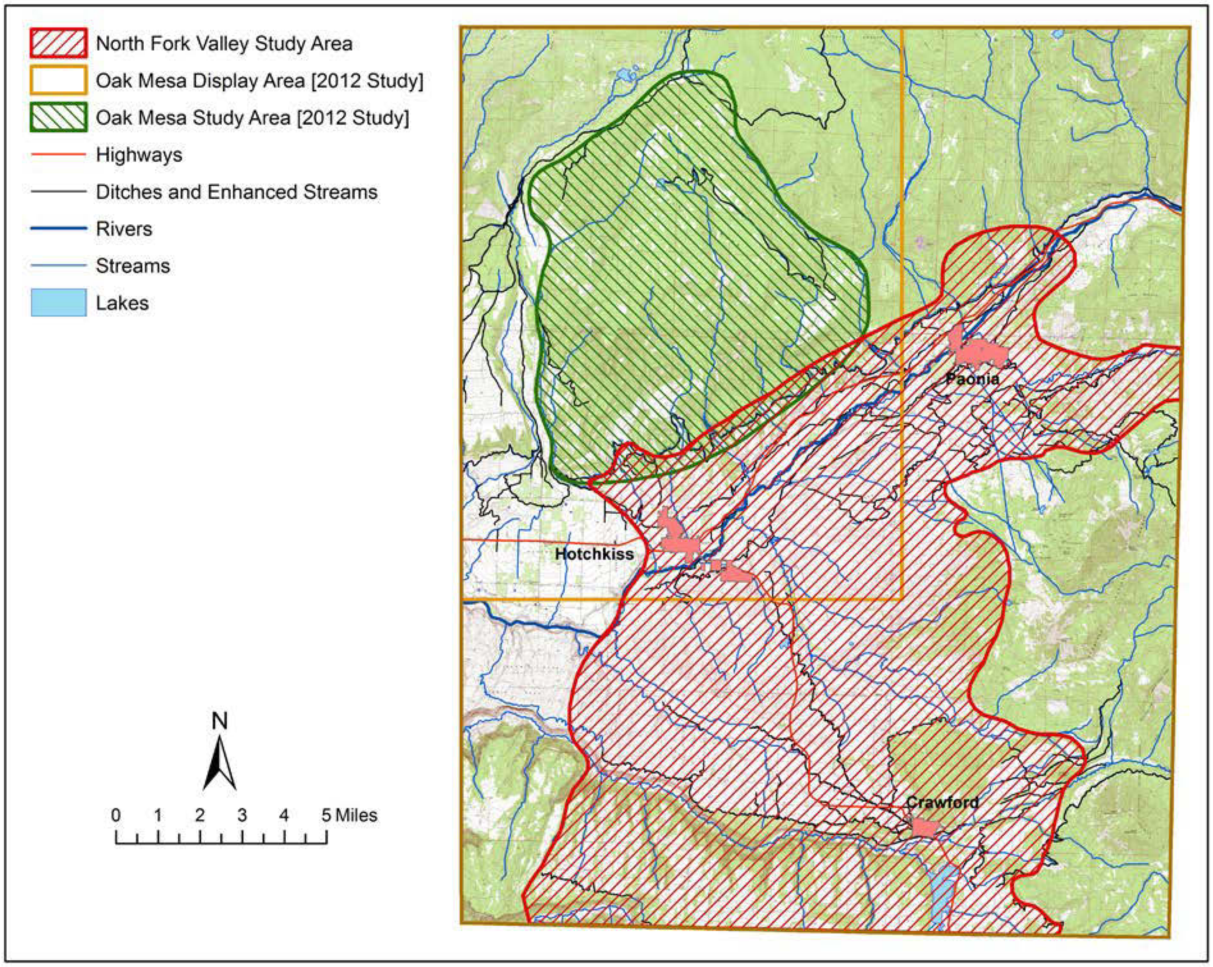

Figure 3. North Fork Valley Display Area, Showing the Oak Mesa and the North Fork Valley and Terraces Study Areas and the Oak Mesa Display Area.

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

2 DEVELOPMENT OF CONCEPTUAL SITE MODELS OF THE NORTH FORK VALLEY AND TERRACES (NFVT) STUDY AREA

HESA is an approach used to conceptualize and characterize relevant features of hydrologic and environmental systems, integrating relevant considerations of climate, topography, geomorphology, groundwater and surface water hydrology, geology, ecosystem structure and function, and the human activities associated with these systems into a holistic, three-dimensional dynamic conceptual site model (CSM). This watershed-based, hierarchical approach is described by Kolm and others (*1996*) and codified in ASTM D5979 Standard Guide for Conceptualization and Characterization of Ground Water Systems *(ASTM 1996(2008))*. The CSM of the NFVT 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 NFVT 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 proposed oil and gas activities is included.

2.1 Climate

The climate in the study area has both local and regional components and includes effects of elevation and slope aspect (*i.e.*, steepness and orientation with respect to the prevailing winds and sun exposure). The presence of Grand Mesa and West Elk Mountains further influences the climate at the lower elevations by orographic precipitation effects, causing enhanced precipitation on the windward side and local and regional rain shadows on the leeward sides. From the relevant weather stations of the National Weather Service (NWS) Cooperative Network (COOP) near the study area Paonia 1SW (COOP 056306), located south of the town of Paonia, has been selected as representative for the study area (Figure 4). Table 1 shows monthly and annual long-term averages for temperature, precipitation, snowfall and snow depth (*WRCC, 2013*); Figure 5 summarizes the average total monthly precipitation (*i.e.*, rain and snowfall SWE - Snow Water Equivalent), snowfall (*i.e.*, thickness of freshly fallen snow), and snow depth (*i.e.*, snow pack) for Paonia for the period 1883 -2013. Note that the long-term average annual precipitation of 15.4 inches for the period 1883-2013 does not differ much from the average annual precipitation of 15.2 inches for the period 1981-2010 (*WRCC, 2013*).

The NWS data were used by the Natural Resources Conservation Service (NRCS) to prepare a map of spatially distributed precipitation corrected for elevation (see Figure 6). As these data sources show, there is a significant precipitation gradient in the area from about 45 inches annually at the top of Grand Mesa and 30 inches on Mount Lamborn to about 16 inches near Paonia and 12 inches near Hotchkiss.

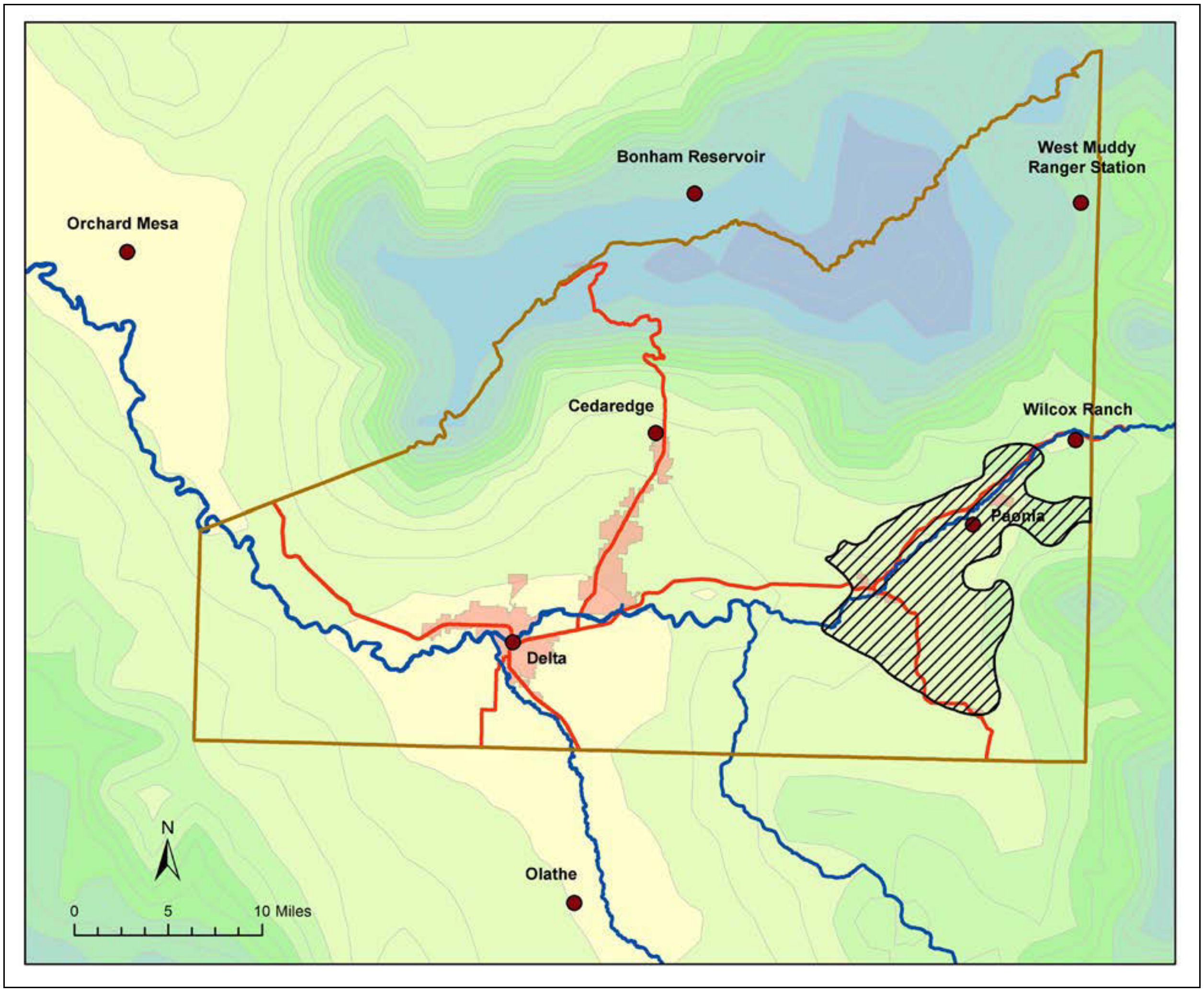

Figure 4. Location of NWS/COOP Weather Stations in and near Delta County.

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

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	38.6	44.9	53.9	63.0	73.0	83.6	89.2	86.5	78.1	66.6	52.4	40.2	64.2
Average Min. Temperature (F)	13.8	20.4	27.5	33.9	41.6	49.3	56.1	54.7	46.8	36.5	26.1	16.2	35.2
Average (Mean) Temperature (F)	26.1	32,6	40.7	48.5	57.3	66.4	72.7	70.6	62.5	51.6	39.3	28.3	49.7
Average Total Precipitation (in.)	1.20	1.19	1.46	1.34	1.37	0.75	1.07	1.33	1.48	1.60	1.26	1.33	15.39
Average Total Snow Fall (in.)	11.9	9.0	6.3	2.4	0.2	0.0	0.0	0.0	0.1	0.8	4.7	11.9	47.1
Average Snow Depth (in.)	4	3	0	0	0	0	0	0	0	0	0	2	1

Table 1. Average Maximum, Minimum and Mean Monthly and Annual Temperature, and Average Monthly and Annual Precipitation, Snow Fall and Snow Depth for Paonia 1 SW (0506306) for period 1/1/1893 to 3/31/2013. (Source: Western Regional Climate Center (WRCC), Desert Research Institute, Reno, Nevada).

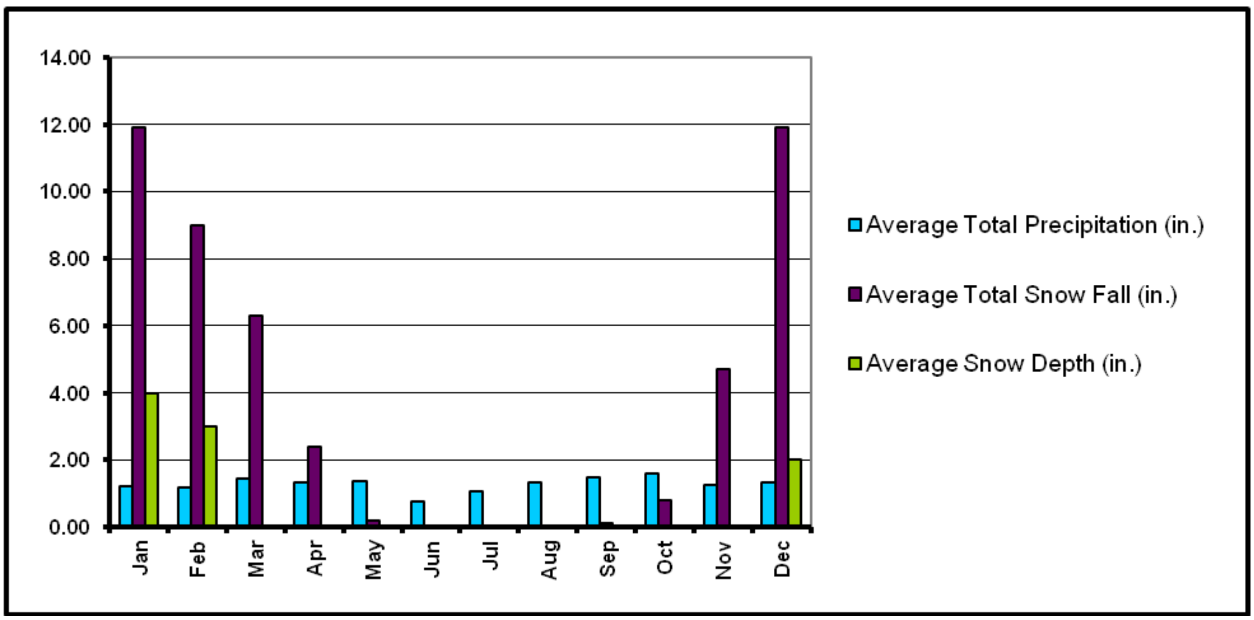

Figure 5. Average Monthly Precipitation, Snow Fall and Snow Depth for Paonia 1 SW (0506306) for period 1/1/1893 to 3/31/2013. (Source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

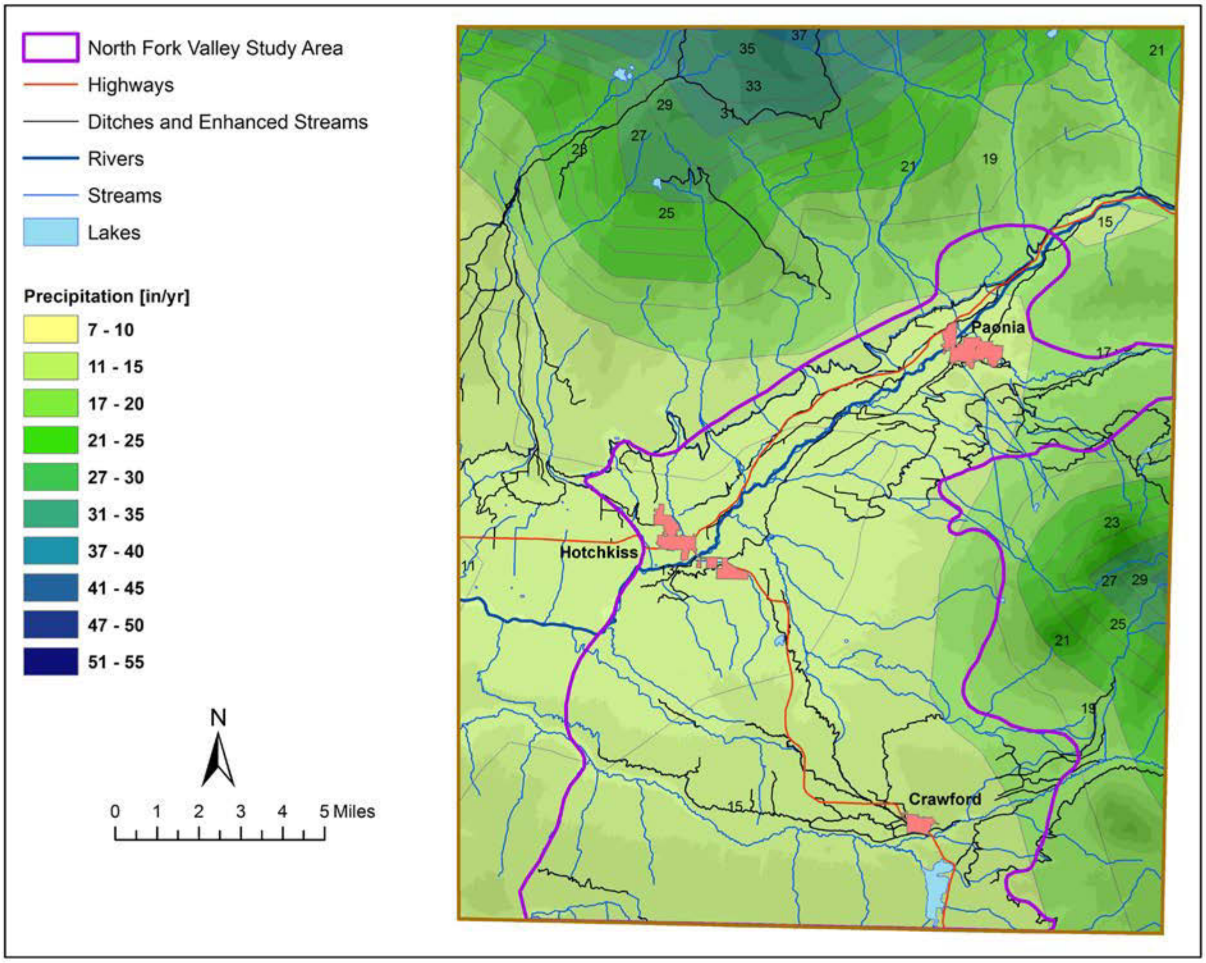

Figure 6. Spatial Distribution of the Average Annual Precipitation in the NFVT Area, Delta County, Colorado (Source: Natural Resources Conservation Service 2011).

2.2 Topography and Geomorphology

The surface elevation in the NFVT study area ranges from about 1,600 m (≈5,200 ft) in the North Fork valley near Hotchkiss to about 2,000 m (≈6,500 ft) on the terraces and mesas along the North Fork and its tributaries (Figure 7). The topography of the study area has three distinct terrains: 1) steeply sloping to gently rolling, gullied bedrock (mostly shale) uplands; 2) poorly dissected, connected and disconnected, continuous and discontinuous hillslope fans and mass wasting features, and alluvial terraces; and 3) continuous alluvial valley bottoms.

On the north side of the North Fork Valley, the fans, mass wasting features, and alluvial terraces are separated by fractured-controlled drainages derived from Grand Mesa. Each of these features functions as separated systems and are not connected across the drainages. On the south side of the North Fork Valley, including Lamborn and Stewart Mesas, the fans, mass wasting features, and alluvial terraces are dissected by local drainages derived from the West Elk Mountains. Each of these features also functions as separated systems and are not connected across the drainages. The effects of the dissection on the groundwater systems will be discussed in the Groundwater System Conceptual Site Models sections.

The deeper bedrock groundwater systems, if not topographically dissected by the surficial processes, will be continuous and regional in nature. Examples of these regional systems are observed in sedimentary bedrock underlying the study area, 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. Most of the alluvial terraces, fans, and river bottoms in the study area are isolated topographically, which causes discrete and localized groundwater systems and can result in discrete and localized springs.

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

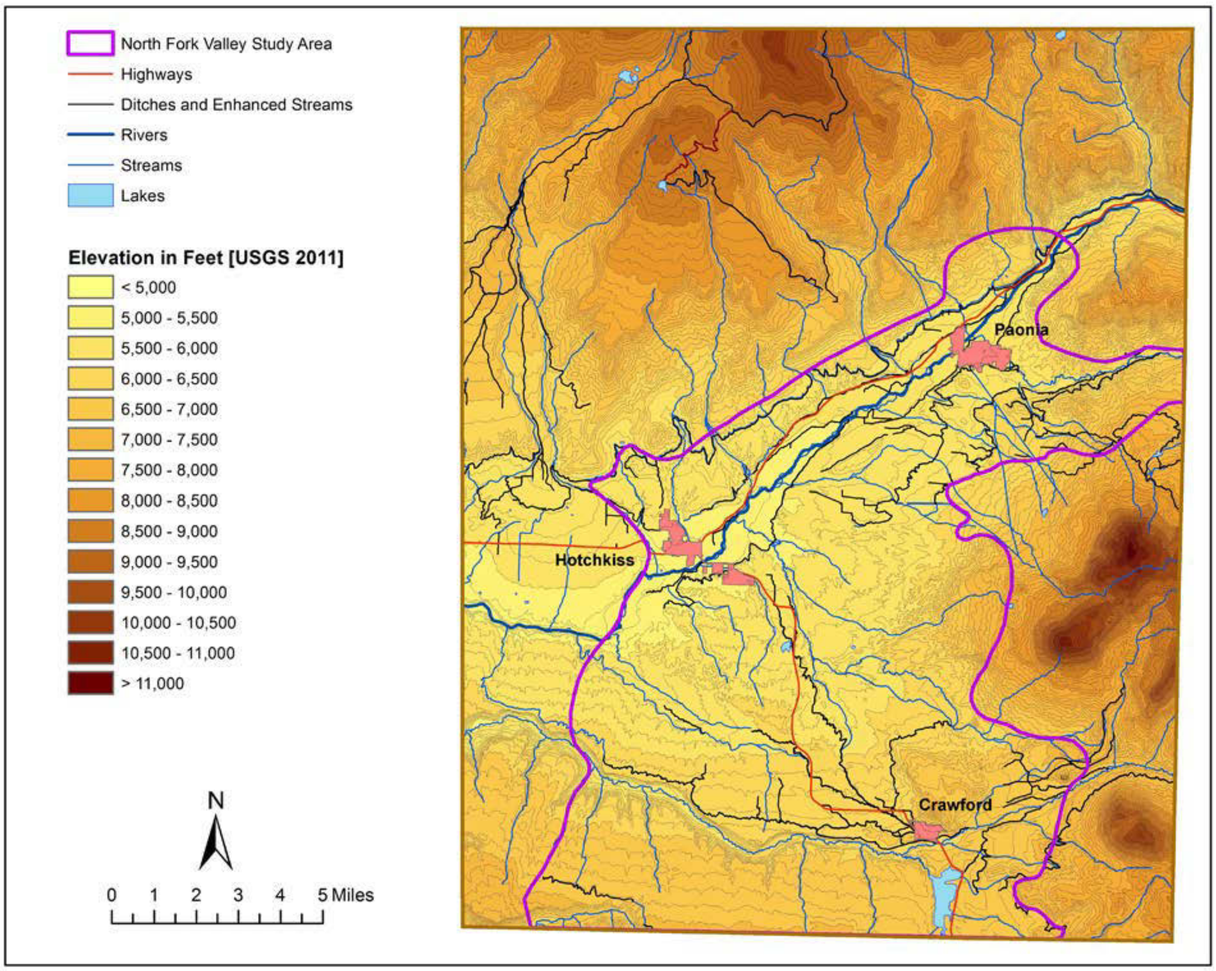

Figure 7. Topography in the NFVT Area.
(Sources: Natural Resources Conservation Service 2011; Delta County 2011).

2.3 Surface Water Characteristics and Springs

The NFVT study area contains parts of two major watersheds: North Fork and Smith Fork, and various tributaries, including Minnesota, German, Reynolds, Bell, McDonald, and Cottonwood Creeks, Alum Gulch, and the lower portions of Leroux Creek, Jay Creek, Roatcap Creek, and Terror Creek (Figure 8). Streams can be gaining (from groundwater) or losing (to groundwater), dependent on local hydrology and time of year. For example, Minnesota Creek and Cottonwood Creek are gaining streams in their upper reaches where springs discharge from the gravels above the contact between the Tertiary intrusions and the Mancos Shale. In the central reaches of these streams, surface water most likely enters (recharges) the alluvium (Qal) along the river and may recharge underlying bedrock, resulting in loosing stretches of these streams. The gaining and losing dynamics of these streams is seasonal, with bank full conditions occurring during the spring runoff, and during monsoon rains resulting in losing conditions, and low water conditions occurring during the rest of the year resulting in gaining conditions. In the lower reaches of these streams near the confluence with the North Fork, the streams would be primarily gaining as ground water would be discharging from the alluvial aquifer back into the stream. There would be a net loss due to well use and irrigation evapotranspiration.

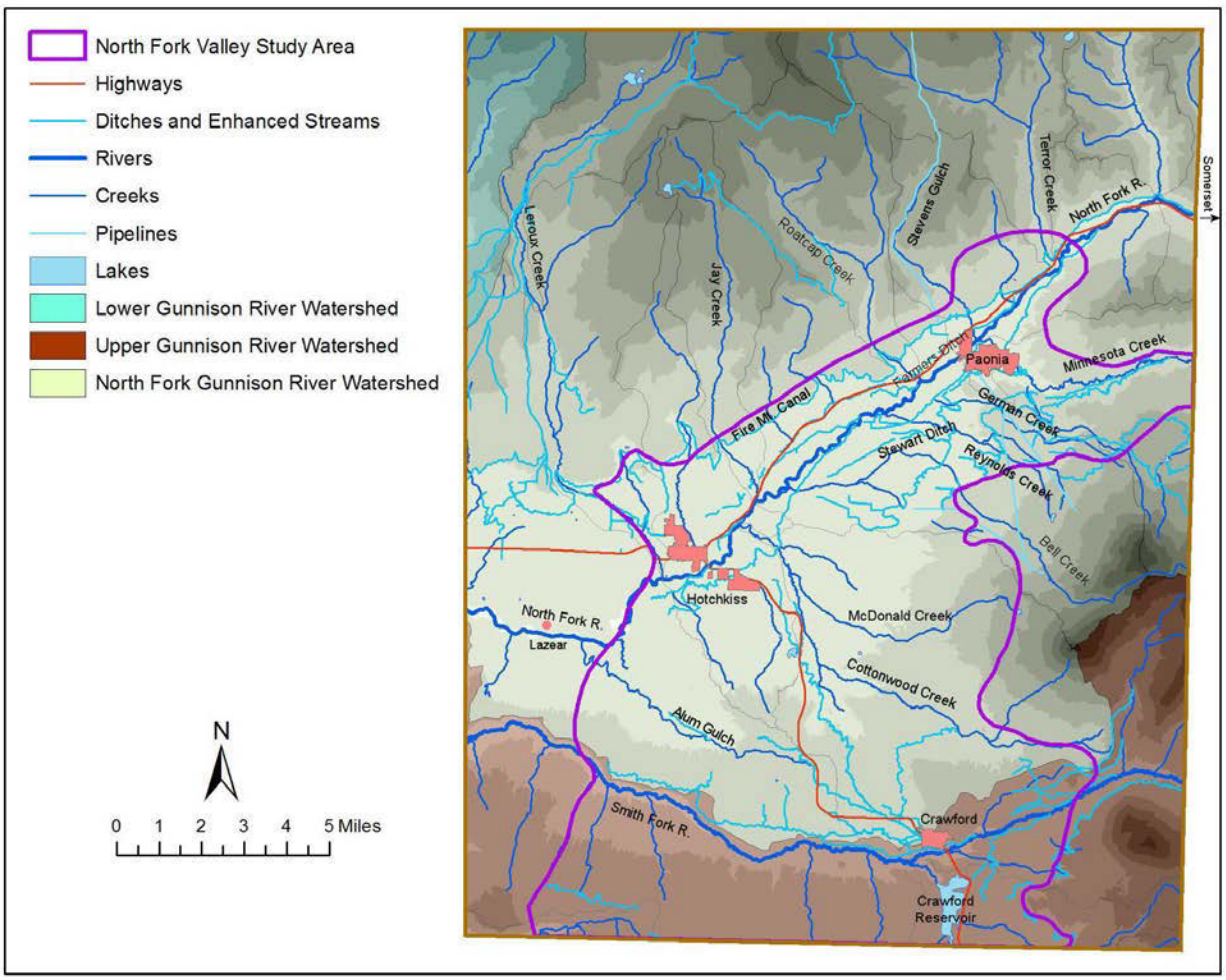

Figure 8. Watersheds, Streams and Ditches in the NFVT Area.
(Sources: Natural Resources Conservation Service 2011; Delta County 2011).

The North Fork River is generally a losing river in the upper reaches of the study area below Somerset due to ditch diversions – specifically into Fire Mountain Canal, irrigation practices, and groundwater recharge to the alluvial aquifer (Qal) (Figure 9). The river is showing a significant loss of streamflow by Paonia (Figure 9). The North Fork River becomes gaining in the reaches near Hotchkiss due to the pinching out of the alluvial system and the added ground water and surface water from Rogers Mesa and the Leroux Creek hydrologic system (see Lazear hydrograph in Figure 9). Groundwater flow back to the River is driven by groundwater recharge in nearby alluvium and upland alluvial terraces from infiltration of precipitation, leaky irrigation ditches, and flood irrigation water, and loosing stretches of tributaries along the edges of the modern alluvial valley. The North Fork may be locally gaining or losing due to local irrigation dynamics, and seasonality of river stage (spring flooding and monsoon storm runoff verses autumn low stream flow).

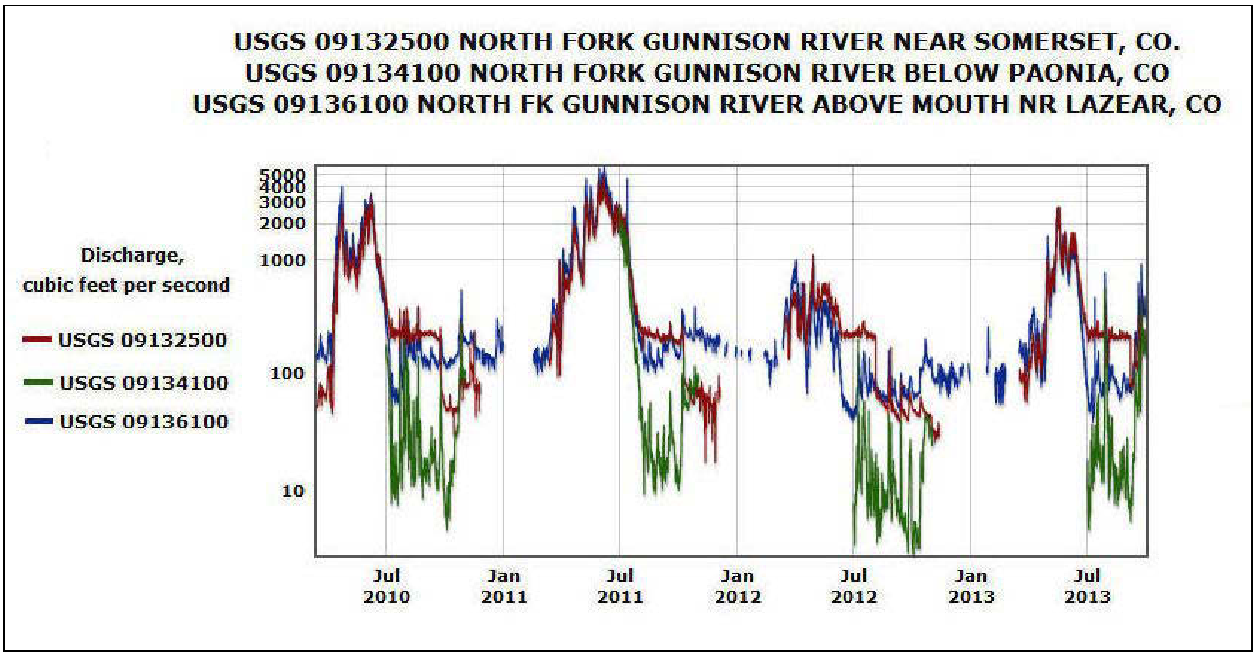

Figure 9. Hydrograph Analysis of Surface Water Stations along the North Fork River [downloaded from USGS National Water Information System, 09/30/2013; Note that for station 09134100, only seasonal records are available).

There are three categories of springs that are identified on the older USGS maps and in the water rights records in Delta County (Figures 10 and 11): 1) Bedrock controlled/derived; 2) Gravel/Shale interface control/derived; and 3) Gravels derived with topographic and geomorphic control. The Bedrock controlled/derived springs are located on the south side of the study area at or near the Tmi/Km interfaces, or in nearby alluvial/glacial gravels where the Tertiary Intrusive bedrock (Tmi), which is the fractured crystalline aquifer, abuts against the Cretaceous Mancos Shale (Km), which is a confining unit, forcing groundwater to the surface (Figure 11). The Gravel/Shale interface springs (Figure 11) are located at the Qs/Km interfaces along drainages or the edges of mesas where the alluvial fans (Qgf) and mass wasting materials (Qs), which are the potential unconsolidated aquifers, abut against the Cretaceous Mancos Shale (Km), which is a confining unit, forcing groundwater to the surface (Figure 11). The Gravels derived with topographic and geomorphic control springs (Figure 11) are located in the modern alluvium (Qal) and alluvial terraces (Qat). These hydrogeologic units will be discussed in section 2.4.

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

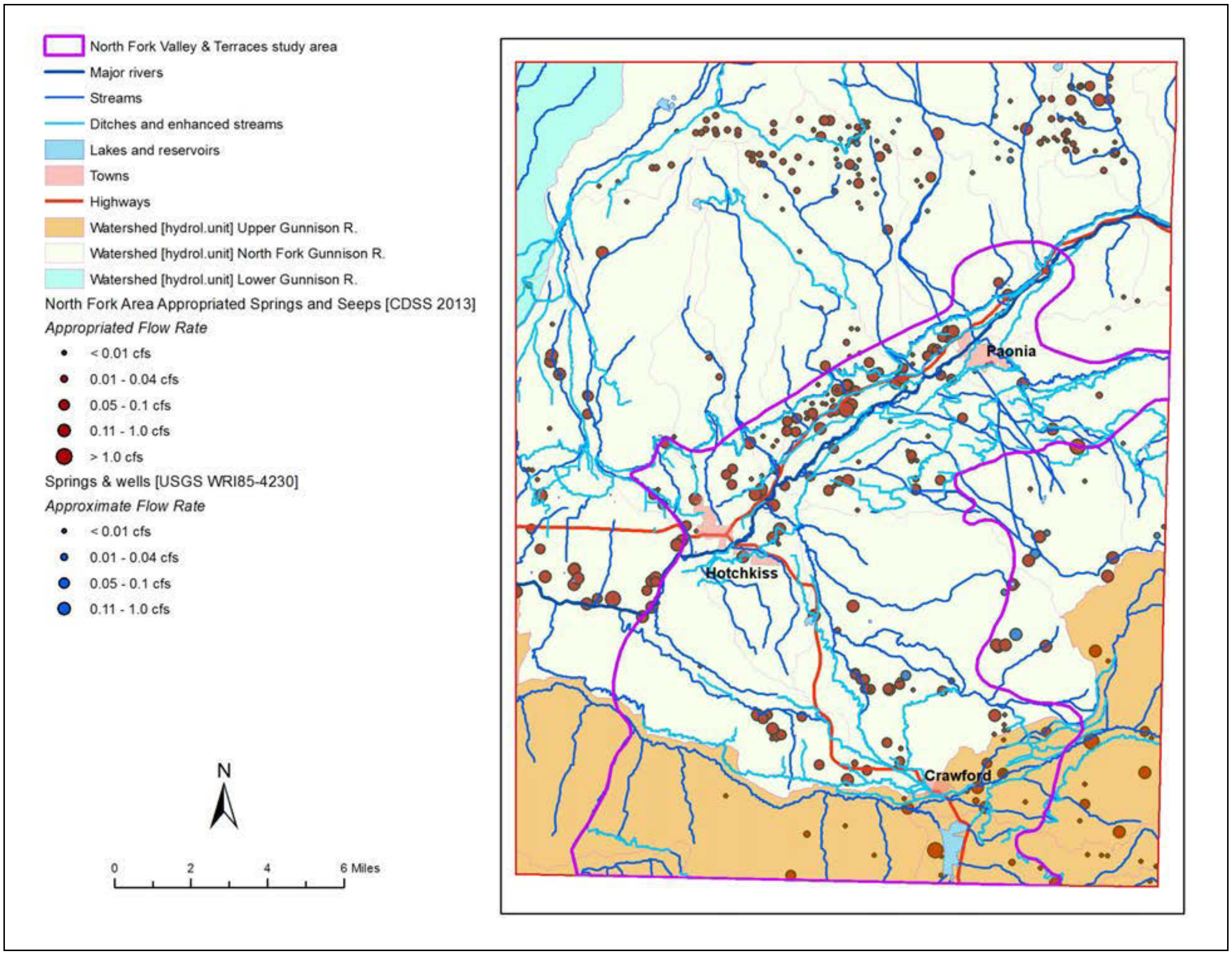

Figure 10. Springs and Seeps in Relationship to Streams and Irrigation Ditches in the NFVT Area. (Sources: USGS 1986; CDSS 2013; see Appendix 1).

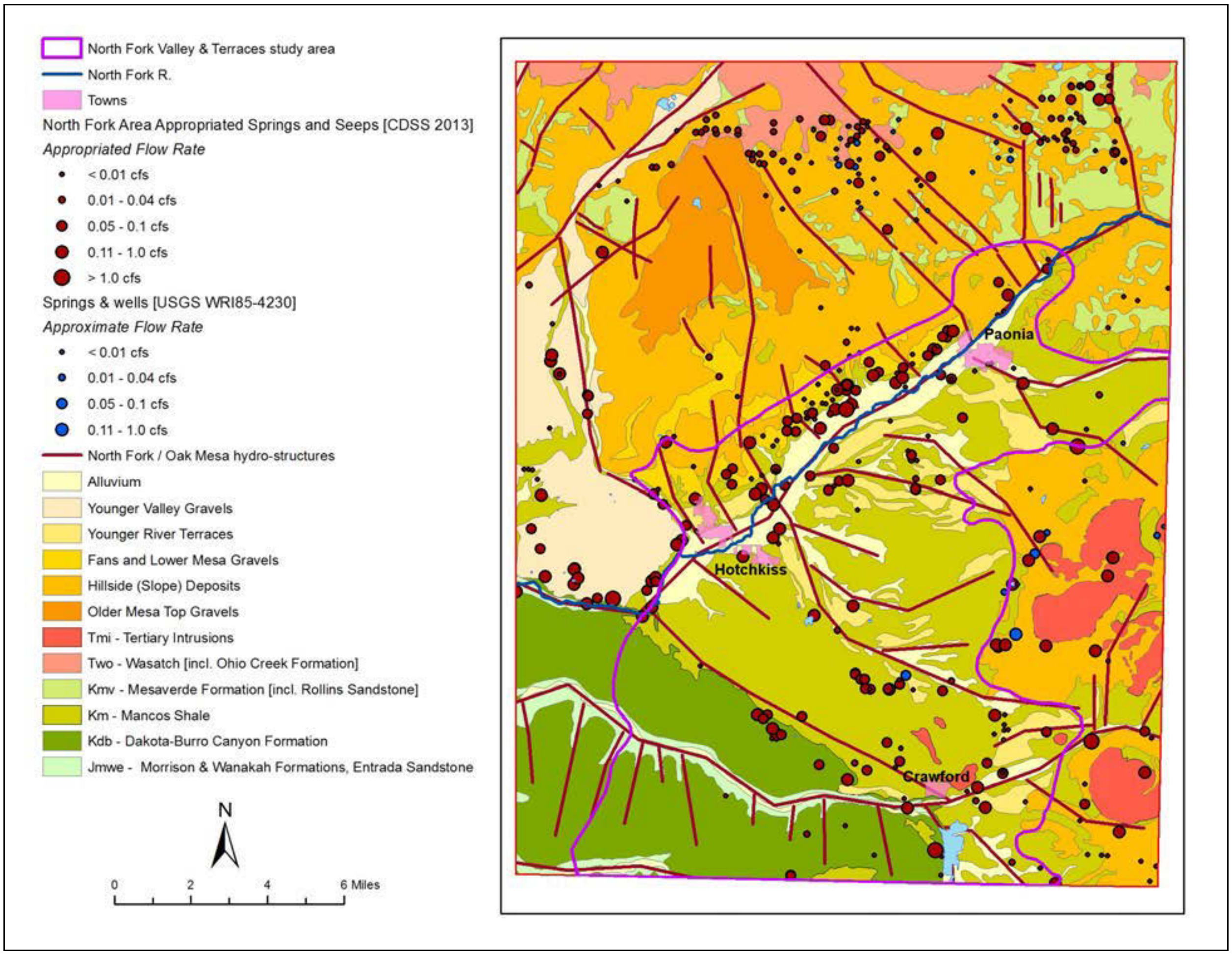

Figure 11. Springs and Seeps in Relationship to the Hydrogeological Units in the NFVT Area. (Sources: USGS 1986; CDSS 2013; see Appendix 1).

The extensive network of ditches has been inventoried by Delta County (Figure 10; see Section 3 for details). Generally, some ditches flow more or less continuously, at least during part of the year, others are only used when fields are being irrigated. Some ditch alignments coincide with stream sections, resulting in so-called "enhanced streamflows" or "enhanced streams." Other ditch alignments contour throughout the landscape, and affect the various streams and mesas that are traversed. Most ditches are unlined, and leak water into the subsurface. More modern practices of piping have minimized this water loss. Wetlands and phreatophyte vegetation are indicators of groundwater discharge to the land surface. The irrigation ditches located on the terraces and along stream valleys often have wetlands, phreatophytes and seeps, indicative of leaky, unlined ditch perimeters, which can be a source of significant groundwater recharge to a hydrogeologic unit that may naturally be dry in normal conditions, but may be an aquifer due to long time ditch leakance into the hydrologic system. Given this situation, there may be an effect of increased surface water flow in springs and drainages due to reservoir and ditch releases that ultimately can affect groundwater recharge to shallow and bedrock systems in various areas. These diversions and anthropogenic changes to the surface water system must be accounted for in the water balance calculations, including springs, for the overall hydrologic system of the NFVT area.

There are two major ditches affiliated with the North Fork River located on the north side of the NFVT study area: 1) Fire Mountain Canal; and 2) Farmer's Ditch (Figure 8). The Fire Mountain Canal, the uppermost of the two ditches, traverses the mesas and tributaries significantly above the modern North Fork floodplain and alluvium. As is indicated by wetlands, phreatophytes, and springs/seeps, this unlined ditch leaks water into the groundwater systems of the upland alluvial fans (Qgf and Qs), and some tributaries (Qal) that are crossed by the ditch, which serve as aquifers used for irrigation and drinking water for landowners located topographically below the ditch. By comparison, the Farmer's Ditch primarily outlines the edge of the modern North Fork alluvium (Qal) and terraces (Qat), and the leaky nature of the ditch directly affects both the alluvial aquifer, and therefore the North Fork stream flows. Both ditches operate independently of each other, and affect different hydrologic systems (groundwater, primarily). However, most of the springs in this area and affiliated water rights will be associated with the effects of the Fire Mountain Canal.

The ditches located south of the North Fork River are mostly affiliated hydrologically with the local drainages that serve as the water source. For example, the Minnesota ditch system is affiliated with Minnesota and German Creeks, although the effects of these ditches extend to Reynolds Creek and most of Lamborn Mesa. The Stewart (Mesa) Ditch is affiliated with Bell Creek and most of Stewart Mesa. Similarly, various ditches are affiliated with Cottonwood Creek. In addition, various pipelines and water storage facilities, intended originally for irrigation and drinking water, have enabled water from springs above the study area to be delivered and distributed through Lamborn and Stewart Mesas. These "cross diversions" will affect the local groundwater systems of Lamborn and Stewart Mesas.

2.4 Hydrogeologic Framework

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

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

Unconsolidated sediments and clastic materials, as found in the North Fork Valley, and observed draping down the west and southwest sides of Mt. Lamborn and Landsend Pk., 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 NFVT study area ranges from less than 1 ft to greater than 100 ft. Estimates of hydraulic conductivity (K) range from 0.1 to 500 ft per day (*Watts, 2008*). These hydrogeologic units most likely contain the greatest amount of groundwater.

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

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

2.4.1 Regional Hydrogeologic Units

From a regional perspective, the county-wide geology is part of the southern edge of the Piceance Basin (Figure 12), 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 13 and 14). 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*).

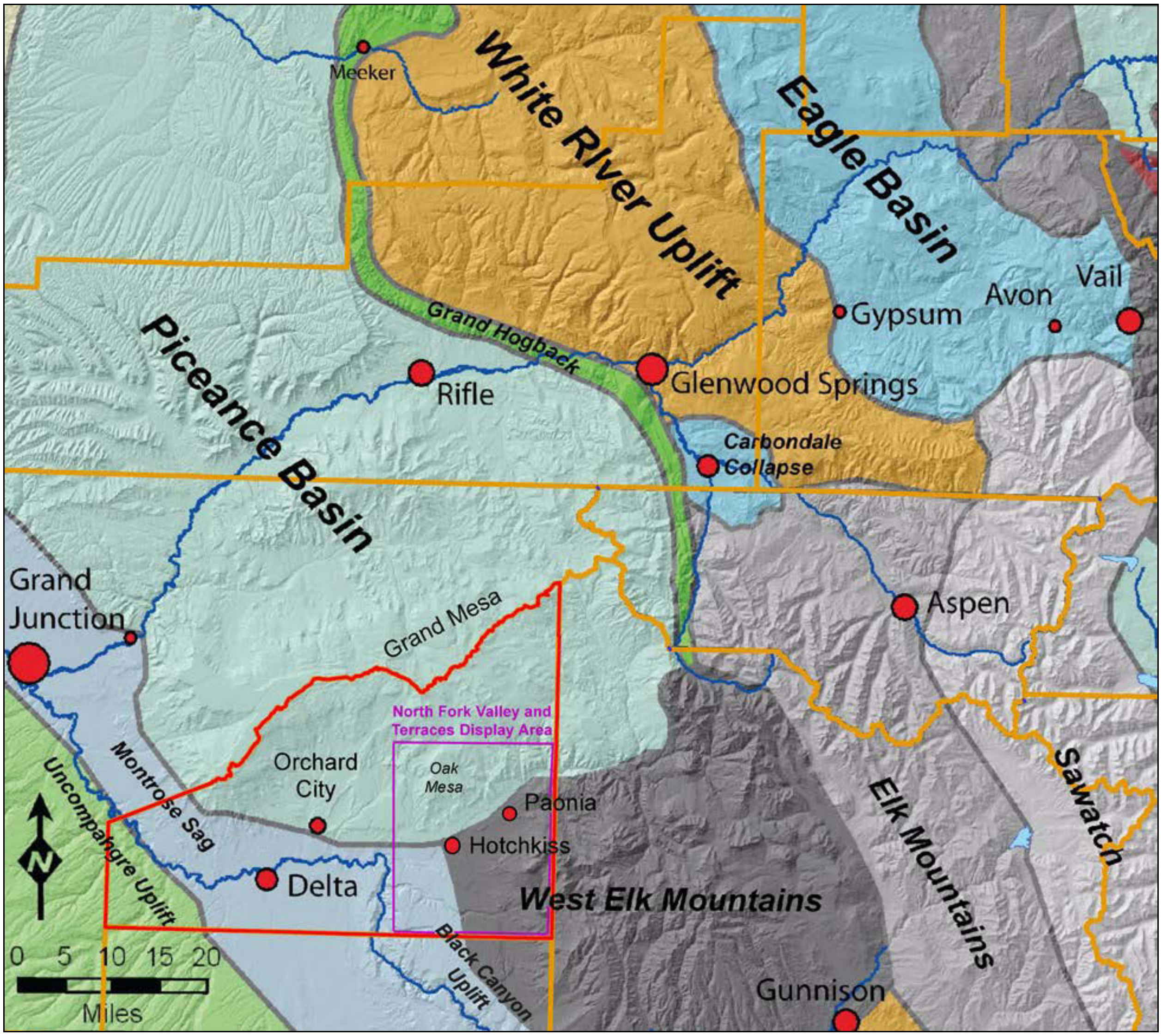

Figure 12. Generalized Map Showing Regional Geographic and Geological Features (*After Topper and others, 2003; Tweto and others, 1978*).

Given the regional geology of the NFVT area, the hydrogeologic framework present in the North Fork watershed is not as complex as the Oak Mesa region studied previously (Kolm and van der Heijde, 2012). Upon reviewing various groundwater reports (*Ackerman and Brooks, 1986; Brooks, 1983; Brooks and Ackerman, 1985;* and *Cordilleran Compliance Services, Inc., 2002*, among others) and (hydro-)geologic maps (*Ellis and others, 1987; Hail, 1972a, 1972b;*

Tweto and others, 1978), it appears that the NFVT 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 15 and 16 and described in Tables 2a and 2b; the major hydrostructural units are presented in Figure 17.

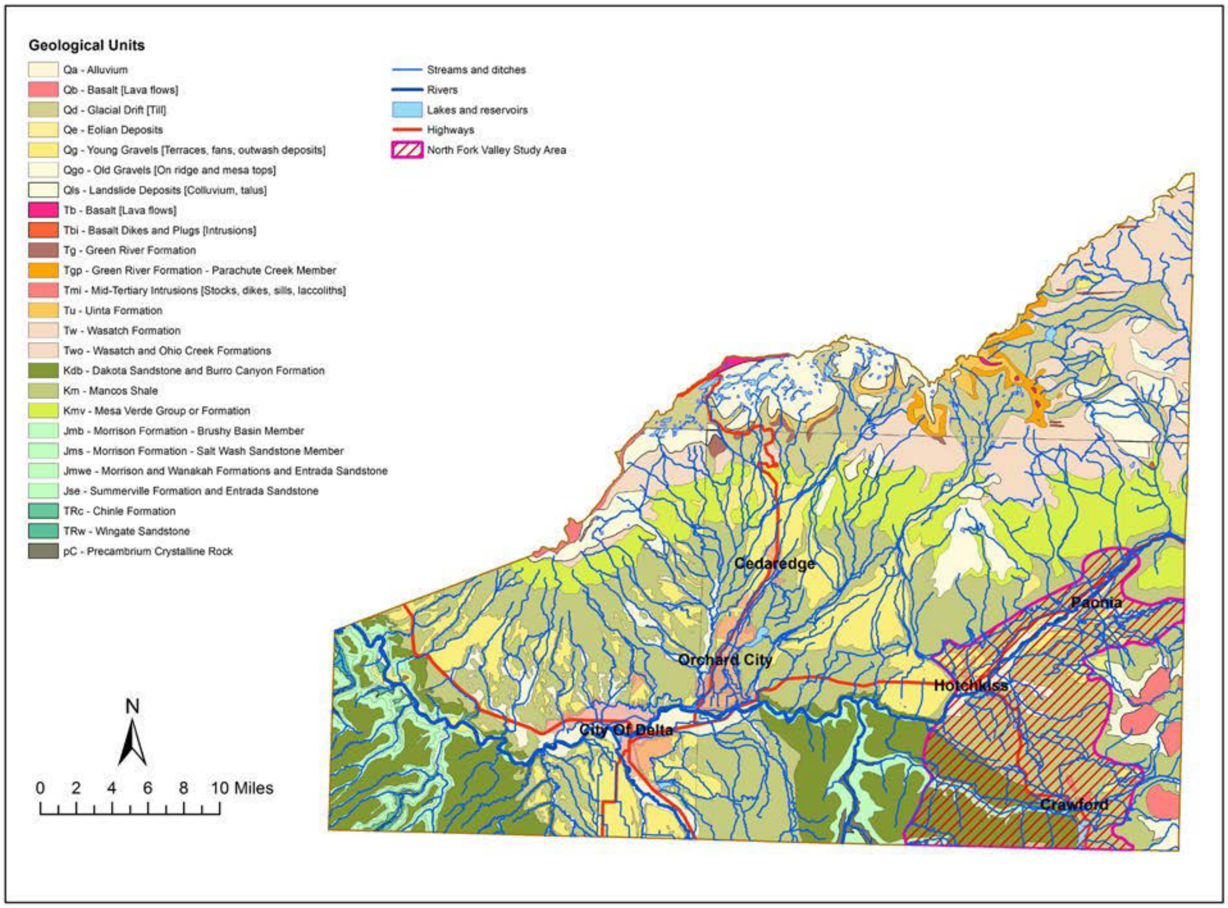

Figure 13. Composite Large Scale Map of the Geology of Delta County
(*Based on Tweto and others, 1976; Tweto and others, 1978; Whitney, 1981; Williams, 1964*).

2.4.2 Hydrogeologic Units of the NFVT Area

There are two significant groups of hydrogeologic units in the NFVT 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) Cretaceous bedrock units (Figure 12; Table 1b), including the following potentially water-bearing unit: Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb). The

Dakota/Burro Canyon hydrogeologic units have porosity values ranging from 0.7 – 12% (*Robson and Banta, 1995*). The Mancos Shale unit (Km) may act as a thick, poorly transmissive confining layer *(Robson and Banta, 1995*). Other units that are mapped in the NFVT area that may influence the hydrologic systems include the Tertiary Intrusive fractured crystalline aquifer near Crawford, CO (Tmi). These Tmi hydrogeologic units are responsible for the very important groundwater systems around Mt. Lamborn and Landsend Pk. that provides spring water as drinking water and irrigation water to the citizens of the NFVT study area.

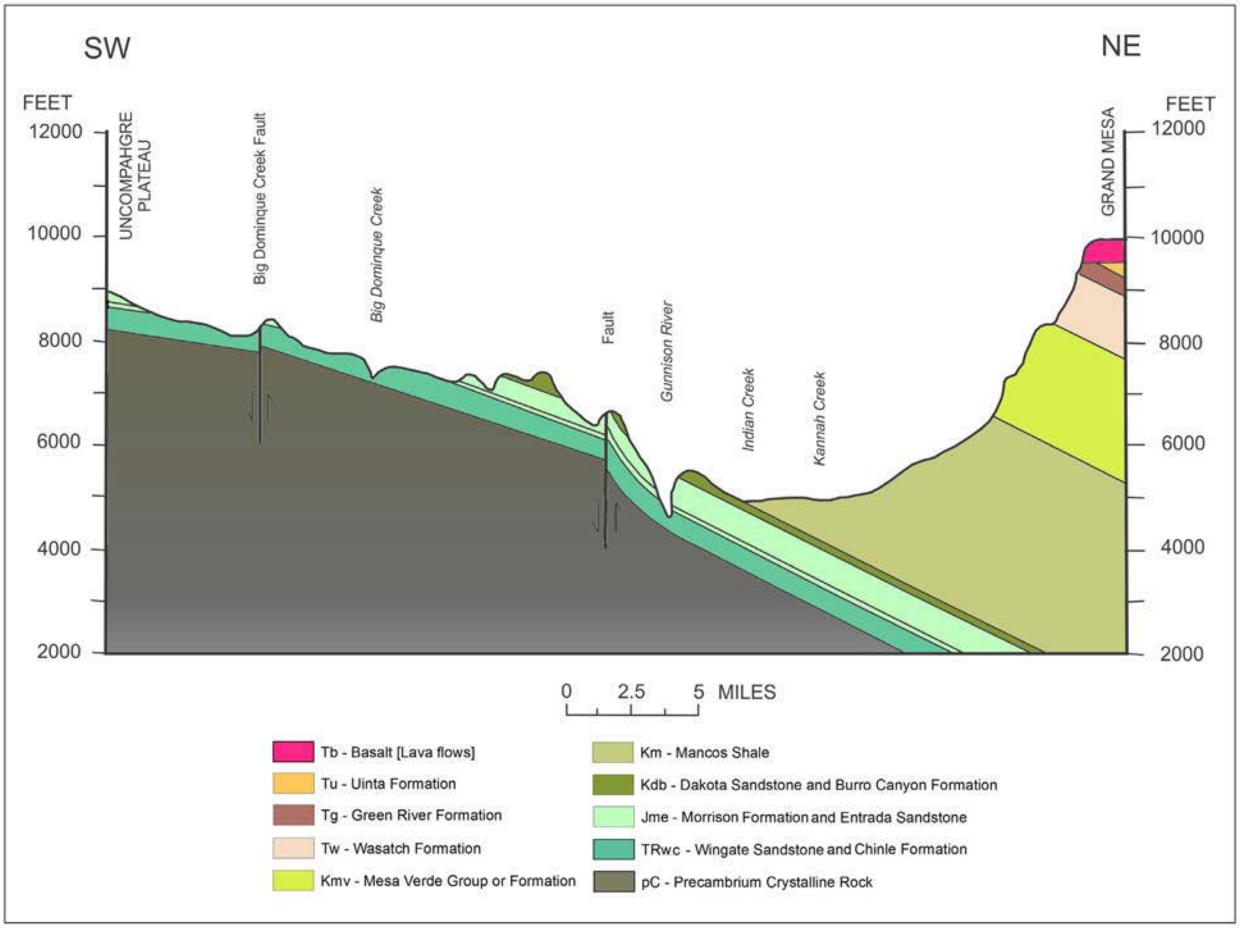

Figure 14. Generalized Northeast-Southwest Geological Cross Section Representative for Delta County. (*From Brooks and Ackerman, 1985*).

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, with the exception of the Tmi units located mostly near Crawford and to the east of the study area, is largely dependent on rock type, large-scale structure and degree of fracturing, layer geometry and orientation, and the spatially variable hydrologic inputs and outputs, and may vary significantly dependent on location. The focus of this project was on both the shallow groundwater flow systems in the Quaternary unconsolidated clastic materials, which is a source of drinking and irrigation water for several municipalities and households, and the Cretaceous Mancos Shale bedrock confining unit that may protect the integrity and water quality of the shallow drinking water systems, particularly from nearby energy development activities. In addition, the Cretaceous Dakota-Burro Canyon and Tertiary intrusive hydrogeologic units are considered as a source for water supply.

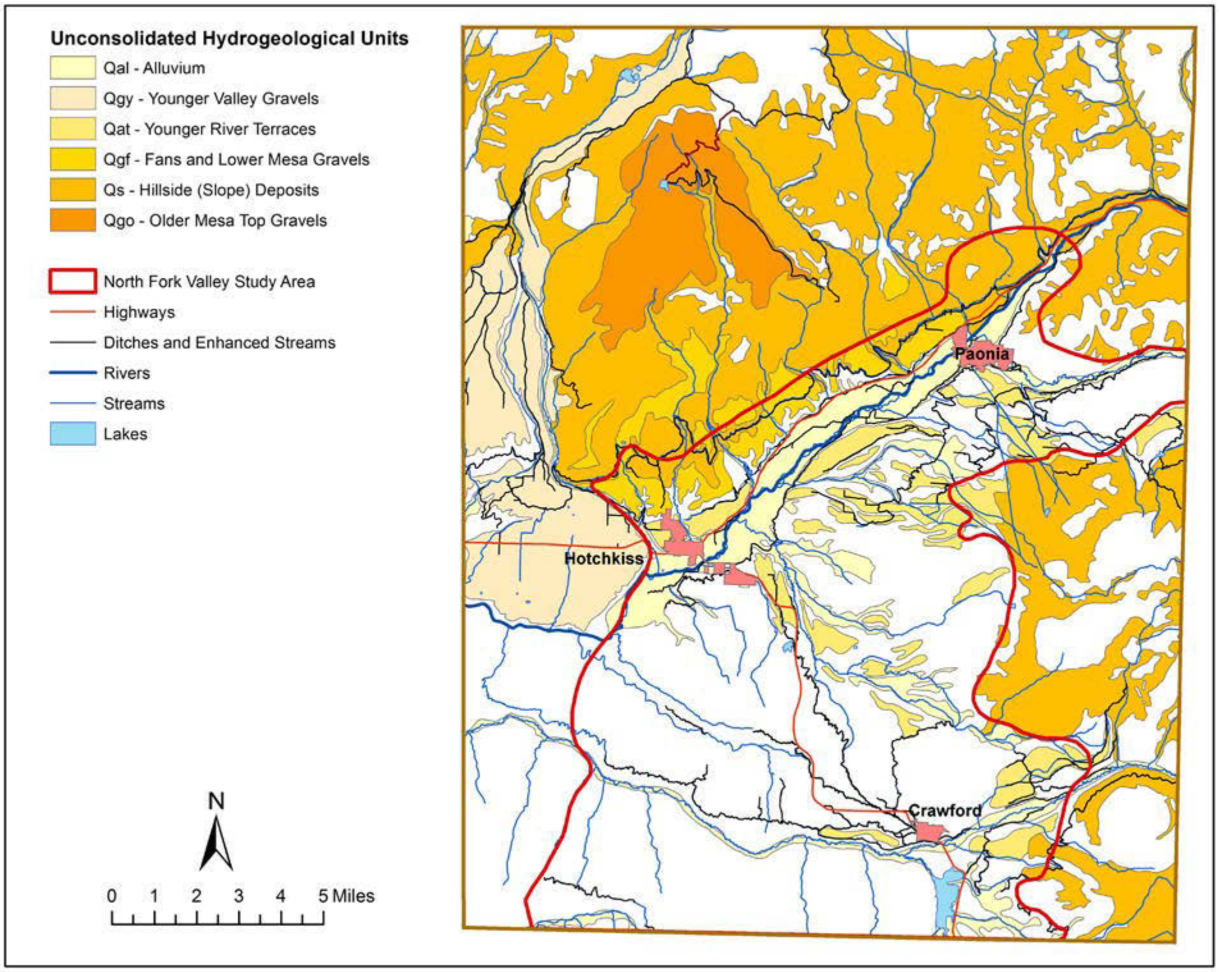

Figure 15. Map Showing the Shallow Unconsolidated Hydrogeologic Units in the NFVT Area.

The Quaternary unconsolidated clastic units (Qal, Qgy, Qat, Qs, Qgf, and Qgo in Table 2a and Figure 15) 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.

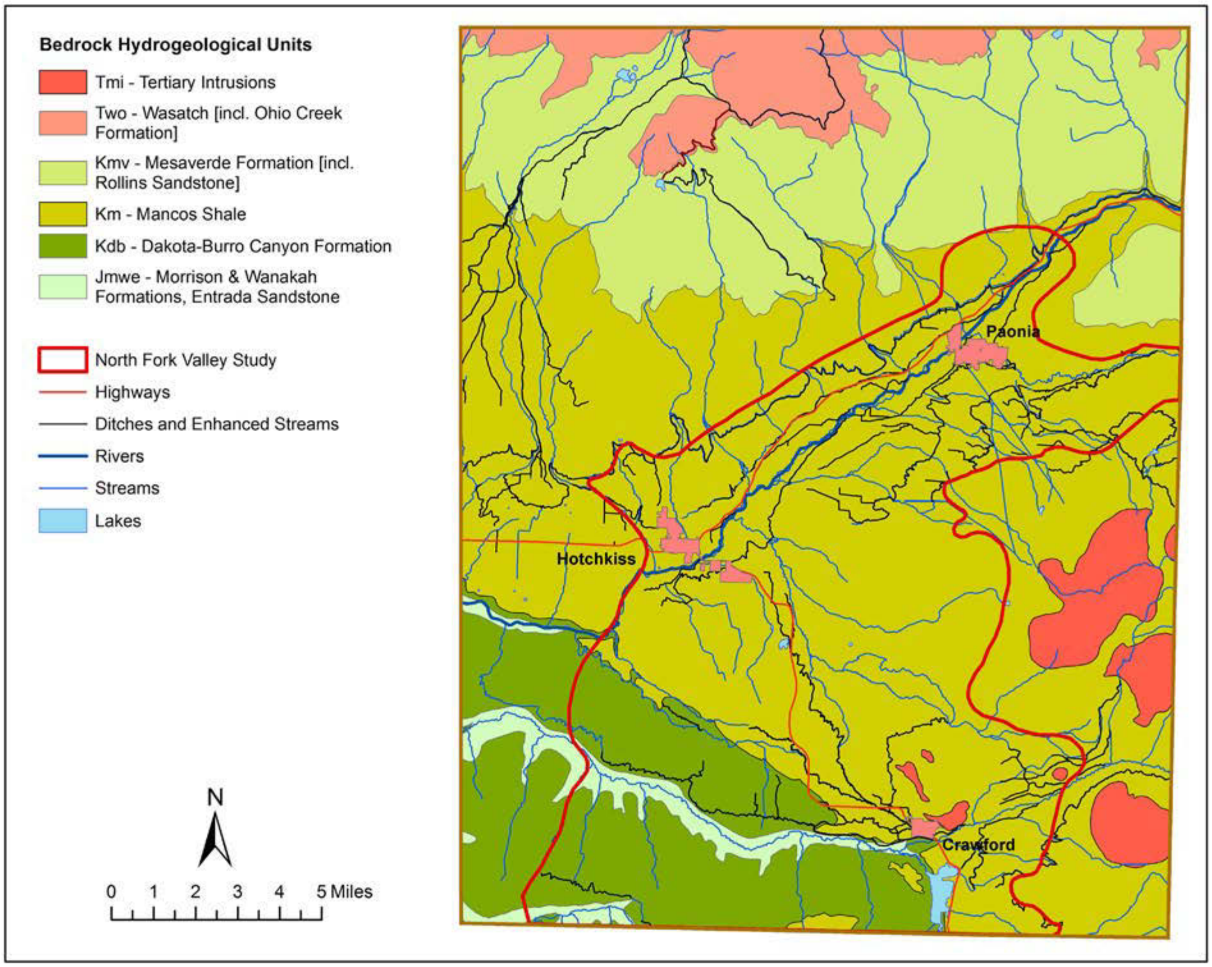

Figure 16. Map Showing Top of Bedrock Hydrogeologic Units in NFVT Area.

2.4.3 Hydrostructural Units of the NFVT Area

Hydrostructures most likely exist subregionally and locally (Figures 12 and 17), and may be responsible for various springs and groundwater discharge and recharge areas observed in lower Terror, lower Roatcap, lower Jay, and lower Leroux Creeks, as well as several unnamed drainages on the north side of the North Fork Valley. In addition, hydrostructures may influence the hydrogeology and hydrologic systems of Cottonwood, McDonald, Bell, German, and Minnesota Creeks, and the main North Fork Valley. 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.

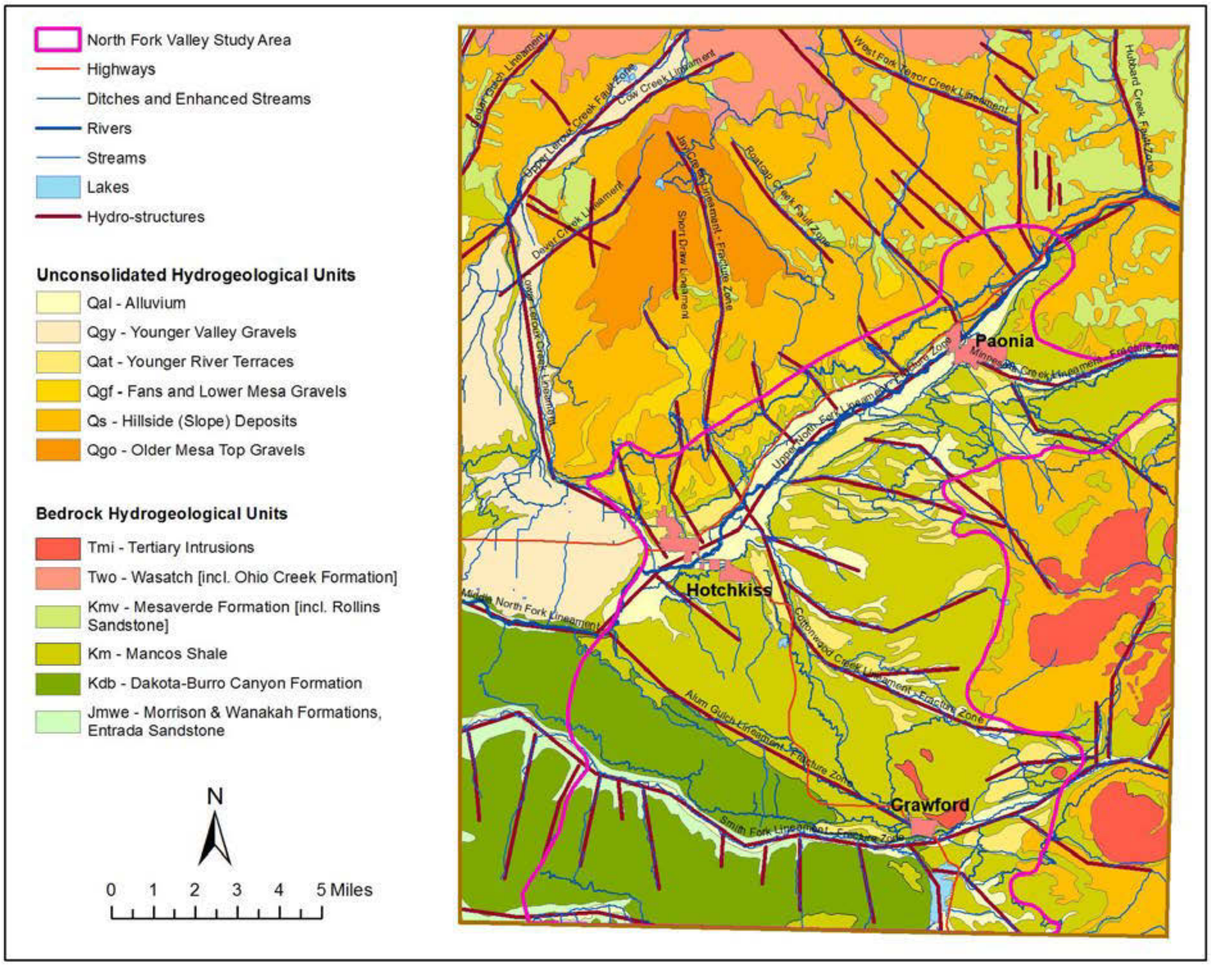

Figure 17. Map Showing Major Hydrostructures (Faults and Fracture Zones) in the NFVT Area.

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

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

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

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

Three broad hydrostructure sets occur in the NFVT area: 1) the northwest-trending fractures that parallel or connect with the Roatcap Creek fault zone and associated en-echelon faults to the east; 2) the northeast-trending North Fork Valley lineament, which parallels the Upper Leroux Creek fault zone; and 3) the radial fracture zone/lineaments that emanate from the West Elk Intrusions of Mt. Lamborn and Landsend Pk., which include the major lineaments of Cottonwood, Bell, and Germen Creeks (Figure 17).

The northwest-trending fractures are relatively young, as the geomorphic systems of lower Roatcap Creek, lower Cottonwood Creek, lower Bell Creek, and lower German Creek are responding with considerable downcutting, allowing for partial to full penetration of the unconsolidated hydrogeologic unit aquifers. It is hypothesized that the northwest fracture zones are "open" and function like French drains. Groundwater moves horizontally and vertically upward along the northwest-trending fracture zone planes, and vertically up along the plane near the lower reaches of the various drainages (evidenced by gaining reaches in streams or increase groundwater head with depth in local wells).

The northeast-trending North Fork Valley lineament and associated en-echelon lineaments and fracture zones, are also "open." For example, along the North Fork Valley, groundwater in bedrock systems moves horizontally along the fault plane, and vertically downward from unconsolidated materials in the upper reaches above Paonia, where it recharges the regional bedrock systems. Groundwater moves vertically upward from bedrock systems into unconsolidated materials in the lower reaches below Hotchkiss, where it discharges into the North Fork River. Therefore, the effects of anthropogenic activities, such as irrigation or oil and gas activity, may propagate to the land surface along the North Fork Valley (Figure 17).

The radial fracture zone/lineaments that emanate from the West Elk Intrusions of Mt. Lamborn and Landsend Pk., which include the major lineaments of Cottonwood, Bell, and Germen Creeks (Figure 17), are relatively young, as evidenced by the geomorphic system where considerable downcutting has occurred allowing for full penetration of the unconsolidated aquifers. These fracture zones are in extension or "open" due to the radial and tangential nature of fracture patterns around intrusive bodies. Groundwater within these fracture zone moves horizontally along the fracture zone plane parallel to the stream, and vertically up along the fracture zone plane near the headwaters (evidenced by springs and gaining streams). Because of orientation and "openness" of the fracture zones, the effects of anthropogenic activities, such as oil and gas development in the uplands to the west of Mt. Lamborn and Landsend Pk., may affect the unconsolidated hydrogeologic units groundwater system to the south of this North Fork Valley (Lamborn and Stewart Mesa areas, for example).

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, oil and gas activity) will affect groundwater movement to varying degrees. The CSM also incorporates topography (steepness, slope aspect, degree of landscape dissection), geomorphology, and soil and rock properties. Because of the time-space variance of these inputs and outputs, a groundwater system often shows significant variations in water levels, water storage, flow velocities, and flow patterns. Some of the variations are seasonal; others may be related to multi-year periods of above-average or below-average precipitation. This results in variations in the availability of water from these hydrogeologic units.

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

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

The Valley Bottom subsystems, where stream-aquifer-wetland interactions occur, are areas of both groundwater recharge and discharge, and groundwater flow can have a rather diffuse character and often flows towards or aligns more or less with the streams and rivers. These subsystems depend primarily on interactions with the North Fork River, and Minnesota and Cottonwood creeks; and the management of subregional ditches and corresponding spring storage.

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

2.6 Groundwater System Conceptual Site Models by Subsystem

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

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

The conceptual models are discussed in forthcoming sections and illustrated by cross-sectional and plan view figures. The locations of representative cross-sections are shown in Figure 18.

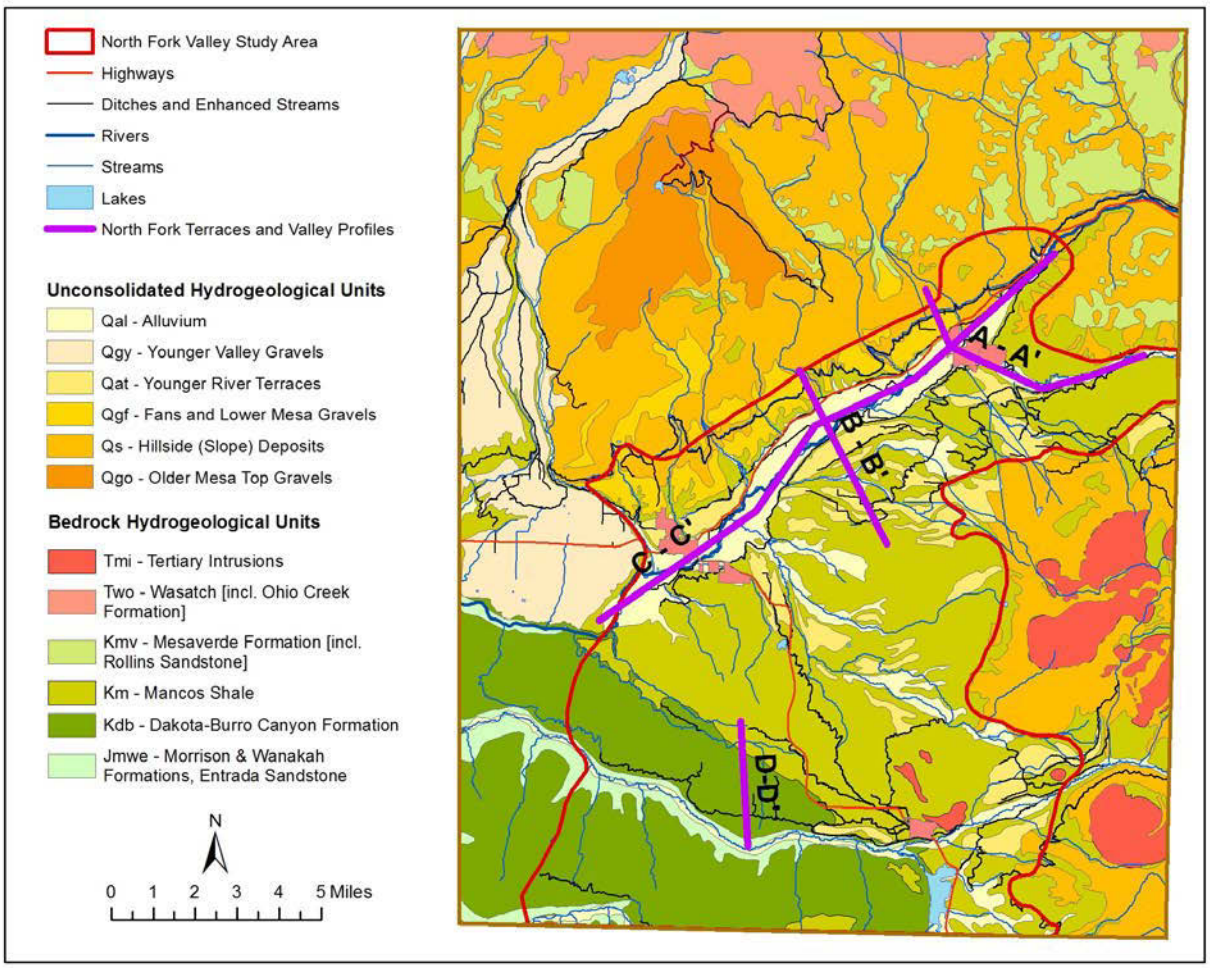

Figure 18. Map Showing the Locations of the Cross-sections Representative for the Conceptual Site Models in the NFVT Area on Top of the Hydrogeologic Units.

2.6.1 Mesa Top and Hillslope Shallow Aquifer Subsystems

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

1. Quaternary unconsolidated clastic units (Qgy, Qat, Qs, Qgf, and Qgo in Table 2a and Figure 15), which are predominantly terrace gravels, and alluvial fans and bajadas; and
2. Cretaceous bedrock unit of the Mancos Shale (Km) (Table 2b and Figure 16).

The shallow Quaternary unconsolidated materials in these subsystems are ubiquitous, and include glacial-alluvial, mass wasting, and paleo-alluvial (terrace) deposits (Figure 15 and Table 2a). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in all of the deposits. These deposits are underlain by a paleotopographic surface carved out by paleofluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated.

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the shallow groundwater on the north side of the North Fork Valley is dominated by the Quaternary unconsolidated materials, which receive natural recharge by infiltration of precipitation (snow and rain), and major recharge from the Fire Mountain Canal, leaky irrigation ditches and reservoirs locally, and return flow from flood irrigation locally (Figures 19 and 20). The unlined Fire Mountain Canal is a “line” groundwater recharge source at the top of the irrigated field areas, and water leaks from the canal into all of the connected gravels underneath and downgradient. In addition, water leaks from the Fire Mountain Canal into the valley bottom alluvium of the cross-drainages, such as Leroux, Jay, and Roatcap Creeks due to the fracture zones that underlie the creeks (Figures 19 and 20) sometimes creating “springs”.

Groundwater flow on top of these local gravel-capped mesas then moves with topography or subsurface paleo-topography to discharge into the incised drainages that bound the mesas, or discharge directly out the front of the mesa (at the gravel/Mancos Shale interface). In both cases, springs may develop and are claimed as being new springs. The shallow groundwater subsystems in this Mesa Top and Hillslope area have little connection to the local bedrock or the regional groundwater systems, or to the alluvial system. Google Earth can be used to visualize these relationships (for example, Figure 21).

Similar systems exist on the south side of the North Fork Valley in the areas designated Lamborn and Stewart Mesa, for example, This region is dominated by the Quaternary unconsolidated materials, which receive natural recharge by infiltration of precipitation (snow and rain), and major recharge from the Minnesota ditch and several leaky irrigation ditches and reservoirs locally, and return flow from flood irrigation locally supplied by the large springs on the flanks of Mt. Lamborn and Landsend Pk and distributed by water tower, pipes, and ditches to the various fields (Figures 19 and 20). The unlined Minnesota Ditch is a “line” groundwater recharge source at the top of the surrounding irrigated field areas, and water leaks from the ditch into all of the connected gravels underneath and downgradient (Figure 8).

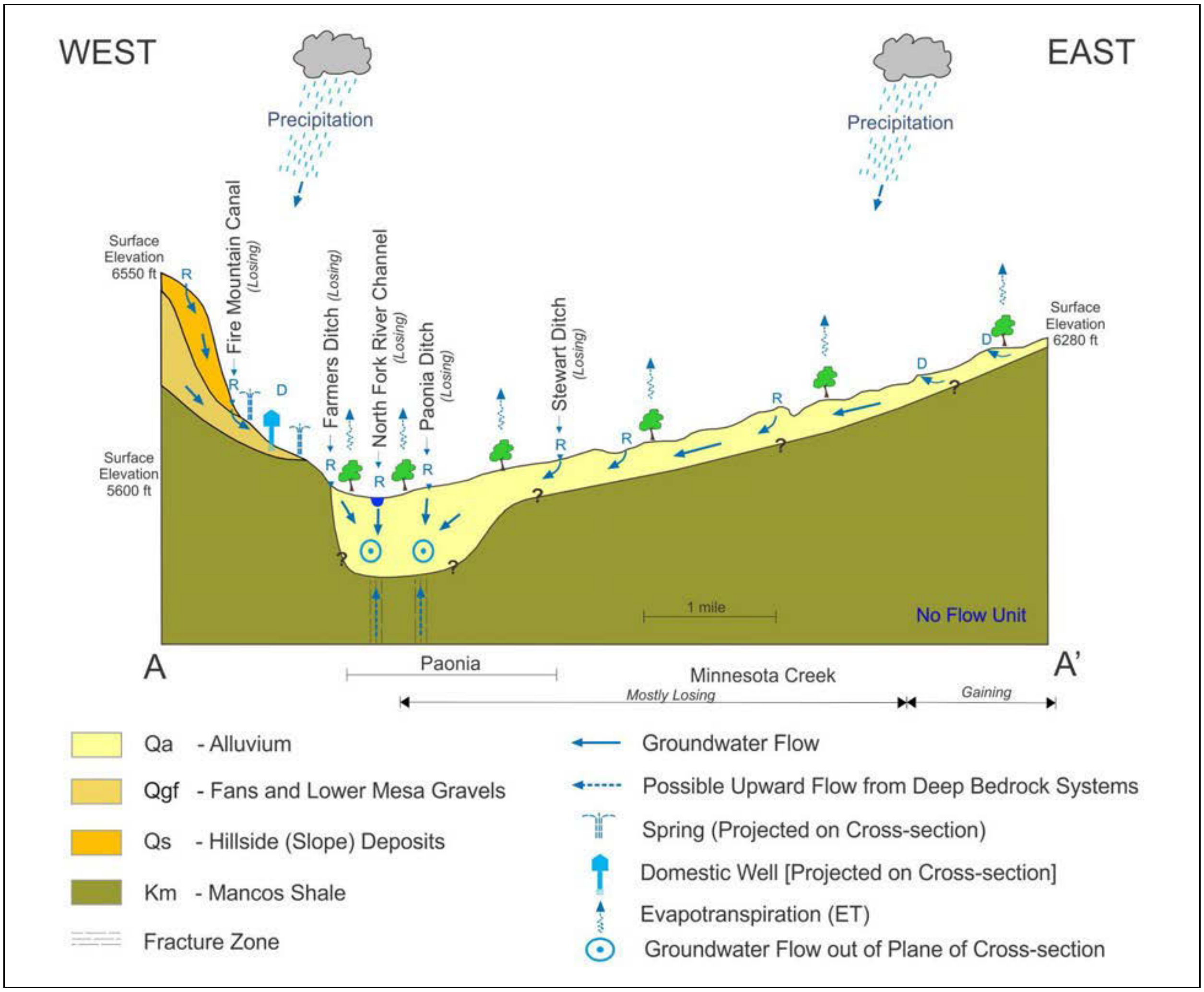

Figure 19. Cross-sectional View of the Conceptual Site Model of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystems (A-A' in Figure 18).

Groundwater flow on top of these local gravel-capped mesas and fans then moves with topography or subsurface paleo-topography to discharge into the incised drainages that bound the mesas, or discharge directly out the front of the mesas (at the gravel/Mancos Shale interface). In both cases, springs may develop and are claimed as being new springs for water rights and water use purposes (Figures 19, 20 and 21). Some springs on the south side of the area discharge directly into the Valley Bottom Subsystems of Minnesota, Bell, German, Reynolds, McDonald, and Cottonwood Creeks (Figures 19, 20 and 22). The shallow groundwater subsystems in this Mesa Top and Hillslope area on Lamborn and Stewart Mesas usually have a strong connection to the Valley Bottom subsystems, but very little connection to local bedrock or the regional groundwater systems due to the underlying Mancos Shale (for visualization, see Figure 22).

2.6.2 Valley Bottom Shallow Aquifer Subsystems

As stated in Section 2.4.2, there are three significant hydrogeologic groups in the Valley Bottom Shallow Aquifer Subsystems:

1. Quaternary unconsolidated clastic materials (Qal and Qat in Table 2a and Figure 15), which are predominantly alluvial valley bottom and terrace deposits;

2. Cretaceous Mancos Shale bedrock unit (Km in Table 2b and Figure 16); and
3. Northeast-trending North Fork Valley lineament hydrostructure (Figure 17).

The shallow Quaternary unconsolidated materials in this subsystem are ubiquitous, and include modern alluvium and terrace deposits (Figure 15 and Table 2a). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in the alluvial deposits (usually coarser sediments on the bottom grading to finer sediments on top). These deposits are underlain by a paleo-topographic surface carved out by paleo-fluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated.

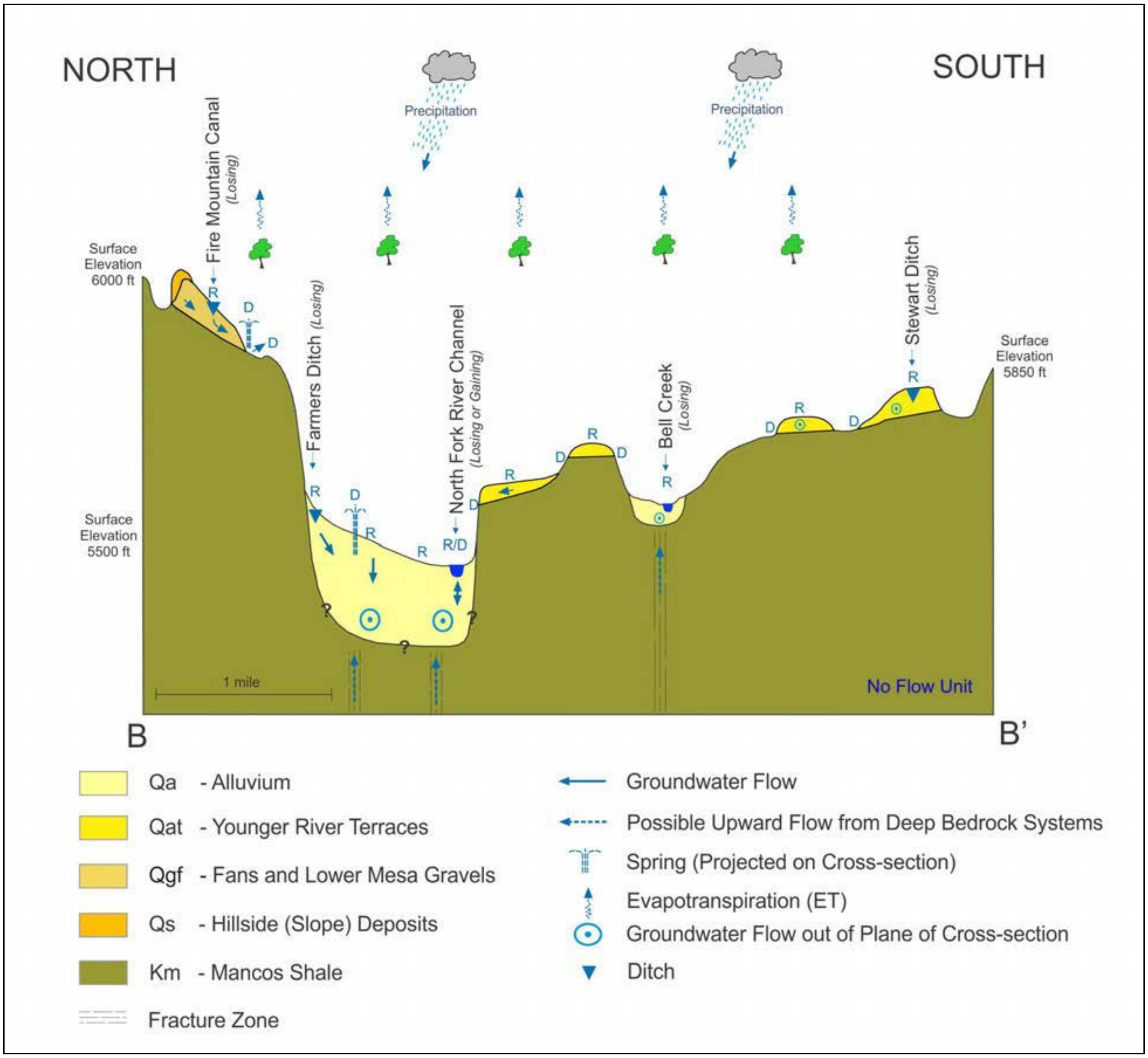

Figure 20. Cross-sectional View of the Conceptual Site Model of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystems (B-B' in Figure 18).

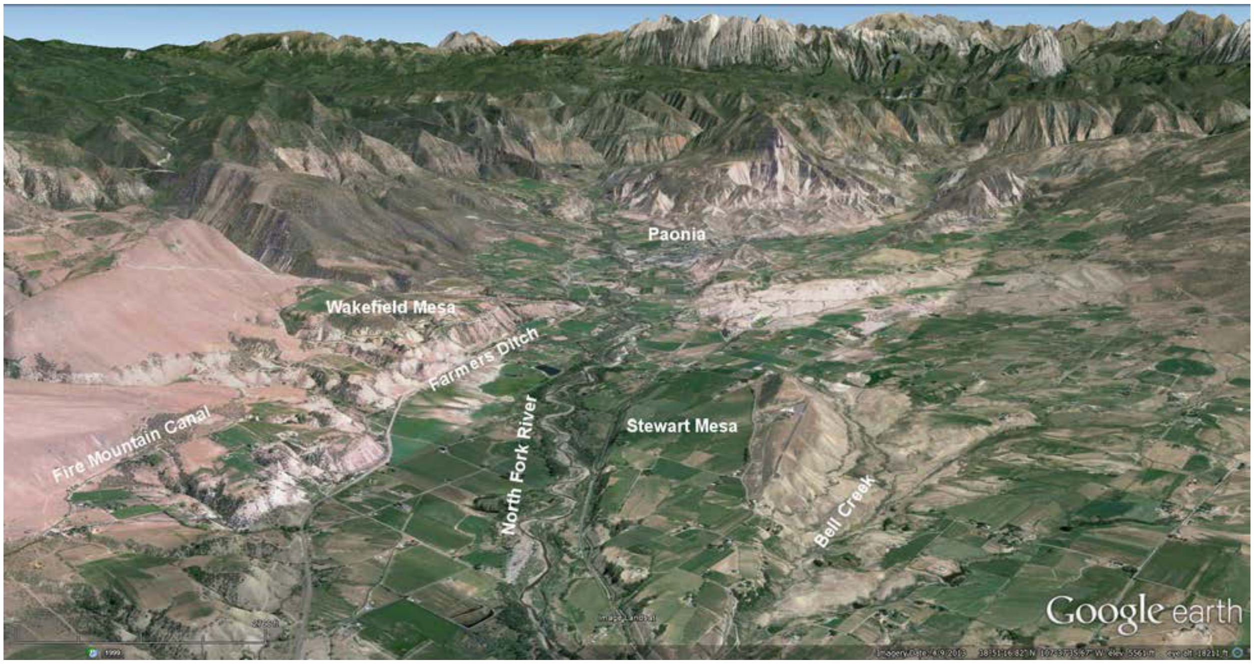

Figure 21. Google Earth View of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystems.

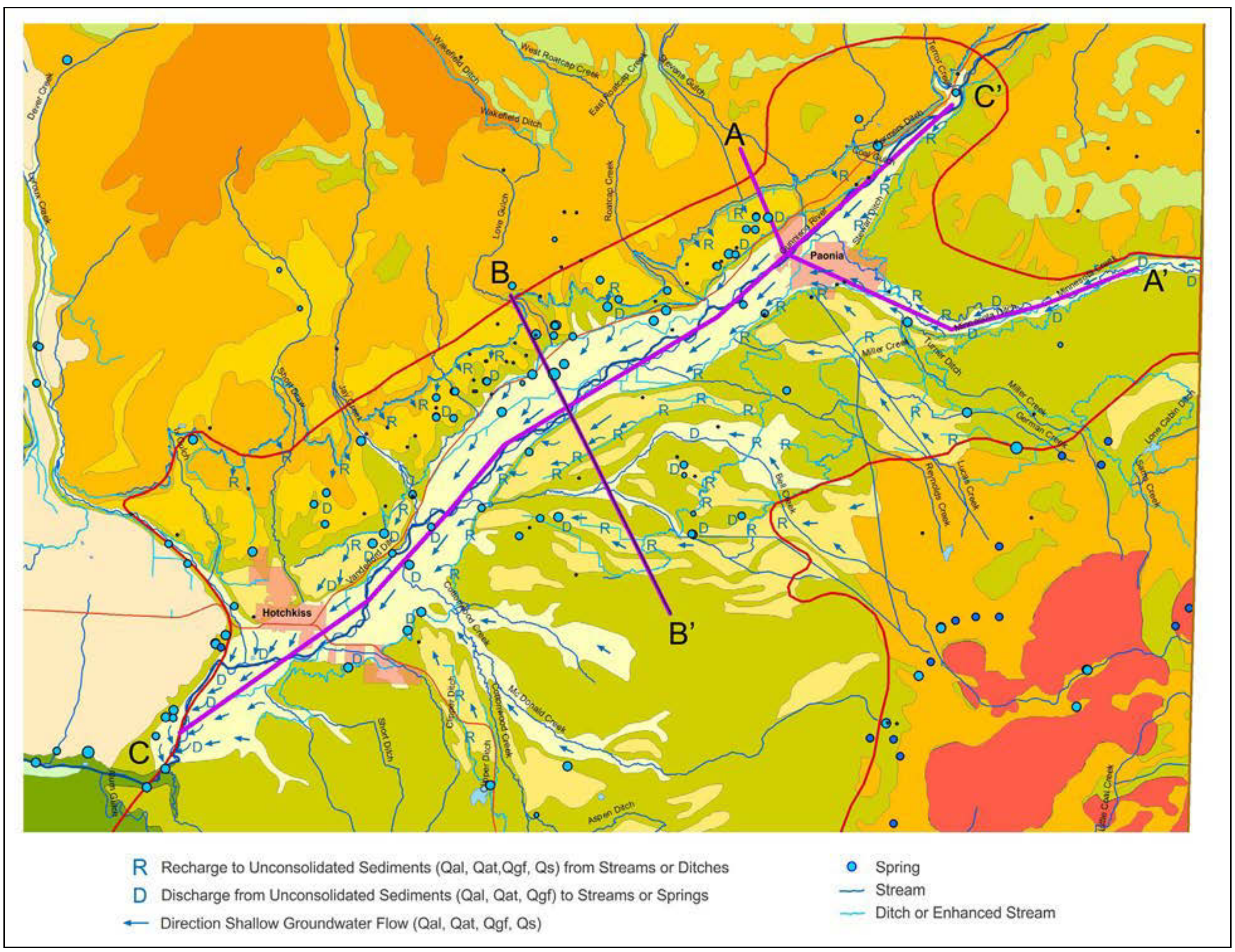

Figure 22. Plan View of the Conceptual Site Model of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystems.

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the groundwater in the North Fork Valley Bottom subsystem is dominated by the Quaternary unconsolidated materials, which receive natural recharge by infiltration of precipitation (snow and rain), and major recharge from the Farmers Ditch, leaky irrigation ditches locally, return flow from flood irrigation locally, groundwater discharge from the Mesa Top and Hillslope subsystems (Figures 19, 20, 22, and 23). The unlined Farmers Ditch is a "line" groundwater recharge source at the top of the irrigated bottomland field areas, and water leaks from the canal into all of the connected sands and gravels underneath and downgradient. In addition, water leaks from the Farmers Ditch directly into "springs" (Figure 10).

Groundwater flow in the Valley Bottom subsystem is generally in the same direction as the North Fork River (Figure 23). However, with the Farmers Ditch on the north side of the River, and the Stewart ditch on the south side of the River, groundwater flow is generally from the valley sides towards the River (Figures 19, 20, 22 and 23). The shallow groundwater system is recharged by water from the surface water system between Somerset and Paonia as well, and groundwater discharges back to the North Fork River near Hotchkiss and Lazear (Figures 8,19, 20, 22 and 23). In addition, the North Fork River northeast-trending hydrostructure underlies the entire valley. If there is connectivity between the deeper aquifers and the Valley Bottom subsystem, it would occur along this lineament probably as an upward gradient between a deeper bedrock system and the Valley Bottom subsystem (Figure 23). Otherwise, the Cretaceous Mancos Shale unit would serve as a confining layer between the bedrock systems and the Valley Bottom subsystem.

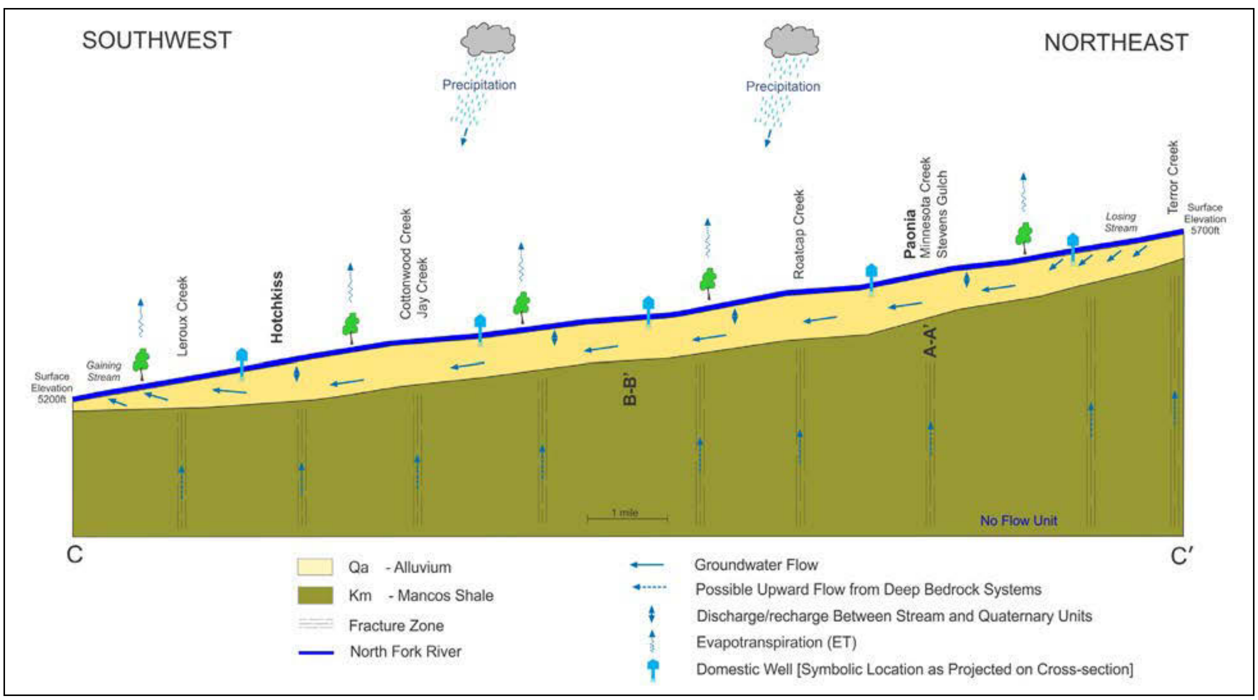

Figure 23. Cross-sectional View of the Conceptual Site Model of the Valley Bottom Shallow Aquifer Subsystems (C-C' in Figure 18).

Similar Valley Bottom subsystems exist on the south side of the North Fork Valley in the Minnesota, Bell, and Cottonwood Creek areas, for example (Figure 19), These creeks are dominated by the Quaternary alluvium and younger gravels, which receive natural recharge by infiltration of precipitation (snow and rain), and major recharge from the leaky irrigation ditches locally, return flow from flood irrigation locally, and groundwater discharge from the Mesa Top and Hillslope subsystems (Figures 19, 20, 22 and 23).

Groundwater flow in these Valley Bottom subsystems is generally in the same direction as the corresponding stream (Figures 22 and 23) . However, with the Mesa Top and Hillslope subsystems discharging groundwater towards the Valley Bottom subsystems, groundwater flow is generally from the valley sides towards the corresponding streams. The shallow groundwater systems are also recharged by water from the surface water systems upstream from the study area (losing stream reaches), and groundwater discharges back to the corresponding streams near their confluence with the North Fork River (Figures 19 and 22). In addition, two sets of hydrostructures: the northwest- trending lineaments and fracture zones, and the radial lineaments/fracture zones may underlies most of the major drainages in the Valley Bottom subsystems. If there is connectivity between the deeper aquifers and the Valley Bottom subsystems, it would occur along these lineaments including Cottonwood, Bell, German, and Minnesota Creeks probably as an upward gradient between a deeper bedrock system and the Valley Bottom subsystem. Otherwise, the Cretaceous Mancos Shale unit would serve as a confining layer between the bedrock systems and the Valley Bottom subsystems (Figures 19 and 22).

2.6.3 Regional Bedrock Aquifer Subsystems

The regional hydrogeologic units in the NFVT study area, discussed in Section 2.4, are the Tertiary and Cretaceous bedrock units (Figure 16 and Table 2b), including the following potentially water-bearing units: Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb); and the Tertiary intrusive rocks (Tmi). The Mancos Shale unit (Km) may act as a thick, poorly transmissive confining layer *(Robson and Banta, 1995*) (Table 2b). The shallow Quaternary unconsolidated materials in this subsystem are not ubiquitous as in other areas of the County, and the overlying materials are primarily soils and eolian materials that provide reasonable conditions that allow recharge to the regional bedrock system mostly in upland areas (Figures 16).

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 Dakota Burro Canyon aquifer is saturated to the north of the outcrop (recharge) area as evidenced by the spring line observed in Alum Gulch parallel to the Smith Fork lineament/fracture zone (see Figures 24 and 26). Groundwater recharge by precipitation (snow and rain) occurs in the outcrop area, and groundwater flows laterally to the north along the dip of the bedrock, where it becomes incorporated into the regional groundwater flow system. The groundwater flow direction in the regional bedrock systems is from south to north beneath the North Fork Valley and Grand Mesa (Figures 14, 24 and 26). This flow direction is toward the oil and gas activities, drinking water supplies, and Delta County in general (for visualization, see Figure 25).

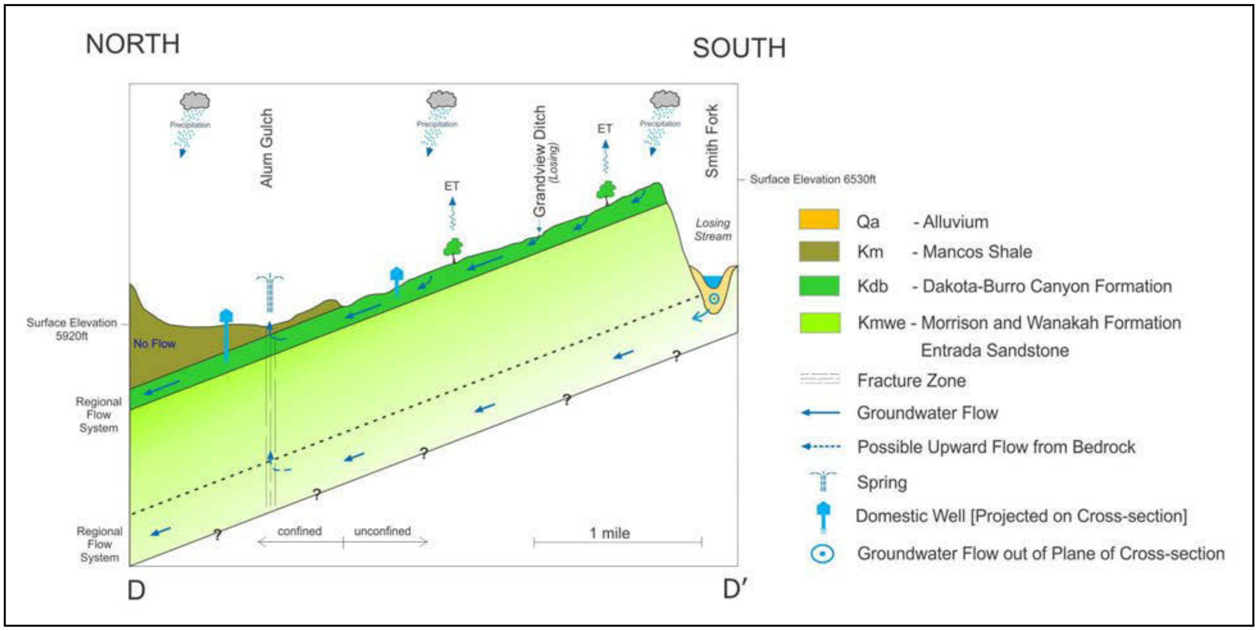

Figure 24. Cross-sectional View of the Conceptual Site Model of the Regional Bedrock Subsystems (D-D' in Figure 18).

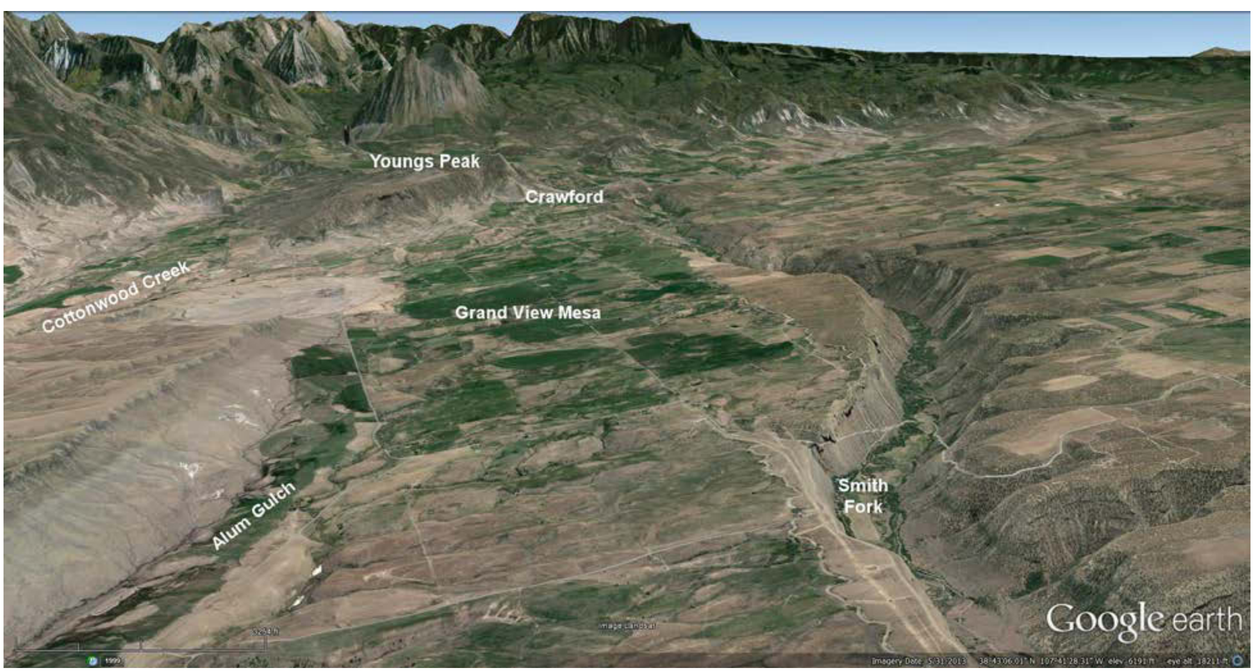

Figure 25. Google Earth View of the Regional Bedrock Aquifer Subsystems.

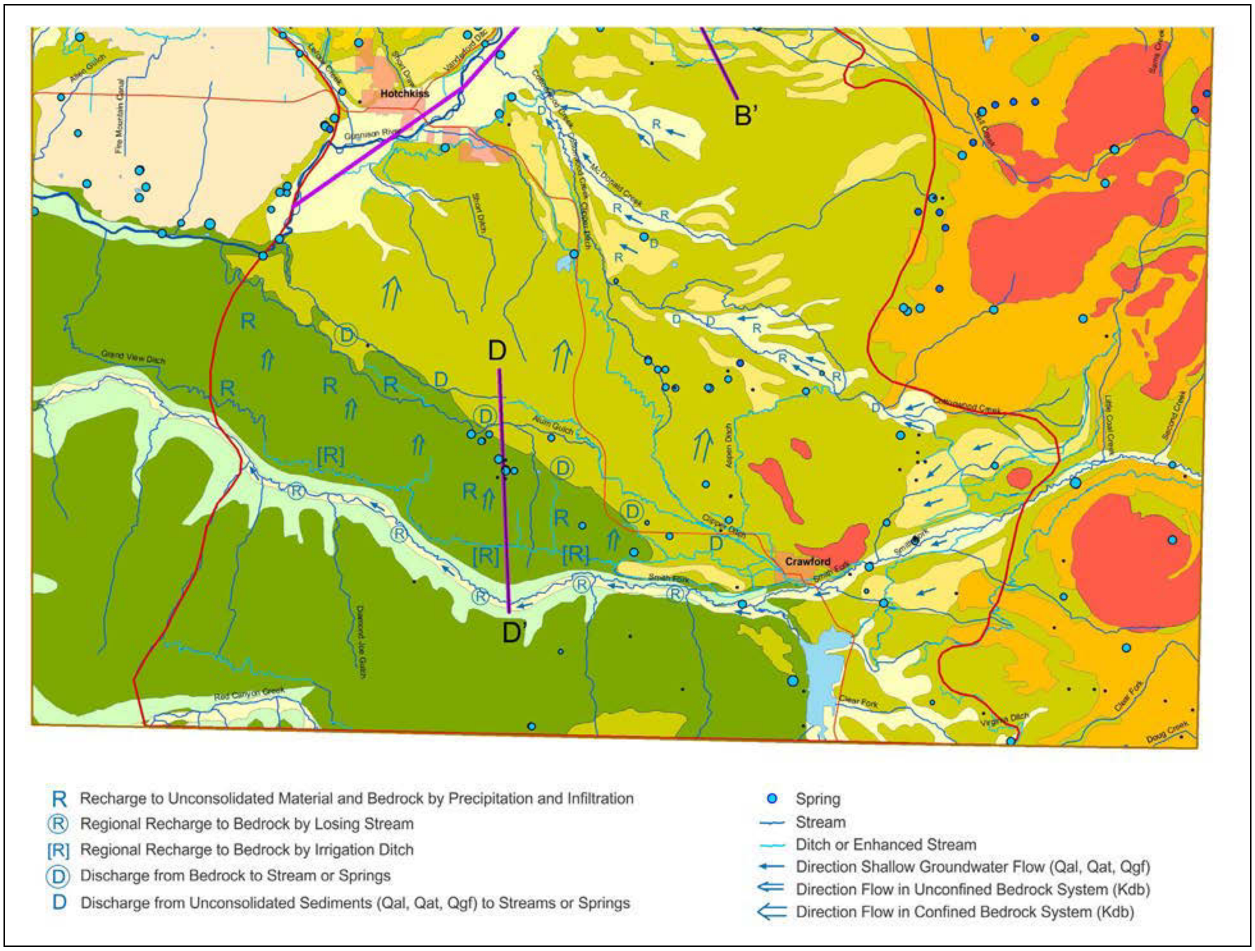

Figure 26. Plan View of the Conceptual Site Model of the Regional Bedrock Subsystems.

2.7 Anthropogenic Influences

Human activity in the NFVT study area has affected both the surface and subsurface parts of the hydrologic systems. Past land use and human activity was mostly associated with agricultural production and reservoir construction and operation, and has resulted in removal of native vegetation, introduction of irrigation and high-ET (evapotranspiration) crops, construction of (often leaking) irrigation ditches, and the drilling of primarily domestic wells. This activity has resulted in long-term increase of water levels in local, shallow aquifers of the Quaternary materials both on top of the Mesa Top and Hillslope subsystems, such as Lamborn and Stewart Mesas, near the major irrigation transport corridors, such as the Fire Mountain Canal and Farmers Ditch, and in the high valleys of Minnesota and Cottonwood Creeks.

2.7.1 Effects of Land Use Changes on Groundwater Systems

Traditionally, agricultural activities take place on the bottomlands and terraces of the valleys, while most grazing activities focus in a relative small area on the uplands. Agricultural production is supported by surface water irrigation, often delivered through an extensive conveyance system. The main irrigation method in use is flood irrigation, which tends to provide more water to the fields than can be consumed by vegetation. Excess water from irrigation results in infiltration to the water table and recharge of the groundwater system (*i.e.*, irrigation return flow). At this time, this part of Delta County is not experiencing a shift from agricultural to nonagricultural land use at the same rate as many other areas of the western United States.

The NFVT study area consists primarily of mesa top, hillslope, bottomland and terraces, limiting the irrigated areas to the top and lower portions of the subsystems (Figures 22 and 25). Here, there are a number of mostly unlined irrigation ditches that are excavated primarily in unconsolidated Quaternary deposits (Figure 27). When carrying water, the ditches may leak, as evidenced by the phreatophytes often found alongside. The ditch system in the study area contains two types of ditches: 1) primary ditches, which carry water during most of the growing season; and 2) secondary ditches, which carry water only during an actual irrigation cycle. The water leaking from the ditches may be used by vegetation and discharged as evapotranspiration, or may recharge the underlying groundwater system, forming a local groundwater mound or divide. As most of the groundwater systems in the study area are local in nature, ditch leakage may contribute significantly to the local water balance, increase the water table elevation, and alter groundwater flow patterns.

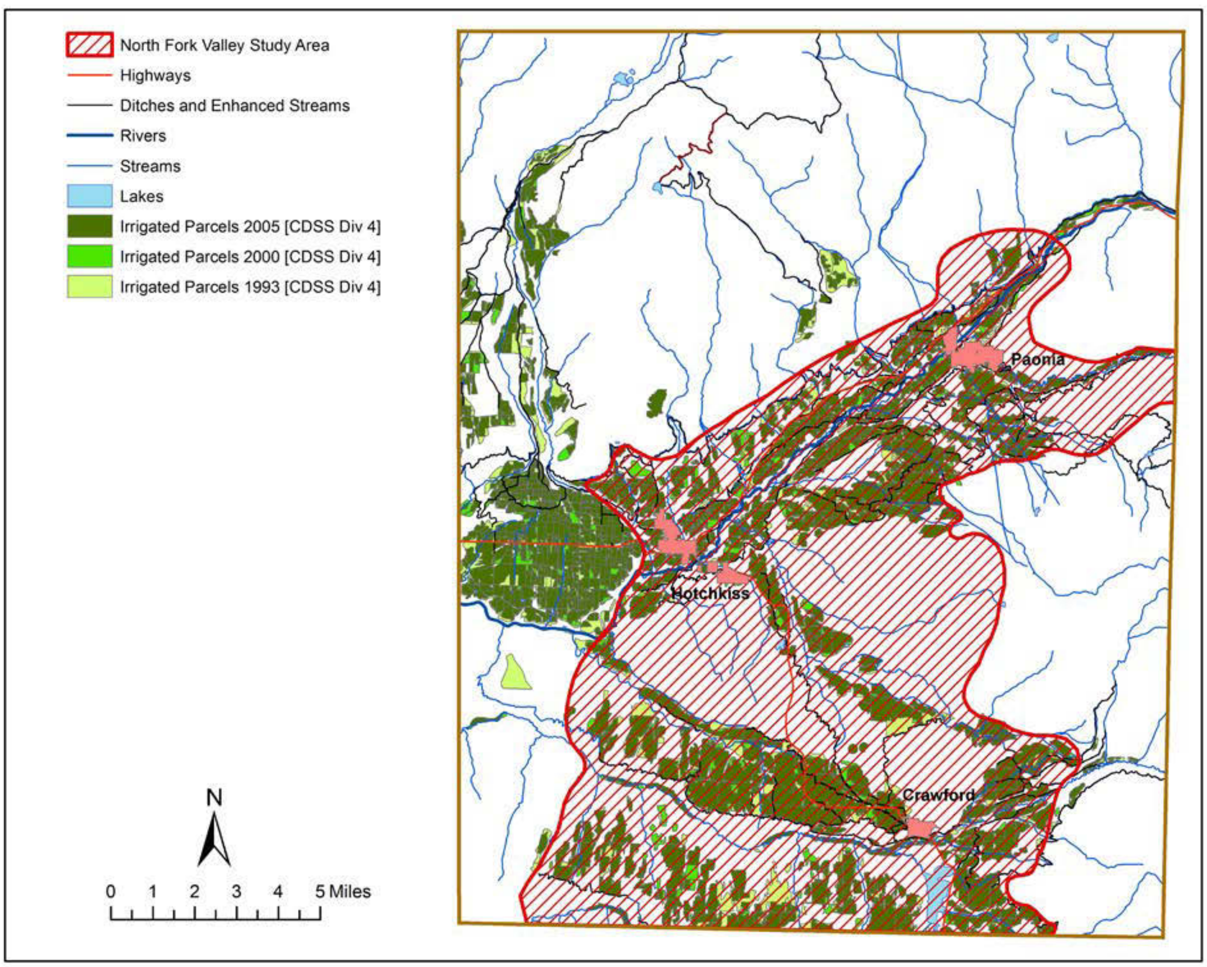

Figure 27. Anthropogenic Influences: Irrigated Areas and Irrigation Ditches in the NFVT Area (Source: Delta County GIS, 2010; CDWR GIS, 2011).

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

The water wells in the NFVT study area are clustered mostly along the North Fork River, and throughout the unconsolidated Quaternary deposits of the Mesa Top, Hillslope, and Valley Bottom subsystems (Figure 28). 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 locally may be significant. However, if additional water is needed by urban or agricultural development, or water is displaced by oil and gas activities, for example, the compound effect on the groundwater system could be more significant in the future, resulting in a possible lowering of the water table, changes in flow direction, decreasing discharge to streams or increasing stream loss to groundwater, draining of wetlands, or even depletion of local aquifers.

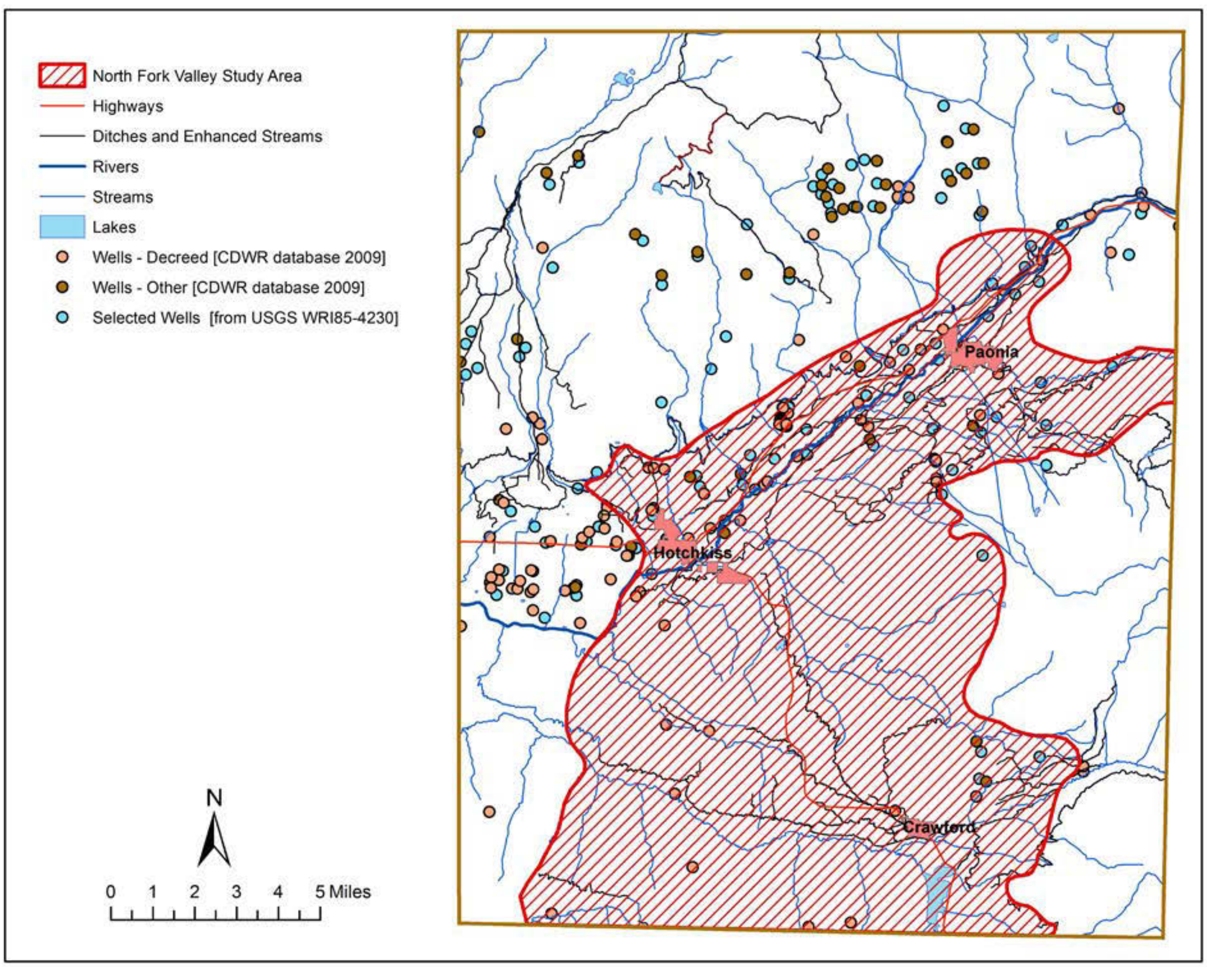

Figure 28. Anthropogenic Influences: Wells in the NFVT Area (Source: CDWR GIS, 2011).

2.7.2 Potential Effects of Oil and Gas on Hydrology

The hydrology of a natural groundwater hydrologic system may be altered by the construction and operation of proposed oil and gas wells. During drilling and fracking, the oil and gas operations may behave like a connection mechanism between the deep and shallow aquifers, mixing water of various chemistries from various bedrock and shallow aquifers. Depending on management strategies for produced water disposal and use, groundwater levels in the shallow unconsolidated systems may be altered with respect to the amount, velocity, storage, and direction of the local groundwater system and related regional groundwater levels and discharges. Changes to the natural groundwater system will likely have ecological, geo-hydrological, and, potentially, legal consequences. The effects of water disposal after fracking and oil and gas well development are not discussed in this report as relevant information on the planned oil and gas development and operations is not available at this time. These management strategies and their effects on the shallow and bedrock aquifer subsystems should be evaluated in more detail. The locations of the oil/gas lease parcels in the NFVT area are shown in Figure 29.

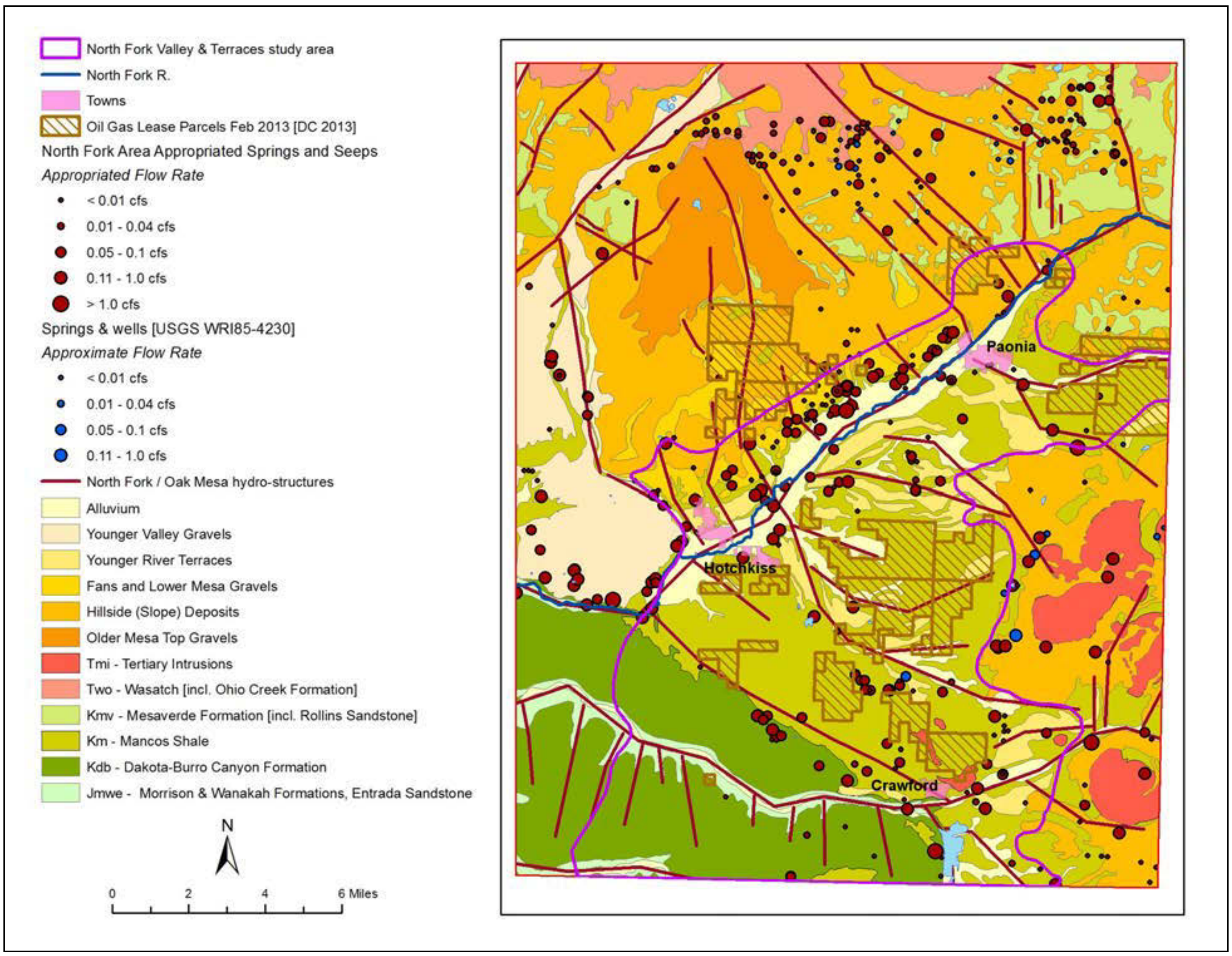

Figure 29. Anthropogenic Influences: Oil/Gas Lease Parcels in Relationship to Hydrogeology in the NFVT Area (Source: Delta County GIS, 2013).

The mesa top and upper hillslope parts of the Mesa Top and Hillslope, and Valley Bottom Shallow Aquifer Subsystem are least likely to be affected by oil and gas operations because they are located in the recharge area and have a shallow groundwater flow system above the bedrock dewatering zone (Figures 19, 20, 22, 23 and 29). However, the potential for groundwater discharge from the deeper bedrock to the shallow aquifers in the Valley Bottom subsystems in the North Fork River Valley, and in the Minnesota, German, Bell, McDonald, and Cottonwood Creek drainages, due to hydrostructures, may be affected by fracking or other oil and gas drilling activities (Figures 19, 20, 22, 23 and 29), which could affect the water supply and water quality. In addition, significant amounts of shallow aquifer water quality may be affected by the surface water runoff and groundwater recharge affected by drill site activities and water disposal (Figures 19, 20, 22, 23 and 29).

The regional groundwater subsystem may be affected by the oil and gas operations, but these systems are not currently being explored for water supplies. However, the interconnectivity between these deeper systems and the shallow unconsolidated systems is currently undetermined (Figures 19, 20, 22, 23 and 29).

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 NFVT 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 NFVT study were prepared using ArcView™ version 8.3 and evaluated using Arc-Desktop™ version 10.2 (ESRI®, Redlands, California).

3.2 Use of GIS in the NFVT Area Study

In this study, GIS has been used in support of the HESA described in Chapter 2 and in the preparation of report figures. In addition, the GIS maps and databases will provide a base for further studies of the hydrology and hydrogeology of NFVT 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 30); and 2) a map with hydrologic and hydrogeologic features of the NFVT area (Figure 31). The GIS maps consist of a number of layers representing various data types relevant to the assessment of the groundwater resources at user-specified locations. Below is a detailed description of the layers and the related data sources.

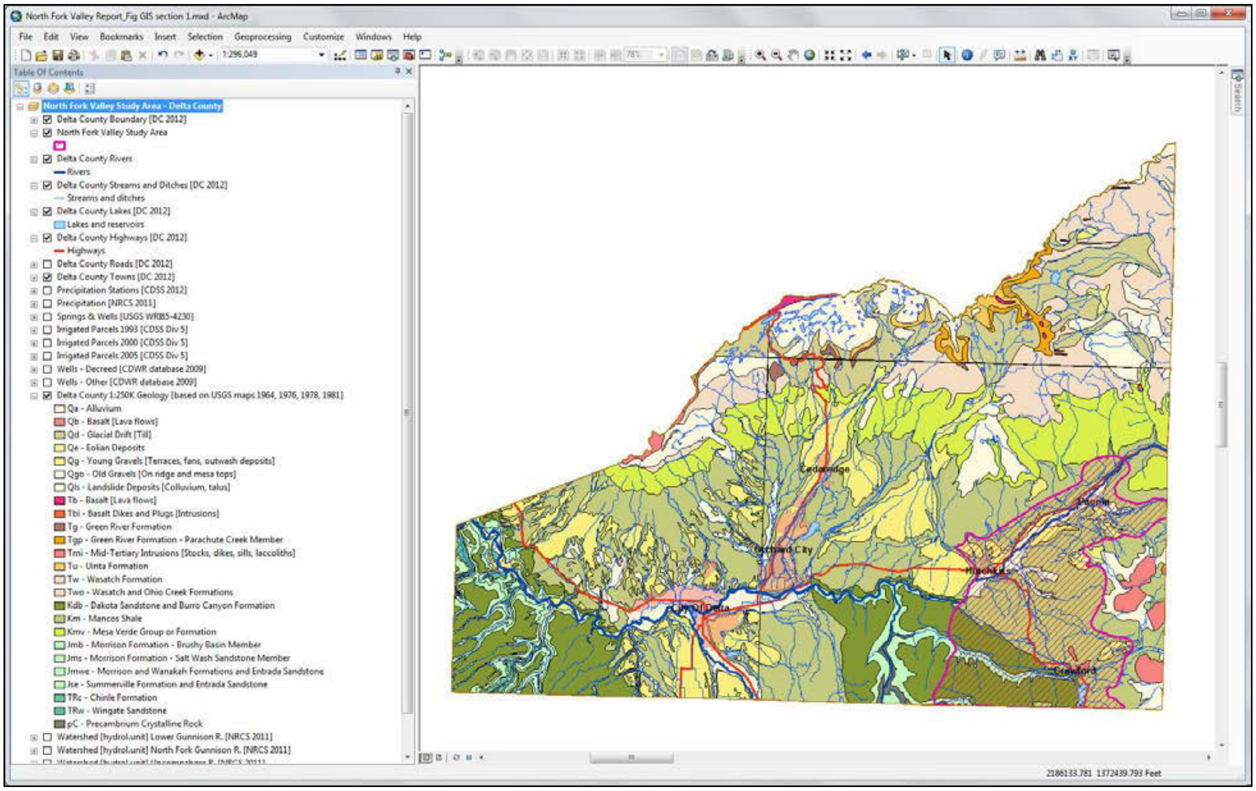

Figure 30. Delta County GIS Map Showing Streams, Ditches and Roads on Top of County-wide Geology.
(The left display area is the table of contents [TOC] showing all available layers;
the right side of the window is the map display area showing the activated layers.)

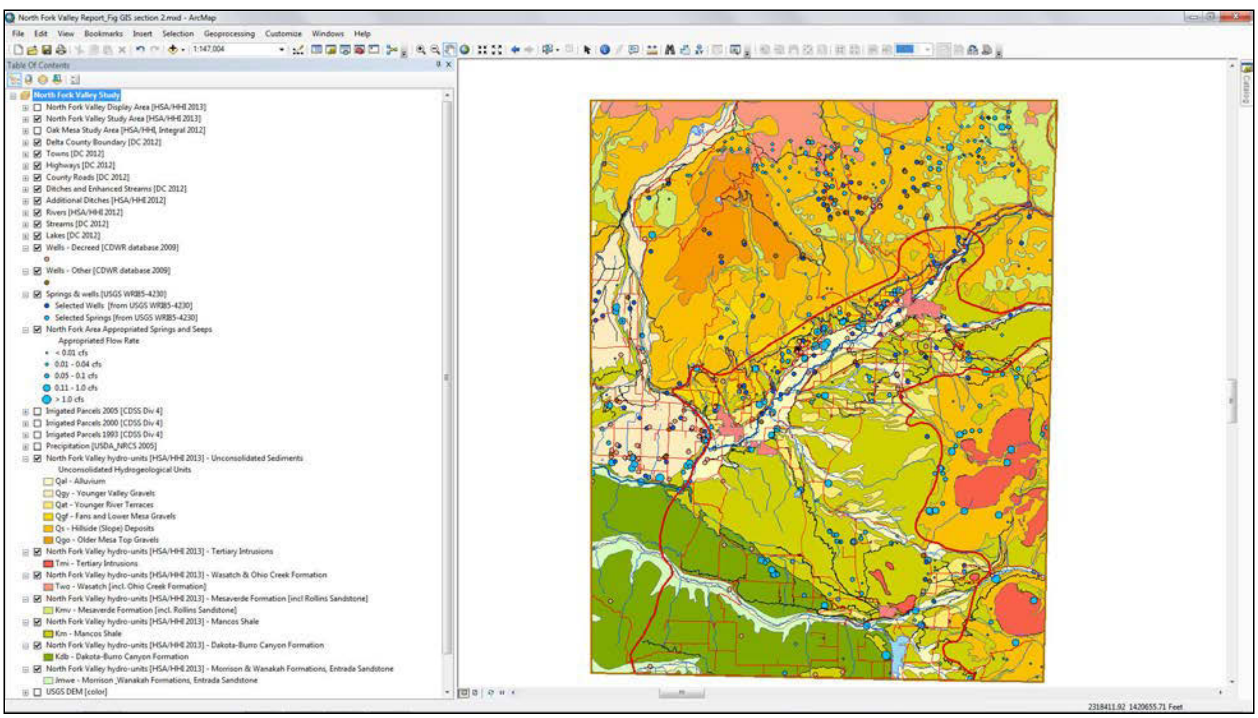

Figure 31. NFVT GIS Map Showing Streams, Ditches and Roads on Top of Hydrogeologic Unconsolidated and Bedrock Units and Hydrogeologic Structures.
(The left display area is the TOC showing all available layers;
the right side of the window is the map display area showing the activated layers.)

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

3.3 GIS Map, Layers, and File Structure

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

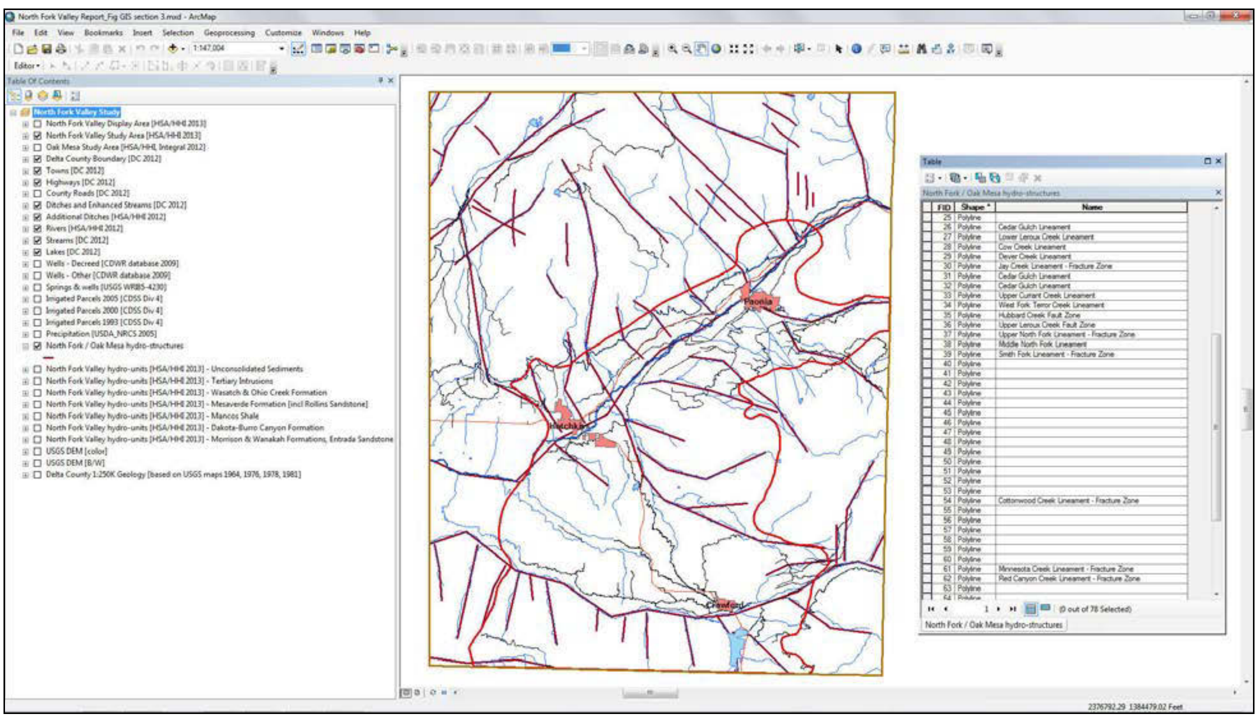

Figure 32. GIS Map Showing the Attribute Table for the Hydro(logic) Structures Layer in the NFVT Area *(right side of figure)*.

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 NFVT area GIS maps retrieve various files included in six relative-path subdirectories: 1) CDOT; 2) CDSS; 3) Delta_County; 4) HHI; 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 NFVT 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 (*Irrigated_Parcels_1993-new* files); 2) irrigated areas in CDWR Division 4 on the Western Slope as of 2000 (*Irrigated_Parcels_2000-new* files); 3) irrigated areas in CDWR Division 4 on the Western Slope as of 2005 (*Irrigated_Parcels_2005* files); 4) decreed wells included in the CDWR's Hydrobase (*co_wells_decreed-new* files); 5) other wells included in the CDWR's Hydrobase (*co_wells_other-new* files), and 6) precipitation stations in Colorado (*co_precipstations* 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 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), water planning areas, and towns. The ditch data provided by the county does not distinguish between primary and secondary ditches. Additional field verification is needed to assess the hydrologic importance of individual ditches. It should be noted that the GIS-based aerial photography provided by the county has been used, in conjunction with GIS-based topographic images obtained from the NRCS data portal and Google™ Earth imagery, to remotely assess topography, vegetation and hydrology.

The *HHI* subdirectory contains the databases produced for this project by Heath Hydrology, Inc. It contains various hydrogeology files (*NorthFork_OakMesa_Hydrogeol_xxx, NorthFork_OakMesa_Hydrostructures, DeltaCounty_Geology, NorthForkArea_Springs, Springs-Wells_USGS1986*); files showing precipitations stations relevant for Delta County climate (*dc_precipstations;* which is a subset of the CDSS database of precipitation stations), and files related to the location of the study area (*OakMesa_DisplayArea, OakMesa_StudyArea, NorthForkValley_ StudyArea*, and *NorthFork_OakMesa_ClippingArea*). The *DeltaCounty_Main_Streams* 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^{o} x 2^{o} quadrangle geologic maps (scale 1:250,000) (*Tweto and Others, 1976; Tweto and Others, 1978; Whitney, 1981; Williams, 1964).* The North Fork/Oak Mesa hydro-structures layer is in part based on the 1:100,000 scale geologic map of the Paonia and Gunnison area (*Ellis and Others, 1987*), and enhanced through analysis of geomorphic features by the project team.

The springs and seeps included in the water rights database (*NorthForkArea_Springs* files) reflect the status of September 2013. *T*he springs and seep data can be found at: *http://cdss.state.co.us/onlineTools/Pages/WaterRights.aspx*. More details about this springs and seeps layer can be found in Appendix 1.

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.

There are seven GIS layers and databases for the hydogeologic units in the NFVT area (*i.e.*, "hydro units" for short) (Figures 15, 16 and 31): 1) a layer showing the Quaternary unconsolidated deposits grouped by their hydrogeological characteristics (*North Fork Valley Hydro Units - Unconsolidated Sediments*); and 2) six layers each showing the extent of an individual bedrock hydrogeologic unit (*North Fork Valley Hydro Units – Tertiary Intrusions, North Fork Valley Hydro Units - Wasatch and Ohio Creek Formation, North Fork Valley Hydro Units - Mesaverde Formation [incl. Ohio Creek member and Rollins Sandstone], North Fork Valley Hydro Units - Mancos Shale, North Fork Valley Hydro Units - Dakota-Burro Canyon,* and *North Fork Valley Hydro Units – Morrison & Wanakah Formations, Entrada Sandstone*). When all six bedrock layers are activated, the GIS map shows top bedrock (see Figure 16).

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*) and topography (*drg_s_co29*). The NRCS data can be downloaded from: *http://datagateway.nrcs.usda.gov/GatewayHome.html*.

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

4 SUMMARY AND CONCLUSIONS

A Hydrologic and Environmental Systems Analysis (HESA) of the groundwater system of the North Fork Valley and Terrace area (NFVT) 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 NFVT study area:

1) Quaternary unconsolidated clastic materials (Figure 15; Table 2a), which are predominantly glacial-fluvial outwash plains and terrace gravels (older mesa top gravels and glacial drift), hillside (slope) deposits, alluvial fans and bajadas (coalescing fans) and lower mesa gravels, younger valley gravels and river terraces, and alluvial valley bottom deposits; overlying 2) Cretaceous and Tertiary bedrock units (Figure 16; Table 2b), including the following potentially water-bearing units: Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb) and the Tertiary Intrusive fractured crystalline aquifer near Crawford, CO (Tmi). The Mancos Shale unit (Km) 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 canal or ditch, and irrigation return flow. These units may be fully or partially saturated based on spatial location and seasonal precipitation events, and 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 intrusive units and Cretaceous sedimentary units in the underlying bedrock formations.

Three broad hydrostructure sets occur in the NFVT area: 1) the northwest-trending fractures that parallel or connect with the Roatcap Creek fault zone and associated en-echelon faults to the east; 2) the northeast-trending North Fork Valley lineament, which parallels the Upper Leroux Creek fault zone; and 3) the radial fracture zone/lineaments that emanate from the West Elk Intrusions of Mt. Lamborn and Landsend Pk., which include the major lineaments of Cottonwood, Bell, and German Creeks (Figure 17). These hydrostructures function as French drains in the bedrock hydrogeologic units, and are responsible for various springs and groundwater discharge areas (gaining reaches) observed in lower Roatcap, lower Cottonwood, lower Bell, and lower German creeks. These hydrostructures move significant quantities of groundwater horizontally and vertically, interconnecting shallow aquifers; and in the North Fork Valley, potentially interconnecting the shallow aquifers with deep bedrock aquifers.

Based on the presence and orientation of various hydrogeologic and hydrostructural units, hydrography and topography, three CSMs observed in the NFVT study area: 1) Mesa Top and Hillslope Shallow Aquifer Subsystems; 2) Valley Bottom Shallow Aquifer Subsystems; and 3) Regional Bedrock Aquifer Subsystems; are discussed. Specifically, the Mesa Top, Hillslope, and Valley Bottom Shallow Aquifer Subsystems in the NFVT area are dominated by the Quaternary unconsolidated materials, which receive recharge by infiltration of precipitation (snow and rain throughout the study area), leaky irrigation ditches (for example, the Fire Mountain, Farmer's, and Stewart ditches), infiltration at irrigation sites and fields (ubiquitous on the slopes north of the North Fork River, along the bottomlands of the North Fork River, and on Stewart and Lamborn Mesas), and losing streams, such as the lower reaches of Minnesota, Cottonwood, Leroux, Jay, Roatcap, Bell, and German creeks and the reaches of the North Fork River above and around Paonia, CO.

Groundwater flows on top of the local gravel-capped mesas, then moves with topography or subsurface paleo-topography to discharge into the incised drainages that bound the mesas, or discharge directly out the front of the mesa (at the gravel/Mancos Shale interface) where springs may develop and are claimed as being new springs. The shallow groundwater subsystems in the Mesa Top and Hillslope area north of the North Fork Valley have little connection to the local bedrock or the regional groundwater systems, or to the alluvial system of the North Fork Valley. By comparison, the shallow groundwater subsystems in the Mesa Top and Hillslope area on Lamborn and Stewart Mesas usually have a strong connection to the local Valley Bottom subsystems, such as Cottonwood and Minnesota Creeks, but very little connection to local bedrock or the regional groundwater systems due to the underlying Mancos Shale.

Groundwater flow in the Valley Bottom subsystem is generally in the same direction as the North Fork River, and with the Farmers Ditch on the north side of the River, and the Stewart Ditch on the south side of the River, groundwater flow is generally from the valley sides towards the River. The shallow groundwater system is recharged by water from the surface water system between Somerset and Paonia, and groundwater discharges back to the North Fork River near Hotchkiss and Lazear. In addition, the North Fork River northeast-trending hydrostructure underlies the entire valley, and if there is connectivity between the deeper aquifers and the Valley Bottom subsystem, it would occur along this lineament probably as an upward gradient between a deeper bedrock system and the Valley Bottom subsystem. Without a large hydrostructure, the Cretaceous Mancos Shale unit would serve as a confining layer between the bedrock systems and the Valley Bottom subsystem. Similar Valley Bottom subsystems exist on the south side of the North Fork Valley in the Minnesota, Bell, and Cottonwood Creek areas. However, with the Mesa Top and Hillslope subsystems discharging groundwater towards the Valley Bottom subsystems, groundwater flow in these smaller drainages is generally from the valley sides towards the corresponding streams.

The Regional Bedrock Subsystems in the NFVT study area include the following potentially water-bearing units: Cretaceous Dakota Sandstone and Burro Canyon Formation (Kdb); and the Tertiary intrusive rocks (Tmi). The bedrock units are variably saturated based on location and proximity to recharge area. The Dakota Sandstone and Burro Canyon aquifer is partially saturated in the recharge area north of the Smith Fork, as evidenced by the springs in the Alum drainage. Groundwater flows laterally downdip to the north as an unconfined or water table system, and becomes part of the regional confined groundwater flow system after passing under the Mancos Shale at Alum Creek. The groundwater flow direction in the regional bedrock systems is from south to north beneath the NFVT study area and Grand Mesa, and Delta County in general.

Land use and human activity is mostly associated with agricultural production and reservoir construction and operation, and has resulted in removal of native vegetation, introduction of irrigation and high-ET (evapotranspiration) crops, construction of (often leaking) irrigation ditches, and the drilling of primarily domestic wells. This activity has resulted in long-term increase of water levels in local, shallow aquifers of the Quaternary materials both on top of the Mesa Top and Hillslope subsystems, such as Lamborn and Stewart Mesas, near the major irrigation transport corridors, such as the Fire Mountain Canal and Farmers Ditch, and in the Valley bottoms of Minnesota and Cottonwood Creeks, and the North Fork River. At this time, this part of Delta County is not experiencing a shift from agricultural to nonagricultural land use at the same rate as many other areas of the western United States.

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

The potential for groundwater discharge from the deeper bedrock to the shallow aquifers in the Valley Bottom subsystems in the North Fork River Valley, and in the Minnesota, German, Bell, McDonald, and Cottonwood Creek drainages, due to hydrostructures, may be affected by fracking or other oil and gas drilling activities, which, in turn, could affect the water supply and water quality. In addition, significant amounts of shallow aquifer water quality may be affected by the surface water runoff and groundwater recharge affected by drill site activities and water disposal.

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

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 NFVT 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 NFVT maps contain three types of geographic information: 1) general geographic information (county border, roads, towns, imagery) used primarily for orientation purposes; 2) hydrologic information (including precipitation, watersheds, streams, lakes/ponds, irrigation ditches, and irrigated areas); and 3) hydrogeologic information (including hydrogeologic units, faults and hydrostructures, springs, and wells.

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APPENDIX 1
GIS LAYER FOR SPRINGS AND SEEPS FROM CDSS WATER RIGHTS INFORMATION DATA BASE

Two of the GIS layers in the NFVT project, the *North Fork Area Appropriated Springs and Seeps [CDWR 2013]* layer and the *Springs & Wells [USGS 1986]* layer, contain information on springs and seeps in the NFVT area. Typically, springs and seeps indicate places where water flows naturally from a rock or the soil onto the land surface or into a body of surface water. They represent the contact between (saturated) groundwater and the land surface at that location. Springs usually emerge from a single point and result in a visible and measurable flow of water, or contribute measurably to the flow of a stream or the volume of a reservoir or pond. Seeps tend to be smaller than springs, with a more distributed character, and often no visible runoff, especially in the (semi) arid West where, in many cases, the water emerging in seeps is lost to evapotranspiration. Springs may be an expression of discharge of shallow groundwater from an unconfined aquifer, or of discharge from deeper aquifers at the contact between (more) permeable and (near) impermeable formations at or near the land surface, in fracture zones, or through karst conduits.

In the NFVT study area, plotting the location of springs and seeps have been very helpful in analyzing the characteristics of localized groundwater systems, and in determining where regional groundwater systems may interact with shallow groundwater systems and streams. Of particular interest is the relationship found between (leaking) irrigation ditches and other water conveyances and spring discharges from shallow groundwater in the NFVT area.

The USGS study of the groundwater resources of the North Fork of the Gunnison watershed, published in 1986 (*Ackerman and Brooks, 1986*), was primarily concerned with water quality as an indicator of the usability of a groundwater resource. The study provided a limited analysis by sampling a number of wells and a few springs in alluvial and bedrock aquifers of the North Fork watershed between 1977 and 1982. The approximate location of the wells was indicated on a plate enclosed with the report. For the purpose of this study, the particular plate was downloaded from the USGS web site and imported and georeferenced in the GIS, after which the location of the wells and springs were determined and entered in the data base of the *Springs & Wells [USGS 1986]* layer. It should be noted that the wells and springs in this report only represent a small subset of all wells and springs in the study area.

The springs and seeps included in the *North Fork Area Appropriated Springs and Seeps [CDWR 2013]* layer are taken from the Water Rights data base of the State of Colorado. According to the web site of the Water Information Program, Durango, Colorado (*www.waterinfo.org/rights.html*; accessed on October 2013), a "water right" under Colorado water law, is the right to utilize the waters of the State based on the priority of a party's appropriation of a specified amount of water, at a specified location, for specified uses. The essence of a water right is its place in the priority system. Colorado's "first in time, first in right" or "prior appropriation" doctrine applies to both surface water and groundwater tributary to a surface stream. Water rights are adjudicated by Water Courts. The Colorado Decision Support System, managed by the Colorado Water Conservation Board (CWCB) and the Colorado Division of Water Resources (CDWR), maintains a data base of all water rights in the state accessible through the Web CDSS Water Rights Data Selector (*http://cdss.state.co.us/onlineTools/Pages/WaterRights.aspx*). This data base provides detailed water rights information for water structures such as ditch diversions, reservoirs, pipelines, springs, seeps and wells. Scanned images of associated water rights decrees can be downloaded for additional information and details. The data base identifies the water right, among others, by category (called ‘structures’), such as ditches, wells (well fields), reservoirs, pipelines, springs, seeps, and mines, among others.

As the Colorado state statutes do not specifically define a spring, the State may consider a water right to be of the type ‘spring’ when it is excluded of other categories, especially wells. If the spring development meets the following conditions, it is excluded from requiring a well permit or compliance with the Water Well Construction Rules (*Guide to Colorado Well Permits, Water Rights, And Water Administration, CDWR 2012)*:

1. The structure or device used to capture or concentrate the natural spring discharge must be located at or within 50 feet of such spring;

2. The structure or device used to capture or concentrate the natural spring discharge must be no more than ten feet below ground surface; and

3. The owner must adjudicate (obtain a water right through the water court) the structure or device as a spring, which would then be subject to administration in the priority system with all other water rights.

If the spring development fails to meet the above conditions, it must be considered a well, which withdraws groundwater, and all of the laws associated with a well apply. If the spring development does meet the above conditions, it is not mandatory that it be considered a spring subject to administration in priority.

In this project, the Water Rights data base has been used to identify springs and seeps that are present or have been identified in the past to be located within the NFVT study area. Although springs in the Water Rights data base may have been categorized in connection with reservoirs or ponds, or with pipelines, in this study the selection is limited to those structures that are labeled ‘springs’ or ‘seeps’ in the Water Rights data base. The location of the springs and seeps is provided in terms of the PLSS legal land description system (Range, Township, Section, and Quarter Sections (Q160 – 160 acre, Q40 – 40 acre, Q10 – 10 acre)). The data base includes a field for the amount of the water right in cfs [cubic feet per second] as defined by a Water Court action, to some extent indicative of the maximum sustained flow rate that may occur at the spring or seep.

For this study, all springs and seeps in the ‘North Fork and Tributaries’ area were selected from the Water Rights data base and exported to a MS Excel file [included with the GIS files]. This file includes, among others, the name of the structure, its unique ID, the appropriation and adjudication dates, and the maximum allowed flow rate of the water right. Based on the PLSS location information in this file, only the springs and seeps within the NFVT display area were entered in the GIS data base. In the GIS, the location of the springs and seeps were taken at the center of the Q10 quarter section. The GIS data base also includes the water right ID, its earliest appropriation date, and its maximum allowed flow rate. Other data are available in the MS Excel files *CDSS Springs North Fork & Tribs in Delta County and CDSS Seeps North Fork & Tribs in Delta County*. Because of the limitations in location accuracy of the PLSS system, the accuracy of the location of the springs and seeps in the GIS is about 100 to 150ft and due diligence and field verification may be needed for any other purpose than this study.

To evaluate the importance of the springs and seep areas in the Water Rights data base for the current study, the appropriated maximum flow rate has been divided in 5 groups (see the *North Fork Area Appropriated Springs and Seeps [CDWR 2013]* layer): 1) <0.01 cfs (< 4.5 gpm); 2) 0.01 – 0.04 cfs (4.5 – ~20 gpm); 3) 0.05 – 0.1 cfs (~20 – 45 gpm); 4) 0.11 – 1.0 cfs (~45 – 450 gpm); and 5) > 1.0 cfs.(> ~450 gpm).

The spring and seep data from the Water Rights and the spring data from the USGS report appear to be rather complementary and cover most of the significant springs and seep areas in the NFVT area, at least to the extent needed for the evaluation of the hydrogeology and groundwater flow systems in this study. Additional spring information may be obtained from the pipeline, reservoir, and pond structures in the Water Rights data base.