DEVELOPMENT OF GIS-BASED GROUND WATER RESOURCES EVALUATION OF THE UPPER AND MIDDLE ROARING FORK VALLEY AREA, PITKIN COUNTY, COLORADO

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Executive Summary

Under an agreement with Pitkin County, Hydrologic Systems Analysis, LLC (HSA) of Golden, Colorado, in cooperation with Heath Hydrology, Inc. (HHI) of Boulder, Colorado, created a GIS-based step-wise ground water resources evaluation procedure for use as decision/land use management tools by Pitkin County. The procedure, supported by two GIS maps and supporting data bases, guides the site-specific analysis with respect to: 1) ground water resources availability in terms of sufficient quantities for the purpose of its usage, and its economical exploitability; 2) long term sustainability of the utilization of the resources for water supply; and 3) the vulnerability of the resources to contamination.

The GIS maps and data bases developed for this project are limited to the area subject to previous studies conducted for Pitkin County by HSA (study area), specifically, (1) Middle Roaring Fork study area or MRF (Kolm and Gillson, 2004); and (2) Upper Roaring Fork study area or URF, comprising of the Upper Roaring Fork watershed including the North Star preserve (Kolm and others, 2000; Hickey and others, 2000). The data bases developed for this project include original GIS layers from the aforementioned studies, as well as GIS layers and data bases from Pitkin County, Colorado Division of Water Resources/Colorado Water Conservation Board, Natural Resources Conservation Survey (USDA), and U.S. Geological Survey.

Three case history examples are presented to illustrate the analysis procedure, using the GIS maps and data bases provided in this report, two in the MRF area and one in the URF area. The two MRF sites illustrate the variability of drinking water supplies, both in availability and sustainability, for sites located near to each other. The URF site illustrates that drinking water supplies in areas with sediment-bedrock connectivity are readily available and sustainable. All three sites are vulnerable to ground water pollution due to the absence of protective low-permeability hydrogeologic units between the ground surface and the aquifer units.

1.0 Introduction

Under an agreement with Pitkin County, Hydrologic Systems Analysis, LLC (HSA) of Golden, Colorado, in cooperation with Heath Hydrology, Inc. (HHI) of Boulder, Colorado, was tasked to create a series of GIS (Geographic Information System) maps for use as decision/land use management tools by Pitkin County. These maps identify locations in designated areas of Pitkin County:

A. Where ground water resources are: (i) available in reasonable, sustainable quantities, at reasonable depths, (ii) available in reasonable quantities, at reasonable depths, but vulnerable/not sustainable (e.g., because of artificial recharge, such as leaking ditches or irrigation), and (iii) not available in reasonable quantities, at reasonable depths.

B. Where the ground water table is likely to fluctuate significantly (e.g., due to spring runoff or upland flood irrigation), resulting in a high water table at different times of the year.

C. Where ground water resources are vulnerable (using a rating of High-Medium-Low) to contamination (e.g., because of the absence of a confining layer, shallow water table and a substrate consisting of unconsolidated gravels, alluvium, etc.).

The GIS maps cover the area subject to previous studies conducted for Pitkin County by HSA (referred to as the *study area*), specifically, (1) *State of Ground and Surface Water in the Central Roaring Fork Valley, Pitkin County, Colorado – A Hierarchical Approach Using GIS and 3-Dimensional Hydrogeologic Modeling, June 1, 2004* (referred to as the *Middle Roaring Fork study area* or *MRF*) (Kolm and Gillson, 2004), (2) *Understanding Mountain Wetland Hydrology; Technical Guidance for Investigating the Hydrologic Function of Wetlands in Complex Terrain, July* 2000 (referred to as the *Upper Roaring Fork study area* or *URF*, comprising of the Upper Roaring Fork watershed above Aspen and including the North Star preserve) (Kolm and others, 2000), and (3) *Preliminary Hydrologic and Biologic Characterization of the North Star Nature Preserve, Pitkin County, Colorado, May 2000* (referred to as the *North Star study area*, a part of the URF) (Hickey and others, 2000). Note that the second study's focus was on wetland hydrology and ecology and did not analyze ground water systems in detail. The covered study area is shown in Figure 1.

Computer-based GIS maps provide a flexible and efficient way to display and analyze geographic information. Data from various sources can be collected in local or remotely accessible databases, which can be easily maintained and updated, independently of the display and analysis procedures. Computer-based GIS maps support optimal usage of data obtained from different sources containing features of significant importance in hydrogeologic evaluations at different scales, geographic distribution densities, and different levels of accuracy and information value.

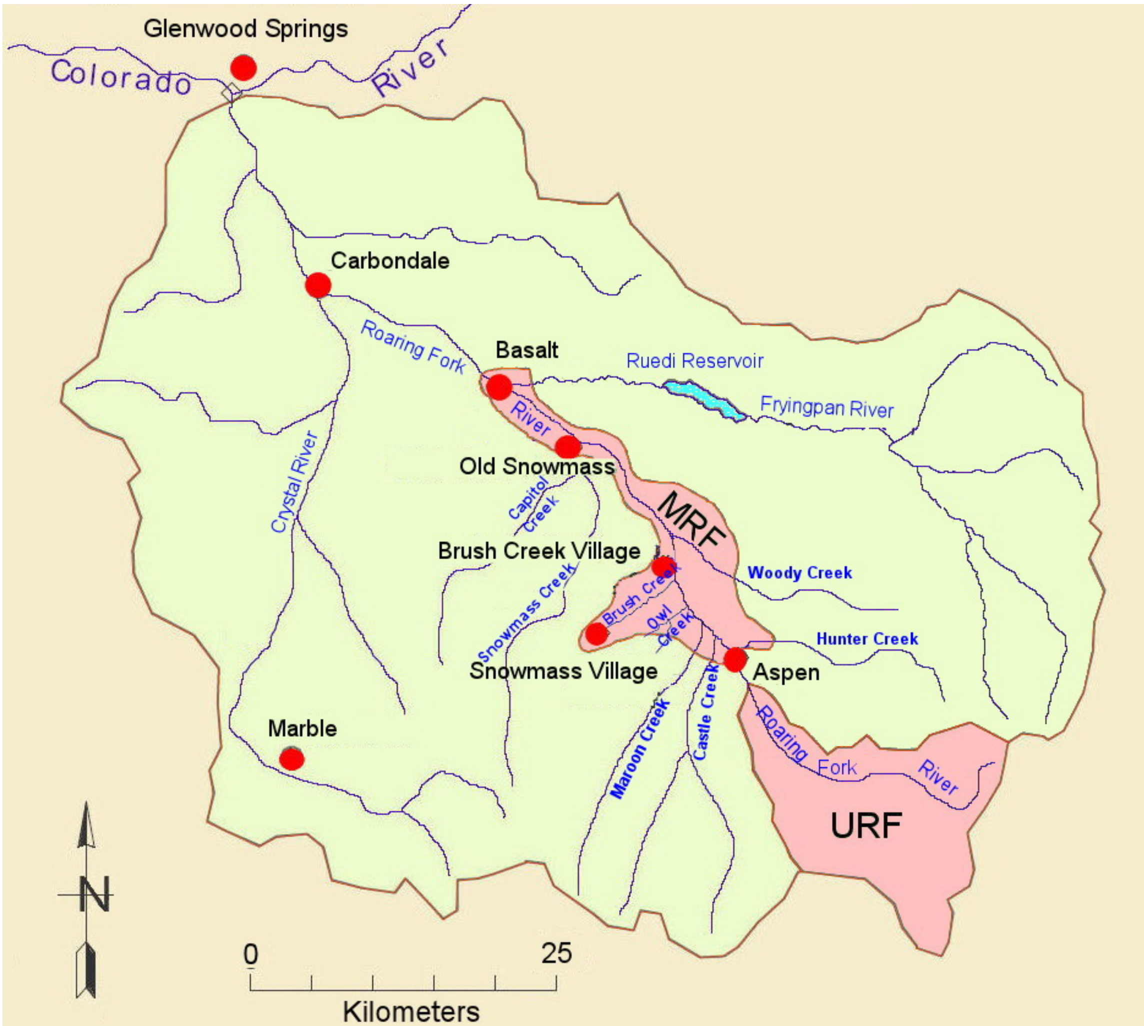

Figure 1. Roaring Fork Watershed and Upper (URF) and Middle (MRF) Roaring Fork Study Areas, Pitkin County, Colorado.

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, landuse, land ownership, wells, etc. Each feature can be further described with linked attribute tables. All data are collected in a geodatabase and/or sets of layer-related files. At each step of a geographic analysis, individual layers can be analyzed, combined, or/and stored (switched on and off) and individual features interrogated with respect to their attributes. 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 randomly visualize (switch) between layers; and the availability of advanced search, selection and overlay capabilities further enhances the utility of a GIS map

The GIS-based evaluation of ground water resources in the MRF and URF study areas makes extensive use of the aforementioned GIS capabilities.

2.0 General Background

2.1 Upper Roaring Fork (URF) Study Area

The Upper Roaring Fork study area hydrologic system, including the North Star wetlands, typically consists of four interrelated subsystems: atmospheric, hillslope, regional ground water, and valley bottom (Figure 2). All subsystems are interrelated by hydrologic fluxes that are continuous across shared subsystem boundaries. Spatial and temporal trends in hydrologic processes of each subsystem are controlled principally by variations in several key components of wetland hydrologic structure. The key structural components of URF are terrain, vegetation, land use, geology, geomorphology and soil.

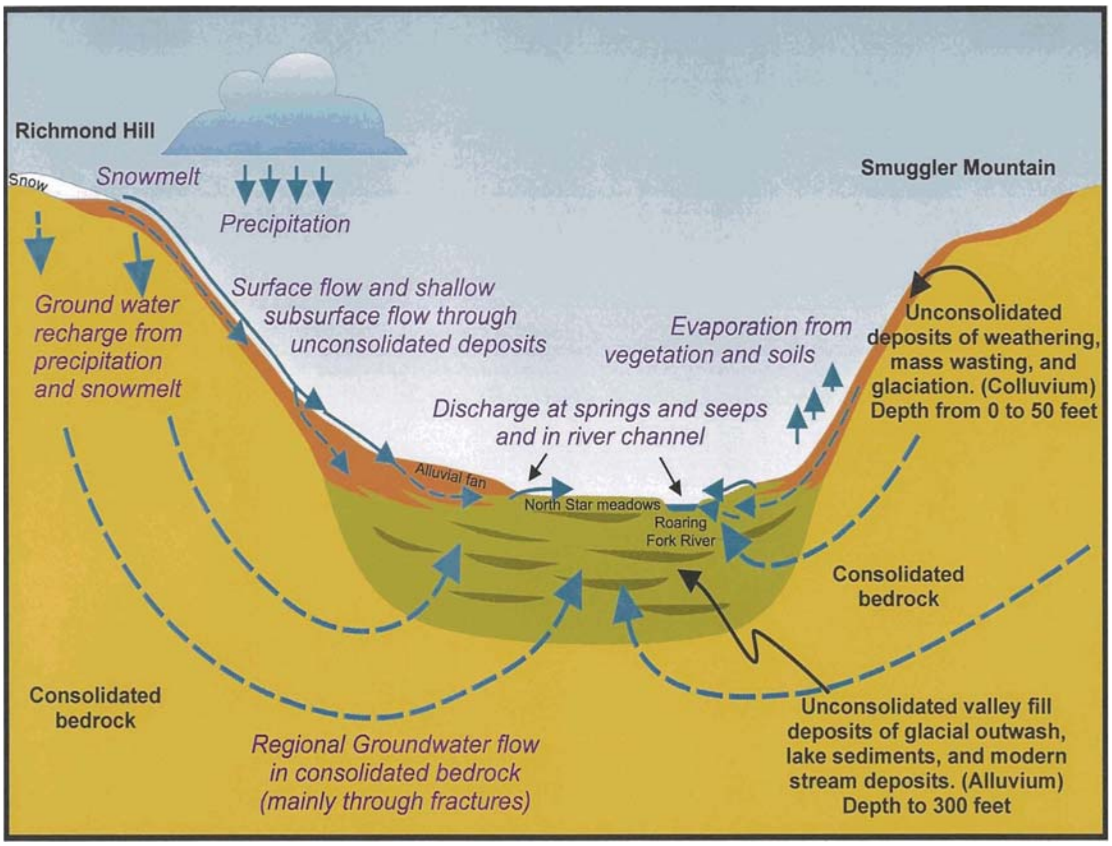

Figure 2. Conceptual Model of the Upper Roaring Fork Hydrologic System.

Terrain and vegetative cover strongly affect the atmospheric subsystem to produce important microclimates. Effects of elevation on precipitation and air temperature are well described, as are effects of slope and aspect on daily solar radiation. Terrain also affects day length, which affects daily solar radiation, as well as local wind speed and direction. Vegetative cover influences evapotranspiration and relative humidity, can reduce solar radiation reaching a snow pack, and modifies heat gain or loss from a snow pack by wind. Geology, geomorphology, and soil have less direct effect on atmospheric processes. However, these components of hydrologic structure can affect the distribution and type of vegetation and land use, which, in turn, can directly influence the atmospheric subsystem. Atmospheric processes serve as driving mechanisms for water entering and leaving the hillslope and valley-bottom subsystems and wetlands within these subsystems.

The key structural components identified previously (terrain, vegetation and land use, geology, geomorphology and soil) affect hillslope hydrologic processes directly and through complex interactions. Terrain controls on the directions and rates of surface and subsurface runoff have been the subject of hydrologic research for several decades. Micro-topography, as well as vegetation and land use, clearly affect surface water storage and infiltration characteristics. The hydraulic properties of soils, geomorphic and geologic deposits control the storage and rate of water movement in the subsurface.

In mountainous terrain, hillslope soils tend to have high infiltration rates and low to moderate water storage capacity. As a result, overland flow tends to be limited and runoff is dominated by other mechanisms such as intermittent interflow or saturated subsurface runoff. The low to moderate water storage capacity of mountain hillslope soils and underlying geomorphic deposits tends to produce hydrologic conditions that are conducive to vertical water movement. As a result, hillslopes tend to act as ground water recharge areas, but will dry rapidly during periods of low precipitation and snowmelt.

In many mountain settings, the contrast between highly permeable geomorphic deposits and less permeable underlying bedrock can produce shallow local-scale zones of subsurface saturation. Water flows laterally along this zone of permeability contrast toward valley bottoms. Flow from hill slope to valley bottom typically occurs at time scales of weeks to months. As a result, inflow to valley bottom wetlands is delayed and attenuated relative to times of precipitation and snowmelt. The existence of shallow zones of saturation within permeable geomorphic deposits also increases the time available for water to recharge the deeper, regional aquifer system.

Ground water movement and storage within the regional ground water subsystem and valley-bottom subsystem are conceptualized as occurring within a two-aquifer framework (Figure 2). An upper, unconfined unit is defined to include thick glacial, colluvial and alluvial deposits, primarily occurring within the valley-bottom subsystem. Limited geophysical data indicated that deposits are stratified and may form two or more vertically distinct hydrogeologic units. However, data are insufficient to map individual units within these unconsolidated deposits. A deeper, regional aquifer is defined to include the fractured crystalline bedrock. Data characterizing thickness and hydraulic properties of this aquifer are very limited. Therefore, the aquifer was considered to operate as a single hydrogeologic unit. Local-scale ground water flow occurs in shallow and discontinuous unconsolidated sediments of the hillslope subsystem. Ground water movement in these sediments occurs relatively rapidly.

Regional ground water movement occurs within a complex three-dimensional framework (Figure 2). Recharge from hillsides moves laterally from unconsolidated geomorphic deposits (glacial, colluvial) through a fractured crystalline bedrock aquifer (granites, volcanic materials) toward valley bottoms. Water then moves vertically into thick, unconsolidated glacial, alluvial and colluvial deposits that are highly permeable.

Discharge is to slope (colluvial and alluvial) and riverine (alluvial) wetlands and the Roaring Fork River. The North Star wetland complex is an important valley-bottom wetland and ground water discharge area for the entire watershed.

Wetlands on hillslopes may occur where geomorphic deposits are conducive to shallow subsurface runoff. Water moving along shallow subsurface flow paths may be forced to the surface of a hillslope where variations in terrain or geologic conditions prevent continued movement in the subsurface toward valley bottoms. Wetlands of this type generally are called slope wetlands and may become dry during late summer and fall when the supply of subsurface runoff is exhausted.

Water movement within the regional ground water subsystem is controlled by the hydraulic properties of the fractured crystalline bedrock. However, few wells have been completed in the bedrock of the upper Roaring Fork watershed and only a general description, based primarily on locations of slope wetlands, springs is possible of spatial variations in flow direction or rate. A potentiometric surface of the bedrock aquifer, constructed with a contour interval of 100 meters, shows that recharge occurs predominantly beneath the hillslope subsystem with water moving laterally toward the valley-bottom subsystem. Discharge from the regional ground water subsystem occurs by upward movement into the valley-bottom subsystem. Annual low flow of the Roaring Fork River near the North Star wetlands typically is 0.6 to 0.8 m^3/s. These values provided useful constraints for ground water subsystem model simulations described in the Kolm and others (2000) report.

Other structural characteristics indirectly influence ground water movement by controlling recharge processes, as describe previously. Terrain variation strongly controls rates and directions of ground water movement. Topographically low areas, such as the principal valley bottoms and streams, act as locations of regional ground water discharge. Regional ground water movement from hillslope recharge areas to valley-bottom discharge areas typically occurs at time scales of years (Figure 2). Consequently, the long-term sustainability of valley-bottom wetlands during years of drought is a direct result of input from regional ground water.

The valley-bottom subsystem (Figure 2) consists of thick unconsolidated sediments of glacial outwash, lake-bed materials, and modern stream deposits overlying crystalline bedrock. Water enters the valley-bottom subsystem as recharge from snowmelt, ground water discharge from thin lateral moraines and colluvial deposits of adjacent hillslopes, and ground water discharge from fractured bedrock of the regional ground water subsystem. Water leaves the valley-bottom subsystem as seepage to the Roaring Fork River or evapotranspiration from wetlands. Primary hydrogeologic controls on wetland distribution are believed to be streambed hydraulic conductivity storage and saturated thickness, the spatial distribution and magnitude of recharge from the regional ground water subsystem, and the distribution of lateral ground water entering the valley-bottom subsystem from adjacent hillslope areas.

Wetland locations within a valley bottom depend on the balance between hydrologic rates of inflow and outflow. In combination with hydraulic properties of geologic and geomorphic deposits, this flow balance controls the water-table elevation in the valley bottom. Where the water table is near or at land surface, wetlands form. In many cases vegetation type can serve as an indicator of a shallow water table, and can be used to estimate evapotranspiration losses.

2.2 Middle Roaring Fork (MRF) Study Area

The hydrogeologic framework of the Middle Roaring Fork study area hydrological system has 4 distinct hydrogeologic units, including 3 bedrock units, and one unconsolidated unit consisting of various Quarternary and Tertiary deposits (Figure 3). The Dakota aquifer is an unconfined system near its recharge area, and a confined system at depth. The Mancos Shale and the Lower Bedrock units, consisting of Morrison and older rocks, are confining layers throughout most of the system. The unconsolidated hydrogeologic unit is an unconfined aquifer at the subregional scale, and can consist of a variety of aquifers and confining units at the local scale.

CORRELATION OF GEOLOGIC AND HYDROGEOLOGIC UNITS

Layer	Unit	Unconsolidated Hydrogeologic Units		
1	Qal	Quaternary Alluvium		
2	Qg	Quaternary Fans and Gravels		
3	Qm	Quaternary Moraine Deposits		
4	Qls	Quaternary Landslide Deposits		
5	Ts	Tertiary Sedimentary Deposits		
		Bedrock Hydrogeologic Units	Unit	**Bedrock Geologic Units**
6	Km	Mancos Shale	Km	Mancos Shale
7	Kd	Dakota Sandstone	Kd	Dakota Sandstone
8	LB	Lower Bedrock	Jm	Morrison Formation
			Je	Entrada Formation
			Trc	Chinle Formation
			Trsb	State Bridge Formation
			PPm	Maroon Formation
			Pg	Gothic Formation
			Pe	Eagle Valley Formation

Figure 3: Correlation of Geological and Hydrogeologic Units in the Middle Roaring Fork Study Area.

The conceptual model of the ground water flow system consists of inputs and outputs based on climate (infiltration of precipitation and snowmelt), stream functions (gaining or losing), vegetation (evapotranspiration), topography (steepness, aspect, degree of landscape dissection), geomorphology and soils, and human activity (mine tunnels, irrigation ditches and irrigation, urbanization, snow making, ISDS), and geology (Figure 4). Based on the hierarchical approach of Kolm and Langer (2001), no regional system has been identified, and subregional and local scale ground water flow systems dominate (Figure 4) in the Middle Roaring Fork study area.

The saturated hydrogeologic units consist of Quaternary landslide, glacial terrace, and alluvial deposits, and Tertiary sediments (Figure 3 and 4). Although, in some specific situations, the Dakota bedrock unit should be considered an aquifer, in general, it is not a saturated hydrogeologic unit of importance in most of the MRF area. Hence, despite its regional presence as a geologic unit, it does not represent a regional ground water subsystem (Figure 4). Deeper bedrock hydrogeologic units, such as the Leadville Fm., are not considered viable as water sources in this area due to costs of acquisition, due to such issues as drilling depths to water and low yields.

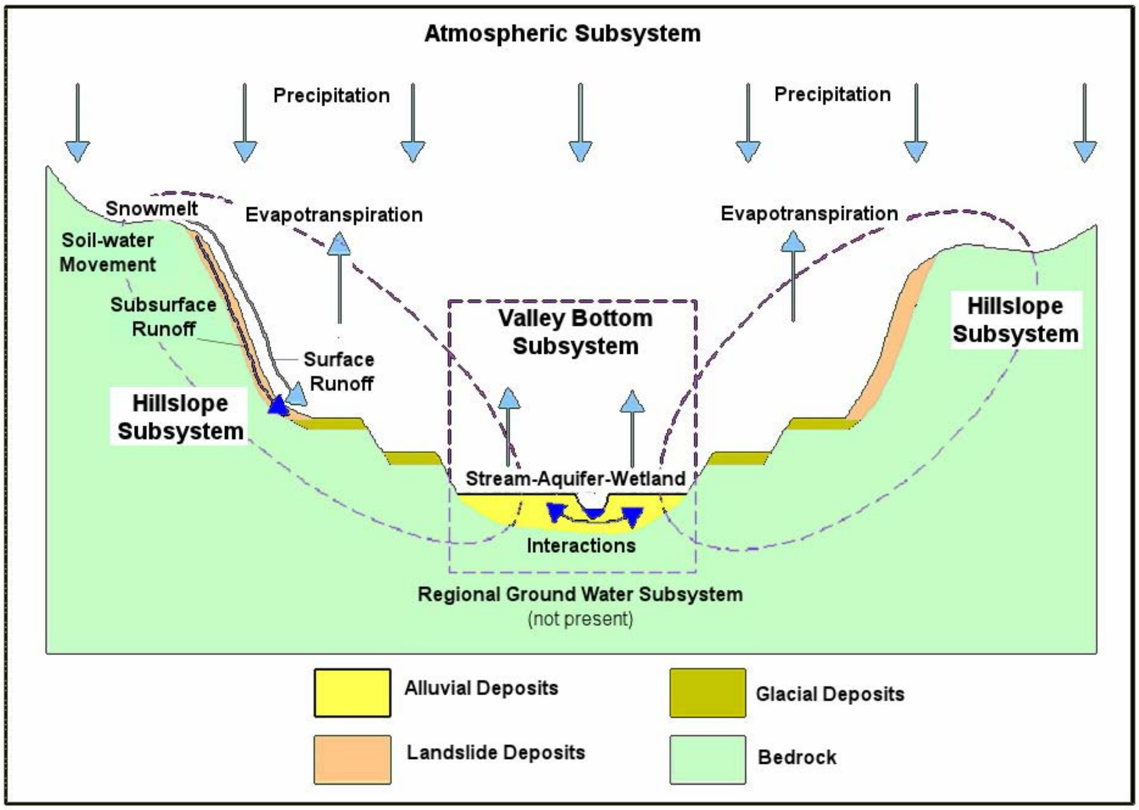

Figure 4. Conceptual Model of Middle Roaring Fork Ground Water Flow System.

The regional hydrologic inputs include infiltration of precipitation as rain and snowmelt, areas of losing streams and water bodies, and upland irrigation areas. The hillslope subsystem consists of the hydrologic processes of surface and near surface runoff (interflow or through flow – light blue arrows on left slope in Figure 4), saturated ground water flow in some areas (dark blue arrows in Figure 4), and discharge to surface springs and by plants as evapotranspiration. The Terrace subsystems have a unique story described in subsequent paragraphs and figures of local conceptual models. The Valley Bottom subsystems, where stream-aquifer-wetland interactions occur, are areas of both ground water recharge and discharge (Figure 4). These subsystems depend primarily on interactions with the Roaring Fork River, and Brush and Owl Creeks, and the associated wetlands are considered riverine given the lack of a supporting regional or subregional ground water system (Figure 4). There are four general conceptual models within the regional scale context of the MRF area (Figure 5): 1) Brush Creek Valley Hillslope (BCH) Subsystem near Snowmass Village; 2) West Roaring Fork Valley Hillslope (WRH) Subsystem; 3) Disconnected Glacial Terrace East Roaring Fork Valley Hillslope (DTH) Subsystem; and 4) Connected Glacial Terrace/Mass Wasting East Roaring Fork Valley Hillslope (CMH) Subsystems.

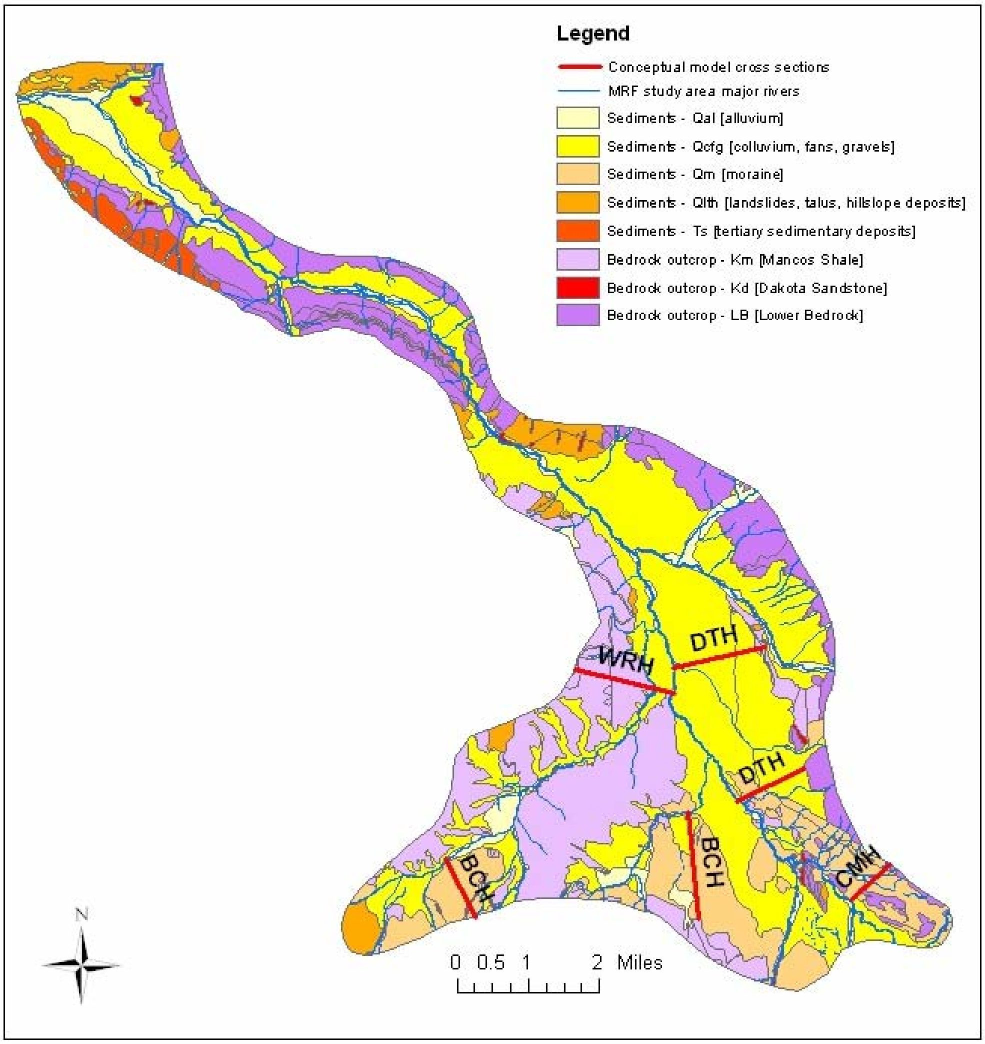

Figure 5. Location MRF Conceptual Models Cross Sections.

There are two significant hydrogeologic units in the BCH area: (1) Quaternary unconsolidated materials, which are predominantly glacial, colluvial, and alluvial deposits, overlying (2) Mancos Shale (bedrock confining layer) (Figure 6). The Quaternary unconsolidated materials are locally heterogeneous, with predominantly coarser materials in the glacial and landslide deposits, and finer materials in the alluvial deposits. The thickness of the sediments ranges from less than 1 ft. to greater than 100 ft. Estimates of hydraulic conductivity (K) ranges from 10 to 100 ft per day (Harlan and others, 1989). The Mancos shale bedrock is the dominant underlying confining layer with small hydraulic conductivity values less than .01 ft per day. It is possible that the underlying Dakota aquifer may be hydraulically connected to the unconsolidated materials in areas around the en echelon normal faults (Kolm and Gillson, 2004).

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the location of open areas, buildings, and parking lots, and to position in the landscape (Figures 6). The unconsolidated units are variably saturated based on spatial location and seasonal precipitation events. There is both lateral and upward recharge from the faulted saturated Dakota Sandstone into the unconsolidated materials in some locations. Otherwise, the Mancos Shale does not allow lateral or upward movement of ground water from the Dakota aquifer into the unconsolidated materials. The unconsolidated units discharge locally into upper Brush Creek, and into minor tributaries of Brush Creek (Figures 6). Therefore, the local flow system is from the unconsolidated glacial and colluvial materials into unconsolidated alluvium and, finally, to springs, seeps, or Brush Creek. In addition, other sources of discharge from the unconsolidated units are evapotranspiration and well withdrawal (Figure 6).

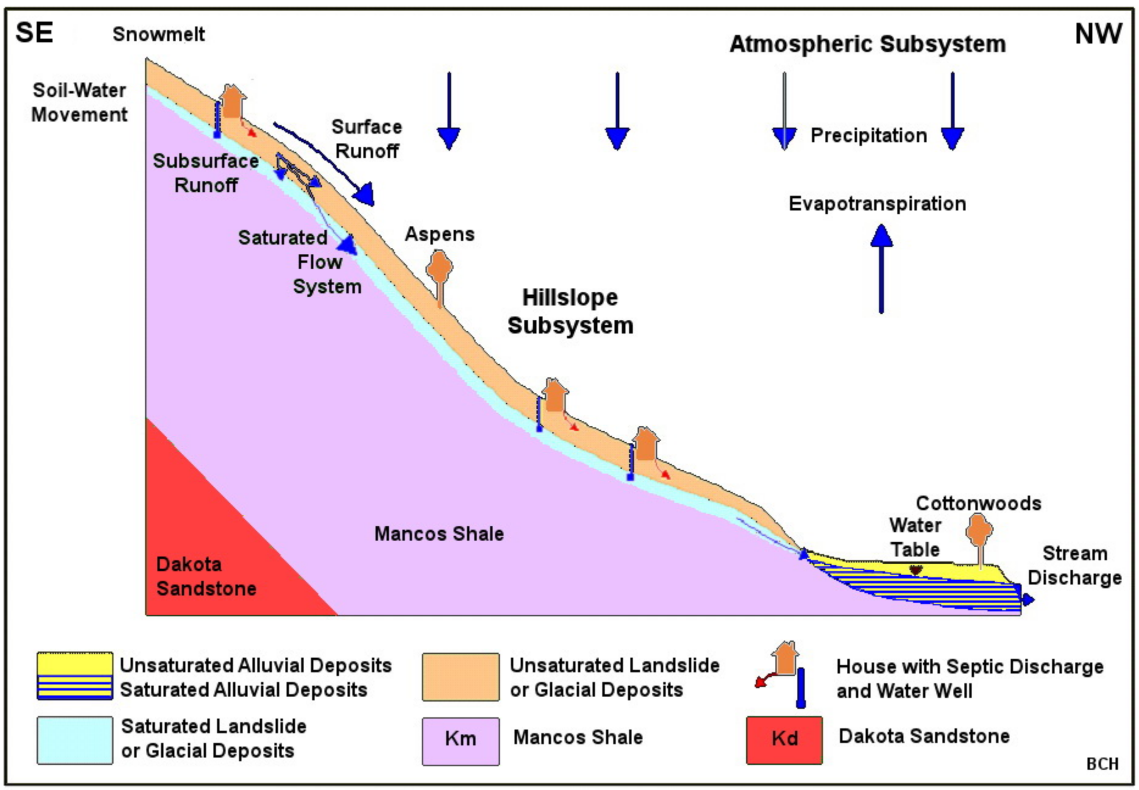

Figure 6. Conceptual Model of the Brush Creek Valley Hillslope (BCH) Subsystem near Snowmass Village.

If it were assumed that the contaminants that are of interest (for example, nutrients from ISDS's and turf grass fertilization) are primarily advective, the contaminant pathways would primarily follow the flow pathways as conceptualized. Given this assumption, several source, transport flow path, and fate scenarios are hypothesized: 1) If the source of contamination is from the ISDS's or turf grass fertilization, then the recharge events due to infiltration of precipitation will move the contaminants from the sources into the unconsolidated materials and ultimately Brush Creek by interflow and saturated ground water flow in the glacial, colluvial, and alluvial materials; and 2) In the few areas where the fault controlled Dakota Sandstone aquifer is connected to the unconsolidated materials, the ground water may flow up into the unconsolidated materials and leach the contaminants from local sources to Brush Creek by saturated ground water flow in the glacial, colluvial, and alluvial materials.

There are two significant hydrogeologic units at the WRH site: Quaternary and recent unconsolidated materials (predominantly colluvium and alluvium) overlying the bedrock unit of Mancos Shale (Figure 7). The Quaternary unconsolidated materials are locally heterogeneous (poorly sorted), and consist of clay, silt, sand, gravel, cobbles, and boulders. The thickness ranges from 1 ft to greater than 100 ft. The estimates of hydraulic conductivity range between 1 to 100 ft per day. The Mancos Shale underlies most of the unconsolidated units at the WRH site (Figures 7). This bedrock unit has minimal transmissivity and storage, and is considered a confining unit in the WRH hydrologic system.

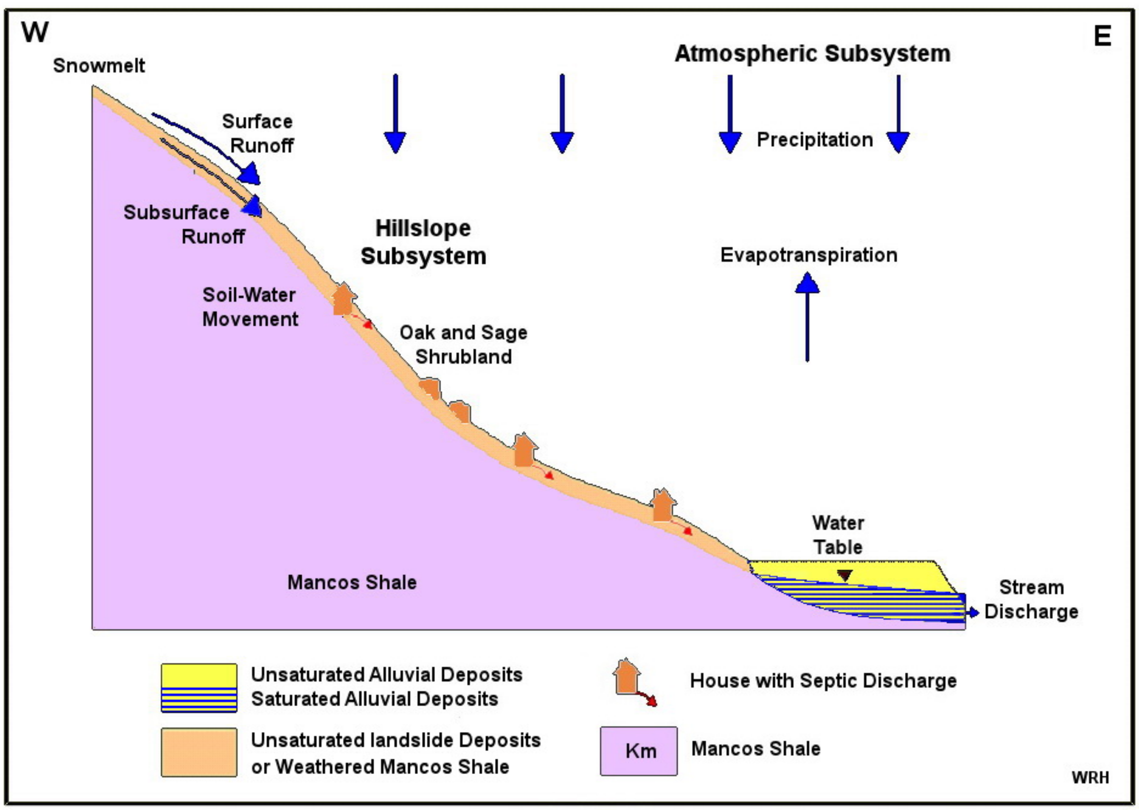

Figure 7. Conceptual Model of the West Roaring Fork Valley Hillslope (WRH) Subsystem.

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the location of open areas, buildings, and parking lots, and position in the landscape. The unconsolidated units are variably saturated based on spatial location and seasonal precipitation events. There is no lateral and upward recharge from deeper bedrock aquifers due the Mancos Shale confining layer (Figure 7).

Ground water moves by primarily interflow and through flow in the unconsolidated units into the alluvium and /or directly into lower Brush Creek and the Roaring Fork River (Figure 7). Other sources of discharge from the unconsolidated alluvium include phreatophytes and well withdrawals.

If it were assumed that the contaminants that are of interest (for example, nutrients from ISDS's and turf grass fertilization; contaminants from the Pitkin County Landfill) are primarily advective, the contaminant pathways would follow the flow pathways as conceptualized. Given this assumption, the following source, transport flow path, and fate scenario is hypothesized: If the source of contamination is from ISDS's and turf grass, and the Pitkin County Landfill located within and over the unconsolidated units, then the recharge events due to infiltration of precipitation will move the contaminants from the sources into the unconsolidated materials and ultimately to the alluvium and to Brush and Owl Creeks, and the Roaring Fork River by interflow or by ground water flow.

There are two significant hydrogeologic units at the DTH site: Quaternary and recent unconsolidated materials (predominantly terrace gravels and alluvium) overlying the bedrock unit of the Mancos Shale (Figure 8). The Quaternary unconsolidated materials are locally heterogeneous, and consist of clay, silt, sand, gravel, cobbles, and boulders. The average thickness is variable ranging from less than 1 ft to over 100 ft. The estimates of hydraulic conductivity range generally between 1 to 100 ft per day (Harlan and others, 1989). The Mancos Shale underlies most of the unconsolidated units at the DTH site (Figure 8). This bedrock unit has minimal transmissivity and storage, and is considered a confining unit in the DTH hydrologic system.

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the location of open areas, buildings, and parking lots, highway and airport location, irrigation ditch location, and position in the landscape. The unconsolidated units are variably saturated based on spatial location and seasonal precipitation events. There is negligible lateral and upward recharge from the underlying bedrock units into the unconsolidated materials in most locations (Figure 8). Ground water in the unconsolidated units laterally recharges the unconsolidated units located topographically below by the interflow process, and the lowest terraces recharge the modern alluvium by interflow (Figure 8). In addition, ditches located on each terrace are influent (losing) and locally recharges the unconsolidated units (Figure 8).

Ground water in the unconsolidated units discharges locally into streams that cut through the terraces, and from the alluvium into the Roaring Fork River. Other sources of discharge from the unconsolidated units include phreatophytes and well withdrawals (Figure 8). Therefore, the local flow system has two components (Figure 8): 1) flow from the unconsolidated materials into cross-cutting streams, into the Roaring Fork River, and 2) flow from infiltration and leakage from the local ditches into the unconsolidated materials, and, finally, into cross-cutting streams and the Roaring Fork River.

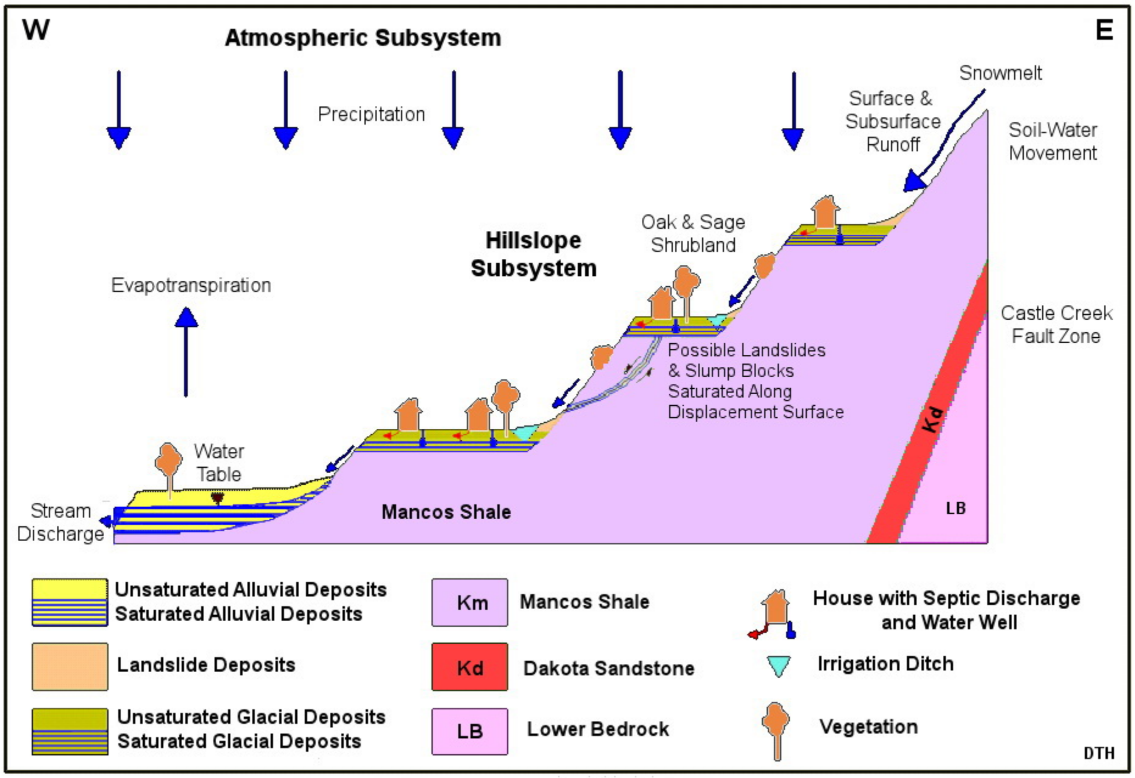

Figure 8. Conceptual Model - Disconnected Glacial Terrace East Roaring Fork Valley Hillslope (DTH) Subsystem.

If it were assumed that the contaminants that are of interest (for example, nutrients from ISDS's and turf grass fertilization; metals and organics from the airport and major highways) are primarily advective, the contaminant pathways would primarily follow the flow pathways as conceptualized. Given this assumption, several source, transport flow path, and fate scenarios are hypothesized: 1) If the irrigation ditches were a source of contaminants, then the contaminants would travel through the unconsolidated terrace gravels to crosscutting streams and transported to the Roaring Fork River; and 2) If the source of contamination is from the ISDS's and turf grass fertilization, or from the airport and highway runoff into the unconsolidated units, then the recharge events due to infiltration of precipitation will move the contaminants from the sources through the unconsolidated materials by interflow or saturated flow, and ultimately to tributaries and/or directly to the Roaring Fork River.

There are two significant hydrogeologic units at the CMH site: Quaternary and recent unconsolidated materials (predominantly terrace gravels and mass wasting deposits) overlying the bedrock unit of the Mancos Shale (Figure 9). The Quaternary unconsolidated materials are locally heterogeneous, and consist of clay, silt, sand, gravel, cobbles, and boulders. The average thickness is variable ranging from less than 1 ft. to greater than 100 ft. The estimates of hydraulic conductivity range generally between 1 to 100 ft per day (Harlan, and others, 1989). The Mancos Shale underlies most of the unconsolidated units at the CTH site (Figure 9). This bedrock unit has minimal transmissivity and storage, and is considered a confining unit in the CMH hydrologic system.

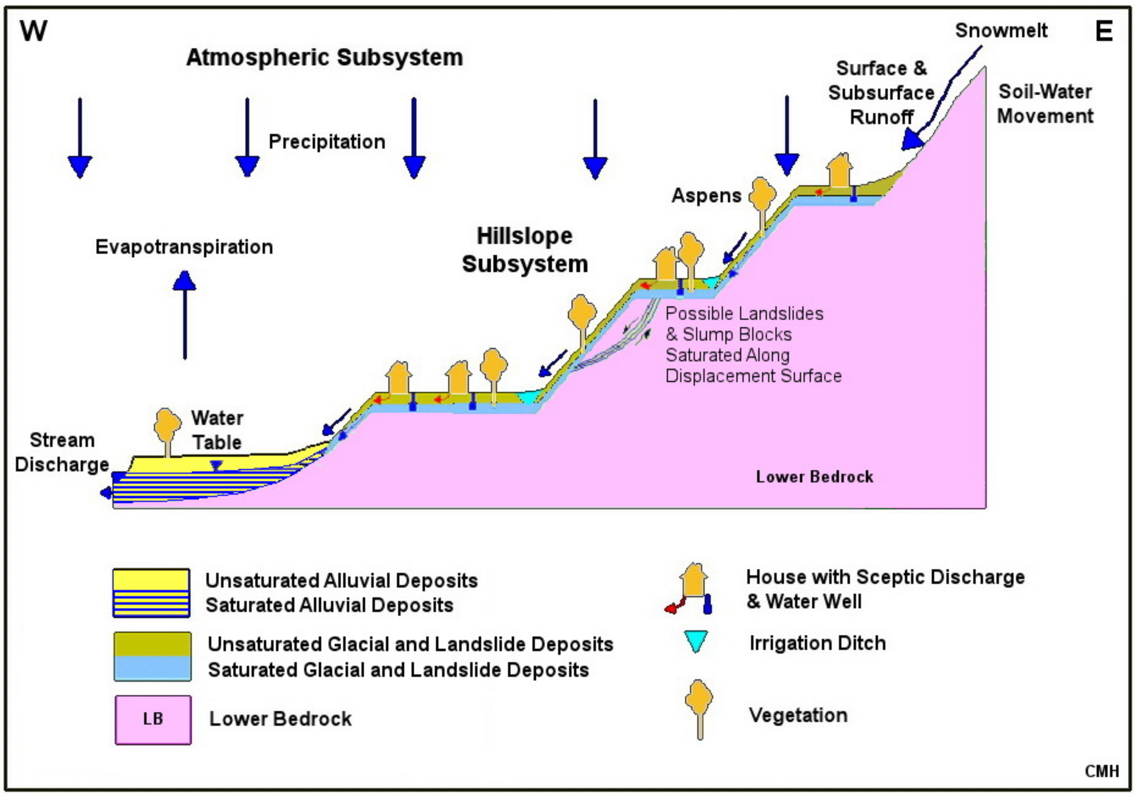

Figure 9. Conceptual Model - Connected Glacial Terrace/Mass Wasting Units East Roaring Fork Valley Hillslope (CMH) Subsystem.

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the location of open areas, buildings, and parking lots, irrigation ditch location, and position in the landscape. The unconsolidated units are variably saturated based on spatial location and seasonal precipitation events. There is negligible lateral and upward recharge from the underlying bedrock units into the unconsolidated materials in most locations (Figure 9). Ground water in the unconsolidated terrace units laterally recharges the unconsolidated terrace units located topographically below by ground water flow through mass wasting units, and the lowest terraces and mass wasting units recharge the modern alluvium by ground water flow (Figure 9). In addition, ditches located on each terrace or mass wasting unit are influent (losing) and locally recharges the unconsolidated units (Figure 9).

Ground water in the unconsolidated units discharges locally into streams that cut through the terraces, and from the alluvium into the Roaring Fork River. Other sources of discharge from the unconsolidated units include phreatophytes and well withdrawals (Figure 9). Therefore, the local flow system has two components (Figure 9): 1) flow from the unconsolidated materials into cross-cutting streams, into the Roaring Fork River, and 2) flow from infiltration and leakage from the local ditches into the unconsolidated materials, and, finally, into cross-cutting streams and the Roaring Fork River.

If it were assumed that the contaminants that are of interest (for example, nutrients from ISDS's and turf grass fertilization) are primarily advective, the contaminant pathways would primarily follow the flow pathways as conceptualized. Given this assumption, several source, transport flow path, and fate scenarios are hypothesized: 1) If the irrigation ditches were a source of contaminants, then the contaminants would travel through the unconsolidated terrace gravels to crosscutting streams and transported to the Roaring Fork River; and 2) If the source of contamination is from the ISDS's and turf grass fertilization, then the recharge events due to infiltration of precipitation will move the contaminants from the sources through the unconsolidated materials by interflow or saturated flow, and ultimately to tributaries and/or directly to the Roaring Fork River.

3.0 GIS Layers Included In The Maps

HSA/HHI prepared two GIS maps within the ArcMAP™ program (version 8.3, 2002) of ArcGIS™ system (ESRI®, Redlands, California):.

1) Map 1: MRF Study Area [file: PitkinCounty_GWGIS_MRF.mxd]; this map focuses on the ground water resources in the Middle Roaring Fork study area as described in Chapter 1 (Figure 10); and
2) Map 2: URF Study Area [file: PitkinCounty_GWGIS_URF.mxd]; this map covers the Upper Roaring Fork watershed while focusing on the ground water resources in its lower section in the vicinity of the North Star preserve upstream from the City of Aspen as described in Chapter 1 (Figure 11).

Utilizing the GIS maps requires running the ArcMAP program version 8.3 or higher. The decision to prepare two separate maps was made to optimally use the disparate format of the available (hydro)geologic information and to retain ease of usage of the maps.

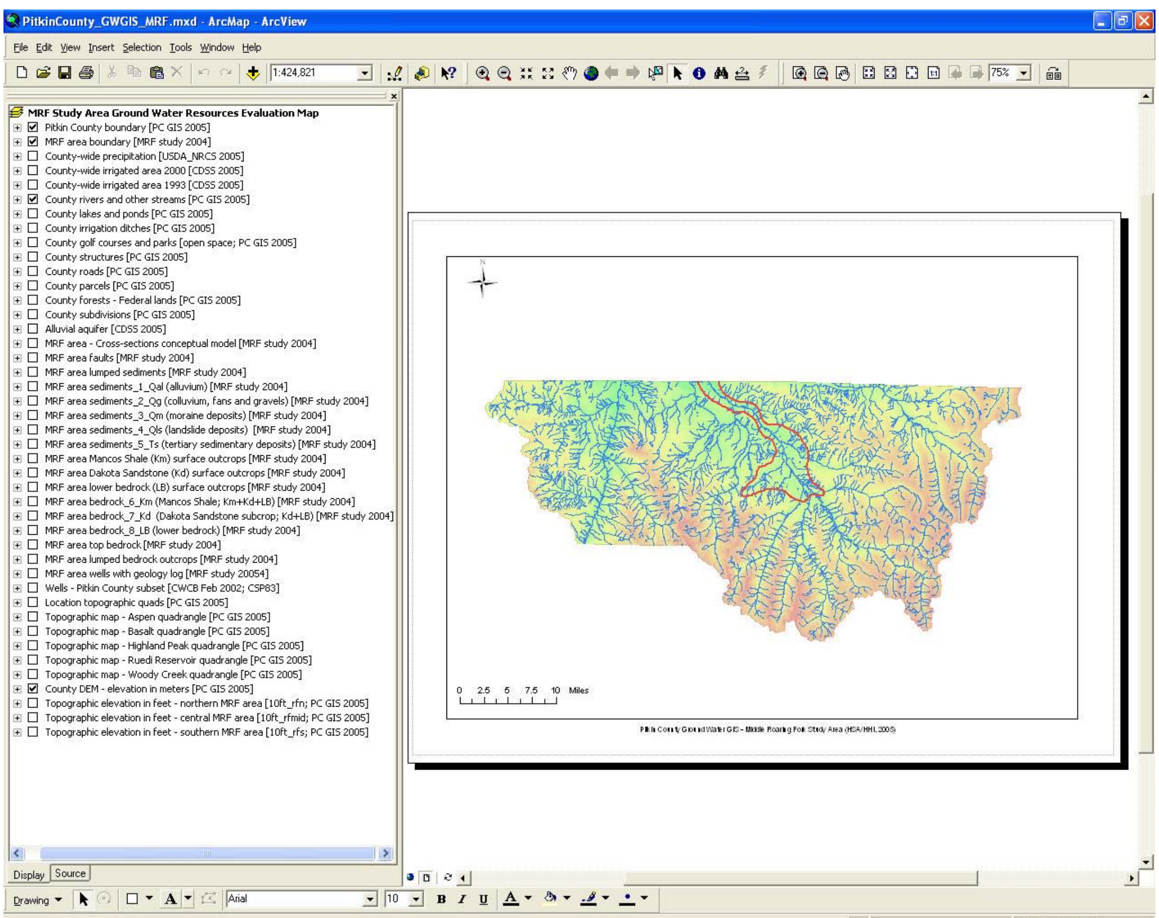

Figure 10. GIS Map of Middle Roaring Fork Study Area with County-wide DEM and Stream Layers.

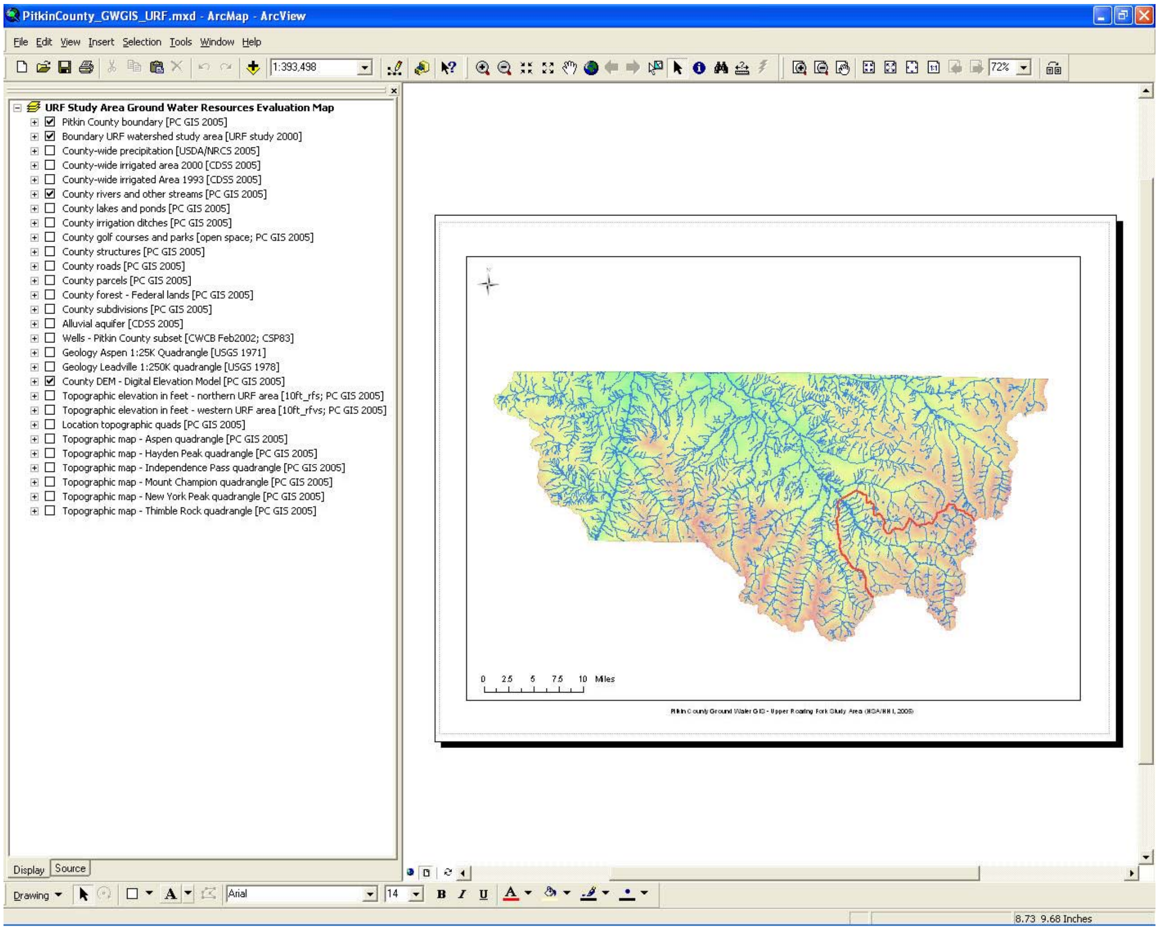

Figure 11. GIS Map of Upper Roaring Fork Study Area with County-wide DEM and Stream Layers.

These maps call various files included in seven relative-path subdirectories: 1) Colorado DSS; 2) Geology Maps; 3) MRF GIS Files; 4) NRCS Data Gateway; 5) Pitkin County GIS; 6) URF GIS Files; and 7) Wells_DWRSC_Pitkin. The directories reflect the various data sources used for the maps. Selection of the relative-path option of ArcMAP provides for straightforward portability between computers. Note, that the files that represent state-wide or multi-county data have been clipped to show only the Pitkin County area coverage.

The 'Colorado DSS' subdirectory contains 3 sets of GIS files downloaded from the Colorado Decision Support System (CDSS), which is under development by the Colorado Water Conservation Board and the Colorado Division of Water Resources (http://165.127.23.116/website/cdss/). These file sets are: 1) state-wide presence of an alluvial aquifer; 2) irrigated areas on the West Slope as of 1993; and 3) irrigated areas on the West Slope as of 2000. Layers based on these data are referenced as 'CDSS 2005'.

The ‘Geology Maps’ subdirectory contains files for the georeferenced and rectified USGS geologic map of the Aspen 1:24,000 quadrangle (*Bruce Bryant, 1971, U.S. Geological Survey Map GQ-933*) and the GIS (shape) files for the USGS Geologic Map of the Leadville 1^o x 2^o Quadrangle (*Ogden Tweto, Robert H. Moench, and John C. Reed, Jr., 1978, U.S. Geological Survey, Misc Investig. Series Map I-999*). These files have been projected on the Colorado State Plane Central Zone (NAD 1983; ft) and are used in the URF map as the main (hydro)geologic data base. The coverage provided by the Aspen geologic map is more detailed than that provided by the Leadville geologic map. Therefore, the Leadville map should only be used in areas outside the coverage of the Aspen map. A separate legend file for both geologic maps is included in their respective subdirectories. The (hydro)geologic maps for the MRF area are described in the next section. Layers based on these data are referenced as ‘USGS 1971’ (Aspen map) and ‘ USGS 1978’ (Leadville map).

The ‘MRF GIS Files’ subdirectory contains original and updated shape files from the Middle Roaring Fork ground water study (see Chapter 1). These files pertain primarily to the area’s (hydro)geology as described in Chapter 2. Layers based on these data are referenced as ‘MRF Study 2004’.

The ‘NRCS Data Gateway’ subdirectory contains county-wide annual precipitation data from the Natural Resources Conservation Service (USDA). These data have been developed using PRISM (Parameter elevation Regression on Independent Slopes Model) which utilizes a rule-based combination of point measurements and a digital elevation model (DEM) (http://datagateway.nrcs.usda.gov/GatewayHome.html). Layers based on these data are referenced as ‘USDA_NRCS 2005’.

The ‘Pitkin County GIS’ subdirectory contains the shape, DEM and DRG files from the Pitkin County GIS as well as the relevant meta files as received in September 2005. Coverages include county border and area; roads; streams, lakes and ponds (waters layer); (irrigation) ditches; parcels, subdivisions, and structures; forest and open space coverage; and 10ft elevation contours for selected areas, topographic maps, and the county-wide digital elevation model (DEM). Pitkin County GIS data are based on the State Plane, Colorado Central Zone projection and the North American Datum of 1983 (NAD83) with units of measure in feet. Pitkin County’s GIS data were made available to HSA by the County as part of the project agreement. Layers based on these data are referenced as ‘PC GIS 2005’.

The ‘URF GIS Files’ subdirectory contains shape files constructed from CAD files (DGN format) from the Upper Roaring Fork studies (see Chapter 1). Note that not all URF shape files have been included in the final URF map as they duplicate other source layers in the map. Layers based on these data are referenced as ‘URF Study 2000’.

The ‘Wells_DWRSC_Pitkin’ subdirectory contains a subset of the February 28, 2002 version of the state-wide well data base, maintained by the State of Colorado Division of Water Resources. This data set was obtained in 2002 from the State on CD as part of the MRF study (http://www.water.state.co.us/pubs/welldata.asp). The subset is restricted to Pitkin County (county code 49) and includes both well permits (drilled or not) and drilled wells. The attribute table [right-click on layer in contents column) includes fields for drill and completion date, total well depth and depth to water (water table). The subdirectory contains the file ‘WELL_DATA FIELDS.doc’ with explanations of the fields in the wells attribute table. This subdirectory also contains well-related shape files from the MRF area ground water study most of which, due to their limited coverage, have not been used in the MRF GIS map. Only the subset containing geologic layer descriptions in the attribute table has been included. Layers based on these data are referenced as ‘CWCB Feb 2002; CSP83’.

Note that the files in the ‘Colorado DSS’, ‘Pitkin County GIS’, ‘NRCS Data Gateway’ and ‘Wells_DWRCS_Pitkin” directories require regular updating from the data source/owner/custodian.

The GIS layers of the MRF and URF maps contain four types of geographic information: 1) general geographic information (county border, roads, parks, parcels, structures, etc); 2) hydrologic information (precipitation, streams, lakes/ponds, ditches, irrigated areas); 3) hydrogeologic information (alluvial aquifer, hydrogeologic units, wells); and 4) topographic information (topo maps, DEM, 10ft elevation contours). Type 1 information is used to locate the site of interest and obtain some general geographic data. Type 2 and Type 3 information is integral to the evaluation of ground water resources. Type 4 information provides elevation and background data as needed. All layers have been georeferenced with respect to Pitkin County’s projection and datum: State Plane, Colorado Central Zone, NAD83 (ft).

The MRF and URF GIS maps consist of a ‘table of contents’ (the left display area of Figures 10 and 11) and a ‘map display area’ (the right display area of Figures 10 and 11). Each line in the table of contents is a GIS layer representing a set of features of the same type, such as streams, parcels, wells, etc. Each layer is linked to one or more files in the GIS database. “Left clicking” the square in front of the layer reveals the layers graphic representation characteristics (e.g, line color, point symbol, colored variable range, etc). “Right clicking” the layer opens a menu that includes an option to ‘Open Attribute Table’ and an option to show ‘Label Features’. The maps are designed to show relevant labels 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.

Individual features can be identified using the ‘Identify’ option (i) from the ‘Tools’ toolbar and selecting the appropriate layer in the pop-up ‘Identify Results’ window. The pop-up table shows the information from the attribute table for the selected feature. Some information in the attribute tables of specific interest to the current project is given in Table 1.

GIS Layer	Attribute Table Field	Comments
County-wide Precipitation	Range	precipitation in inches/year
County-wide Irrigation 1993 & 2000	Crop_type	type of crop
	Irr_type	type of irrigation
	Acres	irrigated acreage
County Rivers and Other Streams	Name	
	Flow_Categ	continuous, intermittent
	Type	river, stream, creek, swamp/bog, reservoir, pond, lake, ditch, island
Irrigation Ditches	Name	name of ditch (if available)
	Length	length of stretch
Wells		many fields of interest such as yield, depth to bottom, depth to water table, surface elevation; see the file WELL_DATA FIELDS.doc of which a hard copy is included in Appendix A.
MRF Wells with Geology	see Wells layer	includes additional fields describing top bedrock, depth to base, thickness and lithology of top 3 geological units

Table 1. Selected Attributes of Interest in Evaluating Ground Water Resources.

4.0 Procedures And Layer Descriptions:

The complexity of the hydrogeology in the Middle and Upper Roaring Fork study area and the disparity in type, distribution and accuracy of available data do not support the preparation of a single-layer, multi-feature map addressing the area's ground water availability, sustainability of its utilization, and its vulnerability. To achieve the project's objectives, an intuitive and flexible analysis procedure has been developed that optimally utilizes the capabilities of the GIS. This stepwise procedure facilitates the evaluation of ground water availability, sustainability and vulnerability on a site-specific base. At each step, notes refer to individual layers in the MRF and URF GIS maps. For ease of reference, each layer in both maps has been numbered as shown in Figures 12a and 12b. When a layer is referenced in the text, a check mark needs to be placed in the layer's box in the contents column of the GIS map for the layer to be viewed. These check marks should be removed when moving to the next step in the procedure.

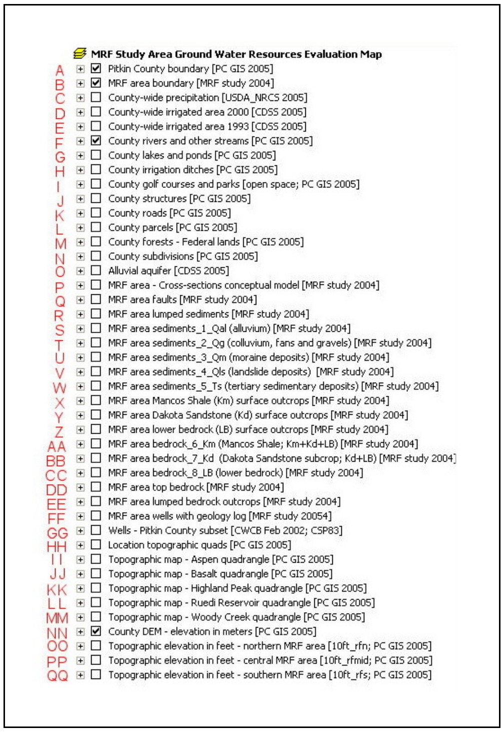

Figure 12a. Table of Contents for MRF GIS Map.

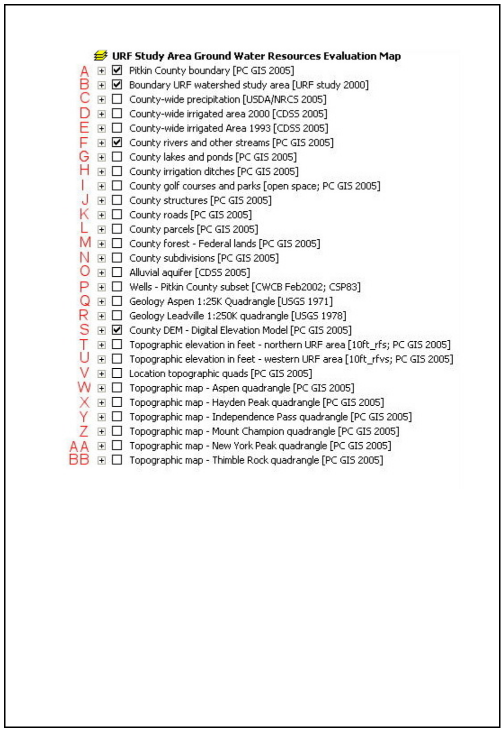

Figure 12b. Table of Contents for URF GIS Map.

It is assumed that the starting point of the analysis procedure is a permit application for development of one or more parcels in the MRF or URF study area. Upon receipt of a permit application, the first step is to determine the precise location or platting of the permit site (PS), and to use this location in conjunction with the hydrology and hydrogeology GIS layers to determine the presence of ground water (Objective 1a). The succeeding tasks include determining the level of ground water availability (Objective 1b), its sustainability as a resource at the site (Objective 2), and its vulnerability to contamination and subsequent loss of supply (Objective 3). It should be noted that due to limitations in data availability and quality, this analysis is primarily qualitative in nature. It does not replace due diligence on the side of the permit applicant.

4.1. Potential Availability Of Ground Water For Water Supply

This section provides a description of how objective 1a is achieved: determining the potential availability of ground water for water supply by identifying the areas covered by hydrogeologic formations that may be an aquifer (either unconsolidated surficial materials or bedrock). Excluded will be areas that consist mainly of shale. The aquifer may be in surficial material or bedrock formations.

4.1.1. Potential Unconfined Surficial Aquifer Material In Study Area

The following surficial materials may be aquifers in the study area:

Unit 1: Modern Alluvium (Qal; alluvium). This material is primarily located along the modern streams, such as Owl Creek and Brush Creek, and rivers, such as the Roaring Fork (Figure 1). These materials usually are natural aquifers that have direct connection to and are sustained by the nearby surface water bodies, and are most likely vulnerable due to being prone to seasonal fluctuations and changes in surface water body use (withdrawal for irrigation, for example). *In the MRF GIS map: switch on layer S (Figure 12a); in the URF GIS map: switch on layer Q or layer R(Figure 12b).*

Unit 2: Terrace Gravels (Q or Qg; young terrace gravels, fans, colluvium). This material is primarily located above the modern stream levels on the hillslopes. These materials usually are dry, or can be aquifers created and sustained by anthropogenic activity, such as irrigation ditches or irrigation return flow. *In the MRF GIS map: switch on layer T (Figure 12a); in the URF GIS map: switch on layer Q or layer R (Figure 12b).*

Unit 3: Moraines (Qm; moraines). This material is primarily located at mountain canyon mouths, such as the Roaring Fork River, and Castle and Maroon Creek canyons, or along the higher hillslope locations near the high glacially carved hanging valleys and cirques, such as the slopes along Burnt Mountain near Snowmass Village. The moraines of the Roaring Fork River and Castle and Maroon Creeks are dry near the surface, but frequently contain natural ground water at depth. The moraines and associated mass wasting deposits of the Owl and Brush Creek areas also contain natural ground water at depth, and are sustained by natural climate and underlying Dakota Formation in some locations. *In the MRF GIS map: switch on layer U (Figure 12a); in the URF GIS map: switch on layer Q or layer R (Figure 12b).*

Unit 4: Landslides (Qls). This material is primarily located along the hillslopes surrounding the populated areas of Pitkin County. These materials are primarily dry, but in areas of irrigation ditches and other anthropogenic activity, may become aquifers. *In the MRF GIS map: switch on layer V (Figure 12a); in the URF GIS map: switch on layer Q or layer R (Figure 12b).*

Unit 5: Older terrace gravels and fans (Ts). This material is primarily located along the hillslopes. These materials usually are dry, or can be aquifers created and sustained by anthropogenic activity, such as irrigation ditches or irrigation return flow. *In the MRF GIS map: switch on layer W (Figure 12a); in the URF GIS map: switch on layer Q or layer R (Figure 12b).*

These surficial materials, when saturated, will be primarily unconfined or water table systems. Therefore, the water table will fluctuate naturally with climate input (seasonal rainfall and snowmelt). In addition, these aquifers will be vulnerable to contamination from land surface activity, such as irrigation, industrial, or urban uses.

4.1.2 Potential Unconfined And Confined Bedrock Aquifer Material

The following bedrock materials may be aquifers in the study area:

Unit 6: Dakota Sandstone (unconfined or confined). This unit is primarily a sandstone that may have either matrix or fracture permeability. Given the age of the unit, fracture permeability is likely to be most significant for water supply. Typically, this unit is located at a depth greater than 200 feet under most of the study area west of the City of Aspen. *In the MRF GIS map: switch on layers Y and/or BB (Figure 12a); in the URF GIS map: switch on layer Q or layer R (Figure 12b).*

Unit 7: Leadville Limestone (Carbonates) (unconfined or confined). This unit is primarily a limestone that has mostly fracture and karst permeability. The unit is located a depths greater than 1,000 feet under most of the study area west of the City of Aspen.

Unit 8: Fractured Crystalline Material (Granite, Gneiss, etc) (unconfined). This unit is primarily igneous or metamorphic crystalline rocks that have mostly fracture permeability. The unit has vast thicknesses, however, the depth to which saturated thickness of this unit is maintained is usually not greater than 500 feet. Note that the fractured crystalline material is found primarily beneath BLM and U.S. Forest Service lands, and is located in the upper Roaring Fork Drainage and North Star area.

For the current study area, only the surficial material, the Dakota Sandstone, and the fractured crystalline rocks are of interest. The Leadville Limestone will be of interest when the study is extended to Aspen and nearby areas. *In the MRF GIS map: switch on layers Z and/or CC (Figure 12a); in the URF GIS map: switch on layer Q or layer R (Figure 12b).*

With the above discussion in mind, there are three layers in the MRF GIS map used to determine the presence of potential aquifer materials:

1) A set of layers showing the outcrops of all hydrogeologic units combined *(MRF layers R and EE combined; Figure 12a)*. All of the potential hydrogeologic units are represented in these two layers. The combined layers show the distribution of all the potential hydrogeologic units as they appear on the land surface in the study area.

2): A set of layers showing the extent of each of the unconsolidated hydrogeologic units *(MRF layers S, T, U, V and W)*. All of the potential unconsolidated hydrogeologic units are represented in these five layers.

3): A set of layers showing the extent of each of the bedrock hydrogeologic units. All of the potential bedrock hydrogeologic units are represented in these three layers *(MRF layers AA, BB and CC)*.

For the URF study area, the presence of potential aquifer materials is determined using layers Q or R. A legend for these layers is included in Appendix A2 and A3 and in the set of GIS files.

4.1.3 Is The Potential Alluvial/Colluvial Aquifer Connected/Not Connected With A Bedrock Aquifer?

If it has been determined (Section 4.1.1) that the site is located in an area with a potential alluvial/colluvial aquifer, the presence of a direct connection with an underlying bedrock aquifer needs to be established. This connection may indicate a more regional availability of ground water than would be the case if only an alluvial/colluvial aquifer is present. This alluvial/colluvial–bedrock aquifer connectivity can be evaluated by locating the permit site with respect to the layers discussed in sections 4.1.1 and 4.1.2. Sites where unconsolidated materials overlie shale (Km) or the combined lower bedrock unit (LB) are areas where no such connectivity is present. Areas where landslide and alluvial material overlie Dakota Sandstone, the Leadville Formation or Precambrian rocks have direct bedrock connectivity.

4.2 Is Alluvial/Colluvial Material Saturated Or Unsaturated?

The final questions in determining the availability of ground water as water supply relate to the actual presence of ground water in the potential aquifer units, the saturated thickness, and the potential yield (Objective 1b). In order to answer these questions, information from nearby wells is evaluated. Only wells located in the same hydrogeologic unit are of interest. Layer GG in the MRF map and layer P in the URF map show the locations of the Pitkin County wells recorded in the state well data base. The attribute table for this layer contains information with respect to depth to water table, screen placing, depth to bottom, saturated thickness (if bottom of aquifer has been reached), and well yields, among others. In some cases, ground elevation is included; if not, it can be obtained from the DEM layer, the 10ft elevation contours layers, or the topographic map layers in the GIS maps.

4.3 Potential Sustainability Of Water Supply From Ground Water

This section describes the approach to accomplish objective 2: potential sustainability of water supply from ground water. This is done through the performance of a 3-step qualitative analysis of the aquifer recharge mechanisms and dynamics. A major consideration in this phase of the analysis procedure is the distinction that exists between aquifers subject primarily to natural recharge (precipitation and influent streams) and aquifers dependent on anthropogenic recharge (leakage from irrigation ditches and irrigation return flow). At this time, data are lacking for a quantitative approach with respect to water budget terms and their fluctuations in time.

4.3.1 Is There Direct Infiltration Of Precipitation Into The Alluvial/Colluvial Aquifer Or The Bedrock Aquifer And How Much?

Every part of the aquifers in the study area has the potential for ground water recharge, and downward gradients potentially exist for all aquifers. Actual recharge is dependent on local slope steepness, slope aspect, soils and geomorphic deposits, bedrock, vegetation type and distribution, human activity, and other factors. Generally, recharge potential is about 10 percent of precipitation in the 10-15 inch per year range, and recharge percentage increases with increasing precipitation above 15 inches per year. To determine the recharge potential from precipitation in the vicinity of the site, a precipitation layer is included in the GIS maps *(layer C in both MRF and URF GIS maps)*. This layer contains an estimated annual precipitation distribution for the county based on point measurements and various characteristics derived from a Digital Elevation Model (DEM) for the area. Note that low-lying areas (valley bottoms) receive significantly less precipitation than higher elevations.

4.3.2 Is The Alluvial/Colluvial Aquifer Connected/Not Connected With A Perennial Stream?

In order to determine if the aquifer of interest is recharged by an influent stream, the presence of a direct hydraulic connection between the aquifer and the stream needs to be established, the stream must be perennial (or at least flowing for most of the year), and the water table near the stream should be below stream level. GIS layer F in both MRF and URF GIS maps is Pitkin County's water GIS layer, containing, among others, a field indicating intermittent stream flow (ephemeral stream) or continuous stream flow (perennial stream). By combining hydrogeologic unit information from layer O (for both MRF and URF GIS maps) with the county's streams layer F, the existence of a hydraulic connection can be established. There is no hydraulic connection between a stream and the aquifer if no streams intersect or border the hydrogeologic unit of interest in the vicinity of the permit site. Sites that are close to a stream may experience seasonal water fluctuations in the water table in sync with those of the stream. Sites located near perennial streams will tend to be sustainable for longer time periods. Finally, determining if the aquifer's water table is below stream level involves comparing water table information from wells in the vicinity of the stream (form the wells layer) with stream elevation data (for example, from the topographic map layers). Note that the existence of a stream/aquifer connection in developing a ground water supply in the area may have implications regarding water rights issues.

4.3.3 Is The Saturated Alluvial/Colluvial Aquifer Connected With An Irrigation Ditch Or Return Flow Of Irrigation Water?

This step determines if recharge occurs as a result of irrigation practices. There are two potential recharge mechanisms related to such practices: infiltration of non-consumed irrigation water (return flow) and leakage from unlined irrigation ditches. Sites located near irrigated acreages and active (i.e., regularly water-carrying) upgradient irrigation ditches are mostly sustained by irrigation activity, and changes in irrigation practices, water rights and long-term land use may greatly affect the sustainability of a ground water supply. In addition, wells in such locations may see fluctuations in water levels based on irrigation schedules.

In order to establish if the saturated portion of the potential aquifer of interest is connected with an irrigation ditch, hydrogeologic unit information from layer O (for both MRF and URF GIS maps) is combined with the county's ditches layer H. There is no recharge if no active ditches intersect or border the hydrogeologic unit of interest in the vicinity of the permit site. The absence in the county's ditch attribute table d information regarding major versus minor ditches, mostly continuous versus intermittent water carrying, in-use versus out-of-use, precludes the quantification of this step in the analysis.

The potential effect of the return flow of irrigated acreage on recharge can be evaluated by plotting the permit site on the 2000 or 1993 irrigated acreage layer (D and E, respectively). There is no recharge if irrigation is not or no longer present at or near the permit site. Note the decrease in irrigated acreage between 1993 and 2000.

4.4 Vulnerability Of Ground Water Supplies To Contamination From The Surface

This section describes the approach to accomplish objective 3: determining the vulnerability of a ground water supply to contamination from the surface. Virtually all of the hydrogeologic units in the study area lack the presence of a confining layer (shale, clay, peat) protecting the aquifer from contamination originating at the land surface or near surface (for example, ISDSs, agricultural chemicals). Therefore, the ranking (high versus low) of the vulnerability of these aquifers is high, except for the areas where Dakota Sandstone is overlain by Mancos Shale.

All ground water in the area shown in the MRF layers R (unconsolidated sediments), Y (Dakota Sandstone outcrops) & Z (Lower Bedrock outcrops) is vulnerable; natural protection is only available in areas shown by the MRF layer DD (extent Mancos Shale) for ground water in the Dakota Sandstone underneath the Mancos Shale; all ground water in Quarternary and Tertiary unconsolidated sediments, landslides and moraines in the URF area are vulnerable (see layers Q and R)].

In order to further evaluate aquifer vulnerability, the potential for occurrence of contamination needs to be determined. The location, characteristics and likelihood of potential contamination sources need to be identified. For example, some sites may be vulnerable to contamination from one or more ISDSs nearby, a rather likely and continuing point source. Others may be vulnerable to contamination from agricultural land use, a seasonal, distributed source. To determine ground water vulnerability, separate potential source layers need to be constructed, for example, showing location and density of ISDS, gas stations, and agricultural land use. However, such an analysis goes beyond the scope of this project.

5.0 Case History Examples And Discussion

Three case history examples are presented to illustrate the approach for determining if ground water can provide the water supply for a given site: 5.1) Unavailable or Undetermined Ground Water Resources in the MRF Study Area; 5.2) Available Ground Water Resources for Water Supplies in the MRF Study Area; and 5.3) Available Ground Water Resources for Water Supplies in the URF Study Area. Example 5.1 and 5.2 illustrates the variability of drinking water supplies, both in availability and sustainability, within the same region of the Middle Roaring Fork region. Example 5.3 illustrates that drinking water supplies are readily available and sustainable for residence wells in the Upper Roaring Fork region. All three sites are vulnerable to ground water pollution. The examples are illustrated using the ArcMAP™ program (version 8.3; ESRI® 2002) of ArcGIS™; examples 5.1 and 5.2 use the PitkinCounty_GWGIS_MRF map; example 5.3 uses the PitkinCounty_GWGIS_URF map.

5.1 Example Of Unavailable Or Undetermined Presence Of Ground Water For Water Supplies (MRF Area)

Example 5.1 is a site located on parcel #264322300015 [at about coordinate 2619602, 1518679], directly south of subdivision 170 [W/J Ranch Homes] (red marker dot; Figures 13 and 14). Parcel details are found by using the 'Identify' function on the menu bar (Figure 14). The site is located in the disconnected glacial terrace region (DTH), and the hydrogeologic conceptual model of what is expected is shown in Figure 8 (Unconsolidated materials located on top of Mancos Shale).

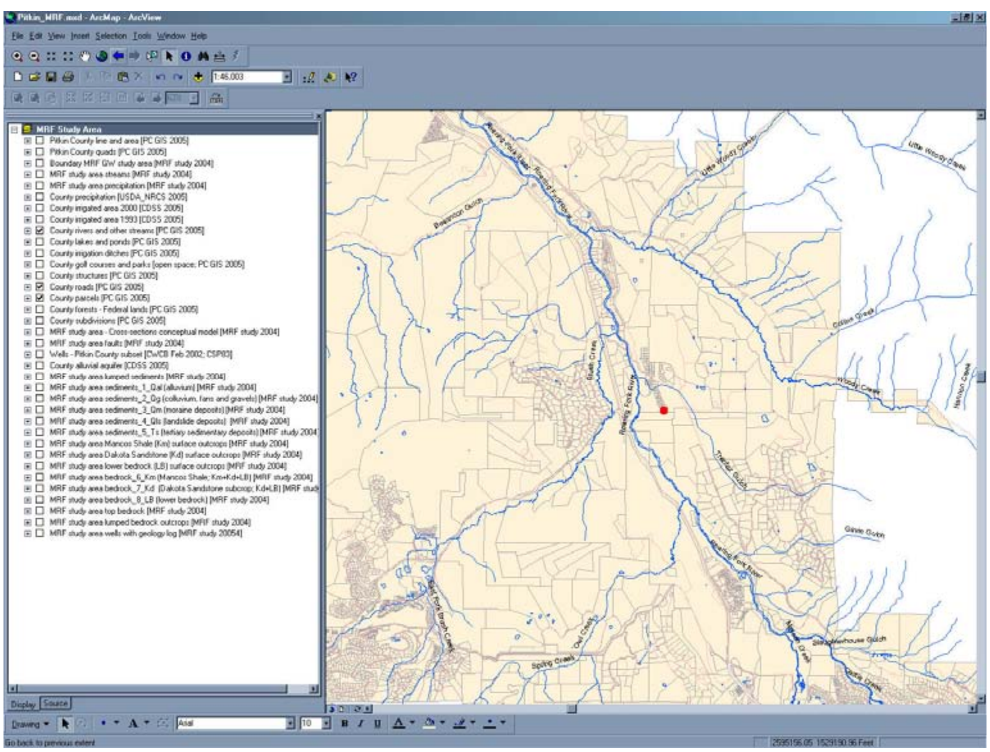

Figure 13. Example 5.1 – Permit Application Site Location [Regional View] – GIS Layers F, K and L.

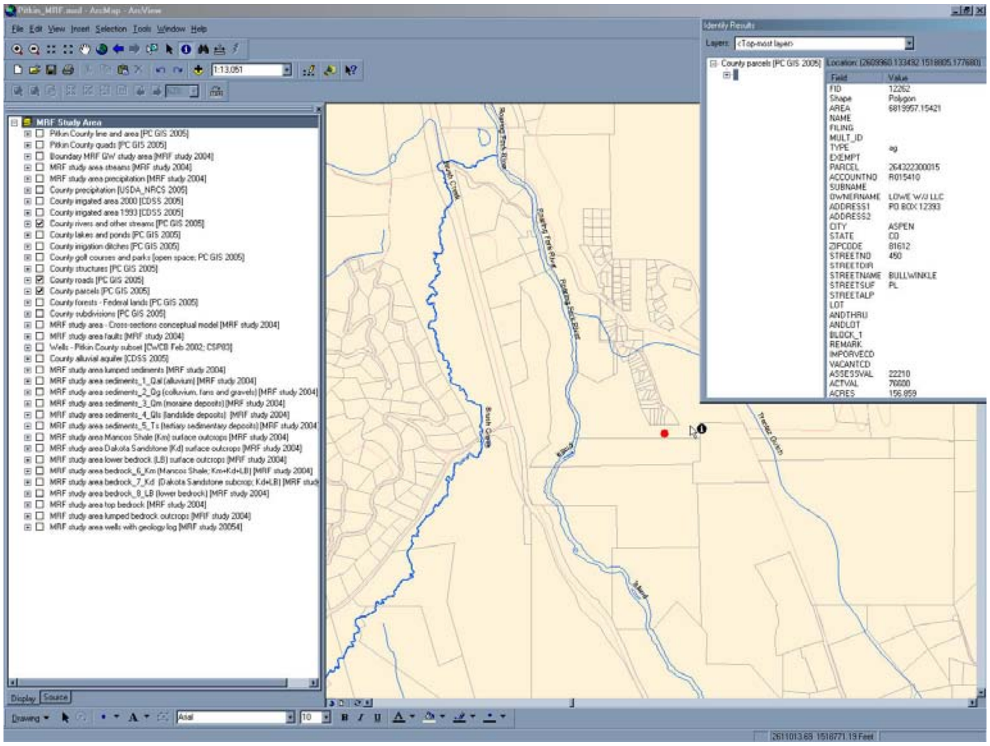

Figure 14. Example 5.1 – Site and Parcel Location [Local View] – GIS Layers F, K and L.

The site is located on unconsolidated materials (Figure 15; see section 4.1.1, layer R). Using the 'Identify' option from the menu bar for layer R, the potential aquifer material is Qg (Figure 15), and from section 4.1.2 (layer DD) follows that the bedrock underneath the Qg is Km (Mancos Shale) (Figure 16).

Using the step described in section 4.1.3, the shallow unconsolidated gravel aquifer materials (Qg) lie directly on top of Mancos Shale (Km) and alluvium/colluvium-bedrock aquifer connectivity is absent. This means that the surficial aquifer is not connected to or sustained by an underlying bedrock aquifer, and that the only shallow potential aquifer is Qg.

The next step is identifying one or more relevant, nearby wells (see section 4.2). In this case, well #23223 is selected by switching on layer GG (Figure 17). According to the well's attributes (use 'Identify' function on the menu bar), this well was drilled to a depth of 73 feet and was dry. The question remains: was the well drilled deep enough, or did the driller stop at the Mancos Shale? Switching on layer FF shows that there are no nearby wells with significant geologic information. No further information is available regarding the elevation of the top of the bedrock. A conservative approach leads to the conclusion that the current location does not have available or sustainable water, and it is recommended that the parcel development is restricted to either being part of a community city water supply system. An alternative course of action requires the performance of an in-depth hydrogeologic study at the site to evaluate the resource for water supply. Note that well data shown were obtained in 2002 and that new wells may have been drilled in the area.

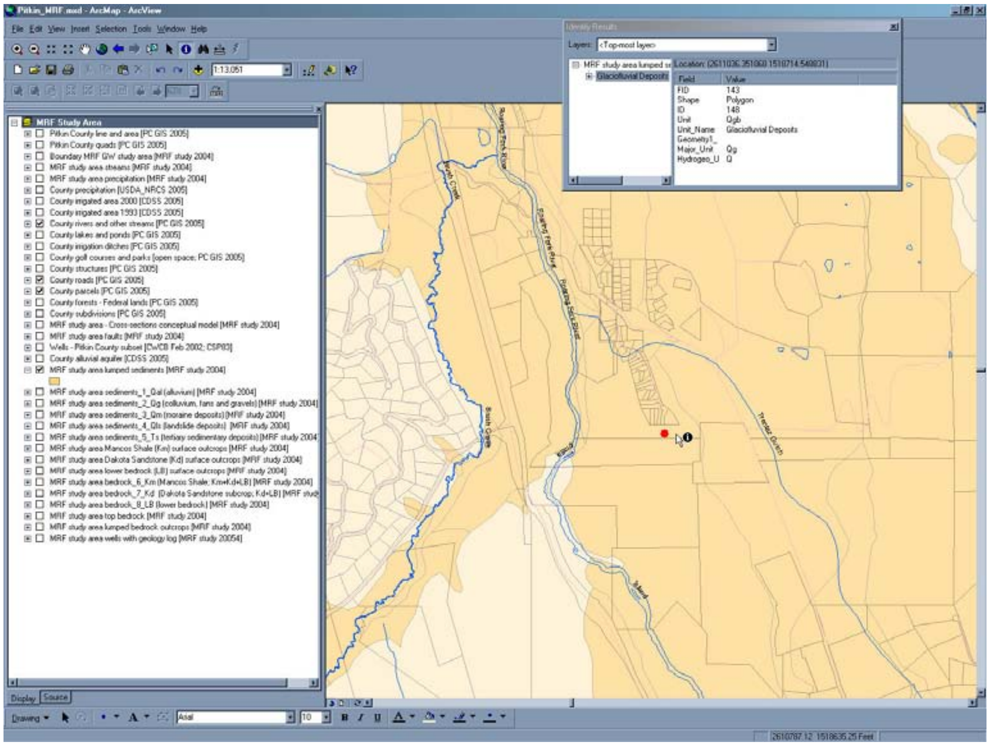

Figure 15. Example 5.1 – Site Is Located in Unconsolidated Sediments (Qg) – GIS Layer R.

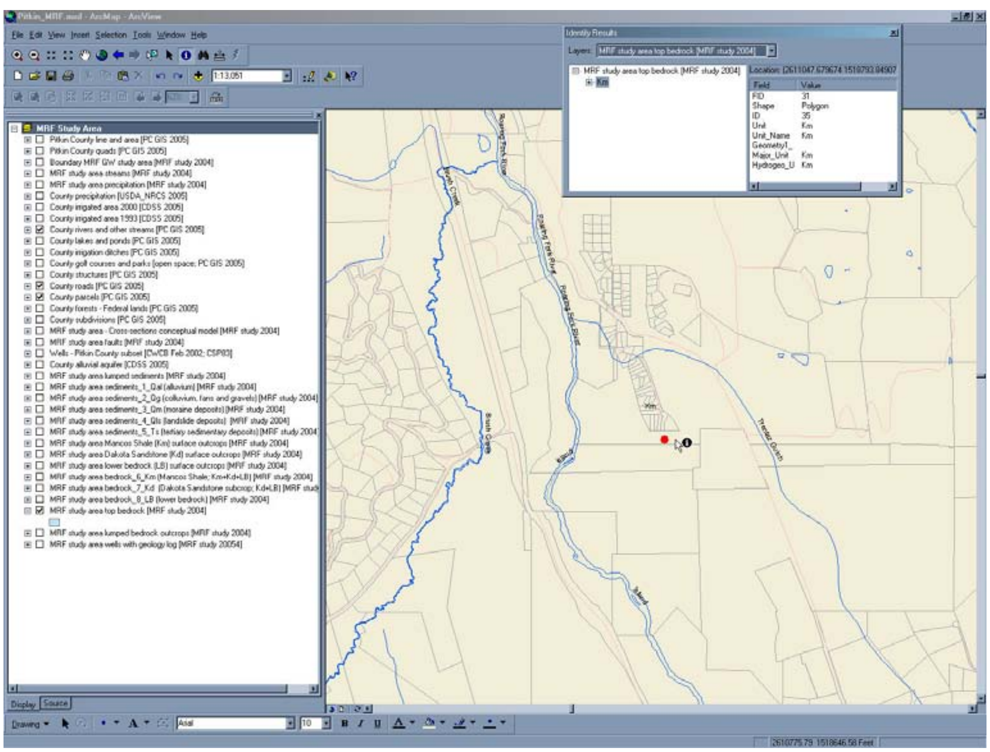

Figure 16. Example 5.1 – Site is Located above Mancos Shale Bedrock (Km) – GIS Layer DD.

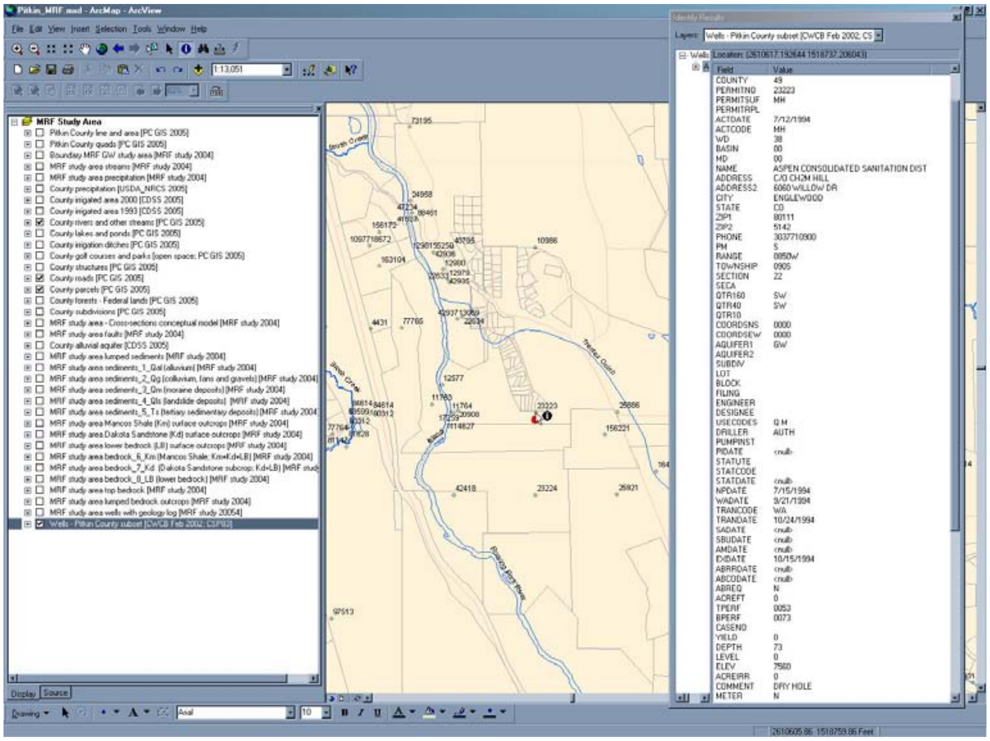

Figure 17. Example 5.1 – Location and Attributes of Nearby Well – GIS Layer GG.

5.2 Example Of Available Ground Water For Drinking Water Supplies (MRF Area)

Example 5.2 is a site located on Parcel # 264327100001, 400 ft west of McLain Flats Road [at about coordinate 2612041, 1517310] (red marker dot; Figures 18 and 19). The site is located in the discontinuous glacial terrace region (DTH), and the hydrogeologic conceptual model of what is expected is shown in Figure 8 (Unconsolidated materials located on top of Mancos Shale).

The site is located on unconsolidated materials (Figure 20; see section 4.1.1, layer R). Using the 'Identify' option from the menu bar for layer R, the potential aquifer material is Qg (Figure 20), and from section 4.1.2 (layer DD) follows that the bedrock underneath the Qg is Km (Mancos Shale) (Figure 21).

Using the step described in section 4.1.3, the shallow unconsolidated gravel aquifer materials (Qg) lie directly on top of Mancos Shale (Km) and alluvium/colluvium-bedrock aquifer connectivity is absent. This means that the surficial aquifer is not connected to or sustained by an underlying bedrock aquifer, and that the only shallow potential aquifer is Qg, as is the case in example 4.1.

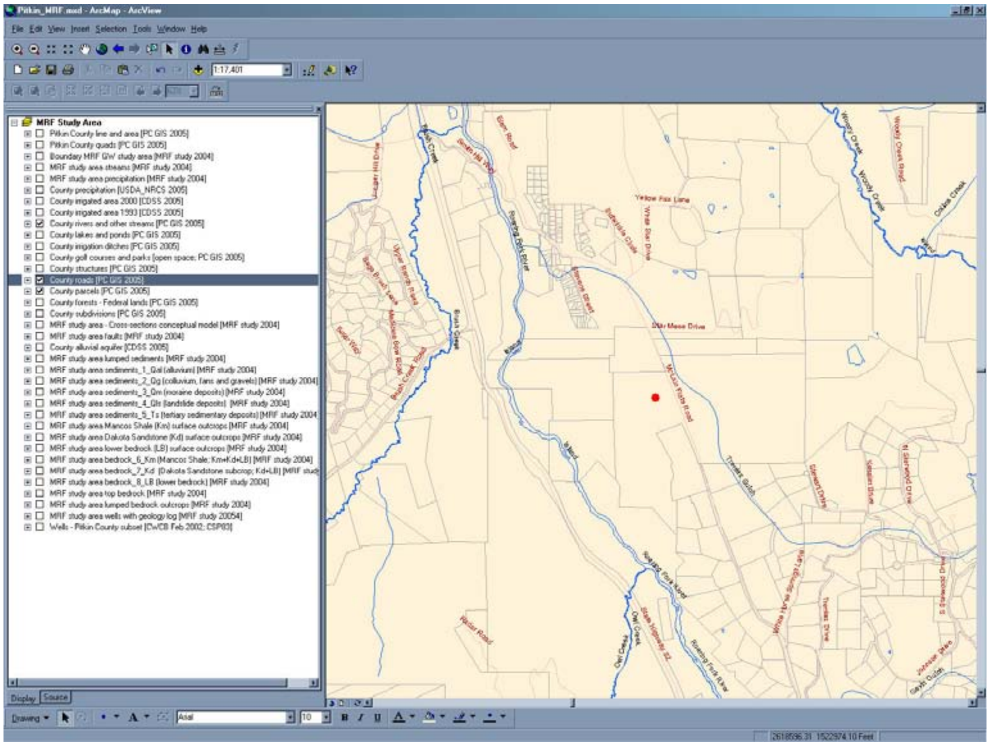

Figure 18. Example 5.2 - Permit Application Site Location [Regional View] – GIS Layers F, K and L.

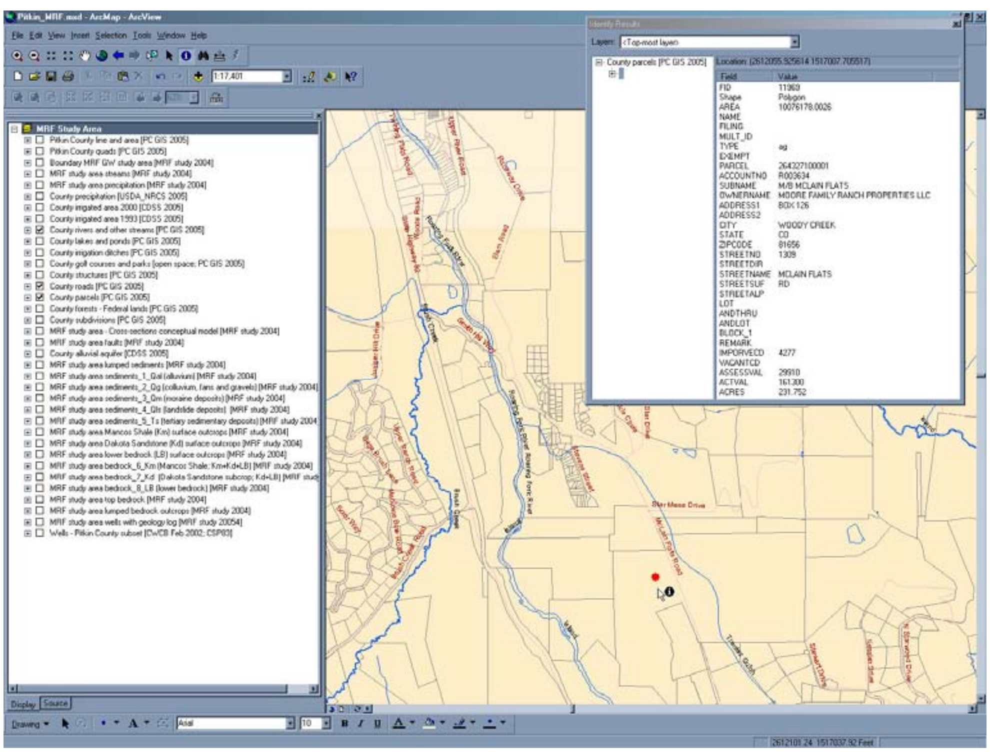

Figure 19. Example 5.2 – Site and Parcel Location [Local View] – GIS Layers F, K and L.

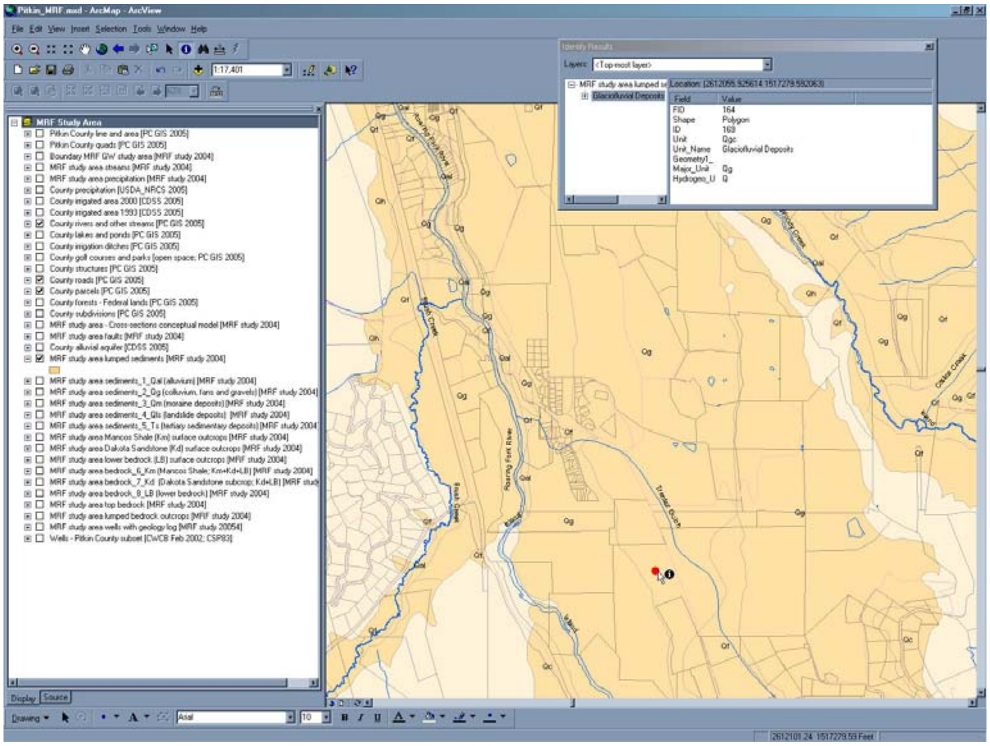

Figure 20. Example 5.2 – Site is Located in Unconsolidated Sediments (Qg) – GIS Layer R.

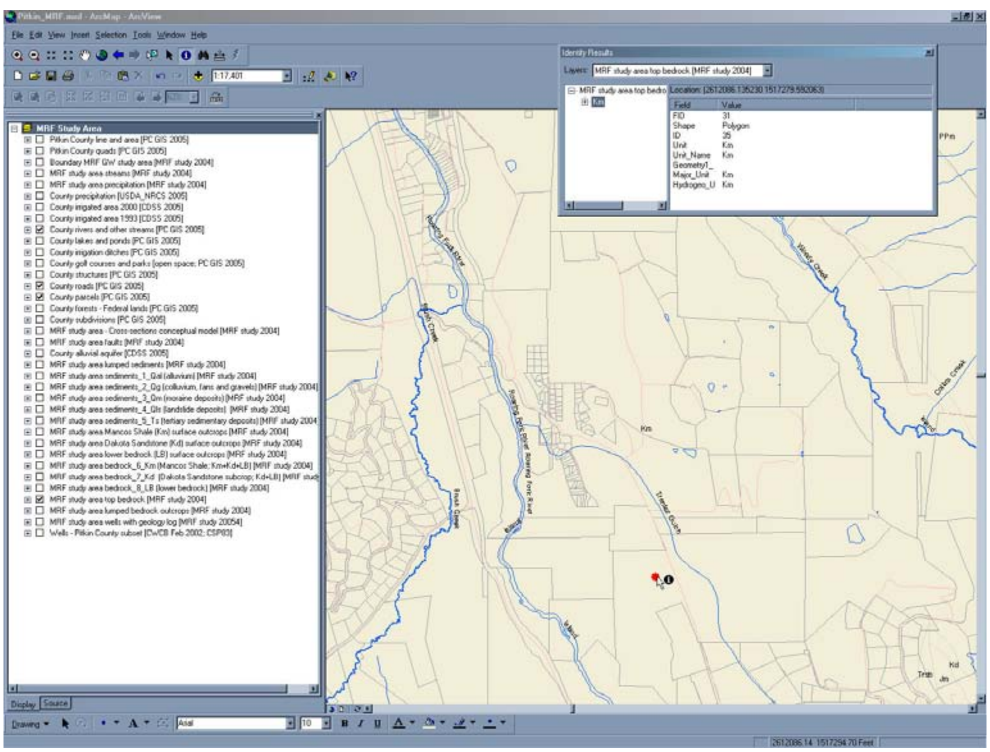

Figure 21. Example 5.2 – Location Site on Top of Mancos Shale Bedrock (Km) – GIS Layer DD.

The next step is identifying one or more relevant wells (see section 4.2). In this case, switching on Layer GG shows that well #25921 is near the site (Figure 22). According to the attribute table, this well was drilled to a depth of 320 feet, encountered water at 110 ft below the surface (saturated thickness of 210 feet), and produced at 15 gal per minute (yield) (Figure 22).

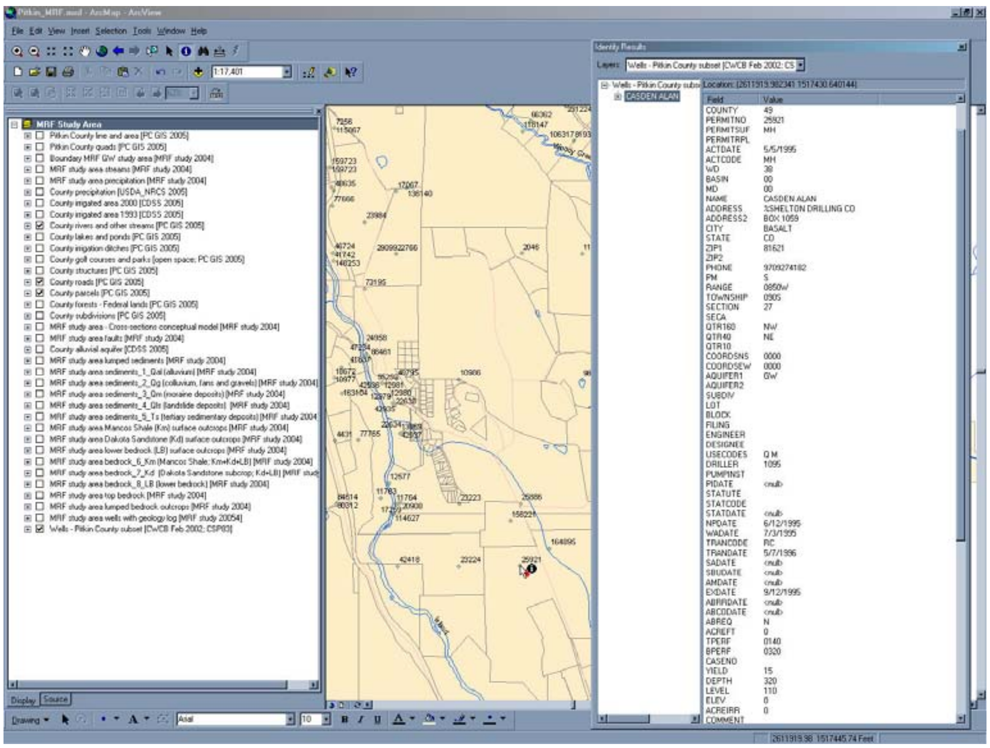

Figure 22. Example 5.2 – Location and Attributes of Nearest Well – GIS Layer GG.

Layer C is activated to evaluate recharge from precipitation (section 4.3.1). The site is located in an area that receives about 20 inches of precipitation on an average year, or an estimate of 2.0 inches of recharge per year (Figure 23).

From layer F and using the 'Measure' function from the 'Tools' toolbar, it appears that the site is located about 655 ft west of Trentez Gulch (Figure 5.24; left lower corner shows distance). According to the attribute table provided by the county, Trentez Gulch is intermittent, which means that reliable ground water recharge from or significant discharge to Trentez Gulch at this site is not expected. This layer also shows that there are no other nearby perennial streams. Therefore, the water table is most likely controlled by other factors (section 4.3.2).

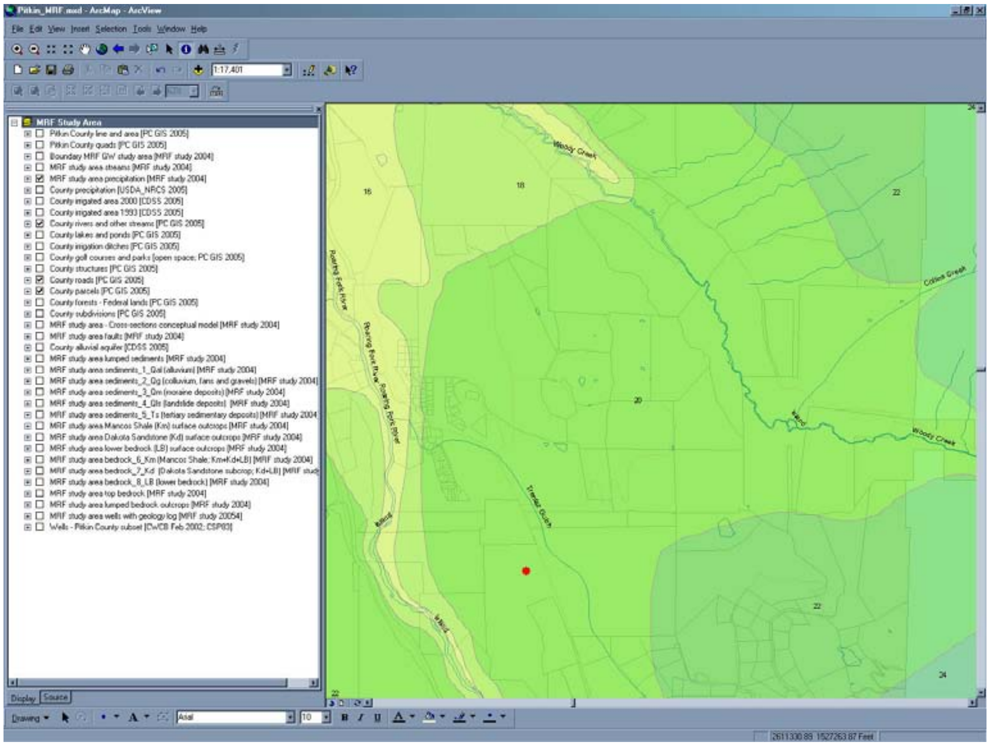

Figure 23. Example 5.2 – Annual Precipitation (inches/year) – GIS Layer C.

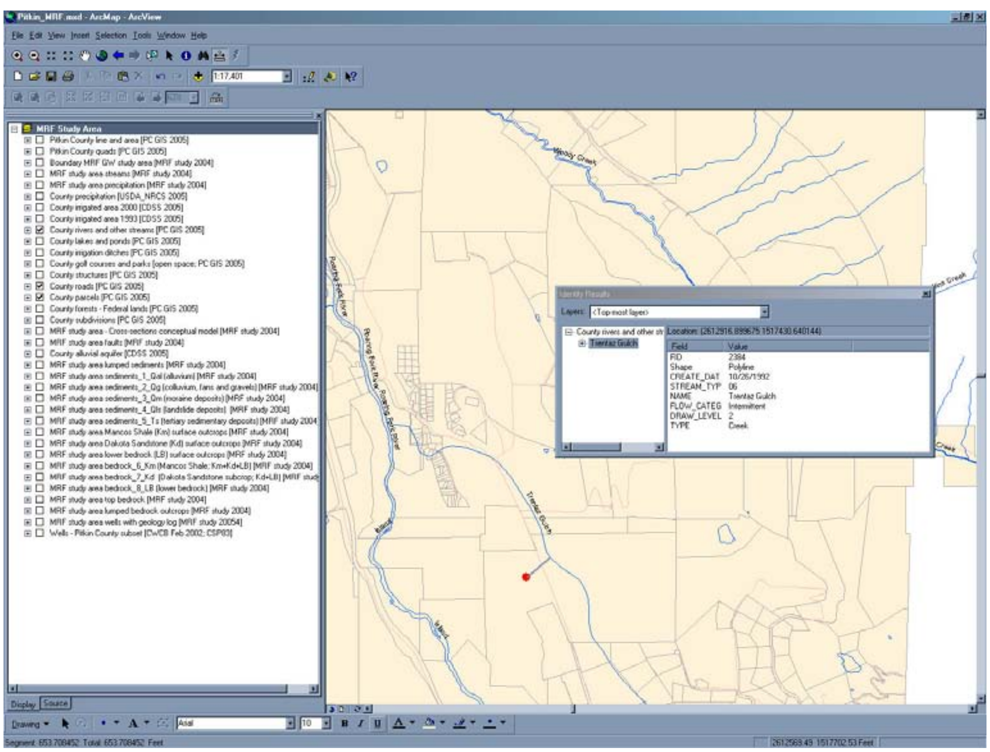

Figure 24. Example 5.2 – Nearby Stream(s) – Layer F.

The next step is evaluating recharge from irrigation ditches and/or irrigation return flow (section 4.3.3). Layer H shows that there are irrigation ditches in the direct vicinity of the site connected to Trentez Gulch (Figure 25). This indicates that the gulch may be the major source of irrigation water contributing to ground water recharge from return flow, and that the site is sustained based on the ditch water flow and water rights. Furthermore, layers D and E show that there is significant irrigated acreage above or near the site (Figure 26). It appears that no perennial ditches are present in the direct vicinity of the site contributing to recharge from leakage. In addition to recharge from precipitation, the ground water resources at this site are sustained by irrigation return flow water. Seasonal fluctuations in the well would be directly related to ditch flow periodicity.

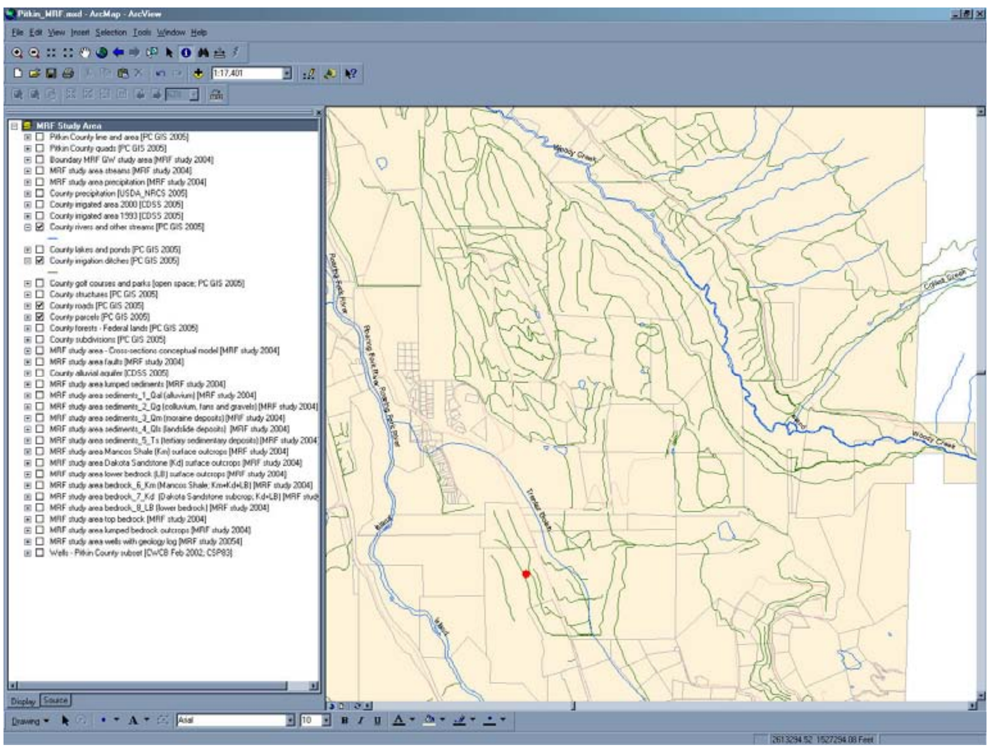

Figure 25. Example 5.2 – Irrigation Ditches near Site – Layer H.

Displaying of layers R and EE (i.e., potential potable aquifers) shows that most of the aquifer materials at the site are not protected by low-permeable or impermeable unconsolidated sediments or rock (section 4.4). Thus the natural vulnerability of the site is high since there is no protective geologic layer to prevent infiltration of pollutants from the (near-) surface (Figure 27). The selected site seems to have available, but not naturally sustainable water, and it is recommended that the site development be studied with regards to irrigation ditch, irrigation return flow, and water rights issues.

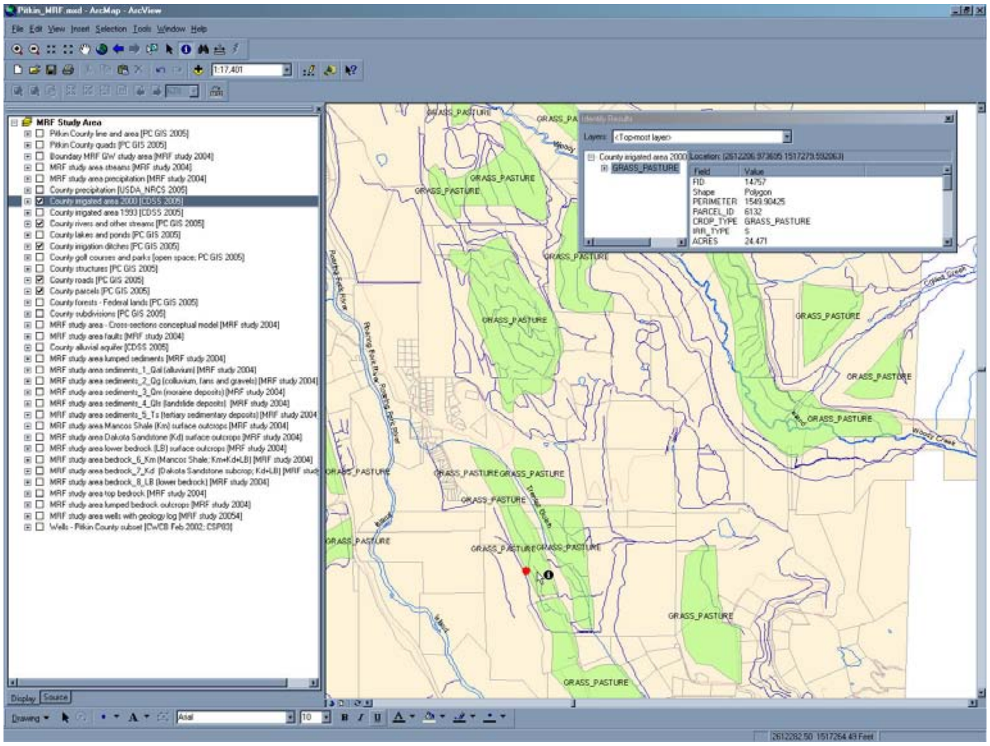

Figure 26. Example 5.2 – Irrigated Areas near Site – GIS Layer D.

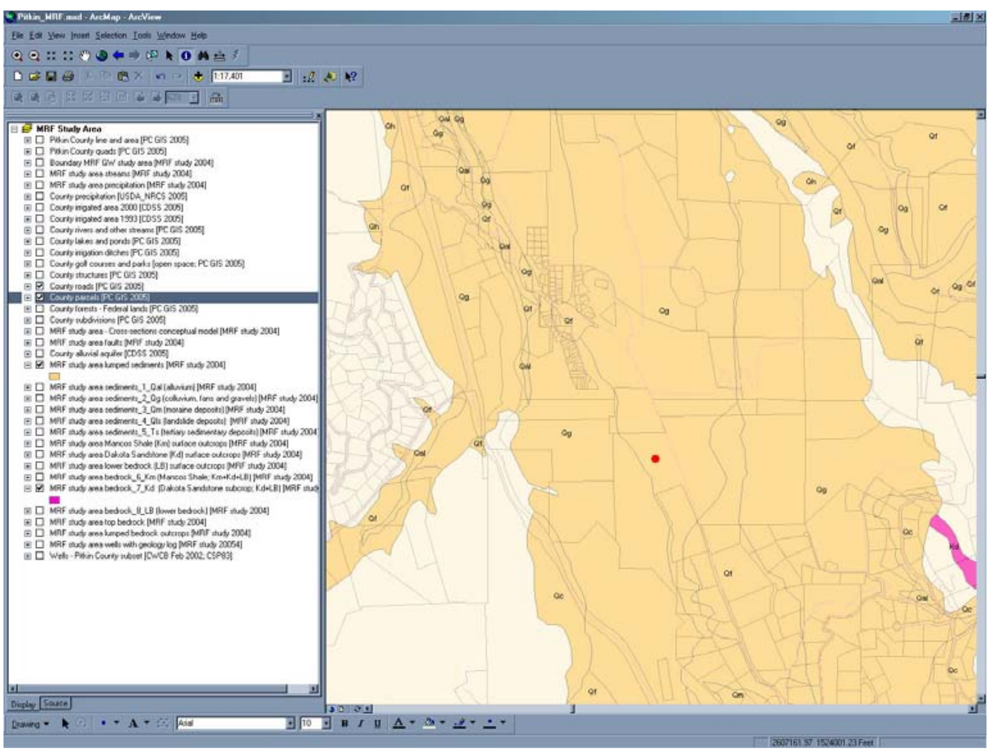

Figure 27. Example 5.2 – Hydrogeologic Site Vulnerability Considerations – GIS Layers R and EE.

5.3 Example Of Available Ground Water For Drinking Water Supplies (URF Area)

Example 5.3 is a site located on parcel #273718120018 between Eastwood Drive and Highway 82 [at about coordinate 2630002, 1494100] (Figure 28). The site is located in the Upper Roaring Fork region, and the hydrogeologic conceptual model of what is expected is shown in Figure 2 (Unconsolidated materials located on top of Precambrian Crystalline Materials).

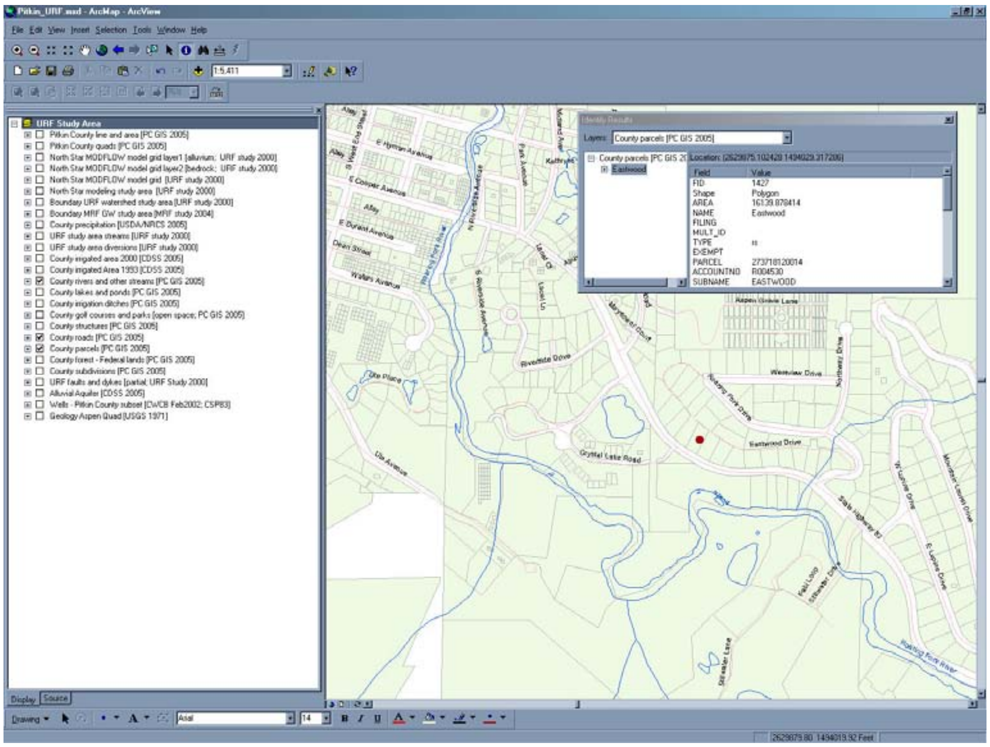

Figure 28. Example 5.3 – Location of Site and Parcel – GIS Layers F, K and L.

Applying the steps described in section 4.1-1-4.1.3 and using layer Q (USGS geology map of the Aspen quadrangle), it appears that the site is located on unconsolidated materials and that the potential aquifer material is Qmb. The underlying bedrock is Precambrian Crystalline Material (Pc) (Figure 29). This shows that the surficial aquifer is connected to and sustained by an underlying bedrock aquifer. Note that the less detailed Leadville geology map (layer R) can be used for URF areas not covered by the Aspen geology map (layer Q) the less detailed Leadville geology map (layer R) can be used.

Using layer P, a nearby well is located (#85737; Figure 30). According to its attributes, this well was drilled to a depth of 256 feet, intersected the water table at 140 feet (116 feet of saturated thickness), and produced 3 gal per min. Apparently, this is a low-yielding bedrock well.

The parcel is located in an area that receives about 19 inches of precipitation on an average year, or an estimate of 2 inches of recharge per year. (Figure 31; layer C).

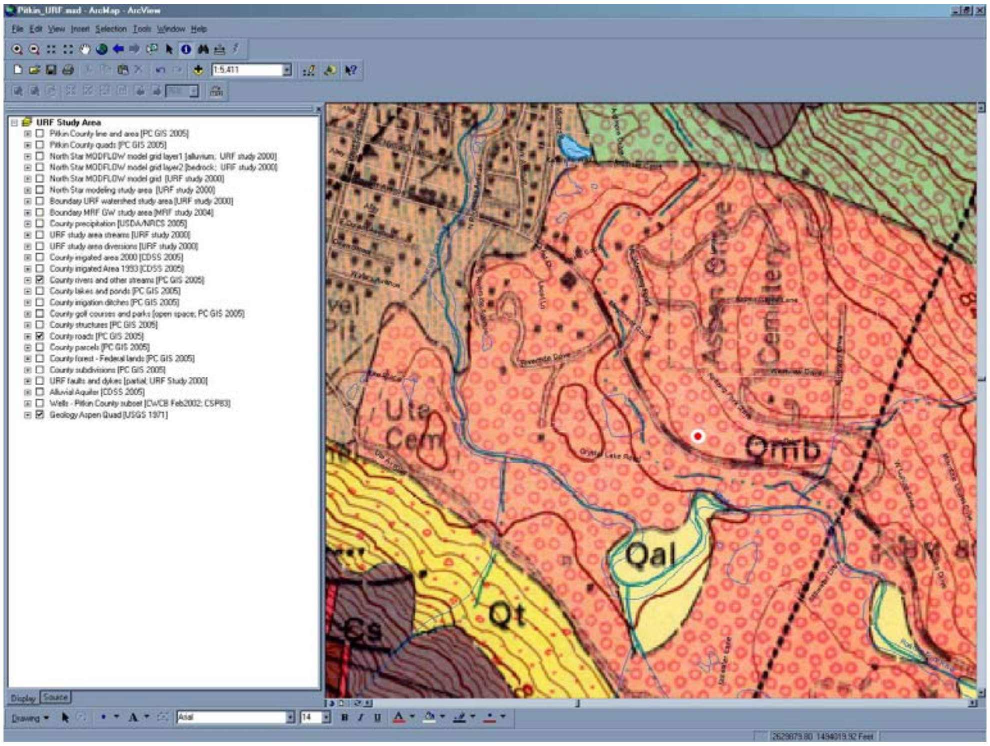

Figure 29. Example 5.3 – Site Location and Hydrogeology – GIS Layer Q.

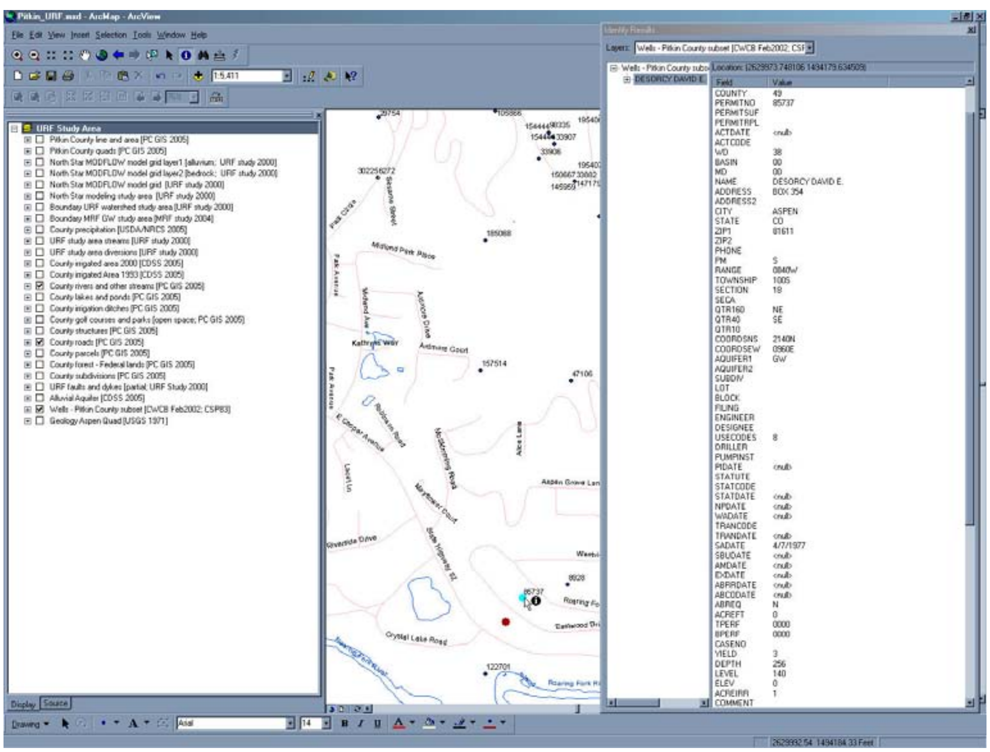

Figure 30. Example 5.3 – Location and Attributes of Nearest Well – GIS Layer P.

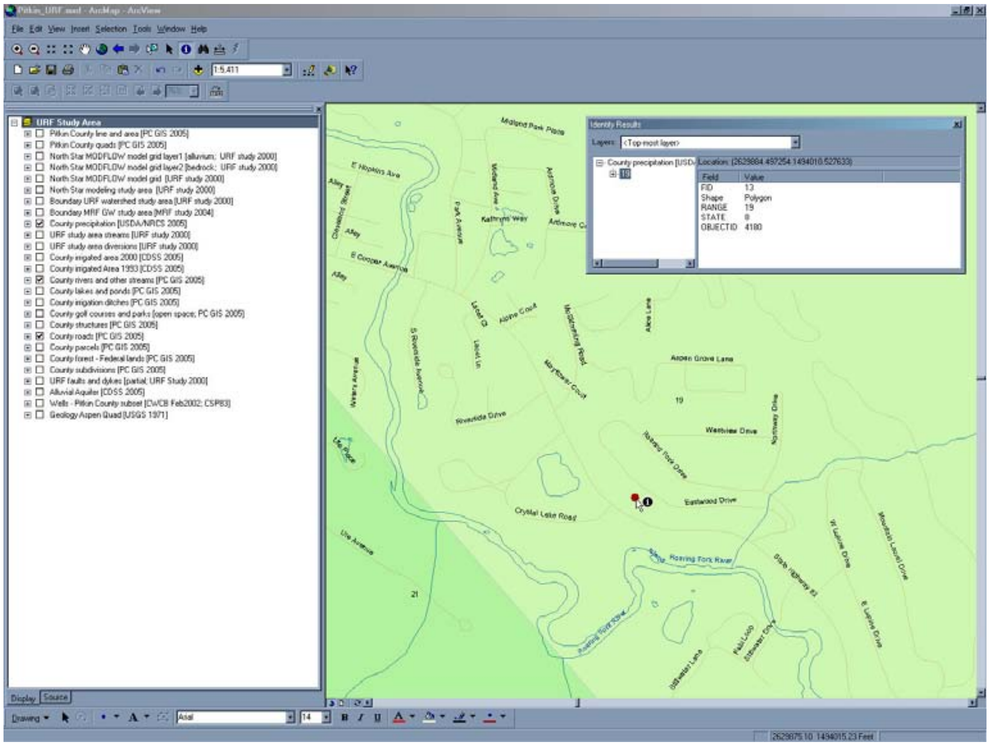

Figure 31. Example 5.3 – Annual Precipitation (inches/year) – GIS Layer C.

Layer F shows that the site is located near the Roaring Fork River (Figure 28). However, at an elevation of 8045 ft (see topographic map or 10ft elevation contours), the site is probably not affected by the seasonality of the River (around 7990 ft). If the site use necessitates a large well pumping rate, hydrologic studies would be necessary to determine if the well cone of depression would affect the River, and therefore be an infringement on surface water rights. Layer F also shows that no other nearby streams are perennial, therefore, the water table is most likely controlled by the bedrock system and would have little seasonal fluctuation.

Layers H and I show that there are no irrigation ditches, golf courses or parks above or near the site. Layers D and E show that there is no irrigated acreage above or near the site. Therefore, the dominant source of water to the well will be from precipitation-induced recharge, and from the regional crystalline aquifer system.

The vulnerability analysis (section 4.4) shows that the site is highly vulnerable since there is no protective geologic layer to prevent infiltration of pollutants (Figure 29; layer Q).

The current location seems to have available and sustainable water, and it is recommended that the parcel development is not restricted except as it may affect neighboring water users. However, the vulnerability of the parcel drinking water supply is high.

6.0 Conclusions And Recommendations

Under an agreement with Pitkin County, Hydrologic Systems Analysis, LLC (HSA) of Golden, Colorado, in cooperation with Heath Hydrology, Inc. (HHI) of Boulder, Colorado, created a GIS-based step-wise ground water resources evaluation procedure for use as decision/land use management tools by Pitkin County. The procedure, supported by two GIS maps and supporting data bases, guides the site-specific analysis with respect to: 1) ground water resources availability in terms of sufficient quantities for the purpose of its usage, and its economical exploitability (e.g., at reasonable depth and with sufficient permeability); 2) long term sustainability of the utilization of the resources for water supply (i.e., presence of long term continuous recharge mechanisms, and absence of excessive water table fluctuations, for example, due to spring runoff or upland flood irrigation); and 3) the vulnerability of the resources to contamination. Note that availability and sustainability should be judged in relation to yield requirements, presence of other resource usages, ecological requirements, water right issues, and physical constraints, such as limitations on drawdown, among others.

The GIS maps and data bases developed for this project are limited to the area subject to previous studies conducted for Pitkin County by HSA (study area), specifically, (1) Middle Roaring Fork study area or MRF (Kolm and Gillson, 2004); and (2) Upper Roaring Fork study area or URF, comprising of the Upper Roaring Fork watershed including the North Star preserve (Kolm and others, 2000; Hickey and others, 2000).

The data bases developed for this project include original GIS layers from the aforementioned studies, as well as GIS layers and data bases from Pitkin County, Colorado Division of Water Resources/Colorado Water Conservation Board, Natural Resources Conservation Survey (USDA), and U.S. Geological Survey.

A key element in the development of the step-wise evaluation procedure of ground water resources presented in this report has been availability of the results from the Hydrologic System Analysis (HSA) performed for the Middle and Upper Roaring Fork study areas (Kolm and Gillson, 2004; Kolm and others, 2000). Expansion of the GIS maps and data bases to other parts of Pitkin County will require the performance of a HSA in conjunction with the development of the supporting data bases.

Three case history examples are presented to illustrate the analysis procedure, using the GIS maps and data bases provided in this report. The examples are: 1) Site without available ground water for water supplies in the Middle Roaring Fork area; 2) Site with available ground water for water supplies in the Middle Roaring Fork area; and 3) Site with available ground water for water supplies in the Upper Roaring Fork area. The two Middle Roaring Fork sites illustrate the variability of drinking water supplies, both in availability and sustainability, within the same region and located near to each other. The Upper Roaring Fork site illustrates that drinking water supplies are readily available and sustainable for house wells in this region. All three sites are vulnerable to ground water pollution. The examples demonstrate the utility of the presented GIS- based analysis procedure and its advantages over simple, one-layer paper maps showing some general ground water characteristics, and. They also demonstrate the need for site-specific hydrogeologic investigation to obtain quantitative resource management answers and well design parameters.

6.1 General Recommendations

Pitkin County has six regions that contain parcels of potentially developable land: 1) Upper Roaring Fork Drainage; 2) Town of Aspen; 3) Middle Roaring Fork Drainage; 4) Castle, Maroon, and Woody Creeks, and Frying Pan River; 5) Snowmass and Capitol Creek Drainage; and 6) Crystal River Drainage. Three levels of information are required in order to fully understand the ground water- derived drinking water availability, sustainability, and vulnerability: 1) Hydrologic Systems Analysis (HSA); 2) Data base and GIS development; and 3) Acquisition of site-specific hydrologic parameters. The hydrogeologic information processing and analysis begins at the conceptual level integrating regional, subregional, and local information, followed by data base development and GIS evaluation. Finally, hydrologic parameters are needed at each specific site based on due diligence.

Examples of Hydrologic Systems Analysis are found in the MRF and URF reports by Kolm and Gillson (2002) and Kolm and others (1998). The ultimate goal of this analysis is a conceptual model describing how the hydrogeologic framework and hydrologic system functions. Data base development and GIS Evaluation are described in this report.

Hydrologic parameters, including quantitative measures of aquifer thickness, water table levels (depth to water table), hydraulic conductivity, recharge amounts and ground-water flow paths, are the result of in-depth site analysis and testing. The goal of the third aspect of this analysis is site-specific drinking water well yields and water quality, and the impact of the drinking water well on surrounding wells and ecosystems. The existing data could be analyzed for specific sites and generalized to hydrogeologic regions. However, each new site will need due diligence by the land owner, and the results of their studies can be integrated into the existing data and each hydrogeologic region can be updated continuously.

6.2 Recommendations By Site

The <u>Upper Roaring Fork Drainage</u> area has a complete HSA, and most of the GIS data base development and evaluation is completed. The hydrogeologic data layers could be improved upon by separating the potential unconsolidated aquifers from the bedrock aquifer. The hydrologic parameters for the State Route 82 corridor would need to be evaluated as these were not assessed as part of the North Star study. The priority for this work is low compared with the assessment needs of other areas.

The Town of Aspen area has no formal HSA completed, and the region is complex due to urbanization, shallow aquifers of various types (moraines, outwash plains, alluvium), and a complex, faulted bedrock system (Leadville Limestone). Some of the GIS data base development is completed, but additional data layers and evaluation are needed – particularly with respect to the hydrogeologic data base. The hydrologic parameters for the Town of Aspen area would need to be evaluated as these were not assessed as part of any of the previous studies. The priority for this work is high compared with the assessment needs of other areas.

The Middle Roaring Fork Drainage area has a complete HSA, and most of the GIS data base development and evaluation is completed. The hydrologic parameters for the Middle Roaring Fork Drainage area would need to be evaluated as these were not assessed in-depth as part of the current study. The priority for this work is low compared with the assessment needs of other areas.

The Castle, Maroon, Woody Creeks, and Frying Pan River areas have no formal HSA completed, and the region is complex due to some urbanization, shallow aquifers of various types (moraines, outwash plains, alluvium), and a complex, faulted bedrock system (including the Leadville Limestone and the Dakota Fm., and Tertiary intrusive rocks). Some of the GIS data base development is completed, but additional data layers and evaluation are needed – particularly with respect to the hydrogeologic data base. The hydrologic parameters for the Castle, Maroon, Woody Creeks, and Frying Pan River areas would need to be evaluated as these were not assessed as part of any of the previous studies. The priority for this work is moderate (Castle and Maroon Creek, and Frying Pan River areas) and high (Woody Creek area) compared with the assessment needs of other areas.

The Snowmass and Capitol Creek areas have no formal HSA completed, and the region is complex due to some urbanization, shallow aquifers of various types (moraines, outwash plains, alluvium), and a complex, faulted bedrock system (possibly including the Dakota Fm.). Some of the GIS data base development is completed, but additional data layers and evaluation are needed – particularly with respect to the hydrogeologic data base. The hydrologic parameters for the Snowmass and Capitol Creek areas would need to be evaluated as these were not assessed as part of any of the previous studies. The priority for this work is high compared with the assessment needs of other areas.

The Crystal River area has no formal HSA completed, and the region is complex due to some urbanization, shallow aquifers of various types (moraines, outwash plains, alluvium), and a complex, faulted bedrock system (possibly including the Leadville Limestone, the Dakota Fm., and Tertiary intrusive bedrock). Some of the GIS data base development is completed, but additional data layers and evaluation are needed – particularly with respect to the hydrogeologic data base. The hydrologic parameters for the Crystal River area would need to be evaluated as these were not assessed as part of any of the previous studies. The priority for this work is high compared with the assessment needs of other areas.

In all of these areas, the completion of HSA and GIS data base and evaluation should be concurrent and of higher priority before the hydrologic parameters analysis being undertaken. The higher priority areas are based on the rate at which urbanization is occurring and corresponding demand for permits.

7.0 References

Hickey, A, J. C. Emerick, and K. E. Kolm. May 2000. *Preliminary Hydrologic and Biologic Characterization of the North Star Nature Preserve, Pitkin County, Colorado*. Colorado School of Mines, Golden, Colorado.

Kolm, K. E., K. C. Glover, and J. C. Emerick. July 2000. *Understanding Mountain Wetland Hydrology; Technical Guidance for Investigating the Hydrologic Function of Wetlands in Complex Terrain*. Colorado School of Mines, Golden, Colorado.

Kolm, K. E., and R. G. Gillson, III. June 1, 2004. *State of Ground and Surface Water in the Central Roaring Fork Valley, Pitkin County, Colorado – A Hierarchical Approach Using GIS and 3-Dimensional Hydrogeologic Modeling*, Hydrologic Systems Analysis, LCC, Golden, Colorado.

Kolm, K.E., and W.H. Langer. 2001, Hierarchical Systems Analysis in Karst Terrains: Part A - Approaches and applications to environmental characterization: U.S. Geological Survey Open File Report 00-429A, CD-ROM.

Appendix A1

State of Colorado Division of Water Resources
DWR Wells Database

(http://www.water.state.co.us/pubs/welldata.asp).

Well System Data Fields

WELL SYSTEM DATA FIELDS

Field Header	Definition
receipt	The receipt number is the number assigned when the fee is paid. The entire receipt number is eight numeric characters followed by one alphabetic character (if required).
div (Division)	Numeric identifier for Water Division (1-8) in which the well is located.
cty (County)	Numeric identifier for Colorado counties (1-63) in which the well is located:

COLORADO COUNTIES NUMERICAL CODE:

County	Code
ADAMS	01
ALAMOSA	02
ARAPAHOE	03
ARCHULETA	04
BACA	05
BENT	06
BOULDER	07
CHAFFEE	08
CHEYENNE	09
CLEAR CREEK	10
CONEJOS	11
COSTILLA	12
CROWLEY	13
CUSTER	14
DELTA	15
DENVER	16
DOLORES	17
DOUGLAS	18
EAGLE	19
ELBERT	20
EL PASO	21
FREMONT	22
GARFIELD	23
GILPIN	24
GRAND	25
GUNNISON	26
HINSDALE	27
HUERFANO	28
JACKSON	29
JEFFERSON	30
KIOWA	31
KIT CARSON	32
LAKE	33
LA PLATA	34
LARIMER	35
LAS ANIMAS	36
LINCOLN	37
LOGAN	38
MESA	39
MINERAL	40
MOFFAT	41
MONTEZUMA	42
MONTROSE	43
MORGAN	44
OTERO	45
OURAY	46
PARK	47
PHILLIPS	48
PITKIN	49
PROWERS	50
PUEBLO	51
RIO BLANCO	52
RIO GRANDE	53
ROUTT	54
SAGUACHE	55
SAN JUAN	56
SAN MIGUEL	57
SEDGWICK	58
SUMMIT	59
TELLER	60
WASHINGTON	61
WELD	62
YUMA	63

permitno (Permit Number)	The well permit number (numeric).
permitsuf (Permit Suffix)	A character field for the well suffix code that follows the permit number.
Permitrpl	Identifier indicating a well's replacement.

actdate Date well permit application received.

actcode The activity code states status of permit application file:

Code	*Desc*
AP =	New application received.
AD =	Application denied. Denial number entered in permit number field and date entered in permit issued date field.
AW =	Application for a permit is withdrawn. Code and date also entered to status code and date fields.
AV =	Verbal approval granted to well construction contractor to construct a well without a permit in place (emergency only).
CA =	Canceled well permit. Code and date also entered to status code and date fields.
CD =	Change description of acres irrigated (designated basins). Entered to status and date fields of existing record upon receipt of application.
CO =	Application to commingle wells (designated basins). Entered to status and date fields of existing record upon receipt of application.
CP =	Amended household use permit to allow watering of user's noncommercial domestic animals.
EX =	Well permit expiration date extended.
MH =	Monitoring hole notice of construction. MH file number and date entered in permit number and permit date fields.
NP =	Well permit issued. Permit number and issue date entered in permit number and permit date fields.
TH =	Test hole notice. Replaced by MH notice in 1988.
TW =	Test well. Replaced by MH notice in 1988.

wd A character field which indicates the Water District in which the well is located (1-80). Defined as a basin on minor drainage within the Water Division.

basin When applicable, a character field indicating the Designated Groundwater Basin Number (1-8):

<u>DESIGNATED BASINS</u>

NORTHERN HIGH PLAINS	01
KIOWA-BIJOU	02
SOUTHERN HIGH PLAINS	03
UPPER BLACK SQUIRREL CREEK	04
LOST CREEK	05
CAMP CREEK	06
UPPER BIG SANDY	07
UPPER CROW CREEK	08

md A character field indicating the Designated Groundwater Basin Management District Number (1-13):

<u>MANAGEMENT DISTRICTS (BASINS)</u>

PLAINS	01
SAND HILLS	02
ARIKAREE	03
FRENCHMAN	04
CENTRAL YUMA	05
W – Y	06
NORTH KIOWA-BIJOU	07
EASTERN CHEYENNE	08
LOST CREEK	09
SOUTHERH HIGH PLAINS	10
MARKS BUTTE	11
UPPER BLACK SQUIRREL	12
UPPER BIG SANDY	13

full name Applicant name (character field).

address1 A character field for the street portion of the primary mailing address of the permit holder.

address2 A character field for the street portion of a secondary mailing address if submitted.

city A character field for the City of the primary mailing address.

state A character field for the State of the primary mailing address

zip1 A character field for the primary zip code.

zip2 A character field for a secondary zip code, if provided.

phone_number A character field for Applicant's phone number.

pm Principal Meridian in which well is located (S = Sixth, N = New Mexico, U = Ute, C = Costilla, B = Baca).

rng (Range) Numeric field for the Range in which well is located.

Rnga Identifies half ranges (“H”)

Rdir Identifies direction (E, W)

ts (Township) Numeric field for Township in which well is located.

Tsa Identifies half ranges (“H”)

Tdir Identifies direction (N, S)

sec (Section) Numeric field for Section in which well is located (1-36).

Seca Reserved for locations containing a U in the section number.

QTR160 Character field for quarter section (160 acre quarter) in which well is located.

QTR40 Character field for the quarter-quarter section (40 acre quarter of 160 acre quarter) in which well is located.

QTR10 Character field for the quarter-quarter section (10 acre quarter of 40 acre quarter) in which well is located.

coordsns Distance (feet) from the north or south section line to the well location.

coordsns_dir Identifies which section line (N,S) from which distance is measured.

coordsew Distance (feet) from the east or west section line to the well location.

coordsew_dir Identifies which section line (E,W) from which distance is measured.

AQUIFER1 Aquifer in which well is located.

AQUIFER CODES:

GW	ALL UNNAMED AQUIFERS	
KA	ARAPAHOE	
UKA	UPPER ARAPAHOE	
LKA	LOWER ARAPAHOE	
JMB	BRUSHY BASIN	
KDB	BURRO CANYON	
KCH	CHEYENNE	
CON	CONFINED	SAN LUIS VALLEY
KD	DAKOTA	
TDW	DAWSON	
UTDW	UPPER DAWSON	
LTDW	LOWER DAWSON	
TKD	DENVER	
JE	ENTRADA	
TG	GREEN RIVER	
PH	HERMOSA	
KI	ILES	
KL	LARAMIE	
KLF	LARAMIE FOX HILLS	
ML	LEADVILLE LIMESTONE	
KM	MANCOS	
KMV	MESA VERDE GROUP	
JM	MORRISON	
TO	OGALLALA	
KP	PIERRE SHALE	
KPU	PURGATOIRE	
JMS	SALT WASH	
UNC	UNCONFINED	SAN LUIS VALLEY
TW	WASATCH	
TW	WHITE RIVER	
KW	WILLIAMS FORK	

AQUIFER2 name of second aquifer if well is known to be multiply completed.

subdiv_name Subdivision name.

lot Lot number in subdivision.

block Block number in subdivision.

filing Filing number.

engineer Engineer who approved permit.

well_name Owners's well designation number or name.

Use1 & Use2 Codes for well Uses:

Data Code	Use Description
1	Crop Irrigation
2	Municipal
3	COMMERCIAL
4	INDUSTRIAL
5	RECREATION
6	FISHERY
7	FIRE
8	DOMESTIC
9	LIVESTOCK
G	GEOTHERMAL
H	HOUSEHOLD USE ONLY

K	SNOWMAKING
O	OTHER
O	MONITORING HOLE/WELL
R	RECHARGE
E	EXCHANGE AND AUGMENTATION
Q	=O (Other, or Monitoring Hole/Well)

Use3

CODE	TYPE
A	AUGMENTATION. All wells in augmentation plans are coded with an "A" in the last position. First position is the actual use of the well.
M	MONITORING WELL (PERMITTED). The first position is "O" followed by "M" in the last position.
Z	HOUSEHOLD USE WELLS ISSUED PRIOR TO HB1111 THAT HAVE BEEN AMENDED PURSUANT TO (3)(b)(II)(b) BY $25.00 APPLICATION. First position code is "H" followed by "Z" in the last position.
L	PERMIT ISSUED UNDER PRESUMPTION (3)(b)(II)(A) FOR DOMESTIC/LIVESTOCK USES AS THE ONLY WELL ON 35 ACRES. First position is either "8" domestic or "9" livestock", or both 1st and 2nd followed by "L" in the last position.
	PERMITS ISSUED UNDER (3)(b)(I) WHERE WATER IS AVAILABLE ARE CODED FIRST POSITIONS AS NECESSARY WITH THE ACTUAL USE. HB1111 does not apply to these wells.
G	GRAVEL PIT WELL PERMIT. This application (PERMIT) is coded as "O" in the first position with "G" in the last position.
C	CLOSED LOOP GEOTHERMAL WELL. First position is codes as "G" for geothermal. Last position is "C".
P	GEOTHERMAL PRODUCTION WELL. First position is coded "G" for geothermal. Last position is "P".
S	OTHER TYPES OF HOLES CONSTRUCTED-ESPECIALLY FOR CATHODIC PROTECTION.
	IDENTIFIES THAT THE PERMIT WAS ISSUED PURSUANT TO SENATE BILL 5 (137 (4). First positions are for the actual use(s) of the well.

driller_lic Water well contractor's license number.

pump_lic Pump installation contractor's license number.

pidate Date the pump installation report is received by DWR.

statute Statute under which the permit was issued using the last four numbers of chapter and paragraph, i.e. 37-92-602(3)..602(3). (see www.intellinetusa.com/statmgr.htm)

statcode Interim status of the application or permit:

Code	*Desc*
AB =	Abandoned well.
AR =	Date application for permit resubmitted to DWR.
AU =	Date application returned to applicant for correction or additional information.
EP =	Expired well permit.
NS =	Exempt wells where no statement of use is required (no longer used).
PI =	Pump Installation Report received (no longer used).
PU =	Pump Installation Report returned to responsible party for correction.
RC =	Record change. A portion of the file was modified.
SA =	Statement of beneficial use accepted (no longer used in statute code).
SP =	Statement of beneficial use received (no longer used in statute code).
SR =	Statement of beneficial use resubmitted to DWR.
SU =	Statement of beneficial use returned to owner for correction.
WA =	Well construction report received (no longer used).

WU = Well construction report returned to responsible party for correction.
WR = Well construction report resubmitted to DWR.
ZZ = Transaction code indicates a portion of the file was updated with general review and update of records.

statdate	Date of the above status code action.
npdate	Date the permit, denial (AD) or monitoring hole was issued.
wadate	Date the Well Construction and Test Report was received in DWR.
trancode	Activity or status code. Last action updated.
trandate	Computer machine date of last update to the record.
sadate	Date of first beneficial use.
sbudate	Date statement of use received.
exdate	Expiration date of well permit.
abrdate	Date abandonment report received.
abcodate	Date well plugged and abandoned.
abreq	Flag if the well requires plugging and sealing upon construction of new well
acreft	Annual appropriation in acre feet.
tperf	Depth to top of first perforated casing.
bperf	Depth to base of last perforated casing.
case_no	Water court case number.
yield	Yield in gallons per minute.
depth	Total depth of well.
level	Depth to static water level.
elev	Ground surface elevation.
area_irr	Acres irrigated.
Irr_meas	Acre irrigated units
comment	Comment field
meter	Totalizing flow meter reqd., installed.
wellxno	Cross reference to another well or record.
Wellxsuf	Cross reference character field for well suffix code (follows the permit number).

Wellxrpl Cross reference identifier indicates well replacement.

Nwcdate Notice of Well Construction Report received (Statewide nontributary rules).

Nbudate Notice of Commencement of Beneficial Use received (Statewide nontributary rules).

wcdate Date well construction completed.

pcdate Date pump installation completed

log Flag to indicate if a geophysical is required and received.

qual Water quality information available, y or n.

user1 Initials of last staff member to update file.

pyield Proposed yield of well in gpm.

pdepth Proposed depth of well.

pacreft Proposed annual appropriation.

well_type Calculated value to determine if record is exempt, non exempt or georthermal.

valid_permit Calculated value to determine if a well permit is valid. (must be verified)

parcel_no Parcel identifier

parcel_size Parcel size in acres. Number of acres on well site.

noticedate Notice sent to owner indicating permit about to expire. (Not yet used)

utm_x A numeric field for the UTM-X coordinate. Note some UTM values are calculated from legal description. All UTM values are Zone 13 based on NAD 27 and Clark 1866 projections.

utm_x A numeric field for the UTM-X coordinate. Note some UTM values are calculated from legal description. All UTM values are Zone 13 based on NAD 27 and Clark 1866 projections.

utm_y A numeric field for the UTM-X coordinate. Note some UTM values are calculated from legal description. All UTM values are Zone 13 based on NAD 27 and Clark 1866 projections.

loc_source Identifies source of UTM coordinates. If blank, the applicant provided the coordinates otherwise the version of the program used to determine the coordinates is given.

d:documents/word.Well_data fields.doc (6/25/01, ebt)
Modified from wellsys.doc 1/27/97 rab.
`c:officedoc.wellsys.doc`

Appendix A2

Geologic Quadrangle Map
Aspen Quadrangle
Colorado

U.S. Geological Survey
GQ-933

Legend

GEOLOGIC QUADRANGLE MAP
ASPEN QUADRANGLE, COLORADO
GQ-933

EXPLANATION

Qal — Alluvium

Sand, silt, gravel, and peaty material on valley floor; includes some swamp deposits

Qf — Alluvial-fan deposits

Generally poorly sorted material ranging from silt to boulders

Qt — Talus

Angular rock fragments ranging from ½ inch to several feet in diameter; locally well sorted. Grades to colluvium with increase in sand and silt content

Qc — Colluvium

Poorly sorted material ranging from silt to boulders; finer fractions usually predominate; supports vegetation

Qs — Solifluction deposits

Angular rock fragments in a matrix of silt and sand that have moved down a gentle slope. Not mapped where bedrock contacts can be traced

Ql — Landslide deposits

A heterogeneous mixture of blocks as much as several tens of feet in diameter and small angular fragments and, commonly, also sand and silt

Qma, Qmb, Qmc, Qmd, Qme — Glacial deposits*

Poorly sorted moraine deposits ranging from silt to boulders. Commonly contain subrounded boulders derived from valley heads but may also be composed of relatively angular boulders locally derived. In many places has hummocky or ridge-and-trough topography. Locally indistinguishable from landslides containing morainal material or from colluvium developed on Precambrian rocks. Qma is the youngest moraine; it includes some deposits in cirque in southwest corner of quadrangle younger than Qma of the main valleys

Stippled pattern indicates trend of prominent lateral and terminal morainal ridges

Qga, Qgb, Qgc, Qgd — Glaciofluvial deposits*

Outwash gravels, crudely bedded, poorly sorted. Qga, is the youngest

Qrg — Gravel

In terraces a few tens of feet above present flood plain in Woody Creek valley; not correlated with gravel sequence in Roaring Fork River valley

Qof — Older alluvial-fan deposits

Alluvial fan not graded to present drainage

TKd — Hornblende quartz diorite

Greenish-gray to bluish-gray porphyritic rock containing phenocrysts of chloritized hornblende 1-2 mm in length, but locally as much as 5 mm in length, and of saussuritized plagioclase as much as 0.5 mm in length in a fine-grained groundmass of quartz, albite, calcite, sericite, and opaque minerals

TKq — Quartz porphyry

White porphyry containing conspicuous euhedral phenocrysts of quartz, and locally of muscovite, 2-5 mm in diameter, and inconspicuous phenocrysts of plagioclase and biotite, 0.5-2 mm in diameter, in an aphanitic white matrix. Grades into aplite. Muscovite from quartz porphyry in Highland tunnel gives K-Ar age of 72.2±2.2 m.y. (Obradovich and others, 1969)

TKa — Aplite

White to gray fine-grained rock containing sparse phenocrysts of plagioclase, quartz, and biotite

TKap — Aplite porphyry

Very light gray to light-greenish-gray porphyritic rock containing phenocrysts of mostly altered plagioclase in a fine-grained groundmass of quartz, feldspar, and sericite

Kmu, Kmf, Kml — Mancos Shale

Kmu, *upper shale member: dark-gray shale and silty shale with a few beds of fine-grained silty sandstone. Some thin-bedded shaly limestone in lower part. About 3,500 feet preserved in quadrangle*

Kmf, *Fort Hays Limestone Member: dark-gray limestone in beds 1-2 feet thick; weathers light gray; contains thin interbeds of shaly limestone. About 40 feet thick*

Kml, *lower shale member: dark-gray silty shale with thin beds of siltstone and fine-grained sandstone, especially near base. Near top are several beds of fossiliferous calcarenite which have a fetid odor when freshly broken. About 400 feet thick*

Kdb — Dakota Sandstone and Burro Canyon Formation

Dakota Sandstone: upper part, dark-gray, in part carbonaceous, siltstone and shale are interbedded with medium-gray sandstone containing fragments of carbonaceous material in some beds. Lower part, grayish-orange, light-brown, and gray crossbedded quartz sandstone with a few lenses of quartz and chert pebble conglomerate. About 100 feet thick

Burro Canyon Formation: light-gray to white quartz sandstone with chert and quartz pebble conglomerate and interbeds of greenish-gray claystone, light-bluish-gray claystone, silty shale, sandy siltstone, and silty sandstone. 60-80 feet thick

The two formations are mapped together because sandstone debris usually covers the distinctive claystone and siltstone beds of the Burro Canyon Formation

Jm — Morrison Formation

Grayish-red and greenish-gray siltstone and claystone and calcareous siltstone and claystone, grading downward into yellowish-gray-weathering silty limestone and limestone, grading downward into yellowish-gray calcareous sandstone with interbedded gray shaly limestone. The sandstone- and limestone-rich parts constitute less than one-fourth of its thickness which ranges from 400-530 feet

Je — Entrada Sandstone

Yellowish- to pinkish-gray crossbedded medium- to coarse-grained sandstone with 1-2 mm spherical quartz grains and sparse grains of chert in a finer grained matrix. 30-40 feet thick

UNCONFORMITY

Ŧc — Chinle Formation

Very dark red to dusky-red calcareous siltstone with some pale-orange mottling in lenses and stringers, especially near the base. Contains beds of moderate-red to very light gray silty limestone and conglomerate composed of angular fragments of limestone as much as 2 cm in diameter in a matrix of calcareous siltstone or silty limestone. Siltstone characterized by hackly fracture. About 400 feet thick

UNCONFORMITY

ŦPs, ŦPss — State Bridge Formation

Pale- to dark-reddish-brown calcareous and micaceous siltstone, sandstone, and polymictic conglomerate. Characterized by oscillatory ripple marks, crossbedding, and rounded shape of quartz grains 1-2 mm in diameter. Thin sandstone beds are more persistent than in underlying Maroon Formation. Two well-developed conglomerate horizons are on ridge between Castle and Maroon Creeks where formation is 1,000 feet thick

ŦPss, *sandstone member: moderate-orange-pink to pale-reddish-brown fine-grained thinly laminated crossbedded sandstone. Yellowish-gray on Red Butte, 0-60 feet thick*

UNCONFORMITY

PPm — Maroon Formation

Grayish-red, reddish-brown, pale-red, and gray interbedded generally calcareous sandstone, siltstone, mudstone, conglomerate, and limestone. Crossbedded; has mud cracks, raindrop impressions, and current ripple marks. About 1,000 feet of siltstone and fine-grained sandstone at top. Conglomerate sparse in northern part of quadrangle. About 5,500 feet of the upper part of the formation exposed west of Castle Creek and about 12,000 feet of the lower and middle parts exposed on Woody Creek and west to the Castle Creek fault zone

Pg — Gothic Formation by Langenheim (1952)

Predominantly gray, tan, and brown calcareous sandstone, siltstone, shale, silty limestone, and limestone. Contains a few thin greenish-gray and reddish-brown beds, especially near upper contact. Much rock characteristically weathers grayish orange to moderate orangish brown. Gradational contacts with overlying Maroon and underlying Belden. 1,000-2,800 feet thick

Pe — Eagle Valley Formation

Interbedded gray, greenish-gray, grayish-red, and reddish-brown calcareous siltstone and sandstone and silty limestone and limestone. About 1,200 feet thick at Woody Creek and 2,500 feet thick at the northern edge of the quadrangle. As mapped is transitional between and intertongues with red beds of the Maroon Formation and gray beds of the Gothic Formation

Pb — Belden Formation

Dark-gray to black limestone, dolomite, shale, and carbonaceous shale containing a few thin sandstone beds. Contains breccia zones subparallel to bedding and a few lenses of anhydrite (exposed only in tunnels). Some beds quite rich in pyrite. Nodules and lenses of black and white chert locally in carbonate rocks. Apparent thickness 500-800 feet

UNCONFORMITY

Ml — Leadville Limestone

Blue-gray thick-bedded to massive limestone in upper part; gray to dark-gray thin- to thick-bedded dolomite and a few beds of limestone in lower part. Gilman Sandstone Member at base consists of several beds of dolomitic sandstone, sandy dolomite, and sedimentary breccia. Breccia at contact between upper and lower parts of formation in Spar Gulch area may represent brecciated cave deposits. The upper part is missing north of the Roaring Fork River, probably due to faulting. 150-200 feet thick where complete section; about 100 feet thick north of the Roaring Fork River valley

UNCONFORMITY

Dcd, Dcp — Chaffee Formation

Dcd, *Dyer Dolomite Member: light- to dark-gray thin- to thick-bedded dolomite containing some shaly partings and beds of dark-gray limestone. 50-100 feet thick*

Dcp, *Parting Member: white to tan poorly sorted crossbedded quartzite, gray, greenish-gray, and dusky-red shale and dolomitic shale, gray to tan siltstone, and grayish-yellow dolomite. 50-100 feet thick*

UNCONFORMITY

Om — Manitou Dolomite

Gray medium-bedded dolomite with irregular bedding planes. White chert stringers and nodules characteristic of upper part of formation. Gradational contact with underlying Peerless Formation. 150-250 feet thick

Cp — Peerless Formation

Grayish-orange to moderately orange brown weathering, locally glauconitic, dolomitic sandstone and sandy dolomite, and dusky-red to yellowish- and light-greenish-gray shale. Contains a few beds of white quartzite, especially near the base. 100-150 feet thick

Cs — Sawatch Quartzite

White quartzite containing some brown-weathering beds of dolomitic sandstone. Quartz pebble conglomerate at base as much as 6 feet thick but generally a foot or less. Local crossbedding, especially near base. 150-250 feet thick

UNCONFORMITY

pCq — Quartz monzonite

Predominantly muscovite-biotite quartz monzonite; contains some granite and granodiorite and a few inclusions of biotite-muscovite schist and gneiss and migmatite, especially near eastern margin of quadrangle. Contains a few pegmatites. Pattern indicates zone of sheared rock

LINE SYMBOLS

Dashed where approximately located; dotted where concealed

Contact
Short dashed where formations intertongue

Fault
U, upthrown side; D, downthrown side

Thrust fault
Sawteeth on upper plate

Syncline
Showing trace of axial plane and direction of plunge

PLANAR FEATURES

Planar and linear symbols may be combined and are joined at point of observation

20 Inclined — Vertical — 80 Overturned
Strike and dip of beds

40 Inclined — Vertical
Strike and dip of foliation

80
Strike and dip of foliation and layering

LINEAR FEATURE

10
Bearing and plunge of mineral alinement

j — Jasperoid

Light-brown, locally vuggy, fine-grained, quartz-rich rock probably derived by silicification of lower Paleozoic unit(s) no longer identifiable through replacement by hydrothermal solutions along fault

D 6029
USGS Mesozoic Fossil locality
Showing Denver catalog number

*Mapping and correlation of outwash gravels and moraines based principally on topographic relations, but in the Roaring Fork River valley soil development suggests that Qmb and directly adjacent Qgb may have formed during two different glacial episodes.

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Langenheim, R. L., Jr., 1952, Pennsylvanian and Permian stratigraphy in Crested Butte quadrangle, Gunnison County, Colorado: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 4, p. 543-574.

Obradovich, J. D., Mutschler, F. E., and Bryant, Bruce, 1969, Potassium-argon ages bearing on the igneous and tectonic history of the Elk Mountains and vicinity, Colorado—a preliminary report: Geol. Soc. America Bull., v. 80, no. 9, p. 1749-1756.

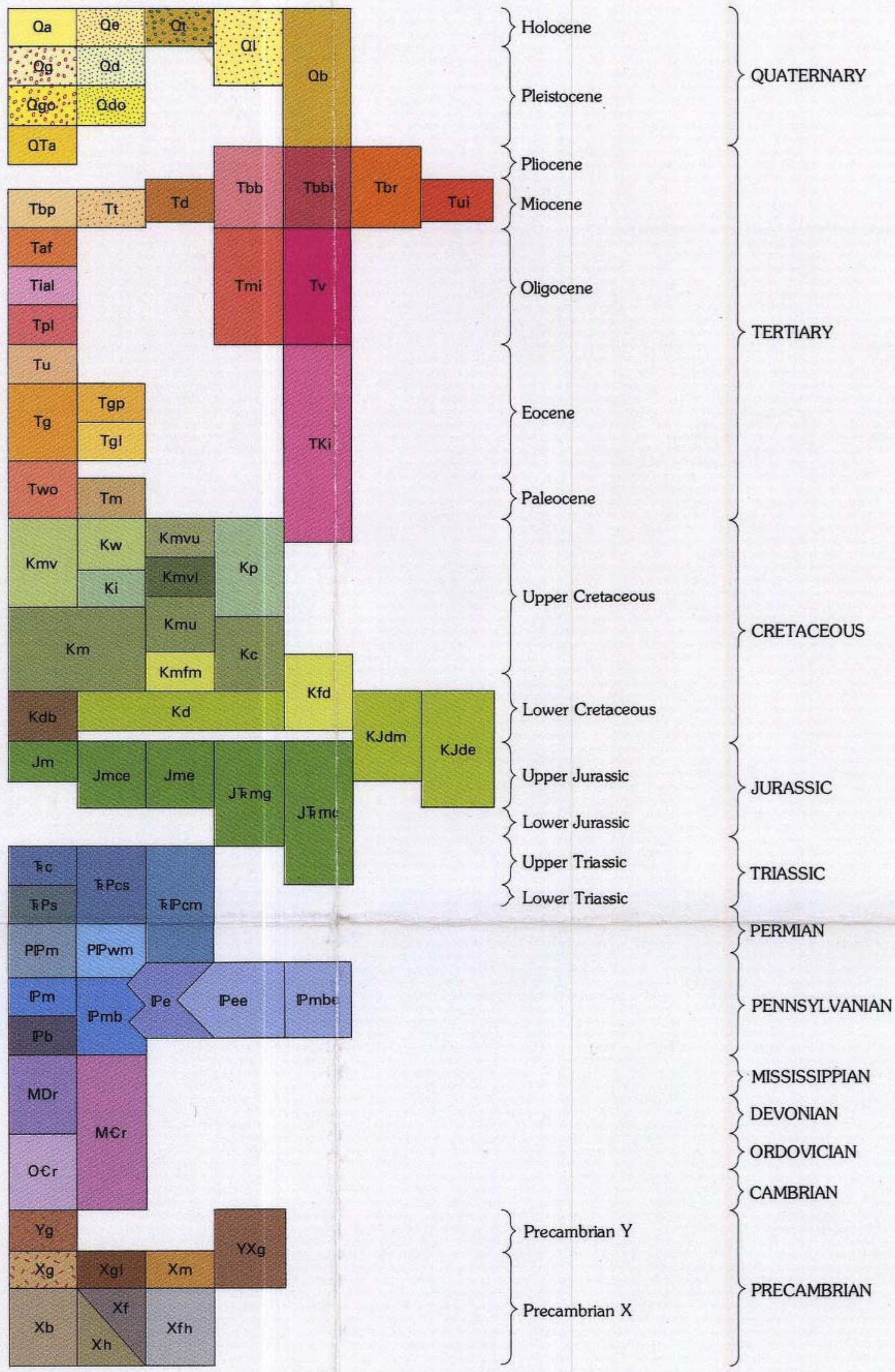
Appendix A3

Geologic Map
Leadville 1^o x 2^o Quadrangle
Colorado

U.S. Geological Survey
Miscellaneous Investigations Series Map I-999

Legend

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Formations for which no map symbol is shown are grouped with other stratigraphic units to form map units

UNCONSOLIDATED DEPOSITS (HOLOCENE):

Qa Alluvium—Gravel, sand, and silt in stream valleys and alluvial fans

Qe Eolian deposits—Windblown sand and silt

Qt Talus deposits and rock glaciers

Ql LANDSLIDE DEPOSITS (HOLOCENE AND PLEISTOCENE)—On Grand and Battlement Mesas (southwestern corner of quadrangle), consist principally of large slump blocks of basalt irregularly veneered with young (Pinedale) glacial drift. Elsewhere, include mudflow and some talus deposits. Many small bodies not mapped

Qb YOUNG BASALT (HOLOCENE AND PLEISTOCENE)—In Roaring Fork valley north of Aspen, 1.5 m.y. (million years) old; along Rock Creek north of McCoy, 0.64 m.y. old (Larson and others, 1975, p. 166). Near Dotsero, 4,150 years old (Giegengack, 1962)

• Volcanic cinder cone or crater

UNCONSOLIDATED DEPOSITS (PLEISTOCENE):

Qg Young gravels (Bull Lake and younger)—Stream, terrace, and outwash gravels

Qd Young glacial drift (Bull Lake and younger)—Unsorted bouldery glacial deposits (till) and associated sand and gravel deposits

Qgo Old gravels and alluviums (pre-Bull Lake)—Terrace, outwash, and pediment gravels

Qdo Old glacial drift (pre-Bull Lake)—Unsorted bouldery glacial deposits (till); morainal form subdued or lacking

QTa HIGH-LEVEL ALLUVIUM (PLEISTOCENE AND/OR PLIOCENE)—Fine-grained to bouldery alluvial deposits and gravels; preserved mainly on ridge tops; may not all be of same age; in southwest part of quadrangle, characterized by abundant basalt boulders and in places has been mapped previously as basalt

Tbp BROWNS PARK FORMATION (MIOCENE)—Fluvial ashy siltstone, claystone, sandstone, conglomerate, and thin beds of air-fall ash; loosely consolidated; conglomerate at base. Locally interbedded with basalt (Tbb unit). Thickness >1,000 ft (305 m) south of State Bridge

Tt TROUBLESOME FORMATION (MIOCENE)—Chiefly siltstone; contains many beds of volcanic ash and some of sandstone and conglomerate. Thickness >500 ft (152 m) in Williams Fork valley. Term is used in Middle Park for Miocene rocks largely equivalent to Browns Park Formation west of the Gore Range

Td DRY UNION FORMATION (PLIOCENE AND MIOCENE)—Light-brown sandy siltstone and interbedded friable sandstone, conglomerate, and volcanic ash. Thickness >3,000 ft (915 m) in Arkansas River valley southwest of Leadville

Tbb BASALT OF BIMODAL SUITE (PLIOCENE AND MIOCENE)—Dense black resistant alkali basalt in lava-flow layers 5–200 ft (1.6–61 m) thick, and interbedded tuffs and volcanic conglomerates. Greatest preserved thicknesses are 900 ft (275 m) on White River Plateau and 800 ft (244 m) on Grand Mesa. Ages determined from several localities range from 8 to 23 m.y. (Larson and others, 1975)

Tbbi BASALTIC DIKES AND PLUGS (PLIOCENE AND MIOCENE)—Probable feeders of basalt flows of Tbb unit; also intrusive into the flows

Tbbi Dike

Tbr RHYOLITIC ROCKS OF BIMODAL SUITE (PLIOCENE AND MIOCENE)—In plugs, dikes, and small flows

Tbr Dike

Tui UPPER TERTIARY INTRUSIVE ROCKS (MIOCENE)—Sodic granite of Treasure Mountain south of Marble, and satellitic plugs and dikes. About 12.5 m.y. in age (Obradovich and others, 1969)

Taf ASH-FLOW TUFF (OLIGOCENE)—Dense silicic welded tuff and vitrophyre; principally in Grizzly caldera south of Independence Pass in Sawatch Range

Tial INTER-ASH FLOW ANDESITIC LAVAS AND BRECCIAS (OLIGOCENE)—Mapped only at Buffalo Peaks in southeast corner of quadrangle

Tpl PRE-ASH FLOW ANDESITIC LAVAS AND BRECCIAS (OLIGOCENE)—Mapped only in Grizzly caldera area south of Independence Pass in Sawatch Range

Tmi MIDDLE TERTIARY INTRUSIVE ROCKS (OLIGOCENE; 26–38 m.y.)—Granodiorite and quartz monzonite; generally porphyritic but equigranular in some large bodies; in stocks, dikes, sills, and irregular bodies

Tmi Dike or sill

Tv VOLCANIC ROCKS OF GREEN MOUNTAIN AREA (OLIGOCENE)—Trachytic lavas related to Green Mountain intrusive and volcanic center in Blue River valley dated by fission-track method at 30 m.y. (Naeser and others, 1973)

Tu UINTA FORMATION (EOCENE)—Siltstone, sandstone, and marlstone. Maximum preserved thickness on Battlement Mesa about 1,000 ft (305 m)

Tg GREEN RIVER FORMATION (EOCENE)—Marlstone, oil shale, siltstone, and sandstone. Undivided unit mapped only at depositional edge of formation in southwest corner of quadrangle

Tgp Parachute Creek Member—Oil shale and marlstone. Thickness 1,200 ft (365 m) on Roan Plateau northwest of Rifle; thins southward to wedge edge near south boundary of quadrangle

Tgl Lower part of Green River Formation—Shale, sandstone, and marlstone in the Anvil Points, Garden Gulch, and Douglas Creek Members. Thickness >2,000 ft (610 m) on Roan Plateau northwest of Rifle; thins southward to wedge edge near south boundary of quadrangle

Two WASATCH AND OHIO CREEK FORMATIONS:

Wasatch Formation (Eocene and Paleocene)—Variegated claystone, siltstone, sandstone, and conglomerate; carbonaceous shale and lignite near base. Maximum thickness about 5,800 ft (1,770 m)

Ohio Creek Formation (Paleocene)—Sandstone and conglomerate. Thickness 400 ft (122 m) near south boundary of quadrangle; thins northward to about 50 ft (15 m) along Grand Hogback north of Rifle

Tm MIDDLE PARK FORMATION-UPPER PART (PALEOCENE)—Arkosic grit, conglomerate, sandstone, and mudstone; contains abundant volcanic detritus. Preserved thickness at northeast corner of quadrangle >2,000 ft (610 m)

TKi LARAMIDE INTRUSIVE ROCKS (EOCENE, PALEOCENE, AND UPPER CRETACEOUS; 40–72(?) m.y.)—Quartz monzonite, granodiorite, and quartz diorite porphyries in stocks, sills, and dikes

TKi Dike or sill

Kmv MESAVERDE GROUP UNDIVIDED OR MESAVERDE FORMATION (UPPER CRETACEOUS)

Kw Williams Fork Formation—Light-brown to white sandstone, gray to black shale, and coal beds. Maximum thickness along Grand Hogback north of Rifle is 4,500 ft (1,372 m)

Ki Iles Formation—Massive beds of light-brown to white sandstone and interbedded shale and coal. Trout Creek Sandstone Member at top. Maximum thickness along Grand Hogback north of Rifle is 1,600 ft (488 m)

Kmvu Upper part of Mesaverde Formation—Sandstone, shale, and minor coal beds. Maximum thickness along Grand Hogback south of Colorado River is 2,700 ft (823 m)

Kmvl Lower part of Mesaverde Formation—Sandstone, shale, and coal. Unit thins southward by wedging of lower sandstone beds into Mancos Shale. Thickness near Colorado River is 2,400 ft (732 m); near Carbondale, where Rollins Sandstone Member is at base, 1,400 ft (427 m)

Kp PIERRE SHALE (UPPER CRETACEOUS)—Dark-gray marine shale containing a few thick beds of fine-grained sandstone. Maximum preserved thickness 5,000–6,000 ft (1,525–1,830 m)

CONTACT

FAULT—Dotted where concealed. Bar and ball on downthrown side

THRUST FAULT—Dotted where concealed. Sawteeth on upper plate

INFERRED FAULT IN VALLEY-FILL DEPOSITS—Largely concealed; location approximate or conjectural. Bar and ball on downthrown side

PRECAMBRIAN SHEAR ZONE—Dotted where concealed

ANTICLINE—Showing crestline; dotted where concealed

SYNCLINE—Showing troughline; dotted where concealed

MONOCLINE—Showing anticlinal crestline of steep dip; dotted where concealed

Km MANCOS SHALE (UPPER AND LOWER CRETACEOUS)—Gray to dark-gray marine shale. Sandstone beds near the top. Calcareous sandstone of Upper Cretaceous Frontier Sandstone Member 300–400 ft (90–122 m) above base, overlain by calcareous shale zone equivalent to Niobrara Formation. Silver-gray siliceous shale of Lower Cretaceous Mowry Shale Member at base. Thickness north of Colorado River about 5,000 ft (1,525 m); south of river, >6,000 ft (1,820 m)

Kmu Upper unit of Mancos Shale (Upper Cretaceous)—Mancos Shale above the Frontier Sandstone Member

Kmfm Frontier Sandstone and Mowry Shale Members and intervening shale zone (Upper and Lower Cretaceous)—Thickness about 500 ft (152 m)

Kc COLORADO GROUP (UPPER AND LOWER CRETACEOUS)—Consists of Upper Cretaceous Niobrara Formation (calcareous shale and marly limestone) and Upper and Lower Cretaceous Benton Shale, which has calcareous sandstone equivalent to Frontier Sandstone Member of Mancos Shale at top and siliceous shale equivalent to Mowry Shale Member at base. Thickness 800–1,000 ft (244–305 m)

Kd DAKOTA SANDSTONE (LOWER CRETACEOUS)—Light-gray and tan sandstone or quartzite; some interbedded dark shale and shaly sandstone. Resistant, widely exposed unit but too thin to show separately at map scale in many areas. Thickness 125–225 ft (37–68 m)

Kdb DAKOTA SANDSTONE AND BURRO CANYON FORMATION (LOWER CRETACEOUS)—Mapped only in Aspen-Basalt area

Burro Canyon Formation—Yellow sandstone and green claystone. Maximum thickness 225 ft (68 m)

Kfd FRONTIER SANDSTONE AND MOWRY SHALE MEMBERS OF MANCOS SHALE AND DAKOTA SANDSTONE

Jm MORRISON FORMATION (UPPER JURASSIC)—Variegated shale and mudstone, light-gray sandstone, and local beds of gray and green-gray limestone. Locally conglomeratic near base. Thickness about 500 ft (152 m) along Grand Hogback and along Colorado River near Burns; thins eastward and southeastward to <200 ft (60 m) in Blue River valley

CURTIS FORMATION (UPPER JURASSIC)—Yellowish-gray to pale-green glauconitic sandstone and oolitic limestone. Thickness <100 ft (30 m)

ENTRADA SANDSTONE (UPPER JURASSIC)—Light-gray to orange crossbedded sandstone. Thickness 75–150 ft (23–46 m) in northwest and central parts of quadrangle; wedges out southward in Aspen area and eastward at Gore Range

KJdm DAKOTA FORMATION AND MORRISON FORMATION

KJde DAKOTA, MORRISON, CURTIS, AND ENTRADA FORMATIONS ALONG COLORADO RIVER NEAR BURNS AND STATE BRIDGE; ELSEWHERE, DAKOTA, MORRISON, AND ENTRADA FORMATIONS

Jmce MORRISON, CURTIS, AND ENTRADA FORMATIONS

Jme MORRISON AND ENTRADA FORMATIONS

GLEN CANYON SANDSTONE (LOWER JURASSIC AND UPPER TRIASSIC)—Light-brown to light-gray crossbedded sandstone that closely resembles the overlying Entrada Sandstone, from which it is separated by a subtle unconformity. Maximum thickness 75 ft (23 m)

JTRmg MORRISON, ENTRADA, AND GLEN CANYON FORMATIONS

TRc CHINLE FORMATION (UPPER TRIASSIC)—Brownish- and purplish-red calcareous siltstone, mudstone, and sandstone; limestone-pellet conglomerate in lower part; Gartra Sandstone Member at base (pale-purple to white pebbly sandstone 25 ft or 8 m thick). Thickness 1,200 ft (365 m) near Brush Creek south of Eagle; thins from there in all directions; wedges out beneath pre-Entrada unconformity along west side of Gore Range and in Elk Mountains southwest of Aspen

JTRmc MORRISON, ENTRADA, AND CHINLE FORMATIONS—Along Grand Hogback south of T. 6 S., Chinle is represented only by the Gartra Member

TRPs STATE BRIDGE FORMATION (LOWER TRIASSIC AND PERMIAN)—Orange-red to red-brown siltstone and sandstone. Thickness at least 5,000 ft (1,525 m) in local depositional basin in Hardscrabble Mountain area south of Eagle. To the north, unit is 500 ft (152 m) thick and thins eastward to wedge out along west flank of Gore Range. To the southwest, unit is 2,400 ft (732 m) thick along Fryingpan River east of Basalt but absent beneath pre-Chinle and pre-Entrada unconformities at Grand Hogback and in Elk Mountains

TRPcs CHINLE AND STATE BRIDGE FORMATIONS

PIPm MAROON FORMATION (PERMIAN AND PENNSYLVANIAN)—Maroon and grayish-red sandstone, conglomerate, and mudstone; lower part intertongues with Eagle Valley Formation or Evaporite which underlies the Maroon in places. Thickness >9,500 ft (2,900 m) in area southwest of Aspen; thins northeastward to depositional margin along west flank of Gore Range; thinning also due to pre-State Bridge unconformity

WEBER SANDSTONE (PERMIAN AND PENNSYLVANIAN)—Yellow-gray sandstone. Thickness about 100 ft (30 m) near northwest corner of quadrangle; thins toward depositional margin to south and east; present margin south of Glenwood Springs, east of Eagle, and east of Burns results in part from truncation beneath pre-State Bridge unconformity

PIPwm WEBER SANDSTONE AND MAROON FORMATION

TRPIPcm CHINLE, STATE BRIDGE, AND MAROON FORMATIONS

IPm MINTURN FORMATION (PENNSYLVANIAN)—Gray, pale-yellow, and red sandstone, grit, conglomerate, and shale, and scattered beds and reefs of carbonate rocks. Includes rocks of Gothic Formation of Langenheim (1952). Thickness near Minturn >6,000 ft (1,830 m); thins abruptly eastward toward depositional margin along west flank of Gore Range and at Breckenridge. Thins westward and intertongues with Eagle Valley Evaporite in Eagle basin. Thickness on western side of basin, in Elk Mountains, about 3,000 ft (915 m). East and north of Sawatch Range, contact with overlying Maroon Formation is placed at top of highest marine limestone; west of Sawatch Range and White River Plateau, contact is at color change from predominantly gray (Minturn) below to predominantly red (Maroon) above

IPb BELDEN FORMATION (PENNSYLVANIAN)—Dark-gray to black shale, carbonate rocks, and sandstone. Map unit includes local thin lenses of Molas Formation (Pennsylvanian) at base. Maximum thickness in Elk Mountains and White River Plateau area about 900 ft (275 m); thins eastward to depositional margin along Gore Range and near Hoosier Pass

IPmb MINTURN AND BELDEN FORMATIONS

IPmbe Evaporite-bearing facies of Minturn and Belden Formations—Mapped only in South Park, in southeast corner of quadrangle

IPe EAGLE VALLEY FORMATION (PENNSYLVANIAN)—Gray and reddish-gray siltstone, shale, sandstone, carbonate rocks, and local lenses of gypsum. Unit is transitional between the coarse clastic rocks of the Minturn and Maroon Formations and purely evaporitic rocks. Thickness variable, depending on intertonguing relations

IPee EAGLE VALLEY EVAPORITE (PENNSYLVANIAN)—Gypsum, anhydrite, and interbedded siltstone and minor dolomite; contains thick salt at depth in some places, as shown by wells drilled for oil and gas. Intertongues with Minturn, Belden, and Maroon Formations and grades into fine-grained clastic rocks of Eagle Valley Formation. Diapiric in structural configuration in many places, especially in large area in central part of quadrangle. Thickness indeterminate

MDr MISSISSIPPIAN AND DEVONIAN ROCKS—Includes rocks of, Leadville Limestone (or Dolomite) (Mississippian) and Chaffee Group (Mississippian? and Devonian). Leadville thickness variable beneath pre-Belden unconformity; maximum of about 275 ft (84 m) in Elk Mountains; truncated eastward along west flank of Gore Range and near Hoosier Pass. Chaffee Group consists of Gilman Sandstone (Mississippian or Devonian), Dyer Dolomite (Mississippian? and Devonian) and Parting Formation (Devonian). Maximum thickness of Chaffee Group 250 ft (76 m) in White River Plateau area; truncated beneath pre-Belden unconformity along west flank of Gore Range and near Hoosier Pass

O€r ORDOVICIAN AND CAMBRIAN ROCKS—Includes various combinations of: Fremont Limestone (Ordovician), Harding Sandstone (Ordovician), Manitou Dolomite (Ordovician), Dotsero Formation (Cambrian), Peerless Formation (Cambrian), and Sawatch Quartzite (Cambrian). Fremont is present beneath pre-Parting unconformity only in western Elk Mountains. Harding is present beneath pre-Parting and pre-Fremont unconformities only in western Elk Mountains and along Eagle River from Minturn area to Tennessee Pass. Manitou is widespread but in eastern part of quadrangle is absent beneath pre-Harding and younger unconformities from Pando and Breckenridge northward. Dotsero is mapped only in White River Plateau area. Peerless and Sawatch are widespread but are truncated beneath various unconformities along Gore Range and near Breckenridge. Maximum thickness of Ordovician and Cambrian rocks about 750 ft (230 m) in White River Plateau area

M€r MISSISSIPPIAN, DEVONIAN, ORDOVICIAN, AND CAMBRIAN ROCKS

Yg GRANITIC ROCKS (PRECAMBRIAN Y— 1,400 m.y. AGE GROUP)—Includes Silver Plume and St. Kevin Granites and equivalents

Xg GRANITIC ROCKS (PRECAMBRIAN X— 1,700 m.y. AGE GROUP)—Includes Cross Creek Granite of Gore and northern Sawatch Ranges, Denny Creek Granodiorite of central Sawatch Range, and equivalent rocks

Xgl LEUCOCRATIC GRANITIC ROCKS (PRECAMBRIAN X)—Includes trondhjemitic Kroenke Granodiorite in Sawatch Range, and granite at Taylor Pass southeast of Ashcroft Mountain in the Elk Mountains

YXg GRANITIC ROCKS UNDIVIDED (PRECAMBRIAN Y AND X)

Xm MAFIC INTRUSIVE ROCKS (PRECAMBRIAN X)—Noritic gabbro

Xb BIOTITIC GNEISSES AND MIGMATITE (PRECAMBRIAN X)—Unit contains minor interlayered hornblende gneiss and calc-silicate rocks. Parent materials mainly graywacke and shale

Xf FELSIC GNEISSES (PRECAMBRIAN X)—Parent materials probably igneous rocks of intermediate compositions

Xh HORNBLENDIC GNEISSES (PRECAMBRIAN X)—Parent materials probably mainly basaltic and andesitic igneous rocks; some of gneiss is closely associated with calc-silicate rocks and minor marble and probably is metasedimentary

Xfh INTERLAYERED FELSIC AND HORNBLENDIC GNEISSES (PRECAMBRIAN X)

Appendix A4

Summary of Hydrogeologic Units in Upper and Middle Roaring Fork Study Area Pitkin County, Colorado

Hydrogeological Units in Upper and Middle Roaring Fork Study Area
Pitkin County, Colorado

Hydrologic Systems Analysis, LLC., Golden, Colorado

1. Surficial Aquifer Materials

Modern Alluvium *(Qal; alluvium)*. Sand, silt, gravel and peaty material on valley floor [USGS GQ-933, 1971]. This material is primarily located along the modern streams, such as Owl Creek and Brush Creek, and rivers, such as the Roaring Fork. These materials usually are natural aquifers that have direct connection to and are sustained by the nearby surface water bodies, and are most likely vulnerable due to being prone to seasonal fluctuations and changes in surface water body use (withdrawal for irrigation, for example).

Terrace Gravels *(Q, Qg, Qf, and Qc; young terrace gravels, fans, colluvium)*. Combination of primarily glaciofluvial deposits (Qg, outwash gravels, crudely bedded, poorly sorted), and some alluvial fan deposits (Qf, poorly sorted material ranging from silt to boulders), and colluvium (Qc, poorly sorted material ranging from silt to boulders; finer fraction usually dominates) [USGS GQ-933, 1971]. This material is primarily located above the modern stream levels on the hillslopes. These materials usually are dry, or can be aquifers created and sustained by anthropogenic activity, such as irrigation ditches or irrigation return flow.

Moraines *(Qm; terminal and lateral moraines)*. Poorly sorted glacial deposits ranging from silt to boulders; locally indistinguishable from landslide deposits or colluvium [USGS GQ-933, 1971]. This material is primarily located at mountain canyon mouths, such as the Roaring Fork River, and Castle and Maroon Creek canyons, or along the higher hillslope locations near the high glacially carved hanging valleys and cirques, such as the slopes along Burnt Mountain near Snowmass Village. The moraines of the Roaring Fork River and Castle and Maroon Creeks are dry near the surface, but frequently contain natural ground water at depth. The moraines and associated mass wasting deposits of the Owl and Brush Creek areas also contain natural ground water at depth, and are sustained by natural climate and underlying Dakota Formation in some locations.

Landslides *(Ql, Qls, landslide deposits)*. A heterogeneous mixture of blocks as much as several tens of feet in diameter and smaller angular fragments and , commonly also sand and silt [USGS GQ-933, 1971]. This material is primarily located along the hillslopes surrounding the populated areas of Pitkin County. These materials are mostly dry, but in areas of irrigation ditches and other anthropogenic activity, may become aquifers.

Older terrace gravels and fans *(Ts, Qof; Tertiary/Pleistocene(?) deposits; see terrace gravels and fans)*. This material is primarily located along the hillslopes. These materials usually are dry, or can be aquifers created and sustained by anthropogenic activity, such as irrigation ditches or irrigation return flow.

These surficial materials, when saturated, will be primarily unconfined or water table systems. Therefore, the water table will fluctuate naturally with climate input (seasonal rainfall and snowmelt). In addition, these aquifers, in the absence of overlying low-

permeability units, will be vulnerable to contamination from land surface activity, such as irrigation, industrial, or urban uses.

2. Bedrock Aquifer Material

Dakota Sandstone *(Kd, Lower Cretaceous)*. This unit is primarily a sandstone that may have either matrix or fracture permeability. Aquifer conditions may be unconfined or confined dependent on overlying geologic unit. Given the age of the unit, fracture permeability is likely to be most significant for water supply. Typically, this unit is located at a depth greater than 200 feet under most of the study area west of the City of Aspen.

Leadville Limestone *(Ml, Mississippian; Carbonates)* This unit is primarily a limestone that has mostly fracture and karst permeability. Aquifer conditions may be unconfined or confined dependent on overlying geologic unit. The unit is located a depths greater than 1,000 feet under most of the study area west of the City of Aspen.

Fractured Crystalline Material *(Granite, Gneiss, etc)*. This unit is primarily igneous or metamorphic crystalline rocks that have mostly fracture permeability. The unit has vast thicknesses, however, the depth to which saturated thickness of this (mostly unconfined) unit is maintained is usually not greater than 500 feet. Note that the fractured crystalline material is found primarily beneath BLM and U.S. Forest Service lands, and is located in the upper Roaring Fork Drainage and North Star area.

For the current study area, only the surficial material, the Dakota Sandstone, and the fractured crystalline rocks are of interest. The Leadville Limestone is of interest when the study is extended to Aspen and nearby areas.

3. Bedrock Aquitard Material

Mancos Shale *(Km, Upper Cretaceous)*. This unit consists of an upper and lower shale member of significant thickness, separated by an up to 40 ft thick limestone member (Fort Hays Limestone). This very low-permeability unit serves as a confining layer when present, primarily in the western half of the Middle Roaring Fork study area.

Appendix A5

Stepwise Approach to Assessing Ground Water Availability, Sustainability, and Vulnerability in Upper and Middle Roaring Fork Study Area, Pitkin County, Colorado

Stepwise Approach to Assessing Ground Water Availability, Sustainability, and Vulnerability in Upper and Middle Roaring Fork Study Area, Pitkin County, Colorado

Hydrologic Systems Analysis, LLC., Golden, Colorado

Steps 1 – 2 prompt the user to initiate the GIS and locate the site being evaluated.

Step 1. Start ARCMAP™ Version 8.3 (ESRI®, Redlands, California) or higher and load the Middle Roaring Fork (MRF) or Upper Roaring Fork (URF) annotated map dependent on the location of the site [*file: PitkinCounty_GWGIS_MRFannotated.mxd or PitkinCounty_GWGIS_URFannotated.mxd*].

Step 2. The precise location or platting of the permit site (PS) should be plotted on the URF or MRF map using the appropriate layers in the GIS (e.g., using site coordinates or location information on existing wells, roads, parcels, etc.). This location is used in conjunction with the hydrology and hydrogeology GIS layers to determine the presence of ground water (Steps 3 - 6). The succeeding tasks include determining the level of ground water sustainability as a resource at the site (Steps 7-9), and its vulnerability to contamination and subsequent loss of supply (Step 10). It should be noted that due to limitations in data availability and quality, this analysis is primarily qualitative in nature. It does not replace due diligence on the side of the permit applicant.

Steps 3 – 6 allow the user to determine the potential availability of ground water for water supply at the site by identifying the areas covered by hydrogeologic formations that may be an aquifer (either unconsolidated surficial materials or bedrock) and evaluating the presence or absence of ground water in these formations (see document *HSA_Hydrogeology_Legend.pdf* for descriptions of hydrogeological units).

Step 3. Determine the potential unconfined surficial aquifer material at the site. Check to see if the site is located in one of the following units:

For Unit 1: Modern Alluvium (Qal; alluvium). *In the MRF GIS map, switch on layer S; in the URF GIS map, switch on layer Q or layer R.*

For Unit 2: Terrace Gravels (Q or Qg; young terrace gravels, fans, colluvium). *In the MRF GIS map, switch on layer T; in the URF GIS map, switch on layer Q or layer R.*

For Unit 3: Moraines (Qm; moraines). *In the MRF GIS map, switch on layer U; in the URF GIS map, switch on layer Q or layer R.*

For Unit 4: Landslides (Qls). *In the MRF GIS map, switch on layer V; in the URF GIS map, switch on layer Q or layer R.*

For Unit 5: Older terrace gravels and fans (Ts). *In the MRF GIS map, switch on layer W; in the URF GIS map, switch on layer Q or layer R.*

Step 4. Determine potential unconfined and confined bedrock aquifer material at site. Check to see if the site is located in one of the following units:

For Unit 7: Dakota Sandstone (unconfined or confined). *In the MRF GIS map, switch on layers Y and/or BB; in the URF GIS map, switch on layer Q or layer R.*

For Unit 8a: Leadville Limestone (Carbonates) (unconfined or confined). *In the MRF GIS map, switch on layers Y and/or BB; in the URF GIS map, switch on layer Q or layer R.*

For Unit 8b: Fractured Crystalline Material (Granite, Gneiss, etc) (unconfined). *In the MRF GIS map, switch on layers Y and/or BB; in the URF GIS map, switch on layer Q or layer R.*

Note that Hydrogeologic Unit 6 is Mancos Shale, a potential aquitard.

Alternatively, step 3 and 4 combined (MRF only); use: 1) Locate the site in a set of layers showing the outcrops of all hydrogeologic units combined: *switch on MRF layers R and EE together*; or 2) Locate site with respect to each of the unconsolidated hydrogeologic units (*switch on MRF layers S, T, U, V and W, separately)* and each of the potential bedrock aquifers (switch on *MRF layers BB and CC, separately).*

Step 5. Determine if the potential alluvial/colluvial aquifer is connected/not connected with a bedrock aquifer. This step determines if the alluvial/colluvial aquifer is sustained by a bedrock aquifer, or sustained solely by surface processes, such as a nearby river. For the MRF, presence of Mancos Shale indicates absence of connectivity; for the URF, additional professional judgment may be needed to interpret geologic map. Overlay the surficial layers over the bedrock layers to determine connectivity: *in the MRF GIS map, switch on layers R and EE and check presence of unit 6 (Mancos Shale); in the URF GIS map, switch on layer Q or layer R, determine geologic stack, and check for connectivity.*

Step 6. Determine if the alluvial/colluvial material is saturated or unsaturated. This step shows the availability of ground water for the site. Identify one or more relevant wells based on distance to PS and comparable hydrogeology (*switch on layer GG and combine with layers identified as relevant in steps 3-5)*. Using the accompanying attribute table in layer GG, well depth, depth to encountered water below the surface (and calculated saturated thickness, and well production (gal per minute yield) may be determined. This step could be used to quantitatively determine the amount of ground water available, but requires professional judgment using standard practices.

Steps 7 – 10 allow the user to determine the potential sustainability and vulnerability of ground water for use as a water supply for the site.

Step 7. Determine amount of direct infiltration of precipitation into the alluvial/colluvial aquifer or the bedrock aquifer. This step is performed to determine recharge to the aquifer from precipitation. To assess the recharge potential from precipitation in the vicinity of the site, a precipitation layer is included in the GIS maps *(layer C in both MRF and URF GIS maps)*. Calculation of actual recharge amounts (a fraction of precipitation) requires professional judgment using standard practices.

Step 8. Determine if the alluvial/colluvial aquifer is connected/not connected with a perennial stream. This step is performed to determine recharge to the aquifer from any nearby surface water system. The attribute table of Pitkin County's water GIS layer *(GIS layer F in both MRF and URF GIS maps)* contains, among others, a field in the attribute table indicating intermittent stream flow (ephemeral stream) or continuous stream flow (perennial stream). By combining hydrogeologic information from the alluvial aquifer layer (*layer O in both MRF and URF GIS maps*), or the information resulting from steps 3-6, with the county's streams layer F, the existence of a hydraulic connection can be established. Calculation of actual recharge amounts and effect of new well on stream requires professional judgment using standard practices.

Step 9. Determine if the saturated alluvial/colluvial aquifer is connected with an irrigation ditch or return flow of irrigation water. This step is performed to determine recharge to the aquifer from any irrigation practices, which may not sustain a ground water supply if water uses and water rights ownership change. In order to establish if the saturated portion of the potential aquifer of interest is connected with an irrigation ditch, hydrogeologic information from the alluvial aquifer layer (*layer O in both MRF and URF GIS maps*), or the information resulting from steps 3-6, is combined with the county's ditches layer (*layer H in both MRF and URF GIS maps*). The potential effect of the return flow of irrigated acreage on recharge can be evaluated by plotting the PS on the 2000 or 1993 irrigated acreage layer (*layer D and E, respectively*). Calculation of actual recharge amounts requires professional judgment using standard practices.

Step 10. Determine the vulnerability of ground water supplies to contamination from the surface for the site. Natural protection from overlying confining units, such as the Mancos Shale, is important for maintaining natural water quality, However, all ground water in the area shown in the MRF layers R (unconsolidated sediments), Y (Dakota Sandstone outcrops) & Z (Lower Bedrock outcrops) is vulnerable; natural protection is only available in areas shown by the MRF layer DD (extent Mancos Shale) for ground water in the Dakota Sandstone underneath the Mancos Shale. *In the MRF GIS map, switch on layer EE and check presence of unit 6 (Mancos Shale) at PS; in the URF GIS map, switch on layer Q or layer R and check geologic stack for presence of Mancos Shale (or other potentially confining layers).* If the Mancos Shale is present, determine if there is an underlying aquifer (Dakota) that may be a source of ground water: *in the MRF GIS map, switch on layer FF and check presence of unit 7 (Dakota Sandstone) at PS; in the URF GIS map, switch on layer Q or layer R and check geologic stack for presence of Dakota Sandstone underneath Mancos Shale.* Calculation of actual risk (both qualitatively and quantitatively) requires professional judgment using standard practices.