GIS-BASED GROUND WATER RESOURCES EVALUATION OF THE CRYSTAL RIVER AND WEST SOPRIS CREEK (CRWS) STUDY AREA, PITKIN COUNTY, COLORADO

By:

Dr. Kenneth E. Kolm
Hydrologic Systems Analysis, LLC.
Golden, Colorado

Paul K.M. van der Heijde
Heath Hydrology, Inc.
Boulder, Colorado

Marieke Dechesne
Boulder, Colorado

for:

Pitkin County
Board of County Commissioners
Colorado

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1. 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 and a ground water resources evaluation methodology for use as decision/land use management tools by Pitkin County. The GIS maps and ground water resources evaluation methodology cover the non-Federal lands in the Crystal River watershed, as well as the non-Federal lands in the West Sopris Creek watershed, the lower section of the East Sopris watershed, and the Sopris Creek watershed below the confluence of East and West Sopris Creeks. The study area is located in the western part of Pitkin County (CRWS; Figure 1). The 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 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.).

C. 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.

D. Where, if feasible, (1) augmentation plans have been required, due to a well's impact on surface water resources, and (2) instances where well permits have been denied, due to potential deleterious impact on surface water resources.

The maps and methodology are produced following the procedure developed in a previous HSA study for the Upper and Middle Roaring Fork areas (URF/MRF; *Kolm and van der Heijde, 2006*), and for the Snowmass and Capitol Creek areas (CSC; *Kolm and Others, 2007*) (see Figure 1 for location).

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.

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. Selected features can be further described with associated attribute tables. All data are collected in 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) 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 CRWS study area makes extensive use of the fore mentioned GIS capabilities.

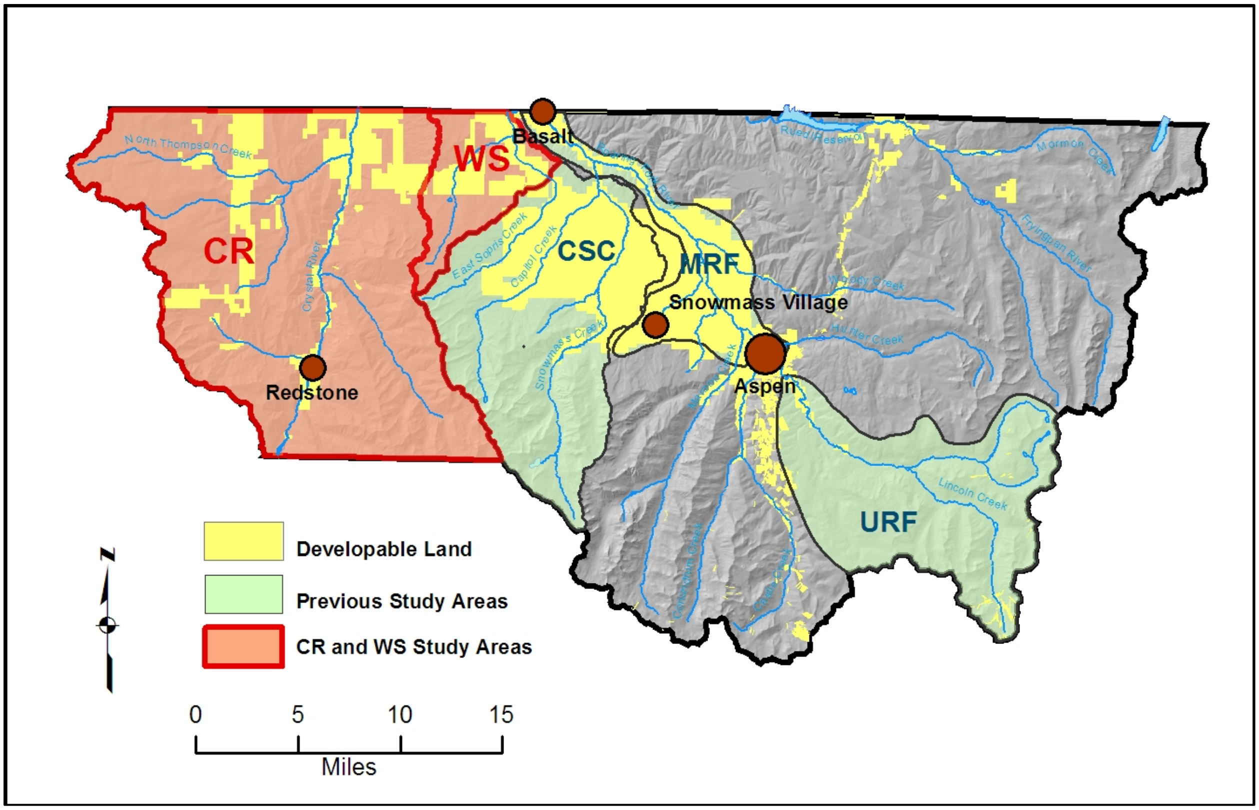


Figure 1. Location of the Crystal River and West Sopris Creek (CRWS), Capitol and Snowmass Creek (CSC), Middle Roaring Fork (MRF), and Upper Roaring Fork (URF) Study Areas, Pitkin County, Colorado.

1.1 Availability, Sustainability, Vulnerability, and Augmentation

The following text addresses the terminology used in the formulation of project objectives and methodology. It is, to a large extent, based on Kolm and Others *(2007)*.

Availability of a ground water supply, as described under study objective A, is a function of demand (amount of water needed; peak demand versus average demand), local hydrogeology and hydrology (type and thickness of permeable soil and rock formations, presence of fracture zones, depth to water table, seasonal and multi-year water table fluctuations), and environmental and water rights restrictions (stream flow requirements, diversions, wetlands, ecosystems). In the context of this study, availability pertains both to the study area in general (where are the aquifers?) and to site-specific conditions (*i.e.*, at a specific development, parcel, ranch, or structure). Thus, ground water resources availability is evaluated in terms of sufficient quantities for the purpose of usage; absence of excessive drawdowns during pumping and periodic water table fluctuations due to spring runoff or upland flood irrigation; and economical exploitability (*e.g.*, at reasonable depth and with sufficient permeability).

Sustainability in the development of water resources is obtained when the present-time needs are met without compromising the ability of future generations to meet their own needs. The objective of sustainable water use is to maintain the water supply for a prolonged period of time without injuring vested interests (*e.g.*, water rights) or ecological and other values. In nature, increased ground water pumping will be balanced by a change in one or more water balance components: 1) reducing ground water storage, resulting in lowering the water table; 2) reducing evapotranspiration, resulting, among others, in diminishing the water supply for phreatophytes and wetlands; 3) increasing stream bank infiltration, that is, increasing recharge from streams and, thus, reducing in-stream flow; and 4) reducing discharge to streams, resulting in lower flow rates downstream (*Sophocleous, 1998; Devlin and Sophocleous, 2005; Bredehoeft, 2006*). In small, local aquifers and in permeable fracture zones, storage capacity is rather small and changes in other water balance components will dominate. Devlin and Sophocleous *(2005)* note that *sustainability* and *sustainable pumping* are two different concepts, the latter referring to a pumping rate that can be maintained indefinitely without dewatering or mining an aquifer. A particular rate of pumping will result in a new steady state condition over the long term with particular implications for sustainability.

In the approach to sustainability presented in this study, only maintaining a supply for a prolonged time period is considered, not the broader consequences on streams, vegetation, and neighboring wells. A prolonged time period is defined as a period of time in which no major natural or man-made changes in the hydrologic system occur that cause a noticeable change in the water balance components. Thus, to determine sustainability, the question to be answered is: Are there significant, reliable, long-term, recharge mechanisms present? To answer that question, the following is evaluated: 1) source(s) of replenishment/recharge; 2) relevant man-made conditions; and 3) dynamic character of demand. In the study area, replenishment may come from 1) precipitation (rain/snow; seasonal, multi-year effects); 2) stream infiltration (seasonal, multi-year effects); and 3) interflow (displaced recharge). Non-natural processes that may have a major influence on (local) sustainability are: 1) recharge from ponds and reservoirs; 2) recharge from leaking irrigation ditches; and 3) irrigation return flow from agricultural areas and golf courses.

Vulnerability of ground water resources can be defined as the tendency or likelihood for contaminants to reach a specific position in the saturated zone of the subsurface after their introduction at some location at or near the surface (*NRC, 1993*; modified). Vulnerability is not an absolute property, but a relative indication of where contamination is likely to occur. The concept of vulnerability has received broad attention in relation to ground water protection, both from the research community and from the public policy and enforcement sectors (*NRC, 1993*; *van der Heijde and Others, 1997*).

The potential of contaminants to leach into a ground water resource and reach water supply wells depends on many factors, including the composition, structure, texture and permeability of soils and rock, depth to ground water (to allow for natural attenuation and remediation in soils), the topography of the local terrain (specifically slope), the amount of precipitation available for infiltration in the subsurface and subsequent percolation through the unsaturated zone, and type and control of land use. The vulnerability of a site to ground water contamination is determined as follows: 1) identify and characterize potential contaminant sources; 2) determine the presence and nature of contaminant pathways from these potential contaminant sources at or near the land surface to the ground water resource; (3) determine potential impacts from these anthropogenic sources on the ground water flow system and the ground water quality; and 4) evaluate the likelihood of future contamination of the ground water resource (*van der Heijde and Others, 1997*). Determining that ground water at some sites have a high vulnerability with respect to contamination from sources at the land surface may be straightforward, *e.g.*, in the presence of mature karst or alluvial sand and gravel deposits and absence of protecting low-permeable formations. However, it is typically more difficult to determine that an area has a low ground water vulnerability. The integrity of low permeable rock may be compromised by the existence of preferential pathways from faulting and fracturing, or because of the differential rock properties within the formations at a scale not detected by field exploration.

The determination of the vulnerability of the ground water resources in the study area has been limited to a qualitative assessment based on systematic characterization and conceptualization of the local hydrologic system. The assessment of risk posed by the potential sources, a more quantitative procedure by nature, has not been performed due to the complexity of the hydrogeologic system, the lack of ground water level data, the sparseness of hydrogeologic parameter information, and the limited time and funding available for this project. Therefore, the selected study approach was based on extensive and detailed mapping of relevant physical entities, analyzing their impact through GIS-based overlay techniques, and using qualitative classification terminology (*high, medium, low*).

Augmentation —New wells drilled in Colorado require a permit from the Department of Natural Resources (*i.e.*, the State Engineer Office or SEO). The SEO will issue the permit if the well will not injure vested water rights of others. Colorado law distinguishes between two classes of wells: 1) those that are exempt from water administration and are not administered under the priority system, and 2) those that are non-exempt and are governed by the priority system (*CDNR, 2008*). There are several types of exempt well permits. Each well permit contains a specific set of conditions when issued. Exempt wells include: 1) Household Use Only wells (HUO), 2) Domestic and Livestock wells, 3) Commercial Exempt wells, and 4) Unregistered Existing wells. Exempt wells are limited to 15 gallons per minute, and other restrictions may apply, such as the use of non-evaporative wastewater disposal systems (*e.g.*, septic tanks). All other well types are non-exempt, including high flow irrigation wells, high-capacity drinking water supply wells, such as used for subdivisions and municipalities, and any non-exempt water supply well for commercial use in businesses (see *CDNR 2008* for details).

A non-exempt well permit is not available in over-appropriated areas without augmentation. These type of wells are required to replace any out-of-priority stream depletion by having augmentation water available when a *river call* is made. Such augmentation arrangements are described in an augmentation plan that requires approval by the water court before a well permit is issued. Augmentation typically takes the form of providing replacement water. Sources of such replacement water include: surface water ditches, reservoirs or ponds, augmentation wells and (artificial) recharge projects, and leased municipal effluent. (*Stenzel, 2006*). For non-exempt wells in the Roaring Fork watershed, an augmentation plan needs to be submitted to the Water Court or Water Division 5 office in Glenwood Springs. Information regarding approved or pending augmentation plans are also available from that office. For more information visit the Monthly Water Resumes for Colorado Judicial Branch, Water Courts, Division 5 web site: www.courts.state.co.us/supct/watercourts/wat-div5/water5index.htm (starting December 1998).

Three separate well layers are included in the ground water GIS to display information on permit status and augmentation: 1) wells with augmentation plans; 2) wells with approved or denied permits (drilled or not); and 3) wells with given depth, that is, these wells have actually been drilled. Note, that the *receipt* field in the state well database contains the only unique identifier. These layers are linked to the state well database file. The well permitting procedure is illustrated in Figure 2.

1.2 Project Approach

In earlier studies regarding availability, sustainability, and vulnerability of ground water resources in Pitkin County (*Kolm and van der Heijde, 2006; Kolm and Others, 2007*), it was concluded that not enough data were available to take a quantitative approach and prepare specific maps identifying the area of resource availability and sustainability, and that vulnerability could only be assessed using a few categories (*high, medium, low*). Issues included the lack of deep wells, the clustering of shallow wells in the lower sections of stream valleys or in/near a stream's alluvium, the absence of ground water level information (except for the static water level at the time of the drilling of a well); and the lack of any quantitative hydrogeological parameters. Therefore, a step-wise evaluation procedure was developed to use the available data, collected and organized in a GIS, to address the study objectives on a site-specific scale.

In developing the proposal for the CRWS study area, it was recognized that the absence of an understanding of the hydrologic system (in terms of hydrogeologic framework, type and scale of hydrologic processes, process parameters, and water budgets) would prevent the use of the previously developed assessment procedure. A hydrologic system analysis, at least in qualitative terms, was required before proceeding to the preparation of the GIS data files and map, and selecting illustrative examples.

In translating objectives into a project approach, recognizing the limited availability of data, this study is divided in five sections: 1) hydrologic system analysis and conceptual hydrologic model formulation to formulate the physical framework for the availability, sustainability and vulnerability assessments (chapter 2); 2) digitizing existing geologic maps and converting them to hydrogeologic system layers in the GIS (chapter 2 and 3); 3) development of GIS maps and databases from existing data from various sources (chapter 3); 4) adaptation of the previously developed ground water resources evaluation procedure to address the current study objectives (chapter 4); and 5) application of the procedure using examples in characteristic settings (chapter 5). Deliverables include a report of the Hydrologic System Analysis (HSA), a report of the complete study including the HSA, a GIS map and supporting data files, and presentations for the Board of Pitkin County Commissioners and county staff. The study covers the Pitkin County sections of the Crystal River watershed, the West Sopris Creek watershed, the East Sopris Creek watershed north of the CSC study area (*Kolm and Others*, *2007*), and the Sopris Creek watershed.

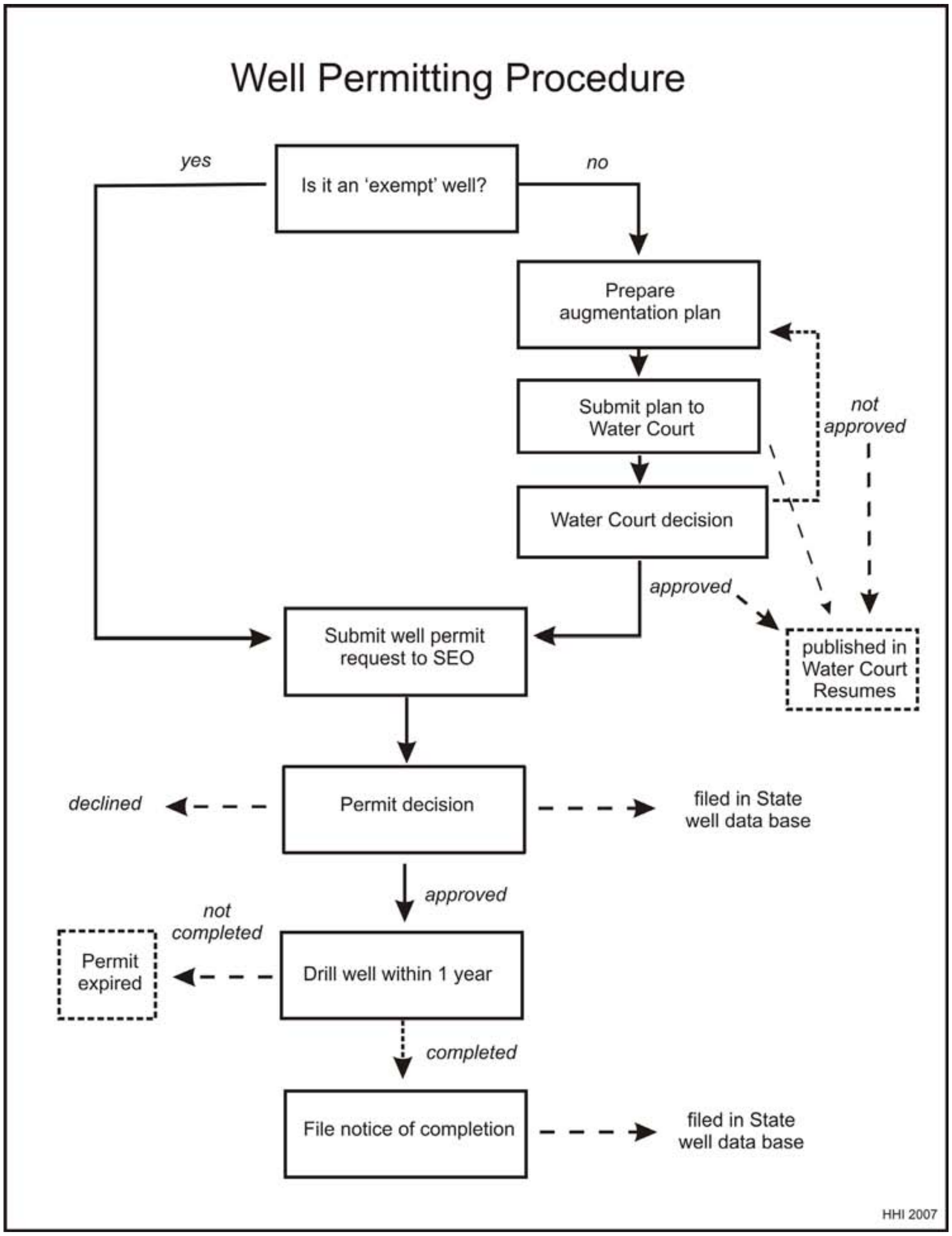


Figure 2. Flow Chart of Well Permitting Procedure (from: *Kolm and Others, 2007*).

2. Development of Conceptual Models of the Crystal River and West Sopris Creek (CRWS) Study Area

The development of the conceptual model of the hydrogeology followed the watershed-based, hierarchical analysis described by Kolm and Langer (*2001*) and codified in ASTM D5979 Standard guide for Conceptualization and Characterization of Ground Water Systems. The conceptual model covers, in a qualitative manner, elements of climate, topography, soils and geomorphology, vegetation distribution, surface water characteristics, hydrogeologic framework, hydrology, and anthropogenic activity as related to the ground water system in the study area.

2.1 Climate

The climate in the study area has both local and regional components and includes effects of elevation and slope aspect (*i.e.*, steepness and orientation with respect to the prevailing winds and sunshine). The presence of nearby ridges and ranges may further influence the climate at the lower elevations, causing local rain and sun shadows. There are two relevant weather stations of the National Weather Service (NWS) Cooperative Network in or near the study area: 1) Basalt (station 05014), specifically of interest for the northeast section of the study area including the West Sopris Creek watershed and the lower Crystal River area near Carbondale; and 2) Redstone 4W (station 056970), relevant for the Upper and Central Crystal River area and the area west of the Crystal River. Figures 3 and 4 summarize the average total monthly precipitation (*i.e.*, rain and snowfall SWE - Snow Water Equivalent), snowfall (*i.e.*, thickness of freshly fallen snow), and snow depth (*i.e.*, snow pack) for Basalt and Redstone, Colorado.

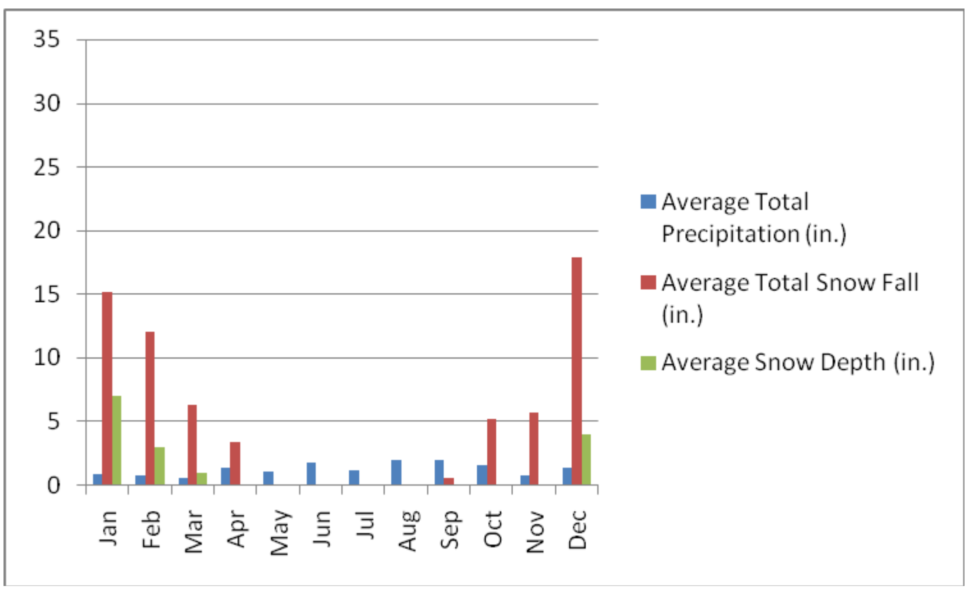


Figure 3. Average Total Monthly Precipitation and Snow Depth for Basalt, Colorado for Period 7/1/1965 – 5/31/1972.
(source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

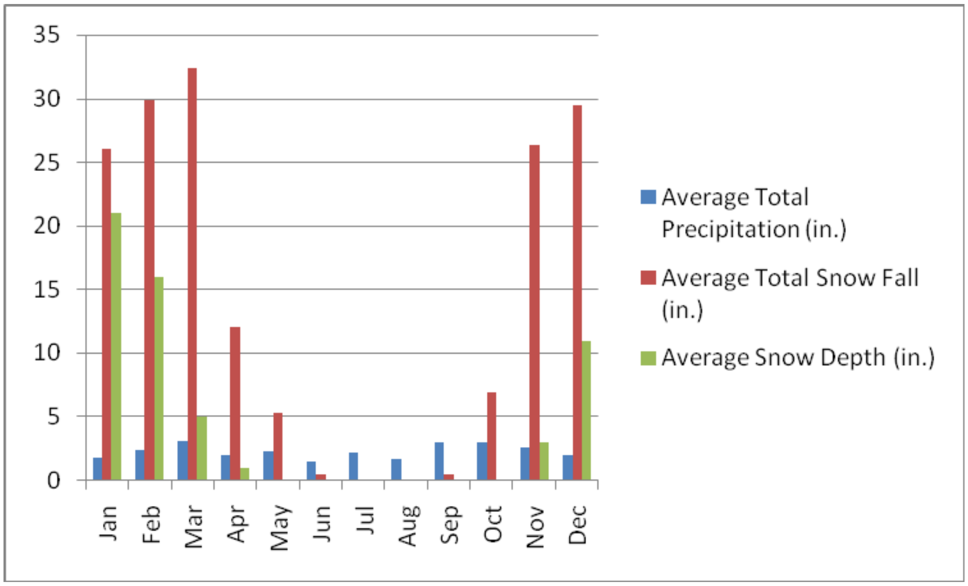


Figure 4. Average Total Monthly Precipitation and Snow Depth for Redstone, Colorado for Period 6/1/1979 – 6/30/1994.
(source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

Figure 5 shows a comparison between the average total monthly precipitation at the Basalt and Redstone stations. Detailed climate data can be found in Appendix 1. Note that the average annual precipitation at Redstone is more than twice that at Basalt, and that the average annual snowfall at Redstone is almost three times that at Basalt. These data provide estimates for the actual precipitation and snow fall in the study area and were used by the Natural Resources Conservation Service to prepare a map of spatially distributed precipitation corrected for elevation (see Figure 6; *NRCS, 2005*).

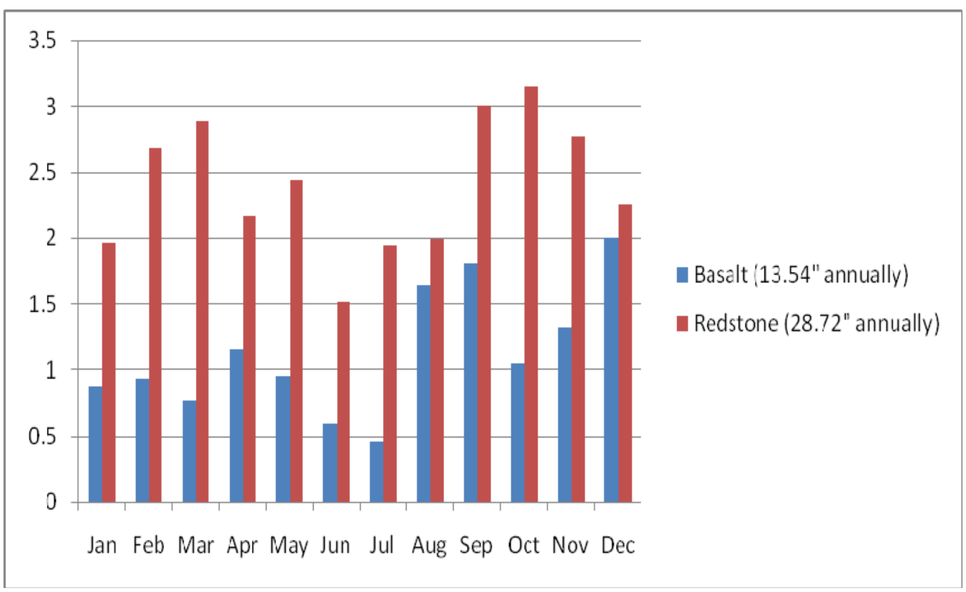


Figure 5. Comparison between the Average Total Monthly Precipitation at the Basalt and Redstone stations for the Period 1/1/1971 – 12/31/2000.
(source: Western Regional Climate Center, Desert Research Institute, Reno, Nevada).

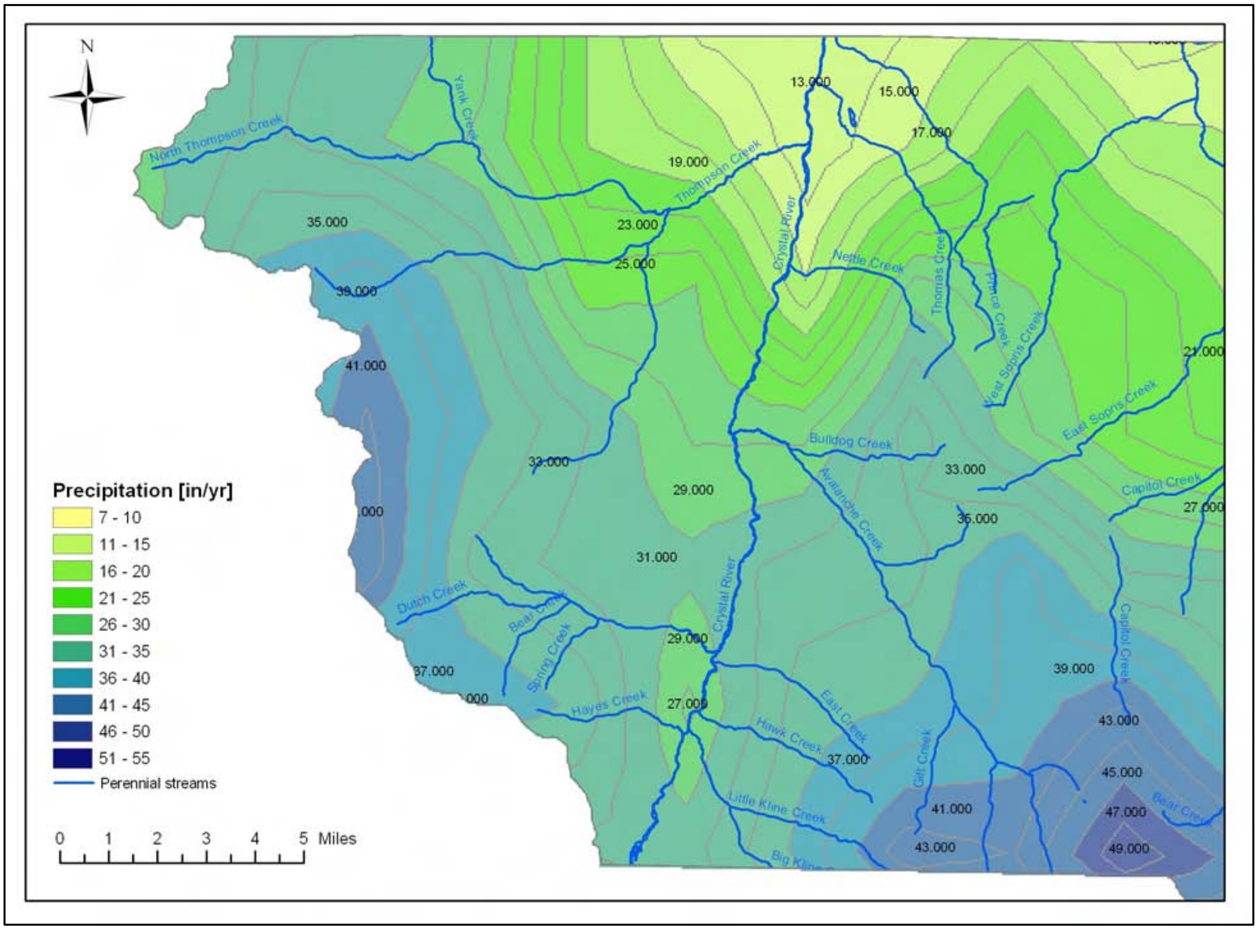


Figure 6. Spatial Distribution of the Average Annual Precipitation in Western Pitkin County, Colorado (*NRCS, 2005*).

2.2 Topography and Geomorphology

The surface elevation in the CRWS area ranges from 1900m (6235ft) to 3860m (12660ft) (Figure 7). The topography of the CRWS area has three distinct terrains: 1) well-dissected uplands and hill-slope terrains; 2) connected and disconnected, continuous and discontinuous terraces and landslides; and 3) well-dissected valley bottoms. The well-dissected uplands indicate that surface water and shallow ground water systems will be localized by topography (subregional system). However, the deeper ground water systems, if not topographically dissected by the surficial processes, will be continuous and regional in nature. Examples of these regional systems are observed in western Pitkin County, such as the Green River, Wasatch, and Mesa Verde formation aquifers associated with the Piceance basin, in much of central Pitkin County, such as the Leadville limestone aquifer, and in the Carbondale collapse area, such as the Tertiary sandstone in the northern Crystal River area. The glacial and alluvial terraces, by comparison, are often topographically isolated representing discrete, localized ground water systems. The topographic gradients in the CRWS study area can be divided into two types (*Kolm and Gillson, 2004*): steep gradient hill slopes (greater than 2% slope); and 2) low gradient valley bottoms and terrace levels (see Figure 8). The topographic gradient is useful in estimating

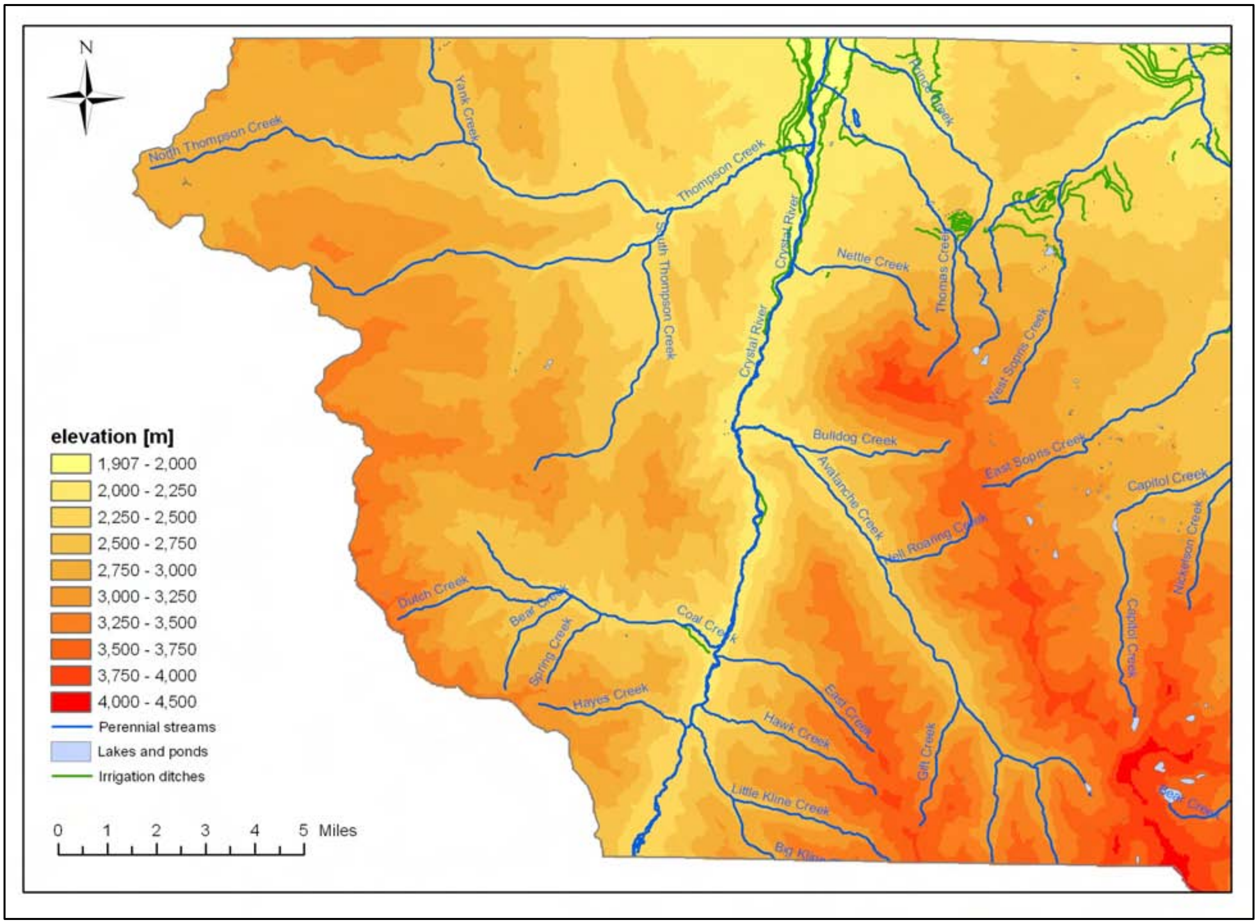


Figure 7. Topography and Surface Water in Western Pitkin County, Colorado.
(source: Pitkin County GIS Department, 2007).

water table surfaces, and estimating the amounts of infiltration versus overland flow and interflow.

Slope aspect of steeper hill sides controls local microclimate and, therefore, the distribution of precipitation, snowmelt, and evapotranspiration. This, in turn, influences the redistribution of available water in time and space between overland flow/interflow and ground water recharge (*Kolm and Gillson, 2004*). Typically, the south and west facing hill slopes are hotter and drier than the north and east facing slopes. These south and west facing slopes will have less winter moisture and snow pack available for the hydrologic system during the spring melt and will have higher evapotranspiration during the growing season. In addition, winter winds are typically westerly, redistributing snow pack to the east facing slopes. Figure 9 shows the south and west facing slopes in the study area.

2.3 Surface Water Characteristics

The study area contains two distinct watersheds (Figure 1): 1) Crystal River watershed, covering most of the study area, including Thompson Creek, Prince Creek, Avalanche Creek and Coal Creek (see Figures 10 and 11); and 2) West Sopris Creek watershed,

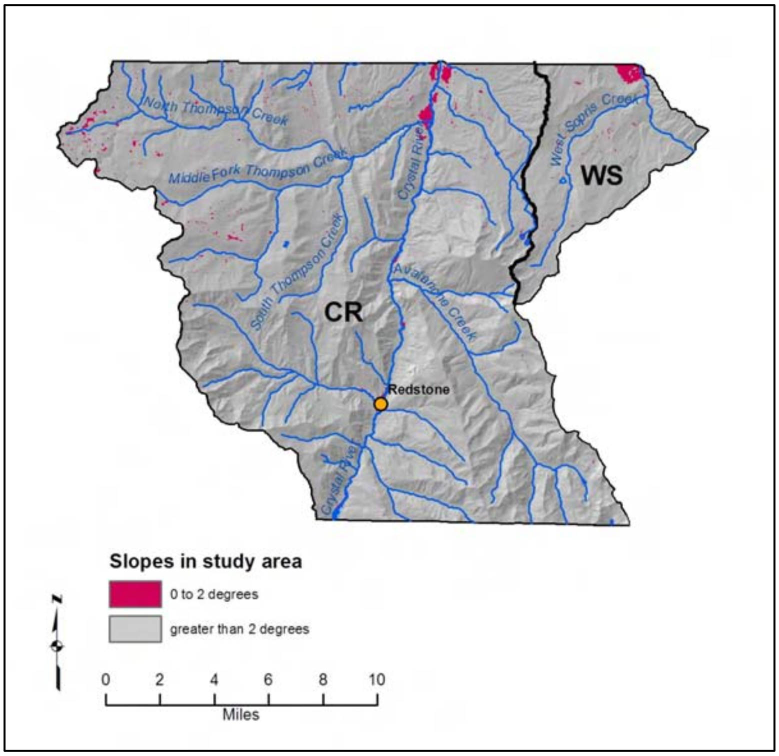


Figure 8. Map Showing Steep Gradient Slopes and Low Gradient Valley Bottoms and Terrace Levels in Study Area.

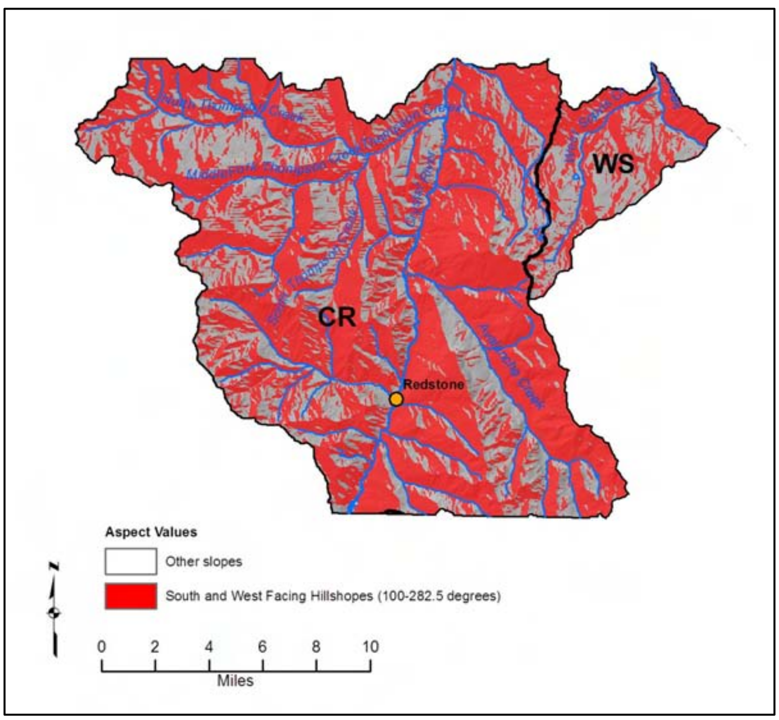


Figure 9. Map Showing Slope Aspect in Study Area.

covering the northeastern corner of the study area. The Crystal River discharges into the Roaring Fork River near Carbondale in Garfield County; West Sopris Creek joins East Sopris Creek at the east end of the study area and discharges as Sopris Creek in the Roaring Fork River just north of the Pitkin County line. A small section in the north-central part of the study area drains directly into the Roaring Fork River. Streams can be gaining (from ground water) or loosing (to ground water), dependent on local hydrology and time of year. The study area also contains various ponds (primarily related to beaver activity, landslides, or to ranchland modifications), and local networks of irrigation and water diversion ditches. Some ditches carry water, at least during part of the year. Springs, seeps, and most wetlands are indicators of ground water discharge to the land surface. The irrigation ditches located on the terraces often have phreatophytes and seeps, indicative of leaky, unlined ditch perimeters. Non-bottomland ditches can transport water over long distances from the diversion points. There are no ditches providing trans-watershed boundary transport of water in the study area.

Figure 10. View of the Crystal River just South of Redstone, Pitkin County, Colorado.

2.4 Hydrogeologic Framework

The study area is located on the boundary of two major physiographic provinces (*Topper and Others, 2003*): 1) Southern Rocky Mountains; and 2) Colorado Plateau. The Southern Rocky Mountains in this area are characterized by Laramide mountain ranges and localized Tertiary intrusions (*e.g.*, Elk Mountains, Sawatch Range, Mount Sopris), intersected by stream valleys (*e.g.*, Roaring Fork, Crystal), while the eastern part of the Colorado Plateau is characterized by structural basins and valleys (*e.g.*, Piceance Basin, Eagle Basin) surrounded by Laramide uplifts

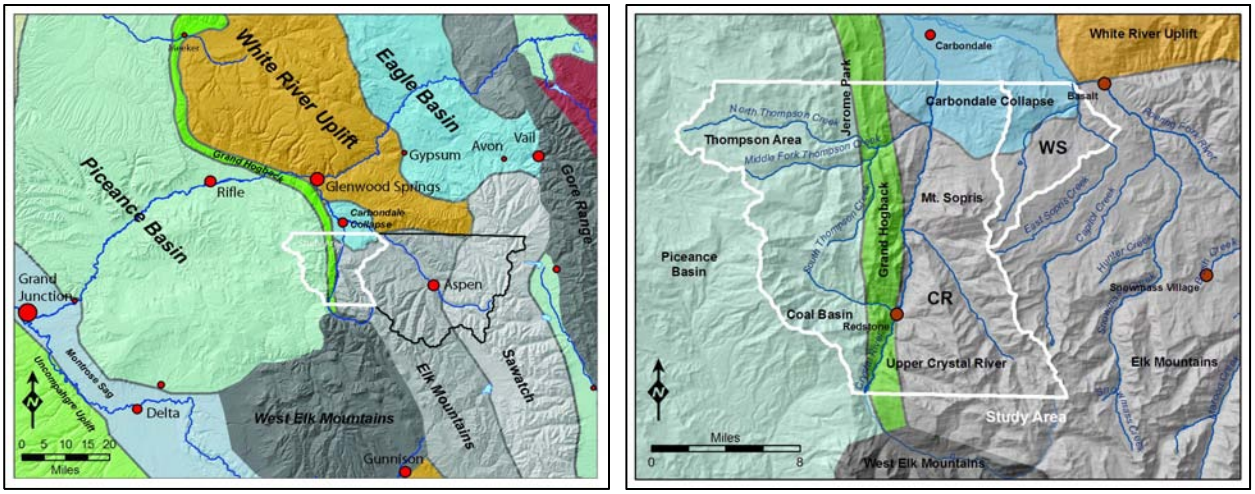
Figure 11. View of Prince Creek, Pitkin County, Colorado.

(*e.g.,* White River Uplift). The study area straddles the eastern edge of the Piceance Basin including a section of the Grand Hogback, and covers the westernmost section of the Sawatch uplift and Elk Range Thrust, and the southernmost section of the Carbondale Collapse (*Topper and Others, 2003*; see Figure 12).

The hydrogeology of the study area consists of two distinct systems covering: 1) the Crystal River watershed; and 2) the West Sopris Creek watershed (see Figure 1). The hydrogeological system present in the Crystal River watershed is complex and quite different form the one in the West Sopris Creek area, which has many of the elements encountered in previous studies (*Kolm and Van der Heijde, 2006; Kolm and Others, 2007*).

2.4.1 Crystal River Study Area

The hydrogeologic framework of the Crystal River study area hydrological system has multiple distinct hydrogeologic units, including multiple bedrock units, and unconsolidated units consisting of various Tertiary- and Quaternary-aged deposits (Figure 13; Table 1) (*Bryant and Martin, 1988; Freethey and Cordy, 1991;Geldon, 2003a, 2003b; Olander and Others, 1974; Streufert and Others, 1998; Streufert, 1999; and Tweto and Others, 1978*). The Mt. Sopris Granodiorite, Green River and Wasatch, Mesa Verde sandstones and coals, Mancos sandstones



a. b.

Figure 12. Generalized Maps Showing Regional (a.) and Local (b.) Geographic and Geological Features.

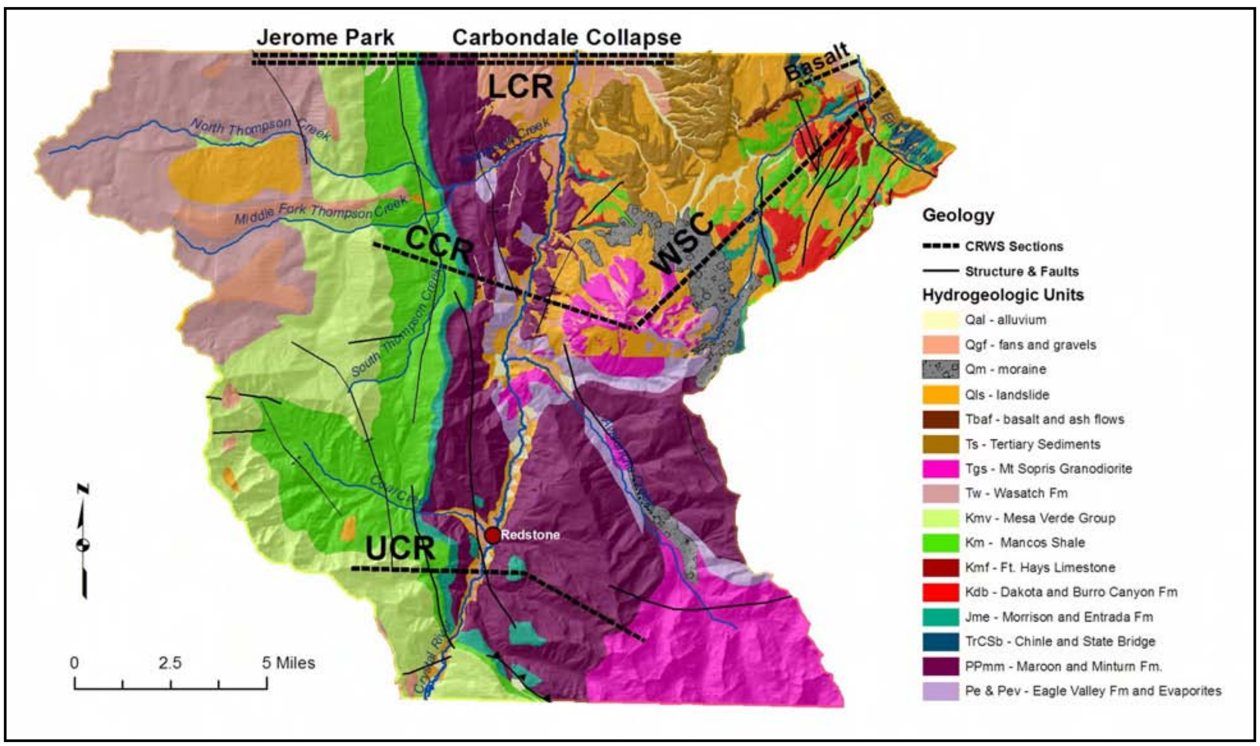


Figure 13. Generalized Map Showing Major Hydrogeologic Units in the Study Area and Location of Cross-sections.

and Ft Hays carbonates, Dakota/Burro Canyon sandstones, Lower Morrison/Entrada sandstones, Maroon and Minturn sandstones and conglomerates, and Eagle Valley sandstones are unconfined bedrock systems near their recharge areas, and confined bedrock systems at depth. The various shale layers of the Green River, Wasatch, Mesa Verde, Mancos, Upper Morrison, Maroon, Minturn, and Eagle

GIS - Layer	Unit Symbol (CRWS study)	Hydrogeological Unit	Composition	Hydrogeological Characteristic	Basalt Quadrangle Geologic Units	Mt Sopris Quadrangle Geologic Units	Roaring Fork and Crystal Valleys Environmental and Engineering Geology Study	Leadville 1° x 2° Quadrangle
1	Qal	Quaternary Alluvium	Poorly sorted sands and gravels, clast supported	Potentially good local aquifer; matrix-based permeability, variable thickness	Stream channel, floodplain and low terrace deposits (Qa), Artifical fill (human) (af), Alluvium and colluvium (Qac, Qaco)	Stream channel, floodplain and low terrace deposits (Qa), Artifical fill (human) (af), Alluvium and colluvium (Qac, Qaco)	Younger Alluvial Deposits (Qy)	Alluvium (Qa), Eolean (Qe)
2	Qgf	Quaternary/Tertiary Gravels, Fans & Terraces	Poorly sorted sands and gravels, clast supported, forms terraces above current river level	Potentially good local aquifer; matrix-based permeability, variable thickness	Terrace Alluvium (Qty, Qtm,Qto), Terrace Alluvium of Capitol Creek (Qt1,Qt2,Qt3), Pleistocene Gravel (Qg)	Terrace Alluvium (Qty, Qtm,Qto,Qtt), Terrace Alluvium of Thompson Creek (Qgt1,Qgt2), High-level gravel (Qtg), Gravel of Nettle Creek (Qgn)	Older Alluvial Deposits (Qo)	High level alluvium (Qta), Gravels (Qg, Qgo)
3	Qm	Quaternary Glacial Deposits (Moraines, Rock Glaciers and Till)	Heterogenous, poorly sorted deposits of boulders, gravel, sand, silt and clay	Potentially good local aquifer, matrix-based pemeability, variable thickness	Till (Qti)	Felsenmeer (Qf), Rock Glacier (Qrg1,Qrg2), Till (Qti)		Glacial drift (Qd, Qdo)
4	Qls	Quaternary colluvial, landslide, hillslope, sheetwash and debris flow deposits	Gravels and rock debris with mixed matrix composition (sand-clay) on valley sides, valley floors and hillslopes, deposited by gravitational processes	Potentially good, highly localized aquifer, matrix based permeability, variable thickness	Landslide deposits (Qlsr, Qls), Colluvium (Qc, Qco), Talus (Qt), Debris flow (Qdfy, Qdfm, Qdfo), Sheetwash (Qcs)	Sheetwash Deposits (Qsw), Colluvium (Qc, Qco), (Qcs), Talus (Qt), Landslide Deposits (Qls), Debris flow deposits (Qdfy, Qdfm, Qdfo)	Colluvial Deposits (Qc)	Talus (Qt), Landslide (Ql)
5	Tbaf	Basalt (Miocene?) and ash-flow tuffs (Eocene)	Basalt columns, weathered and fractured, and bedded-non welded tuffs	Potentially good local aquifer where fractured and weathered	Basalt (Tb) and Ash-flow tuffs (Taf)		Lava Flows (Qb)	Basalt (Tbb) and ash-flow tuffs (Taf)
6	Ts	Sedimentary Deposits (Miocene?)	Weekly indurated to unconsolidated fluvial deposits (pebbels and cobbles in a matrix of silty sand)	Potentially good local or subregional aquifer; matrix based permeability, variable thickness	Sedimentary deposits (Ts)	Sedimentary deposits (Ts)		
7	Tgs	Mount Sopris Granodiorite (Oligocene)	Granodiorite	Locally moderately permeable fractured crystalline aquifer	Granodiorite of Mount Sopris (Tgs)	Granodiorite of Mount Sopris (Tgs)	Igneous Rocks (Ti)	Upper Tertiary Intrusive Rocks (Tui)
8	Tw	Wasatch (Paleocene) and Ohio Creek Formation	Channel sandstones and overbank siltstones and shales, (conglomerates, sandstones, shales and claystones)	Potentially good aquifer; both matrix- (regional scale) and fracture-based (local scale) permeability			Wasatch Formation (Tw) and Ohio Creek Formation (To)	Wasatch and Ohio Creek Formations (Two)

Table 1. Correlation of Geological and Hydrogeological Units in the CRWS Study Area.

GIS - Layer	Unit Symbol (CRWS Study)	Hydrogeological Unit	Composition	Hydrogeological Characteristic	Basalt Quadrangle Geologic Units	Mt Sopris Quadrangle Geologic Units	Roaring Fork and Crystal Valleys Environmental and Engineering Geology Study	Leadville 1° x 2° Quadrangle
9	Kmv	Mesa Verde (Upper Cretaceous)	Interbedded sandstones and siltstones, shales and carbonaceous shales and coals	Potentially good aquifer; both matrix- (regional scale) and fracture-based (local scale) permeability			Mesa Verde formation (Kmv)	Mesa Verder Group (Kmv, Kmvu, Kmvl)
10	Km	Mancos Shale including Fort Hays Limestone (Upper Cretaceous)	Silty to sandy shale with bentonites with minor limestone- and sandstone beds (main Mancos Shale unit) and thick-bedded, coarse-grained limestone (Ft Hays member)	Mostly aquitard; however, locally moderate to poor aquifer in fracture zones or areas with sand lenses; Ft Hays member is a good local or regional fractured-flow aquifer	Mancos Shale (Km, Kmu, Kml); Fort Hays Limestone (Kmf)	Mancos Shale (Km)	Mancos Shale (Km)	Mancos Shale (Km, Kmu)
11	Kdb	Dakota Sandstone and Burro Canyon Formations (Lower Cretaceous)	Well indurated, medium to coarse grained quartzose sandstone and conglomerate with occasional siltstones	Potentially good aquifer; both matrix- (regional scale) and fracture-based (local scale) permeability	Dakota Sandstone and Burro Canyon Formations undivided (Kdb)	Dakota Sandstone and Burro Canyon Formations undivided (Kdb)	Dakota Sandstone and Burror Canyon Formation (Kdb)	Dakota Sandstone (Kd), Dakota Sandstone and Burro Canyon Formation (Kdb)
12	Jme	Morrison and Entrada Formations (Upper Jurassic)	Poorly indurated, fine grained, well sorted sandstones, siltstones and claystones	Entrada is a very good regional aquifer with matrix permeability. The Morrison shales are confining layers, while the lower Morrison sandstones are aquifers.	Morrison Formation (Jm), Entrada Sandstone (Jm), (Jme)	Morrison Formation (Jm), Entrada Sandstone (Jm), (Jme)	Morrison Formation (Km), Entrada formation (Je)	Morrison Formation (Jm), Entrada Formation (Je), (Jme), Morrison, Entrada and Curtis Fm (Jmce)
13	TrCSb	Chinle and State Bridge Formations	Thin, even-bedded red beds of calcareous siltstone (Chinle)	Aquitard; regionally confining layer	Chinle Formation (TrC), State Bridge Formation (TrPsb), (TrPcs), (TrPcm)		Chinle Fm. (TrC), State Bridge Formation (TrPs)	Chinle Formation (TrC), Morrison Entrada and Chinle (JTrmc), State Bridge Formation (TrPs), (TrPcs)
14	PPmm	Maroon and Minturn Formations	Grayish-red to pale-red arkosic sandstones, silt- and mudstones, conglomerates; interbed of shale and limestone (Minturn)	Poor aquifer on the regional scale where metamorphosed and well cemented; at the local scale fractured aquifers can occur.	Maroon Formation (PPm)	Maroon Formation (PPm)	Schoolhouse tongue of the Weber Sandstone (Pw), Maroon Formation (PPm), Minturn Formation (Pm)	Maroon Fm (PPm), Maroon and Weber Sandstone (PPm, TrPcm), Minturn Formation (Pm)
15	Pe	Eagle Valley Formation and Eagle Valley Evaporite (Middle Pennsylvanian)	Tan, reddisch brown to reddisch grey siltstone, gypsum and carbonate rocks. Evaporite contains anhydrite, halite, gypsum and light colored mudstone	Generally poor aquifer except where local sinkholes and karst have developed.	Eagle Valley Formation (Pe), Eagle Valley Evaporite (Pee), (Peu)	Eagle Valley Formation (Pe), Eagle Valley Evaporite (Pee)	Eagle Valley Evaporite (Pev)	Eagle Valley Evaporite (Pee)

Table 1 continued. Correlation of Geological and Hydrogeological Units in the CRWS Study Area.

Valley formations, and the Eagle Valley evaporite are mostly confining bedrock layers throughout most of the system. The unconsolidated hydrogeologic units are unconfined aquifers at the subregional scale, and can consist of a variety of aquifers and confining units at the local scale depending on composition (amount of clay, for example). In this study, hydrogeologic units that are considered significant include the saturated, medium- to high- permeability, unconsolidated sediments, and the water-bearing bedrock units with well-connected fracture zones, as well as the low-permeability, confining bedrock units.

Hydrostructures may exist subregionally and locally. Hydrostructures are folds, and fault and fracture zones that are observed or hypothesized to transmit ground water either vertically or laterally along the bedding planes of competent units, and along fault or fracture planes or zones. These structures may serve as aquifers, or may connect multiple aquifers together. An example of a major hydrostructure is the Crystal River Syncline / fault zone, discussed in a forthcoming section of the report. By comparison, the Elk Range Thrust forms a hydrologic barrier between units, as illustrated in the UCR area.

The major saturated hydrogeologic units consist of: 1) Quaternary landslide, hillslope and sheet wash deposits, and colluvium; 2) glacial gravel deposits, terraces and fans; 3) glacial moraines; 4) alluvial deposits; and 5) Tertiary alluvial deposits in the Carbondale Collapse region (Figure 13 and Table 1). In some specific areas, the Mt. Sopris granodiorite, and the sandstones of the Green River, Wasatch, Mesa Verde, Mancos, Dakota/Burro Canyon, Lower Morrison/Entrada, Maroon, and Eagle Valley Formation bedrock units are aquifers. However, these bedrock units are generally not high-volume, saturated hydrogeologic units of importance in most of the Crystal River area. Hence, despite their regional presence as geologic units, these units do not represent a regional ground water subsystem, except on the western border of Pitkin County in the Piceance Basin region (see Figure 11a). Deeper bedrock hydrogeologic units, such as the Leadville Formation., are not considered viable as water sources in this area due to costs of acquisition, and due to such issues as drilling depths to water and low well yields.

2.4.2 West Sopris Creek Study Area

The hydrogeologic framework of the West Sopris Creek study area hydrological system has multiple distinct hydrogeologic units, including bedrock units, and unconsolidated units consisting of various Quaternary deposits (Figure 13; Table 1) (*Bryant and Martin, 1988; Freethey and Cordy, 1991;Geldon, 2003a, 2003b; Olander and Others, 1974; Streufert and Others, 1998; Streufert, 1999; and Tweto and Others, 1978*). The Dakota/Burro Canyon, Ft. Hays, and Mancos sandstone and limestone aquifers are unconfined systems near their recharge areas, and confined systems at depth. The various shale layers of Mancos Shale and the Lower Bedrock units, consisting of Morrison and older rocks, are confining layers throughout most of the system. The unconsolidated hydrogeologic units are unconfined aquifers at the subregional scale, and can consist of a variety of aquifers and confining units at the local scale depending on composition (amount of clay, for example). In this study, hydrogeologic units that are considered significant include the saturated, medium- to high- permeability, unconsolidated sediments, and the water-bearing bedrock units with well-connected fracture zones, as well as the low-permeability, confining bedrock units.

Hydrostructures may exist subregionally and locally. Hydrostructures are geologic folds, and fault and fracture zones that are observed or hypothesized to transmit ground water either vertically or laterally along dip slopes, or the fault or fracture plane or zone. These hydrostructures may serve as aquifers, or may connect multiple aquifers together. An example of multiple hydrostructures is observed at the northern portion of the West Sopris Creek study area just south of Basalt, Colorado, where multiple faults bring the Dakota sandstones to the surface and near surface, as discussed in a forthcoming section of the report.

The major saturated hydrogeologic units of the West Sopris Creek study area consist of: 1) Quaternary landslide, hillslope and sheet wash deposits, and colluvium; 2) glacial gravel deposits, terraces and fans; 3) glacial moraines; and 4) alluvial deposits (Table 1; Figure 13). In some specific areas, the Upper and Lower Mancos sandstone, Ft. Hays Limestone, Dakota/Burro Canyon, and lower Morrison/Entrada bedrock units are aquifers. However, these bedrock units are generally not high-volume, saturated hydrogeologic units of importance in most of the West Sopris Creek area. Hence, despite their regional presence as geologic units, these units do not represent a regional ground water subsystem (Table 1; Figure 13). Deeper bedrock hydrogeologic units, such as the Maroon, Eagle Valley, or Leadville Formations, are not considered viable as water sources in this area due to costs of acquisition, and due to such issues as drilling depths to water and low well yields.

2.5 Ground Water Flow System

The general 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 (irrigation ditches and irrigation, urbanization, ISDS, wells), and geology. Based on the hierarchical approach of Kolm and Langer (2001), no regional system has been identified as being important, and subregional and local scale ground water flow systems dominate in the CRWS area (Figure 1).

The broad regional hydrologic system inputs include infiltration of precipitation as rain and snowmelt, areas of losing streams and water bodies (reservoirs, ponds), and upland irrigation areas (irrigation return flow). The hillslope subsystem consists of the hydrologic processes of surface runoff (overland flow) and rapid near surface runoff (interflow or shallow through flow), saturated ground water flow in parts of the bedrock units, landslides, terraces, moraines, and valley bottoms, and discharge to springs and seeps, graining streams, and by plants as evapotranspiration. In general, flow in these systems is towards the valley bottom, perpendicular to the major streams. Where bedrock aquifers intersect hill slopes, local recharge may force the ground water into a more regional pattern determined by geological structure and independent from local topography and hydrography.

The Terrace subsystems, located in close proximity to the valley subsystems, have a unique, sometimes complex ground water story, often resulting from human interference as described in subsequent paragraphs and figures of local conceptual models. Under natural conditions, these subsystems have hydrologic system inputs and outputs, as well as location in the landscape, similar to hillslope subsystems. However, anthropogenic influences have frequently attached these subsystems hydrologically to adjacent valley bottom subsystems.

The Valley Bottom subsystems, where stream-aquifer-wetland interactions occur, are areas of both ground water recharge and discharge. Here, ground water flow can have a rather diffuse character and often aligns more or less with the streams. These subsystems depend primarily on interactions with the Crystal River and West Sopris Creeks and subsidiary streams. The associated wetlands are predominantly of the slope-type with some riverine-type classifications in the Crystal River system given the ground water support of various bedrock ground water systems, and the high gradient mass wasting / landslide ground water systems observed on the hill slopes of the Crystal River canyon. The associated wetlands are predominantly riverine in the West Sopris Creek system given the lack of supporting regional or subregional ground water bedrock or hill slope systems.

2.6 Conceptual Ground Water System Models

There are five general conceptual models within the regional scale context of the CRWS area: 1) Upper Crystal River (UCR) Subsystem north and south of Redstone, Colorado; 2) Central Crystal River (CCR) Subsystem in the vicinity of the Tertiary intrusions north of Redstone, including Avalanche Creek; 3) Lower Crystal River (LCR) Subsystem north of the Tertiary intrusions, including Prince Creek; 4) West Sopris Creek (WSC) Subsystem including the lower reach of East Sopris Creek and Sopris Creek; and 5) Thompson & Coal Creek (TCC) Subsystem. The location of representative, generalized cross-sections for these conceptual models are shown in Figure 13. The conceptual models are discussed in forthcoming sections.

2.6.1 Upper Crystal River (UCR) Subsystem

There are two significant groups of hydrogeologic units in the UCR area: (1) Quaternary unconsolidated materials, which are predominantly glacial, colluvial, and alluvial deposits, overlying (2) Pre-Quaternary bedrock units, including the sandstones of the Mesa Verde, Dakota/Burro Canyon, Lower Morrison/Entrada, Maroon, and Eagle Valley Formations that may be water-bearing, and the intervening shale and gypsum that may be poorly transmissive confining layers (Figures 13 and 14; Table 1). The Quaternary unconsolidated materials are locally heterogeneous, with predominantly coarser materials in the glacial moraine and landslide deposits, and a mix of coarser 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 shale bedrock units are the dominant confining layers with small hydraulic conductivity values less than .01 ft per day.

Locally, the sandstone units in the Mesa Verde, Mancos, Dakota/Burro Canyon, Lower Morrison/Entrada, Maroon, Minturn, and Eagle Valley Formations may serve as minor aquifers in areas where glacial gravels are not adequate for water supply (Kmv, Km, Kd/Kbc, Jme, and Ppm in Figures 13 and 14 and in Table 1). These sandstone units occur as tilted/dipping sedimentary beds mainly on the hilltops and hillslopes above the Crystal River Valley, and have

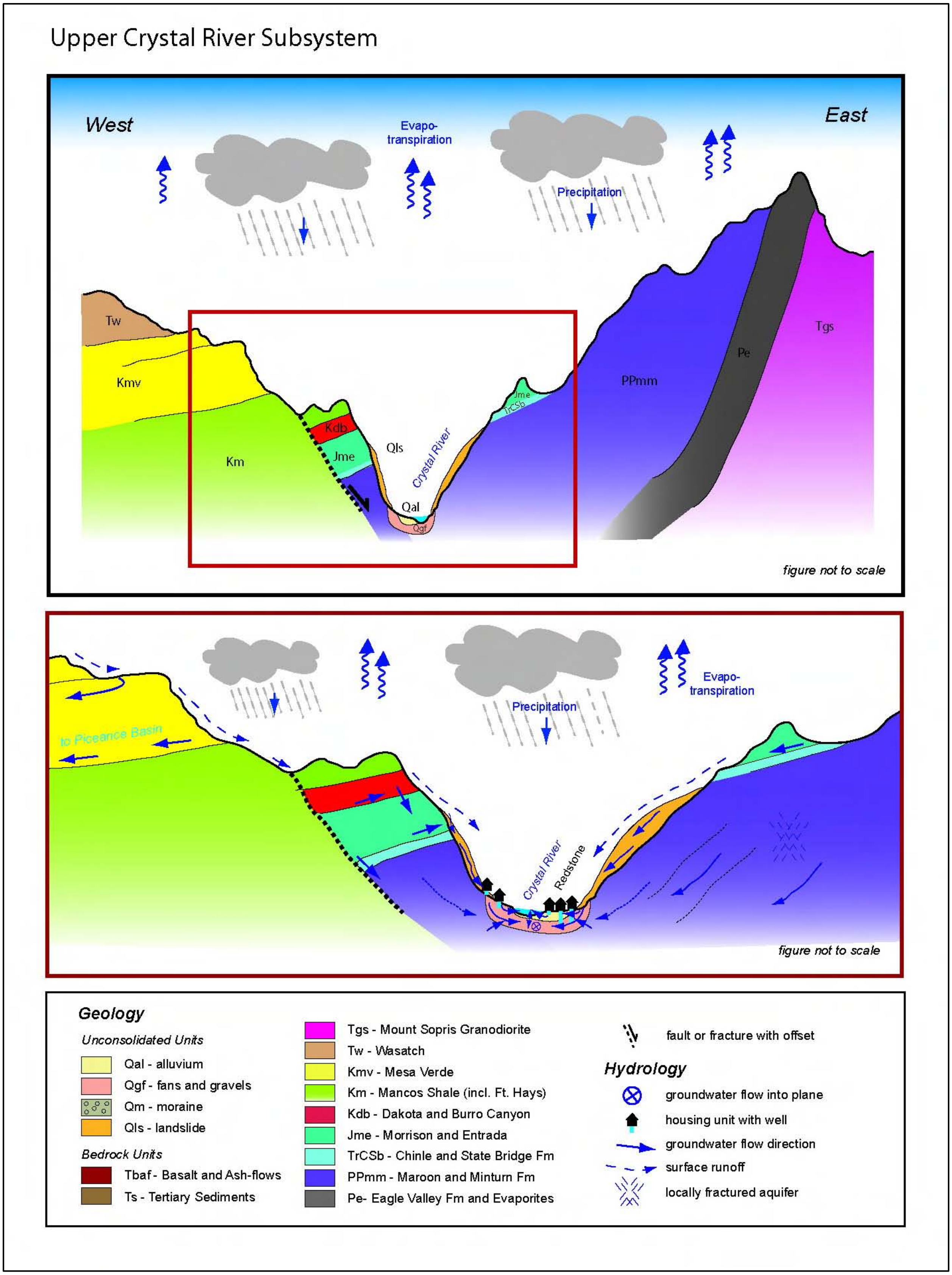


Figure 14. Conceptual Model of the Upper Crystal River (UCR) Subsystem.

both matrix and fracture ground water flow. Given the geometry and the complex matrix / fracture flow nature of these hydrogeologic units, these aquifers have variable thicknesses and hydraulic properties based on the geologic materials, geologic structure and respective landscape location. There are some locations where these units are located directly underneath the unconsolidated materials of the Valley, and the unconsolidated and bedrock aquifers may be in direct hydraulic connection (Figure 14). Most wells have not tapped these potential bedrock aquifers in this area.

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the slope steepness, slope aspect, and to position in the landscape, and by the incidental leaky irrigation ditch (Figure 14). The unconsolidated units are variably to fully saturated based on spatial location and seasonal precipitation events. There may be lateral and vertical connection between the sandstones of the Mesa Verde, Mancos, Dakota/Burro Canyon, Lower Morrison/Entrada, Maroon, Minturn, and Eagle Valley Formations and the unconsolidated materials in some locations (Figure 14). Bedrock aquifers on the east side of the Crystal River Valley have a westerly dip; therefore, ground water in these units would tend to recharge the overlying unconsolidated materials. Bedrock aquifers on the Valley floor and west side of the Crystal River Valley have a similar westerly dip; therefore, ground water in these units would tend to be recharged by the overlying unconsolidated materials and the Crystal River. Otherwise, the intervening shale does not allow significant lateral or upward/downward movement of ground water from the bedrock aquifers into the unconsolidated materials. The unconsolidated units discharge ground water locally into the Crystal River and tributaries (Figure 14). Therefore, the local ground water flow is from the unconsolidated glacial and colluvial materials into unconsolidated alluvium and, finally, to springs, seeps, or the Crystal River and tributaries. Some of the ground water entering the alluvium may flow parallel to the stream for some distance before discharging to the stream. Additional discharges from the unconsolidated units occur as evapotranspiration and well withdrawal (Figure 14). There may be some reaches of the Crystal River where surface water enters the alluvium to recharge the underlying bedrock system as part of the deep regional recharge zone of the greater Piceance Basin (Figure 14).

The bedrock system in the UCR is complex, and needs to be evaluated on a site location basis. Generally, the sandstones of the Maroon and Eagle Valley Formations are located on the east side of the Crystal River Valley, and dip to the west underneath the Valley floor. These sandstones would be recharged by direct infiltration of precipitation, or by ground water moving through the overlying colluvium and unconsolidated glacial materials. Ground water would flow down dip in these sandstones, and would either discharge into the unconsolidated materials of the Crystal River Valley floor, or could flow up through the Crystal River fault and fracture zone to discharge through the alluvium to the Crystal River. In comparison, the sandstones of the Mesa Verde, Mancos, Dakota/Burro Canyon, and Lower Morrison/Entrada Formations are located mostly on the west side of the Crystal River Valley, and dip to the west away from the Valley floor. These younger sandstones would be recharged by direct infiltration of precipitation, or by ground water moving through the overlying colluvium and unconsolidated glacial materials. Ground water would flow down dip in these sandstones and become regional flow into the deeper zones of the Piceance Basin. Groundwater in the older bedrock units located east of the thrust fault would flow vertically downward into underlying Minturn and Maroon bedrock units and discharge into the Crystal River (Figure 14). Figures 15, 16 and 17 provide a landscape view of the topography, geomorphology and hydrography of the UCR subsystem.

Figure 15. Google Earth View of the Upper Crystal River (UCR) Subsystem (looking north).

2.6.2 Central Crystal River (CCR) Subsystem

There are two significant groups of hydrogeologic units in the CCR area: (1) Quaternary unconsolidated materials, which are predominantly glacial, colluvial, and alluvial deposits, overlying (2) Pre-Quaternary bedrock units, including a) the sandstones of the Maroon, Minturn, and Eagle Valley Formations that may be water-bearing, and the intervening shale that may be poorly transmissive confining layers and b) Tertiary Mt. Sopris granodiorite (Figures 13 and 18; Table 1). The Quaternary unconsolidated materials are locally heterogeneous, with predominantly coarser materials in the glacial moraine 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 shale bedrock is the dominant underlying confining layer with small hydraulic conductivity values less than .01 ft per day.

Figure 16. Photograph of the Upper Crystal River (UCR) Subsystem (looking north).

The Crystal River defines the axis of the syncline and a regional fault and fracture zone. The bedrock beneath the river will have increased fracture permeability and will be a linear region of high transmissivity and specific yield similar in concept to that of an engineered French drain.

Locally, the sandstone units in the Maroon, Minturn, and Eagle Valley Formations, and the Tertiary Mt. Sopris granodiorite unit may serve as minor aquifers in areas where glacial gravels are not adequate for water supply (Tg, PPm, and Pev in Figure 18 and Table 1). The sandstone units occur as tilted/dipping sedimentary beds mainly on the hilltops and hillslopes above the Crystal River Valley, and have both matrix and fracture flow characteristics. The Tertiary Mt. Sopris qranodiorite occurs prominently as intrusive bodies along the valley floor near Mt. Sopris, and has fracture flow characteristics. Given the geometry and the complex matrix and fracture flow nature of these hydrogeologic units, these aquifers have variable thicknesses and hydraulic properties based on the geologic materials, geologic structure and respective landscape location. There are some locations where these units are located directly underneath the unconsolidated materials of the Valley, and the unconsolidated and bedrock aquifers may be in direct hydraulic connection (Figure 18). Most wells have not tapped these potential bedrock aquifers in this area.

Figure 17. Photograph of the Upper Crystal River (UCR) Subsystem (looking south from Penny Hot Springs).

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the slope steepness, slope aspect, and to position in the landscape, and by the incidental leaky irrigation ditch (Figure 18). The unconsolidated units are variably to fully saturated based on spatial location and seasonal precipitation events. There may be lateral and vertical connection between the sandstones of the Maroon, and Eagle Valley Formations and the Mt. Sopris granodiorite with the unconsolidated materials in some locations (Figure 18). Bedrock aquifers on both sides of the Crystal River Valley dip toward the valley center due to the Crystal River syncline; therefore, ground water in these bedrock units would tend to be recharged by the overlying unconsolidated materials near the hill tops. Conversely, ground water in these bedrock units would tend to discharge into the overlying unconsolidated materials near the valley bottoms. Bedrock aquifers on the Valley floor would be in direct connection with the unconsolidated materials, and would discharge ground water up through the alluvium into the Crystal River. In areas where the underlying bedrock is shale, there will be no significant lateral or upward/downward movement of ground water from the bedrock aquifers into the unconsolidated materials. The unconsolidated units discharge ground water locally into the Crystal River and tributaries (Figure 18). Therefore, the local ground water flow is from the unconsolidated glacial and colluvial materials into unconsolidated alluvium and, finally, to

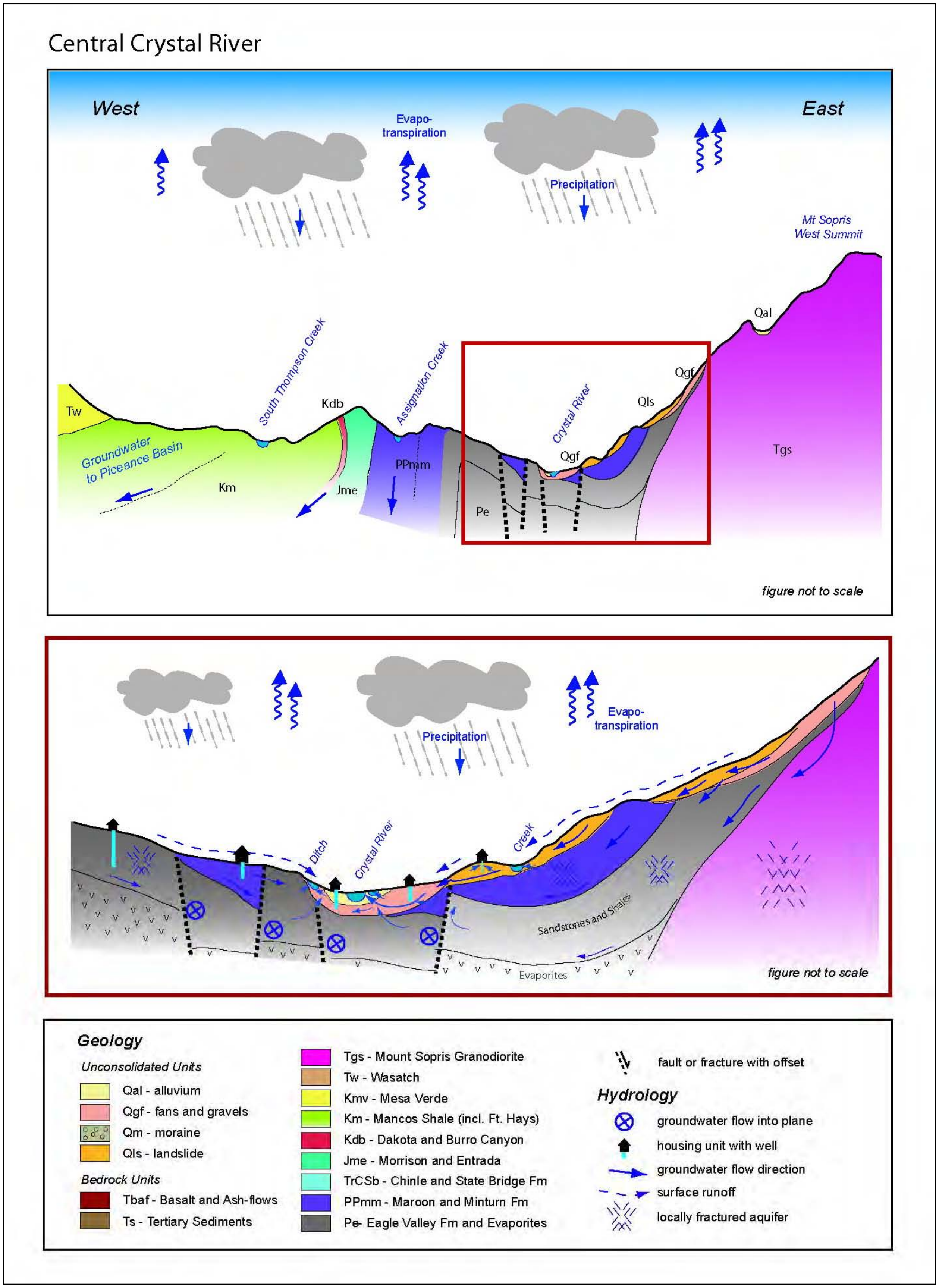


Figure 18. Conceptual Model of the Central Crystal (CCR) Subsystem.

springs, seeps, or the Crystal River and tributaries. Some of the ground water entering the alluvium may flow parallel to the stream for some distance before discharging to the stream. Additional discharges from the unconsolidated units occur as evapotranspiration and well withdrawal (Figure 18).

The bedrock system in the CCR is complex, and needs to be evaluated on a site location basis. Generally, the sandstones of the Maroon, Minturn, and Eagle Valley Formations and the Tertiary Mt. Sopris granodiorite are located on both sides of the Crystal River Valley, and, given the synclinal structure, the sandstones dip towards the Valley floor (Figure 18). These sandstones and granodiorite would be recharged by direct infiltration of precipitation, or by ground water moving through the overlying colluvium and unconsolidated glacial materials. Ground water would flow with topography in the granodiorite and down dip in the sandstones, and would either discharge into the unconsolidated materials of the Crystal River Valley floor, or could flow up through the Crystal River fault and fracture zone to discharge through the alluvium to the Crystal River. In comparison, in areas where shale of the Eagle Valley Fm. or evaporate underlie the unconsolidated materials, ground water in the bedrock aquifers under the valley floor would flow parallel to the Crystal River until direct connection between bedrock aquifer and unconsolidated material was established, as observed near the mouth of the Crystal River Canyon. Some deep bedrock aquifer connections with the surface are observed in places like Penny Hot Springs. Figures 19 and 20 provide a landscape view of the topography, geomorphology and hydrography of the CCR subsystem.

Figure 19. Google Earth View of the Central Crystal River (CCR) Subsystem (looking north).

Figure 20. Photograph of the Crystal River at Penny Hot Springs Looking North towards the Tertiary Intrusion; (the hot springs are in foreground left, a stream gaging station is visible downstream from the hot springs).

2.6.3 Lower Crystal River (LCR) Subsystem

There are two significant groups of hydrogeologic units in the LCR area: (1) Quaternary unconsolidated materials, which are predominantly glacial moraine and landslide deposits, glacial and alluvial terraces or modern alluvial deposits, overlying (2) Pre-Quaternary bedrock units, including a) the sandstones of the Mancos, Dakota/Burro Canyon, Lower Morrison/Entrada, Maroon, Minturn, and Eagle Valley Formations that may be water-bearing, and the intervening shale that may be poorly transmissive confining layers (Table 1, Figures 13 and 21a,b) and b) Tertiary sandstones and alluvial deposits of the Carbondale Collapse (Figures 12b and 21b). The Quaternary unconsolidated materials are locally heterogeneous, with predominantly coarser materials in the glacial moraine and landslide deposits and glacial and alluvial terraces, and finer materials in the modern 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*). Both fractured sandstone and shale bedrock is the underlying hydrologic unit with variable hydraulic conductivity values in the upper part of the LCR, whereas the Tertiary sandstones associated with the Carbondale Collapse is the dominant underlying aquifer with potentially large hydraulic conductivity values of greater than 1 ft per day.

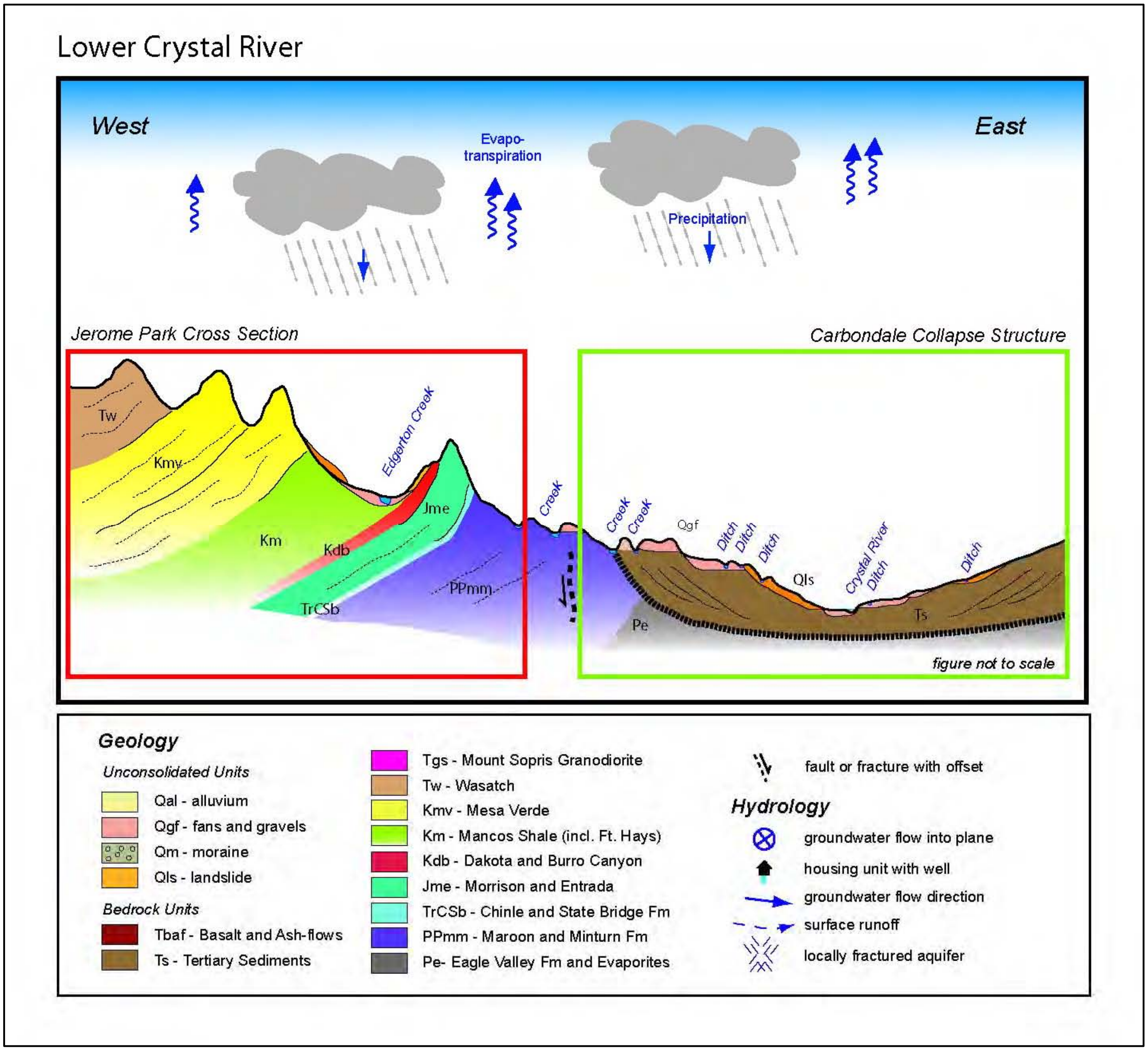


Figure 21a. Conceptual Model of the Lower Crystal River (LCR) Subsystem. A Detailed Cross-section of the Carbondale Collapse Structure is Shown in Figure 21b.

The Tertiary sandstones and alluvium of the Carbondale Collapse (Ts) may serve as a significant aquifer in the LCR area (Table 1; Figures 13, and 21a,b). This alluvial unit occurs as gently dipping sedimentary beds mainly underneath the terraces and unconsolidated deposits of the Crystal River Valley, and has matrix ground water flow characteristics. Given the geometry of the Carbondale Collapse, the Tertiary alluvium is thinnest at the southern, western, and eastern ends of the Carbondale Collapse area located in the southern part of the LCR area; the Tertiary alluvium thickens to the north towards Carbondale (Figure 21a,b). This hydrogeologic unit will have complex matrix flow due to the variable hydraulic properties based on the geologic materials and respective landscape location. The Tertiary alluvium is located directly underneath the Quaternary hydrogeologic units of the LCR area; therefore, these units will be in direct hydraulic connection (Figures 21a,b). Most wells have not tapped the Tertiary alluvial aquifer in this area.

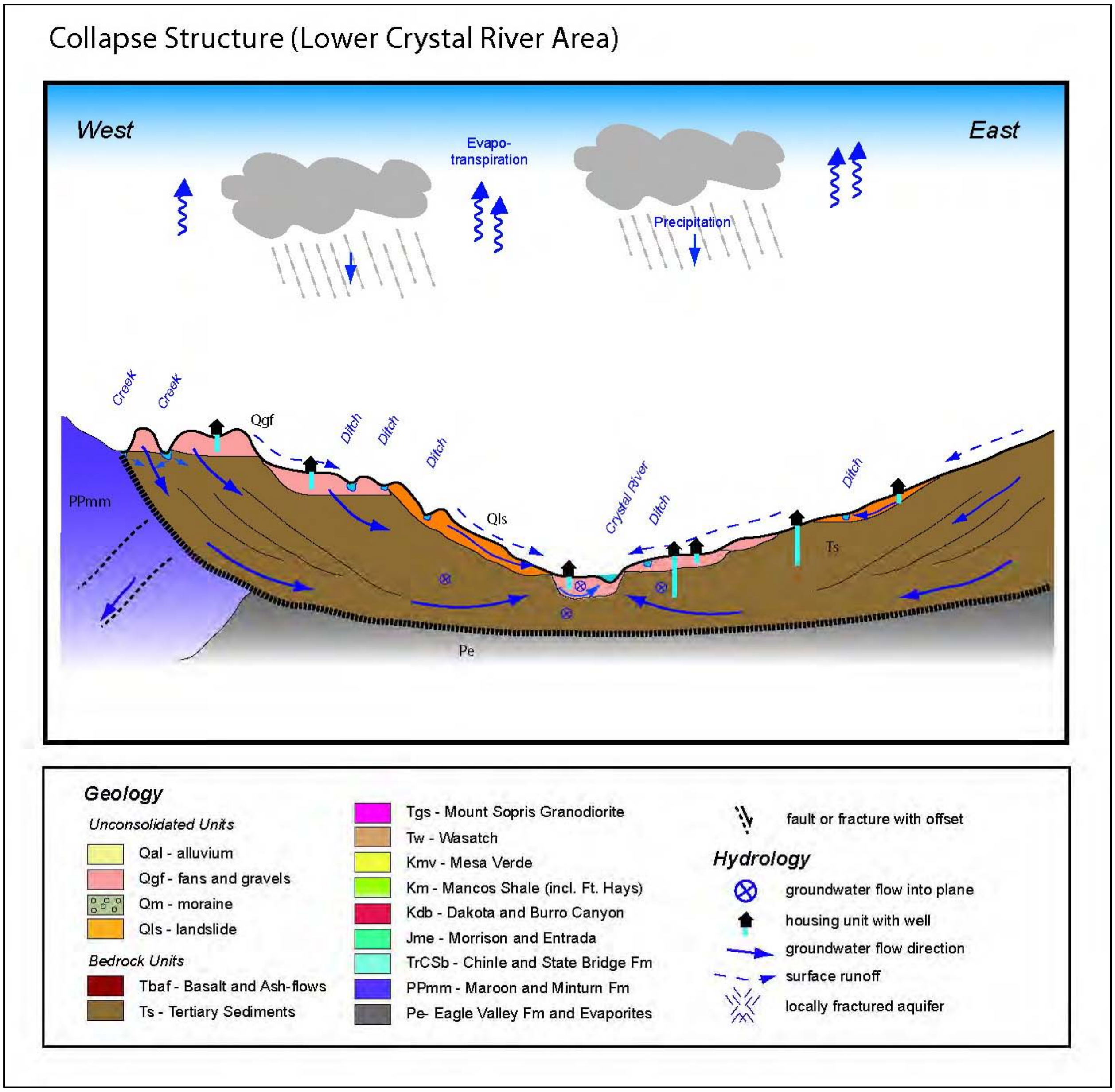


Figure 21b. Conceptual Model of the Carbondale Collapse Structure Section of the Lower Crystal River (LCR) Subsystem.

Locally, the sandstone and limestone units in the Mancos, Dakota/Burro Canyon, Lower Morrison/ Entrada, Maroon, Minturn, and Eagle Valley Formations may serve as minor aquifers in areas where glacial gravels are not adequate for water supply (Kms, Kdb, Jme, PPm, and Pe in Table 1; Figures 13 and 21a,b). The sandstone units occur as tilted/dipping sedimentary beds mainly underneath the terraces and unconsolidated deposits of the Crystal River Valley, and have both matrix and fracture flow characteristics. Given the geometry and the complex matrix and fracture flow nature of these hydrogeologic units, these aquifers have variable thicknesses and hydraulic properties based on the geologic materials, geologic structure and respective landscape location. There are some locations where these units are located directly underneath the Quaternary unconsolidated materials and Tertiary sandstones of the Valley, and are in direct hydraulic connection (Figure 21a,b). Most wells have not tapped these potential bedrock aquifers in this area.

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the location of open areas and position in the landscape. Locally, ditches located on each terrace are influent (losing) and, together with irrigation return flow, recharges the unconsolidated units (Figure 21a,b). The Quaternary unconsolidated units are variably to fully saturated based on spatial location (geographically and proximity to irrigation ditches and irrigated areas) and seasonal precipitation events. Ground water in the unconsolidated units laterally recharges the unconsolidated units located topographically below by the interflow and overland flow processes. Likewise, the lowest terraces recharge the modern alluvium by interflow and overland flow (Figure 21a,b). Ground water in the Quaternary unconsolidated units discharges locally into streams that cut through the terraces, and from the alluvium into the Crystal River and tributaries (Figure 21a,b). Other sources of discharge from the Quaternary unconsolidated units include phreatophytes (evapotranspiration) and well withdrawals. Therefore, the local ground water flow is from the unconsolidated glacial and alluvial terrace materials into the Quaternary unconsolidated alluvium and, finally, to phreatophytes, springs, seeps, or the Crystal River and tributaries. Some of the ground water entering the Quaternary alluvium may flow parallel to the stream for some distance before discharging to the stream, or may flow vertically downward into the Tertiary alluvial system near the edge of the Carbondale Collapse at the southern end of the LCR area (Figure 21a,b). In addition, ground water may flow vertically upward from the Tertiary alluvial systems into the Quaternary alluvium to be discharged into the Crystal River near the center of the Carbondale Collapse near Carbondale, Colorado (outside Pitkin County).

The Tertiary alluvial system (Ts) in the LCR is complex, and needs to be evaluated on a site location basis. Generally, the Tertiary alluvium is located underneath the Quaternary unconsolidated materials in the area of the Carbondale Collapse and, given the basin-like nature of the collapse structure, the alluvium increases in thickness and dips towards Carbondale, Colorado, the center of the feature (Figures 12b, 13 and 21a,b). The Tertiary alluvium is recharged by direct infiltration of precipitation, or by ground water moving through the overlying Quaternary colluvium, glacial and alluvial terraces, and modern alluvium (Figure 21a,b). Ground water would flow in the Tertiary alluvium with the regional dip toward the center of the Carbondale Collapse area, and would discharge through the Quaternary unconsolidated materials to the Crystal River and tributaries.

The bedrock system in the LCR area is complex, and needs to be evaluated on a site location basis. The Quaternary unconsolidated materials may have lateral and vertical connection with the sandstones of the Mancos, Dakota/Burro Canyon, Lower Morrison/Entrada, Maroon, Minturn, and Eagle Valley Formations in some locations (Figure 21a,b). Ground water in these bedrock units would tend to be recharged by the overlying unconsolidated materials. Bedrock aquifers on the west side of the Crystal River Valley dip away from the valley center due to the regional structures. Ground water in these bedrock units would tend to flow into the regional system, not into the overlying Quaternary unconsolidated materials or Tertiary alluvium. In areas where the underlying bedrock is shale, there will be no significant lateral or upward/downward movement of ground water from the bedrock aquifers into the Quaternary unconsolidated materials or Tertiary alluvium. Figures 22, 23, 24 and 25 provide a landscape view of the topography, geomorphology and hydrography of the LCR subsystem.

Figure 22. Google Earth View of the Lower Crystal River (LCR) Subsystem (looking north to Carbondale, Colorado).

Figure 23. Photograph of the Lower Crystal River (LCR) Subsystem (panoramic view near Potato Bill Creek).

Figure 24. Google Earth View of the Lower Crystal River (LCR) Subsystem (looking south to Mt. Sopris).

Figure 25. Photograph of the Lower Crystal River (LCR) Subsystem (panoramic view looking south to Mt. Sopris with Prince Creek Road in foreground).

2.6.4 West Sopris Creek (WSC) Subsystem

The WSC subsystem covers the West Sopris Creek watershed, the lower reach of East Sopris Creek, and Sopris Creek between the confluence of East and West Sopris Creek and the Roaring Fork River at Basalt. There are three significant groups of hydrogeologic units at the WSC site: 1) Quaternary and recent unconsolidated materials (predominantly glacial terrace gravels, colluvium, and modern alluvium) overlying 2) the bedrock unit of the Mancos Shale, and 3) the sandstones and carbonates of the Mancos, Ft. Hays, Dakota/Burro Canyon, and Lower Morrison/Entrada bedrock units (Table 1; Figures 13, 26 and 27).

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 WSC site (Figures 26 and 27). This bedrock unit has minimal transmissivity and storage, and is considered a confining unit in the WSC hydrologic system. Note that the terraces identified on the geologic map of the Basalt quadrangle (*Streufert and Others, 1998*) as Qt1, Qt2, and Qt3 are classified as hydrogeologic unit Qgf (Table 1).

Locally, the sandstone and limestone units in the Mancos; Ft. Hays; Dakota/Burro Canyon; and Lower Morrison/Entrada Formations may serve as minor aquifers in areas where glacial gravels are not adequate for water supply (Kms, Kmf, Kdb, Jme in Table 1 and Figures 26 and 27). The sandstone and limestone units occur as faulted, gently dipping sedimentary beds mainly in the northern area of the West Sopris Creek Valley, and have both matrix and fracture flow characteristics. Given the complex geometry and the complex matrix and fracture flow nature of these hydrogeologic units, these aquifers have variable thicknesses and hydraulic properties based on the geologic materials, geologic structure and respective landscape location.

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the location of open areas, 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 (Figures 26 and 27). 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 (Figures 26 and 27). In addition, ditches located on each terrace or mass wasting unit are influent (losing) and locally recharges the unconsolidated units (Figures 26 and 27). Ground water in the unconsolidated units discharges locally into streams that cut through the terraces, and from the alluvium into West Sopris Creek. Other sources of discharge from the unconsolidated units include phreatophytes and well withdrawals (Figures 26 and 27).

The bedrock system in the WSC area is extremely complex, and needs to be evaluated on a site location basis. Generally, the sandstones and carbonates of the Mancos, Ft. Hays, Dakota/Burro Canyon, Lower Morrison/Entrada, and Maroon and Minturn Formations are located on both sides and underneath the northern part of the West Sopris Creek Valley, and, given the faulted structures, the sandstones have variable dips and continuity (Figures 26 and 27). These sandstones and limestones are recharged by direct infiltration of precipitation, or by ground water moving through the overlying colluvium and unconsolidated materials. Ground water would flow with topography, and would either discharge into the unconsolidated materials of the West Sopris Creek, or could flow up through various fault and fracture zone systems to discharge through the alluvium to West Sopris Creek (Figures 26 and 27). In comparison,

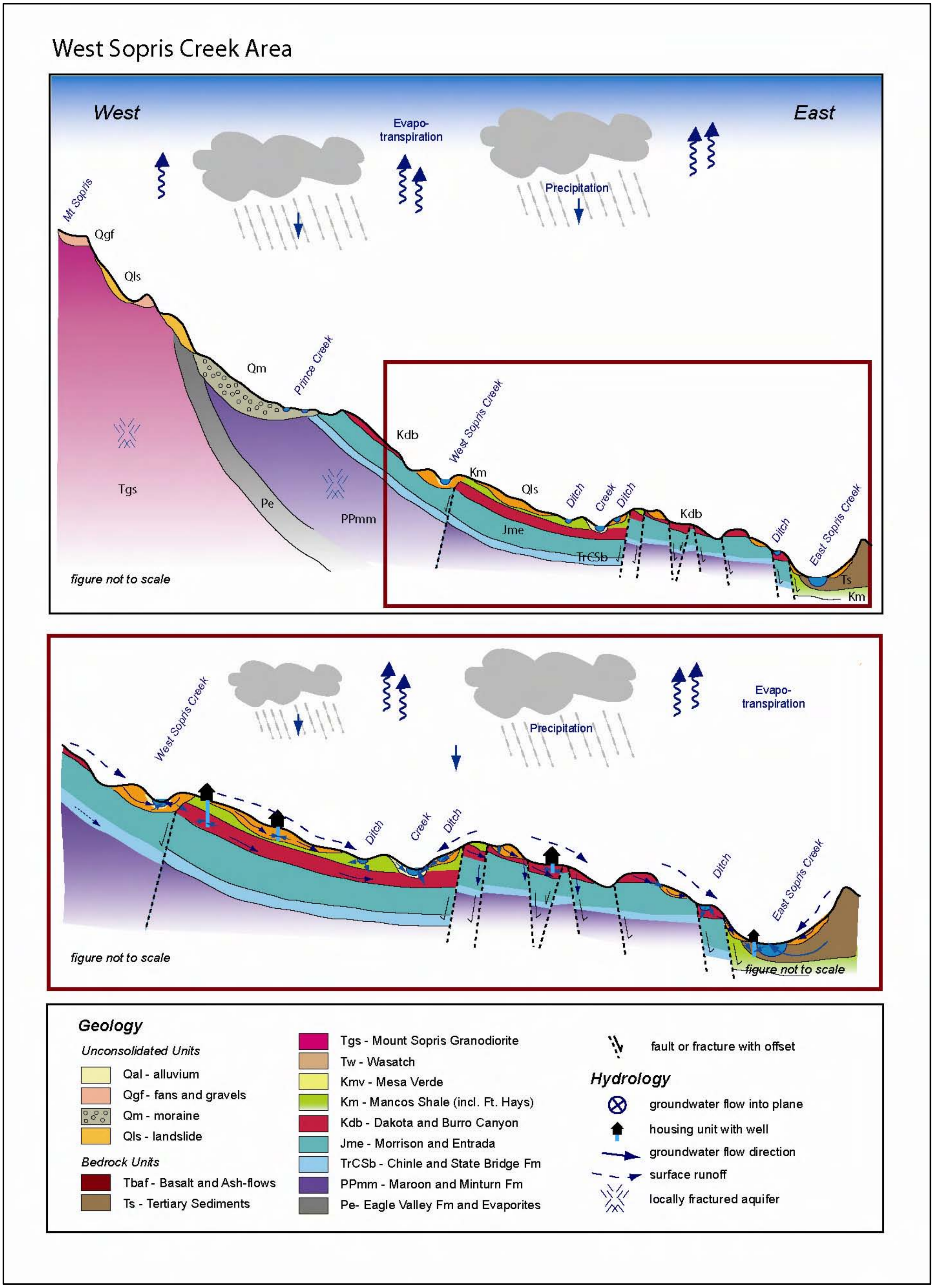


Figure 26. Conceptual Model of the West Sopris Creek Section of the West Sopris Creek (WSC) Subsystem.

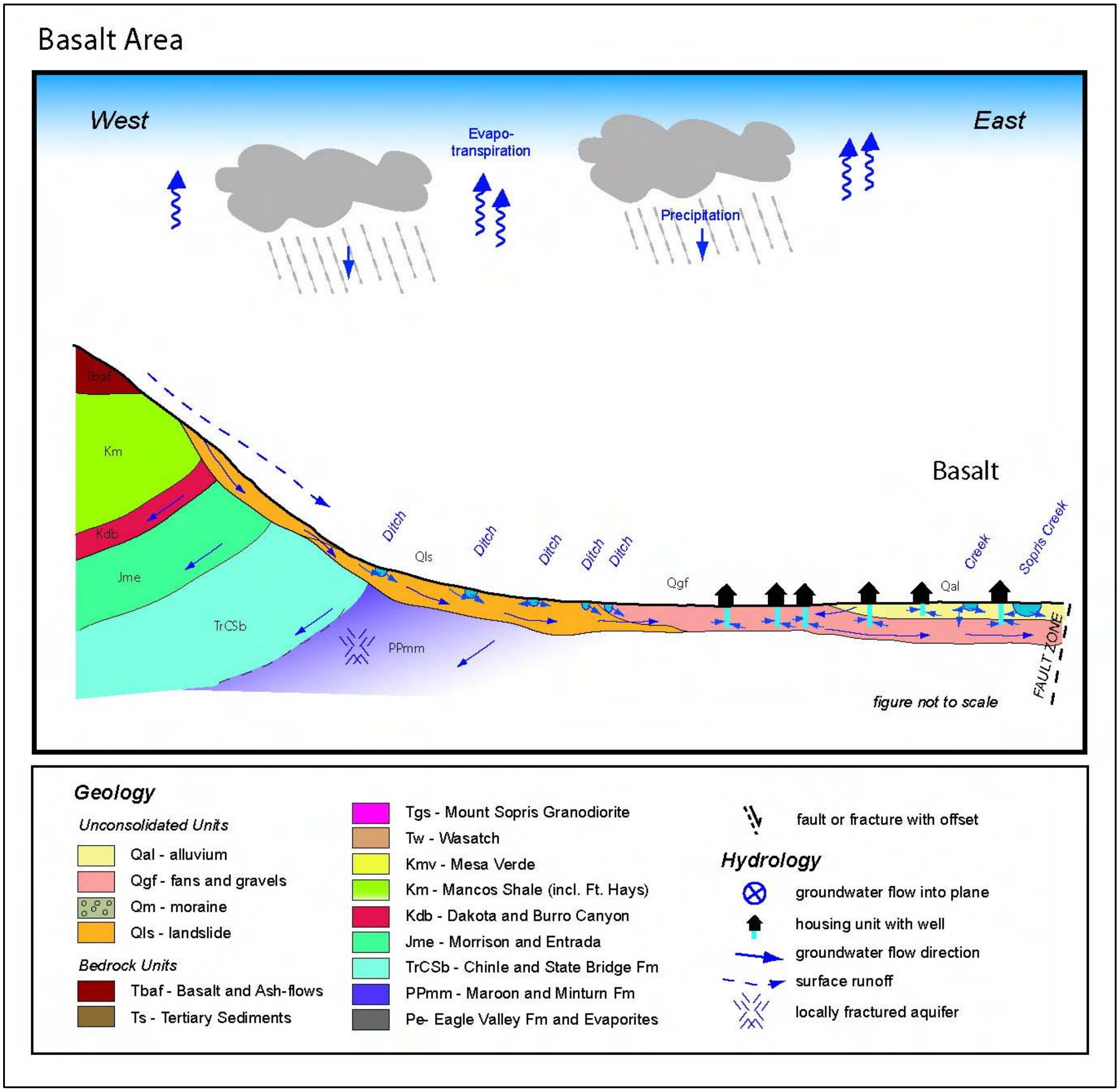


Figure 27. Conceptual Model of the Sopris Creek Section of the West Sopris Creek (WSC) Subsystem.

groundwater in the northern Sopris Creek/Basalt area may flow from the landslide and alluvial deposits into the bedrock system as shown in Figure 27. Figures 28 and 29 provide a landscape view of the topography, geomorphology and hydrography of the LCR subsystem; Figures 30 and 31 show the Sopris Creek portion of the WSC study area in Pitkin County.

2.6.5 Thompson and Coal Creek (TCC) Subsystem

There are two significant groups of hydrogeologic units in the TCC area: (1) Quaternary unconsolidated materials, which are predominantly colluvial and alluvial deposits, overlying (2)

Figure 28. Google Earth View of the West Sopris Creek Portion of the West Sopris Creek (WSC) Subsystem (looking southwest).

Figure 29. Photograph of the West Sopris Creek Portion of the West Sopris Creek (WSC) Subsystem (panoramic view looking south from West Sopris Creek Road).

Figure 30. Photograph of the Lower Reach of East Sopris Creek.

Figure 31. Photograph of the Area near the Confluence of East and West Sopris Creek.

Pre-Quaternary bedrock units, including the sandstones (coals, carbonates) of the Green River, Wasatch, Mesa Verde, Mancos, Dakota/Burro Canyon, and Lower Morrison/Entrada Formations that may be water-bearing, and the intervening shale that may be poorly transmissive confining layers (Table 1; Figures 13 and 32). The Quaternary unconsolidated materials are locally heterogeneous, with predominantly coarser materials in the colluvium, 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 shale bedrock is the dominant underlying confining layer with small hydraulic conductivity values less than .01 ft per day.

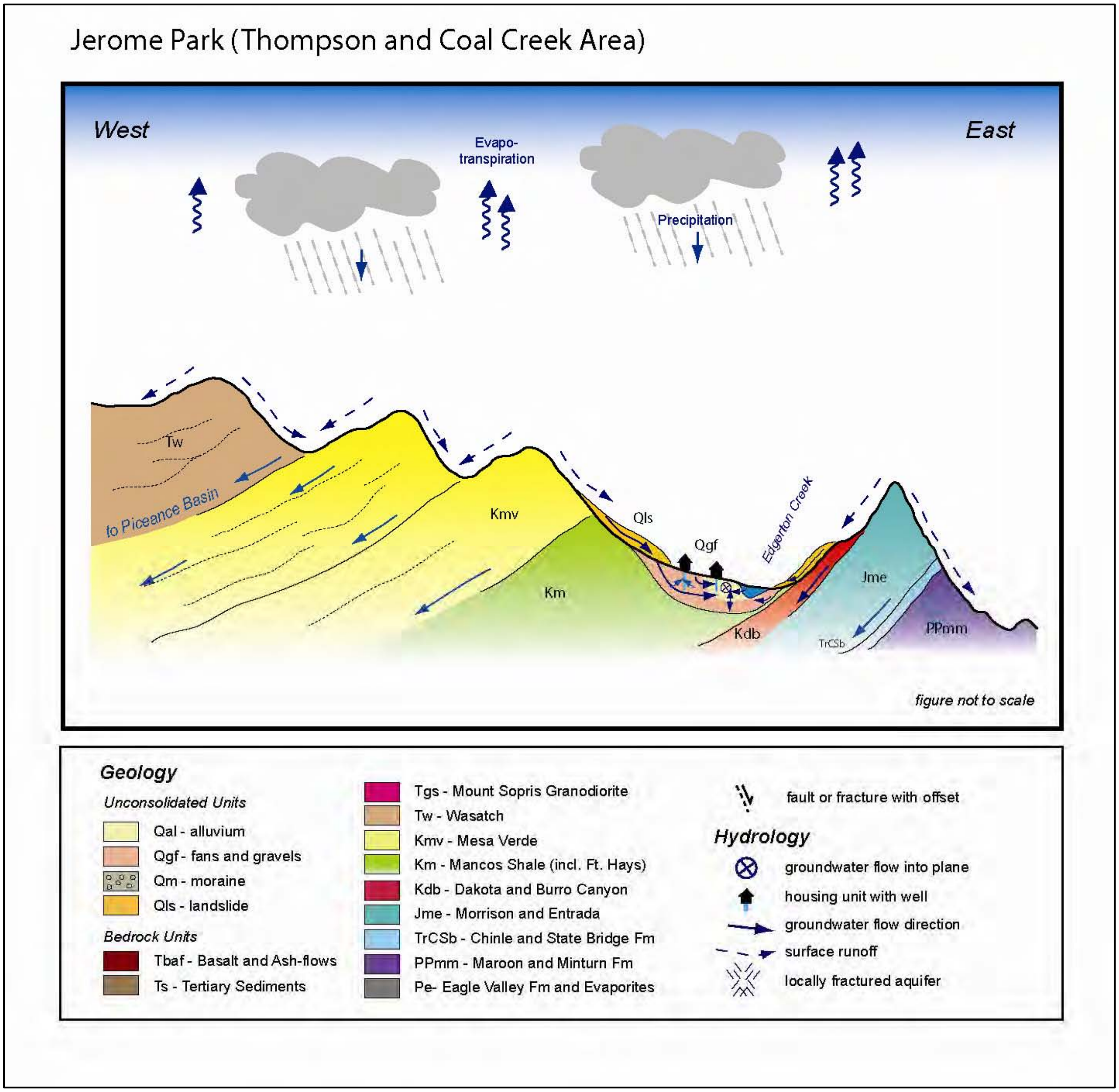


Figure 32. Conceptual Model of the Thompson and Coal Creek (TCC) Subsystem Including Jerome Park.

Locally, the sandstone units in the Green River, Wasatch, Mesa Verde, Mancos, Dakota/Burro Canyon, and Lower Morrison/Entrada Formations may serve as aquifers in areas where the colluvium and alluvium are not adequate for water supply (Tgr, Tw, Kmv, Kms, Kd/Kbc, and Jme in Table 1 and Figure 32). These sandstone units occur as tilted/dipping sedimentary beds mainly on the hilltops and hillslopes above Jerome Park, and Thompson and Coal Creeks, and have both matrix and fracture ground water flow. Given the geometry and the complex matrix / fracture flow nature of these hydrogeologic units, these aquifers have variable thicknesses and hydraulic properties based on the geologic materials, geologic structure and respective landscape location. There are some locations where these units are located directly underneath the unconsolidated materials of the Valley, and the unconsolidated and bedrock aquifers may be in direct hydraulic connection (Figure 32). Most wells have not tapped these potential bedrock aquifers in this area.

The Quaternary unconsolidated materials are recharged by infiltration from precipitation that is non-uniformly distributed due to the slope steepness, slope aspect, and to position in the landscape (Figure 32). The unconsolidated units are variably to fully saturated based on spatial location and seasonal precipitation events. There may be lateral and vertical connection between the sandstones and limestones of the Green River, Wasatch, Mesa Verde, Mancos, Dakota/Burro Canyon, and Lower Morrison/Entrada Formations and the unconsolidated materials in some locations (Figure 32). Bedrock aquifers in the TCC area have a westerly dip; therefore, ground water in these units would tend to be recharged by the overlying unconsolidated materials and Thompson and Coal Creeks and tributaries. Otherwise, the intervening shale does not allow significant lateral or upward/downward movement of ground water from the bedrock aquifers into the unconsolidated materials. The unconsolidated units discharge ground water locally into Thompson and Coal Creeks and tributaries (Figure 32). Therefore, the local ground water flow is from the unconsolidated colluvial materials into unconsolidated alluvium and, finally, to springs, seeps, or to Thompson and Coal Creeks and tributaries. Some of the ground water entering the alluvium may flow parallel to the stream for some distance before discharging to the stream. Additional discharges from the unconsolidated units occur as evapotranspiration and well withdrawal (Figure 32). There may be some reaches of Thompson and Coal Creeks where surface water enters the alluvium to recharge the underlying bedrock system as part of the deep regional recharge zone of the greater Piceance Basin (Figures 12a and 32).

The bedrock system in the TCC area is complex, and needs to be evaluated on a site location basis. The sandstones of the Green River, Wasatch, Mesa Verde, Mancos, Dakota/ Burro Canyon, and lower Morrison/Entrada Formations dip to the west, and are mostly cross cut by Thompson and Coal Creeks and tributaries. These younger sandstones would be recharged by direct infiltration of precipitation, by ground water moving through the overlying colluvium and alluvium, or by losing streams that cross cut the hydrogeologic units. Ground water would flow down dip to the west in these sandstones and become regional flow into the deeper zones of the Piceance Basin beyond the Pitkin County boundaries (Figure 32). Figures 33, 34, 35, 36 and 37 provide a landscape view of the topography, geomorphology and hydrography of the TCC subsystem.

Figure 33. Photograph of the Jerome Park Area of the TCC Subsystem (panoramic view taken near the northern county line).

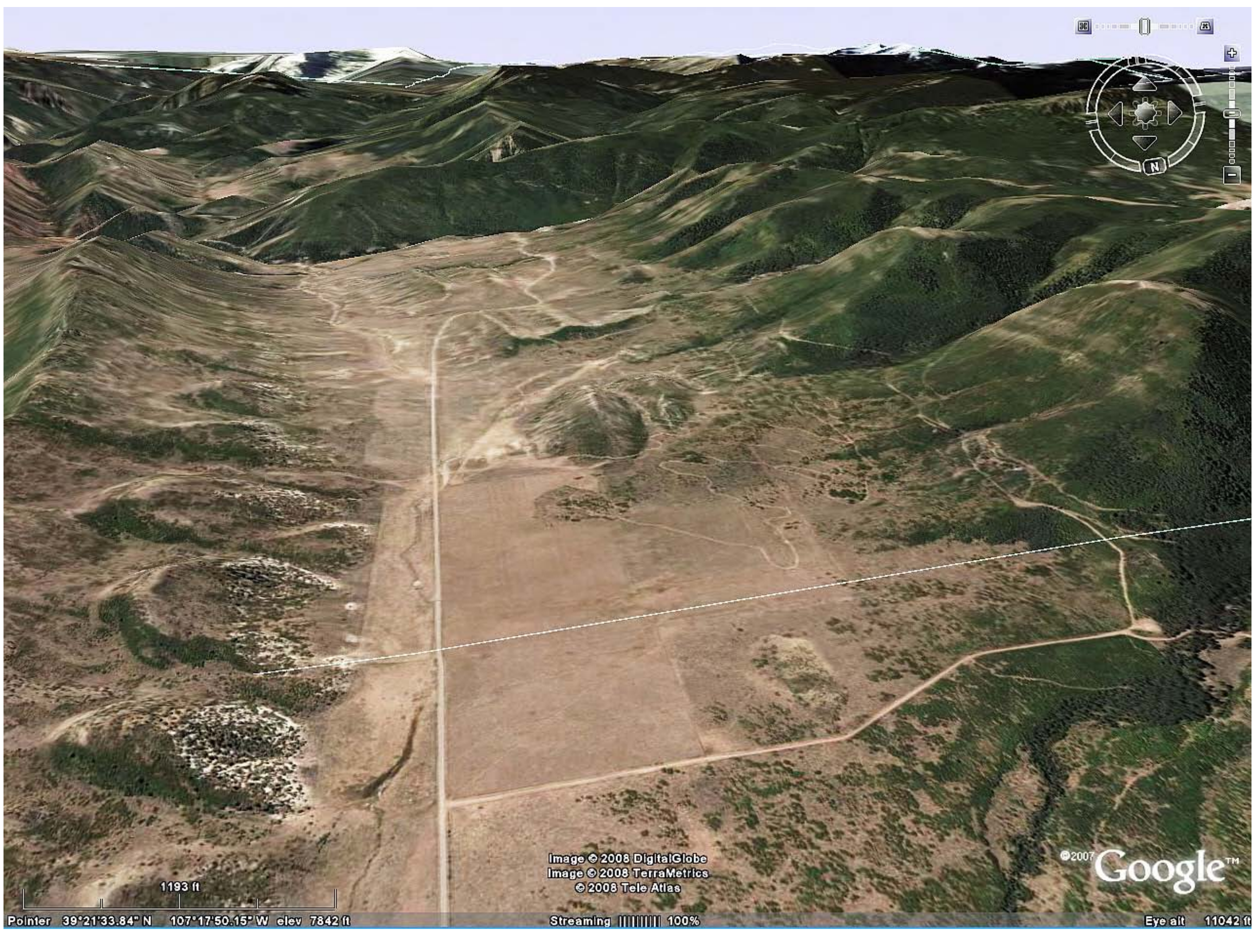


Figure 34. Google Earth View of the Jerome Park Area of the TCC Subsystem (looking south from northern county line).

Figure 35. Photograph of North Thompson Creek Valley near the Confluence with South/Middle Thompson Creek (looking Southeast with Assignation Ridge in Background).

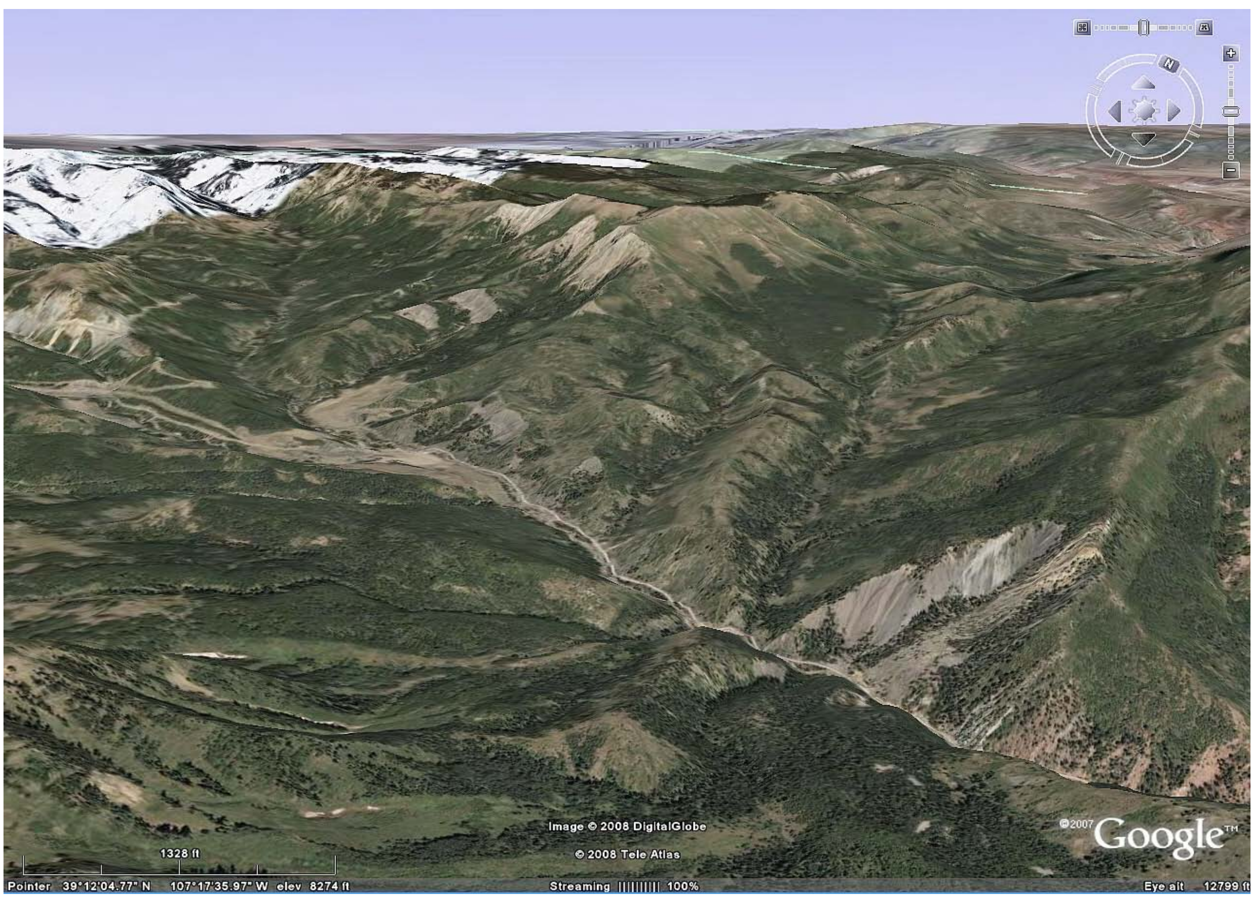


Figure 36. Google Earth View of the Coal Creek Area of the TCC Subsystem (looking west from Redstone).

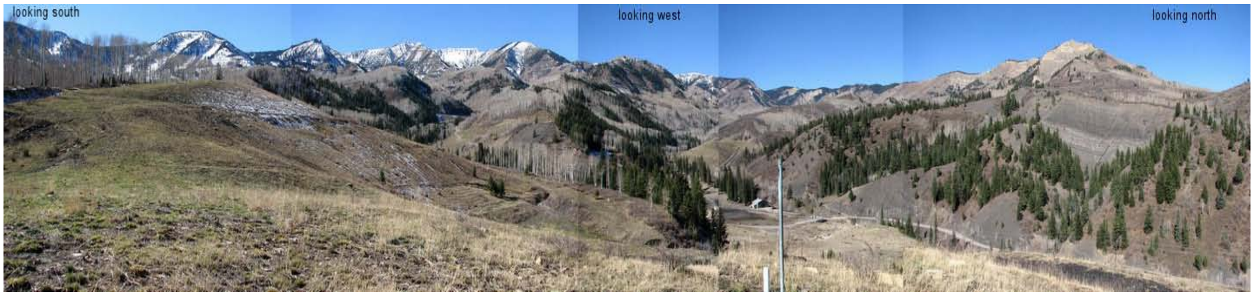


Figure 37. Photograph of the Coal Creek Area of the TCC Subsystem (panoramic view taken near the confluence of Dutch Creek and Coal Creek).

2.7 Anthropogenic Influences

Human activity in hill slope and valley bottom subsystems in the study area has affected both the surface and subsurface parts of the hydrologic systems. Past land use and human activity was mostly associated with agricultural production and coal mining and has resulted in removal of native vegetation, introduction of irrigation, construction of (often leaking) irrigation ditches, drilling of mine tunnels and production of mine tailings, and drilling of primarily domestic wells. More recent human activity included the development of residential subdivisions, especially on the colluvium along the Crystal River and on the terraces in the LCR and WSC areas, resulting in changes in ditch water allocation patterns, increased well pumping and ISDS density, reduced pasture and crop irrigation, increased garden watering, increased soil erosion, and modification of vegetative cover and related evapotranspiration.

There are a number of irrigation ditches in the study area, primarily in the LCC and WSC subsystems (Figures 38 and 39). These ditches are mostly unlined, and may have been excavated in mostly unconsolidated Quaternary deposits, weathered shale, or shale bedrock. When carrying water, the ditches may leak, as evidenced by the phreatophytes often found lining the ditch trajectories. The ditch system in the study area contains two types of ditches: 1) primary ditches, which carry water during most of the growing season; and 2) secondary ditches, which carry water only during an actual irrigation cycle. The water leaking from the ditches may be used by vegetation discharging as evapotranspiration, or may recharge the underlying ground water system forming a local ground water mound. As most of the ground water systems in the study area are local in nature, ditch leakage may contribute significantly to the local water balance, increase the water table elevation, and alter ground water flow directions.

The wells in the study area are clustered along the Crystal River and West Sopris Creek, and in the terraces affected by irrigation practices of flood irrigation with transport of water by leaky ditches (Figure 38). As most of these wells serve domestic water supply needs, their individual influence on the ground water system is limited. However, when they are clustered, their accumulated effect on the ground water system may be significant, resulting in a possible lowering of the water table, changes in flow direction, decreasing discharge to streams or increasing stream loss to ground water, draining of wetlands, or even depleting local aquifers.

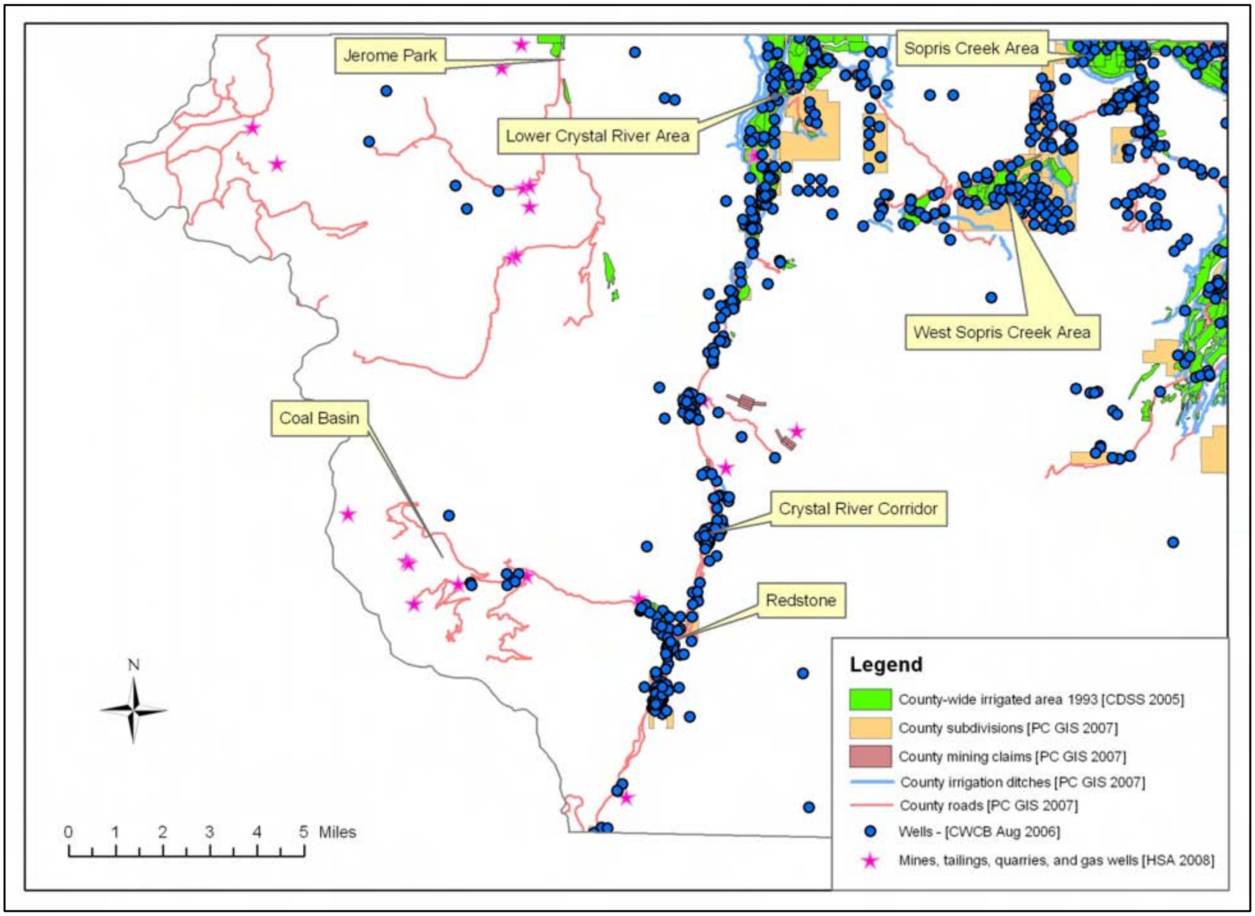


Figure 38. Anthropogenic Influences: Irrigated Areas, Ditches, Wells, Mines, Aggregate Quarries, and Subdivisions in the CRWS Study Area.

Other human interaction with the ground water flow system includes recharge from ISDSs, recharge from irrigation return flow (Figures 31 and 40), and recharge from (leaking) irrigation ditches and ponds. Irrigation return flow and leaky irrigation ditches can be a significant recharge element in the local ground water balance. Taking irrigated fields out of production may cause a lowering of the water table and reduction in ground water flow velocities. Leaking ponds and leaking ditches cause mounding of the water table, increased recharge of the local ground water system, and changes in ground water flow direction.

2.8 Summary and Discussion

The hydrogeologic framework of the Crystal River study area has multiple distinct hydrogeologic units, including: 1) Quaternary landslide, hillslope and sheet wash deposits, and colluvium; 2) glacial gravel deposits, terraces and fans; 3) glacial moraines; 4) alluvial deposits; and 5) Tertiary alluvial deposits in the Carbondale Collapse region. The Mt. Sopris granodiorite, and the sandstones and carbonates of the Green River, Wasatch, Mesa Verde, Mancos, Dakota/Burro Canyon, lower Morrison/Entrada, Maroon, Minturn, and Eagle Valley Formation bedrock units are less significant aquifers. West Sopris Creek has a unique set of hydrogeologic units, including: 1) Quaternary landslide, hillslope and sheet wash deposits, and colluvium; 2) glacial gravel deposits, terraces and fans; 3) glacial moraines; and 4) alluvial deposits. The Upper and Lower Mancos sandstone, Ft. Hays Limestone, Dakota/Burro Canyon, and Lower Morrison/Entrada bedrock units are less significant aquifers. Hydrostructures, which include geologic folds, and fault and fracture zones are observed or hypothesized to transmit ground water either vertically or laterally along dip slopes, fault or fracture planes or zones. These structures may serve as aquifers or connect multiple aquifers together in the CRWS area, or may laterally block local and regional groundwater flow. Prominent examples of significant hydrostructures include the westerly dipping of aquifer units into the Piceance Basin, the Crystal River syncline – Crystal River fault and fracture zone, the Elk Range Thrust in the Upper Crystal River region, the Carbondale Collapse features and resulting formation of the Tertiary sandstone hydrogeologic unit, and multiple folds and fault zones observed at the northern area of West Sopris Creek just south of Basalt, CO., where multiple faults bring the Mancos, Dakota/Burro Canyon, and Lower Morrison/Entrada sandstones to the surface and near surface.

Figure 39. Photograph of Irrigation Ditch Intake in the LCR area (Sweet Jessup Canal Intake at the Crystal River).

The general 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), springs and seeps; vegetation and wetlands (evapotranspiration); topography (steepness, aspect, degree of landscape dissection), geomorphology and soils; human activity (irrigation ditches and irrigation, ponds and reservoirs, urbanization, wells and ISDS); and geology. Based on the hierarchical approach of Kolm and Langer (*2001*), no regional system has been identified as being important, whereas subregional and site-scale ground water flow systems are important in the Crystal River – West Sopris Creek (CRWS) study area.

Figure 40. Google Earth View of Irrigated Areas in the WSC subsystem (looking north).

Based on field work and Hydrologic Systems Analysis, five general conceptual models are identified and discussed within the subregional scale context of the CRWS area: 1) Upper Crystal River (UCR) Subsystem near Redstone, CO; 2) Central Crystal River (CCR) Subsystem; 3) Lower Crystal River (LCR) Subsystem; 4) West Sopris Creek (WSC) Subsystem; and 5) Thompson & Coal Creek (TCC) Subsystem. Each of the five subsystems has a unique set of natural hydrogeologic and hydrologic system parameters. In general, the most important anthropogenic hydrologic system parameters are ground water recharge from irrigation and irrigation ditches, ground water discharge from wells, and ground water recharge from ISDS. If water rights and allocations should change for these ditches, the hydrodynamics of the

Quaternary glacial and alluvial aquifers would change, and water supplies from ground water may decline or vanish. These considerations will be addressed in following chapters integrating the GIS-based analysis and maps with the Hydrologic System Conceptual Model presented in this chapter.

3. GIS Map, Layers, and Data Sources

3.1 GIS and GIS Maps

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

A GIS map consists of a series of layers, each containing a single or multiple topological features. These features can represent a variety of geographic items, such as rivers and lakes, roads, towns and cities, landuse, land ownership, wells, etc. Selected features can be further described with associated attribute tables and linked to other types of information by their attribute tables or via their spatial location. At each step of a geographic analysis, individual features can be displayed, analyzed, and combined with other features via layers, and individual features interrogated with respect to their attributes. Switching scales, like enlarging (zooming in to) a particular detail or regionalizing (zooming out) to encompass a larger set of features can be accomplished at any time; the ability to 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 CRWS study areas makes extensive use of the aforementioned GIS capabilities. The database formats that have been used in this study include: ESRI shape files, database tables (*e.g.*, the well database), georeferenced images (*e.g.*, aerial photographs and topographic maps) and ESRI GRID file (for the digital elevation model (DEM)).

The GIS map and database for the CRWS study were prepared using ArcGIS™ (ESRI®, Redlands, California), and requires ArcGIS™ version 8.3 or higher to utilize. The ArcGIS system contains three components: ArcMap, ArcCatalog and ArcToolbox. ArcCatalog is specifically used as a GIS data browser and data management tool. ArcMap is used to view and analyze GIS data and compile maps serving a particular application. ArcToolbox is the component of ArcGIS which is primarily used for data conversion operations. For applying the ground water resources evaluation procedure in the CRWS study area, the use of ArcMap is sufficient.

3.2 Use of GIS in the CRWS Study

In this report, the ground water resources evaluation procedure developed by HSA/HHI for Pitkin County *(Kolm and van der Heijde, 2006; Kolm and Others, 2007)* has been applied to the CRWS study area using a multi-layer GIS map [ArcGIS™ file: PitkinCounty_GWGIS_CRWS.mxd] (Figure 41). The GIS map consists of a number of layers representing various data types relevant to the assessment of the ground water resources at user-specified locations. Below is a detailed description of the layers and the related data sources.

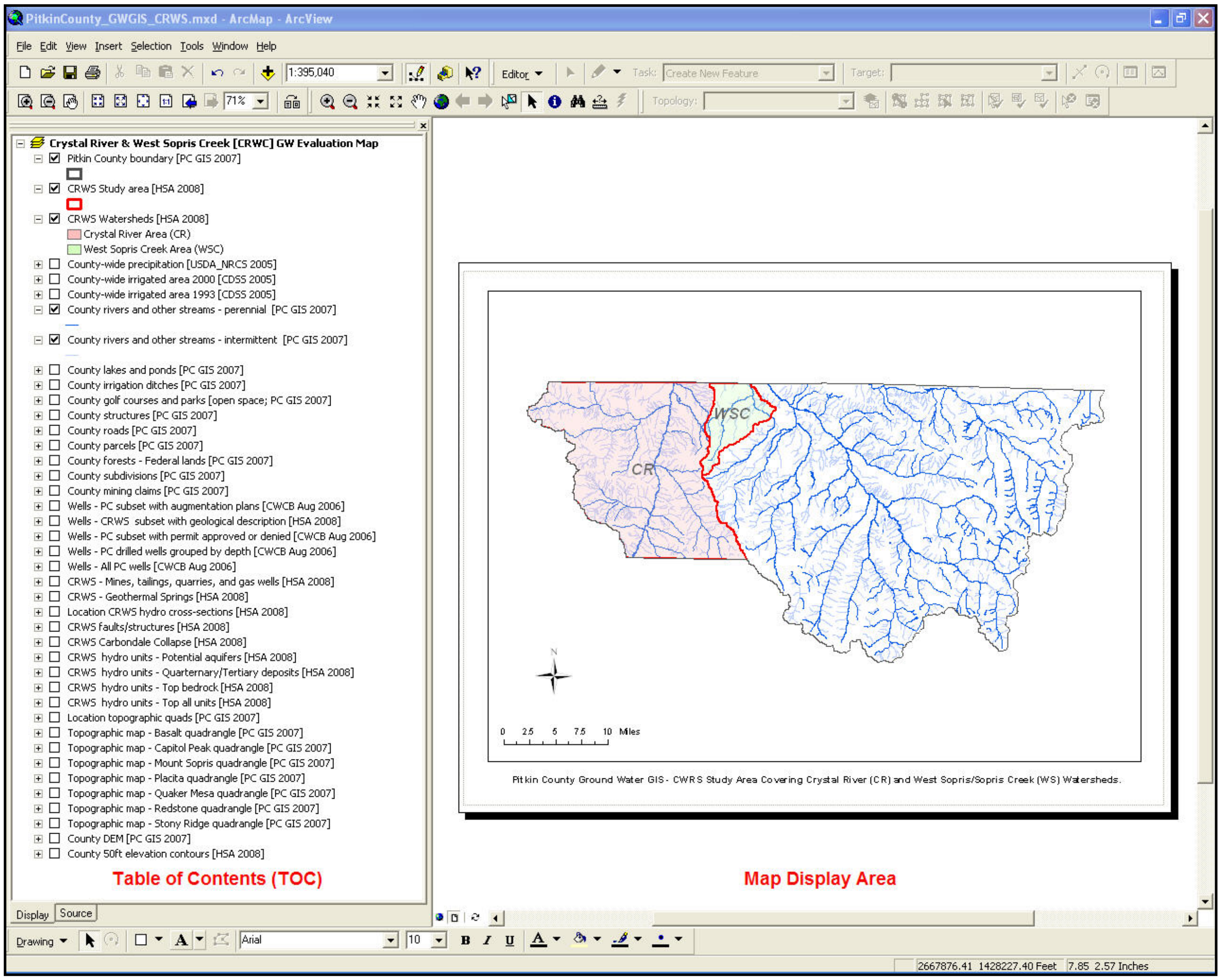


Figure 41. Pitkin County GIS Map Showing the CRWS Study Area Covering the In-County Sections of the Crystal River (CR) and West Sopris/Sopris Creek (WS) Watersheds on Top of the County-Wide Stream Layer. (The Left Display Area is the Table of Contents (TOC) Showing All Available Layers; the Right Side of the Window Is the Map Display Area showing the Activated Layers.)

The CRWS GIS map consists of a *Table of Contents* (TOC; the left display area of Figure 41) and a *Map Display* area (the right display area of Figure 41). The GIS layers of the CRWS map contain four types of geographic information (Figure 42): 1) general geographic and land use information (county border, roads, parks, parcels, structures, mine locations, etc.); 2) hydrologic information (including precipitation, watersheds, perennial and intermittent streams, lakes/ponds, irrigation ditches, and irrigated areas); 3) hydrogeologic information (including hydrogeologic units, faults and hydro-structures, geothermal springs, and wells); and 4) topographic information (topo maps, DEM, and 50m elevation contours). Type 1 information is used to locate the site of interest and obtain some general geographic and land use data potentially indicative of anthropogenic influences on the ground water systems. Type 2 and Type 3 information is integral to the evaluation of ground water resources. Type 4 information provides elevations and background data as needed and has been used in the delineation of the Crystal River and West Sopris/Sopris Creek watersheds and the determination of slope aspect and low versus high gradient areas. All layers have been georeferenced with respect to Pitkin County's projection and datum: State Plane, Colorado Central Zone, NAD83 (units of measure in feet).

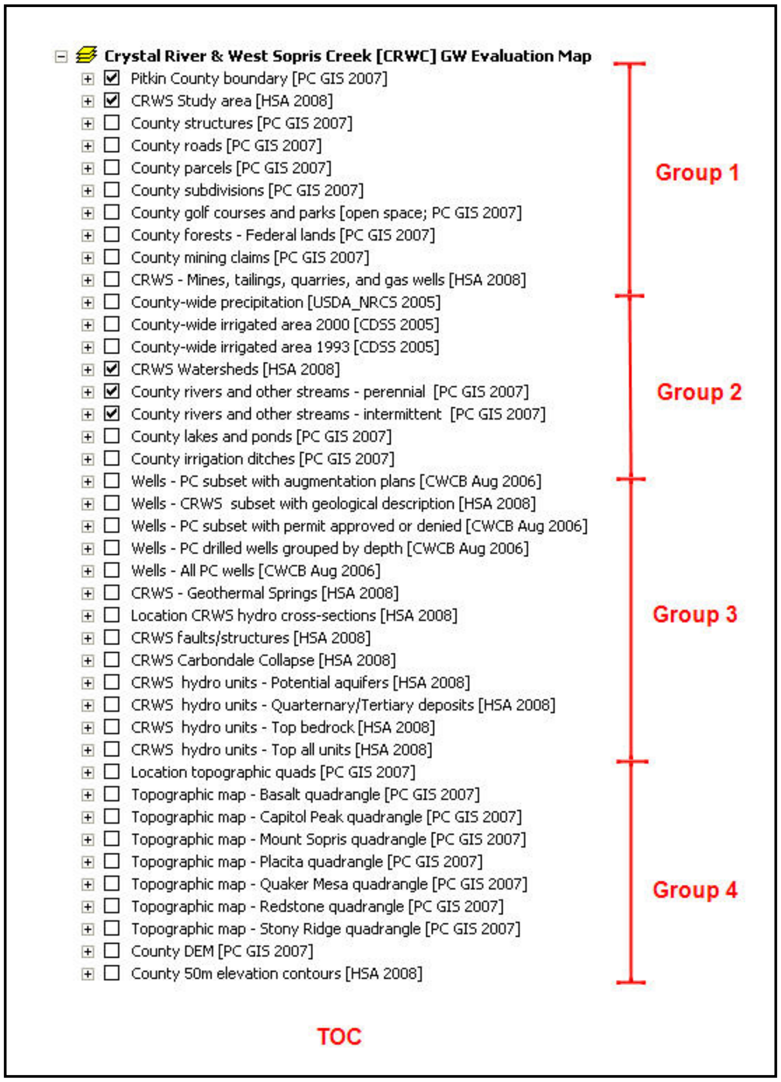


Figure 42. Table of Contents of the Pitkin County Ground Water GIS Map with Layers Grouped by Information Types.

3.3 GIS Map, Layers, and File Structure

Each line in the Table of Contents (TOC) is a GIS layer representing a set of features of the same type, such as streams, parcels, wells, etc. By clicking on a check box in the TOC, elements of the activated layer become visible in the map display area. A layer may consist of point values (*e.g.*, wells), line features (*e.g.*, roads, streams, ditches), and area features (*e.g.*, parcels, parks, lakes, hydrogeologic units). Right-clicking on a layer and selecting the *open* *attribute table* option, provides additional information on the layer, such as the names of particular features (Figure 43). This additional information can be used to label the features in the map display area.

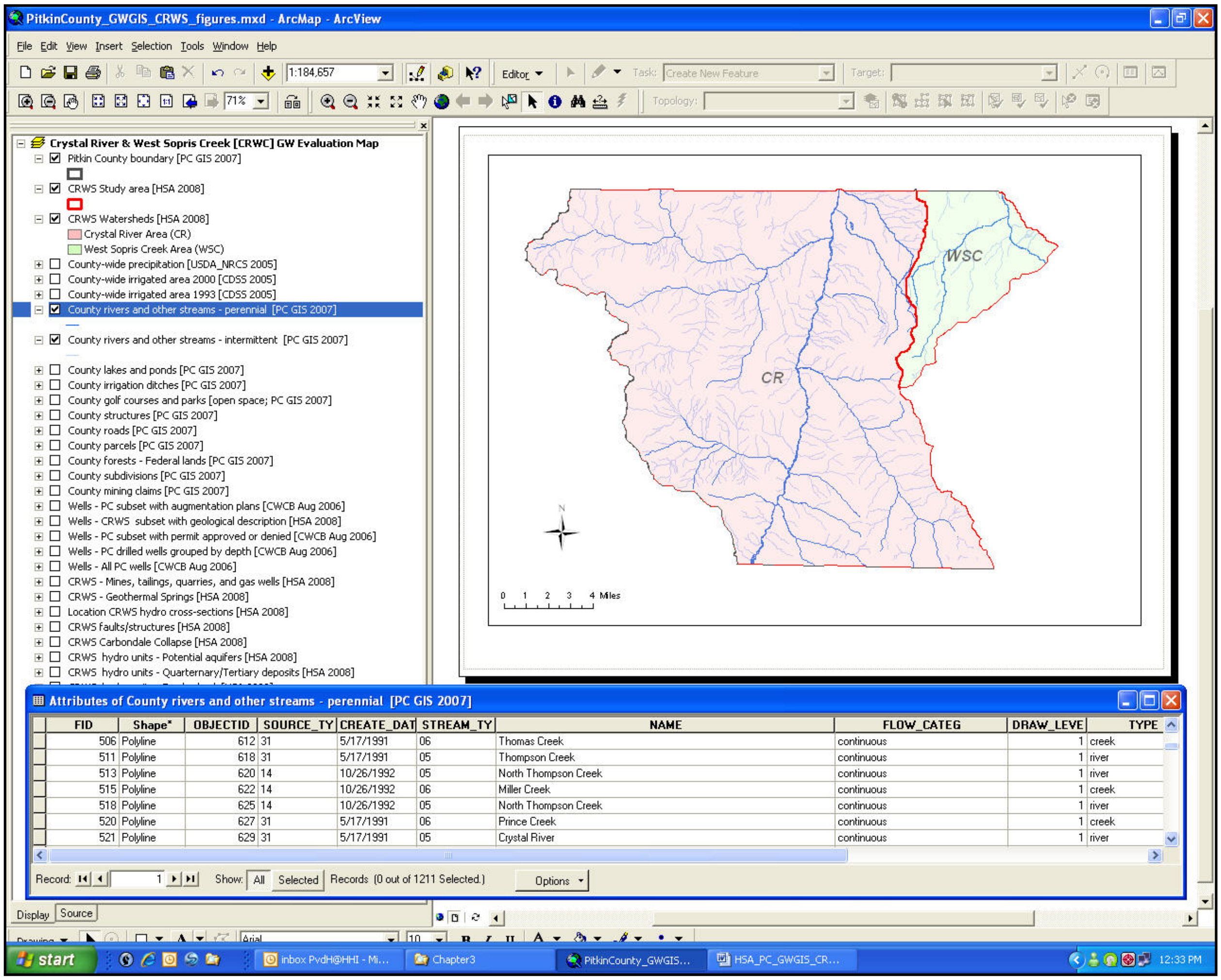


Figure 43. Pitkin County Ground Water GIS Map Showing the Main Watersheds and Perennial and Intermittent Streams in the CRWS Study Area.
(At the bottom the Attribute Table of the Perennial Streams Layer Is Shown.)

The layers in the CRWS GIS map are purposely listed in the order as shown in Figure 41 to enable the use of the GIS based ground water resources assessment procedure described in Chapter 4. When enabled, a layer is shown on top of the layer listed below it in the table of contents. When this layer is opaque, the layer beneath it is not visible. Some layers are (partially) transparent, others are opaque, dependent on the type of information they display and the use in the assessment procedure. Layer transparency/opaqueness can be changed by the user using the layer properties option under the display tab. The order of the layers can be changed by the user by dragging a layer to the desired location in the table of contents.

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

3.4 Data Sources

The CRWS ground water GIS map calls up various files included in five relative-path subdirectories: 1) NRCS_Data_Gateway; 2) Colorado_DSS (CDSS); 3) Pitkin_County_GIS; 4) HSA_PCGIS; and 5) Wells_DWRSC_Pitkin. The directories reflect the various data sources used for the map. Selection of the relative-path option of ArcMAP provides for straightforward portability between computers. Note, that layers that refer to a state-wide data set (such as the NRCS precipitation file) or a multi-county data set (such as the CDSS irrigated areas files) have been clipped on the map to show only the Pitkin County area coverage.

The *NRCS_Data_Gateway* subdirectory contains state-wide averaged annual precipitation data from the Natural Resources Conservation Service of the USDA (*precip_a_co* files). 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) and includes consideration of topographic facets. A description of PRISM can be found in the *PRISGUID.PDF* file in the metadata subdirectory *(Daly and Johnson, 1999)*. The NRCS data source and additional information can be found at: http://datagateway.nrcs.usda.gov/GatewayHome.html. The GIS map layer based on this data set is referenced as *USDA_NRCS 2005* (Figure 44).

The *Colorado_DSS* subdirectory contains 2 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) irrigated areas on the Western Slope as of 1993 (*WS_Irrig_93* files); and 2) irrigated areas on the Western Slope as of 2000 (*WS_Irrig_2000* files). Layers based on these data are referenced as *CDSS 2005*. The irrigated areas layers are based on compilations of the irrigated lands data from the 4 Western Slope Divisions of the Colorado Division of Water Resources. These data sets provide a single year snapshot of the irrigated lands and crop types of the western slope of Colorado. In the GIS map, the 2000 data layer lies on top of the 1993 data layer, showing the irrigated acreage taken out between 1993 and 2000 in pink (Figure 45). According to the 2005 Annual Report of the CDSS, a new compilation of the irrigated land data is planned, covering the 2006 irrigation season. Thus far, the results have not been published.

The information presented in these layers indicates that only a small portion of the study area is or has been subject to irrigation, primarily in the Crystal River valley near the northern county boundary, the major portion of the West Sopris Creek watershed, and the area between the confluence of East Sopris and West Sopris Creeks and the Roaring Fork River. Initially, a third layer from the CDSS was considered, showing the state-wide presence of an alluvial aquifer. Information provide by this latter layer, together with information from many other sources, has been used in the development of the hydrogeological layers presented in this report.

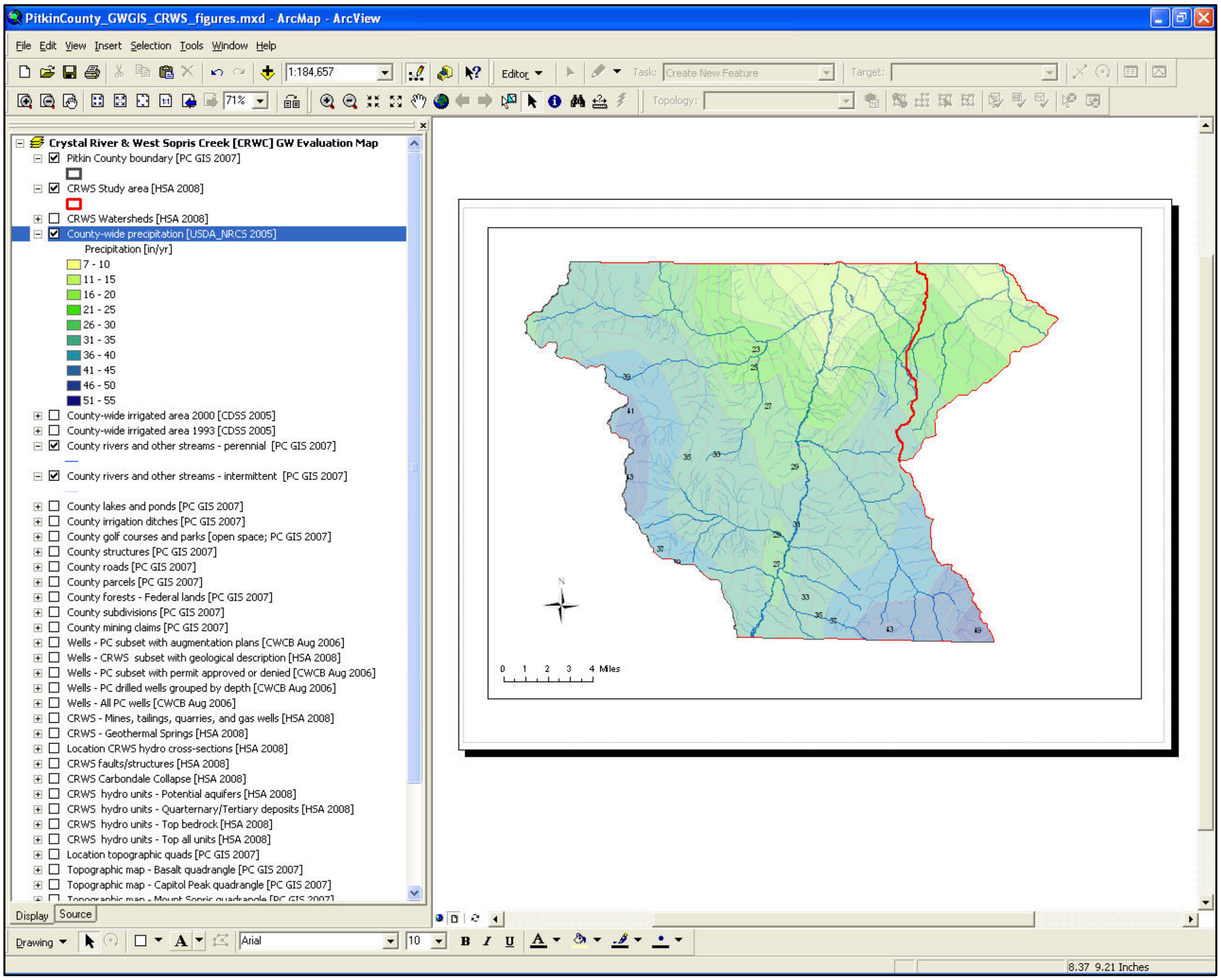


Figure 44. Detail of the Pitkin County GIS Map Showing the CRWS Study Area with Streams and Spatially Distributed Precipitation.

The *Pitkin County GIS* subdirectory for the CRWS study areas contains the shape, DEM and DRG files from the Pitkin County GIS, as well as the relevant meta files, as received in February 2007. Coverages include county border and area, roads, streams (*water_line* files), lakes and ponds (*water_poly* files), irrigation ditches, parcels, subdivisions, structures, forest and open space coverage, mining claims, relevant topographic maps, and the county-wide digital elevation model (DEM). The *water_line* files have been used to create two separate layers: *streams-perennial* (or continuous) and *streams-intermittent*. Examples of layers based on the county GIS data are the stream layers presented in Figure 43, the ditch layer in Figure 46, and the various land use layers shown in Figure 47. Note that the ditch layer includes active and non-active ditches, and primary, secondary and tertiary ditches, but the distinction between active and inactive ditches as well as size of the ditches cannot be determined within this GIS layer. Additional field verification is needed to assess the hydrologic importance of individual ditches. 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 2007*.

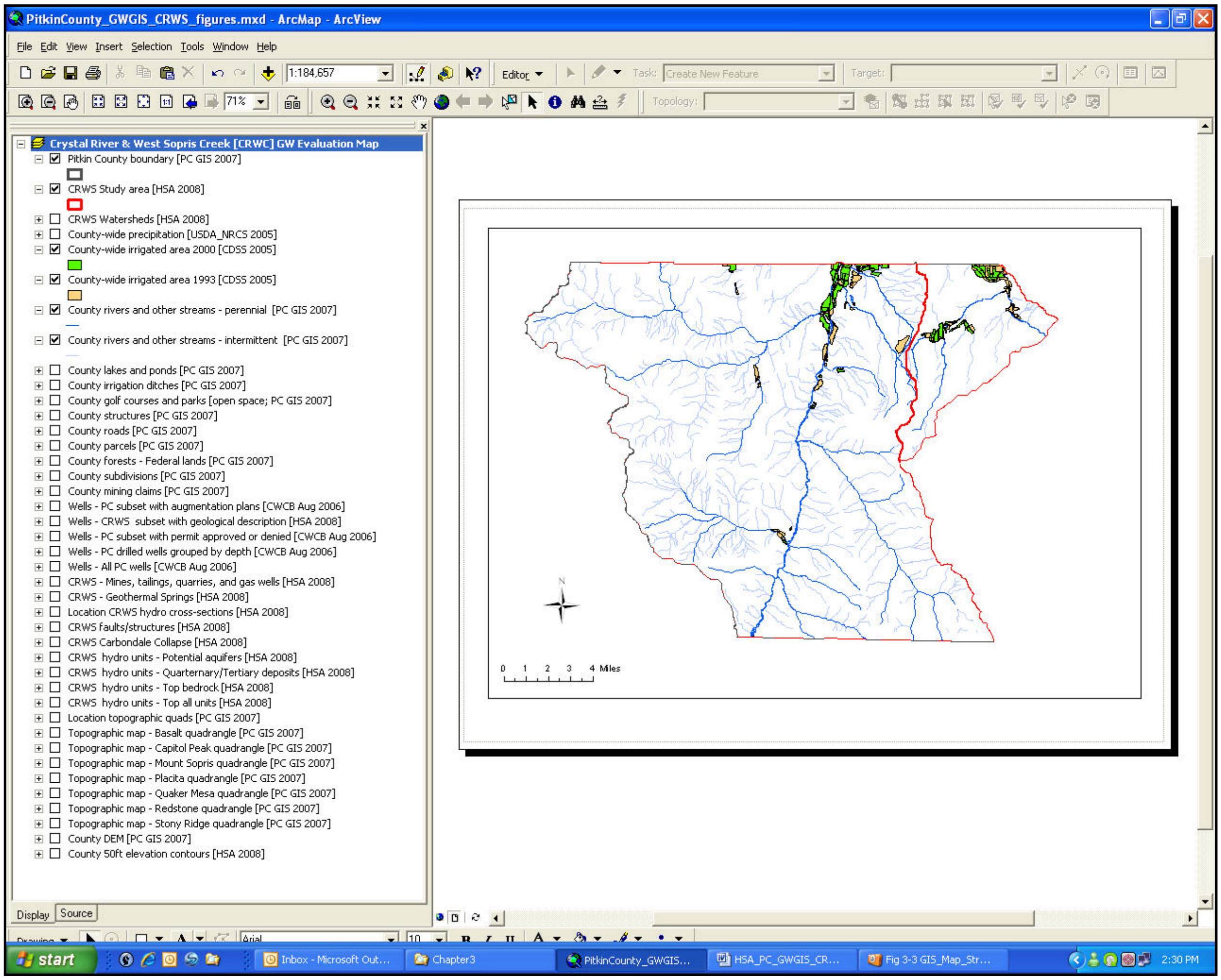


Figure 45. Detail of the Pitkin County GIS Map Showing the CRWS Study Area and the CDSS 1993 and 2000 Irrigation Layers.

The *HSA_PCGIS* subdirectory contains the HSA/HHI-produced file for the CRWS study area outline and includes the boundary of the two main watersheds in the study area: 1) Crystal River (CR) and West Sopris/Sopris Creek (WS) (*CRWS_studyareas* files) (Figure 41). The study area focuses on the portion of the two watersheds that contain non-public lands (Figure 47). The watershed boundaries were derived by a watershed analysis performed on the DEM

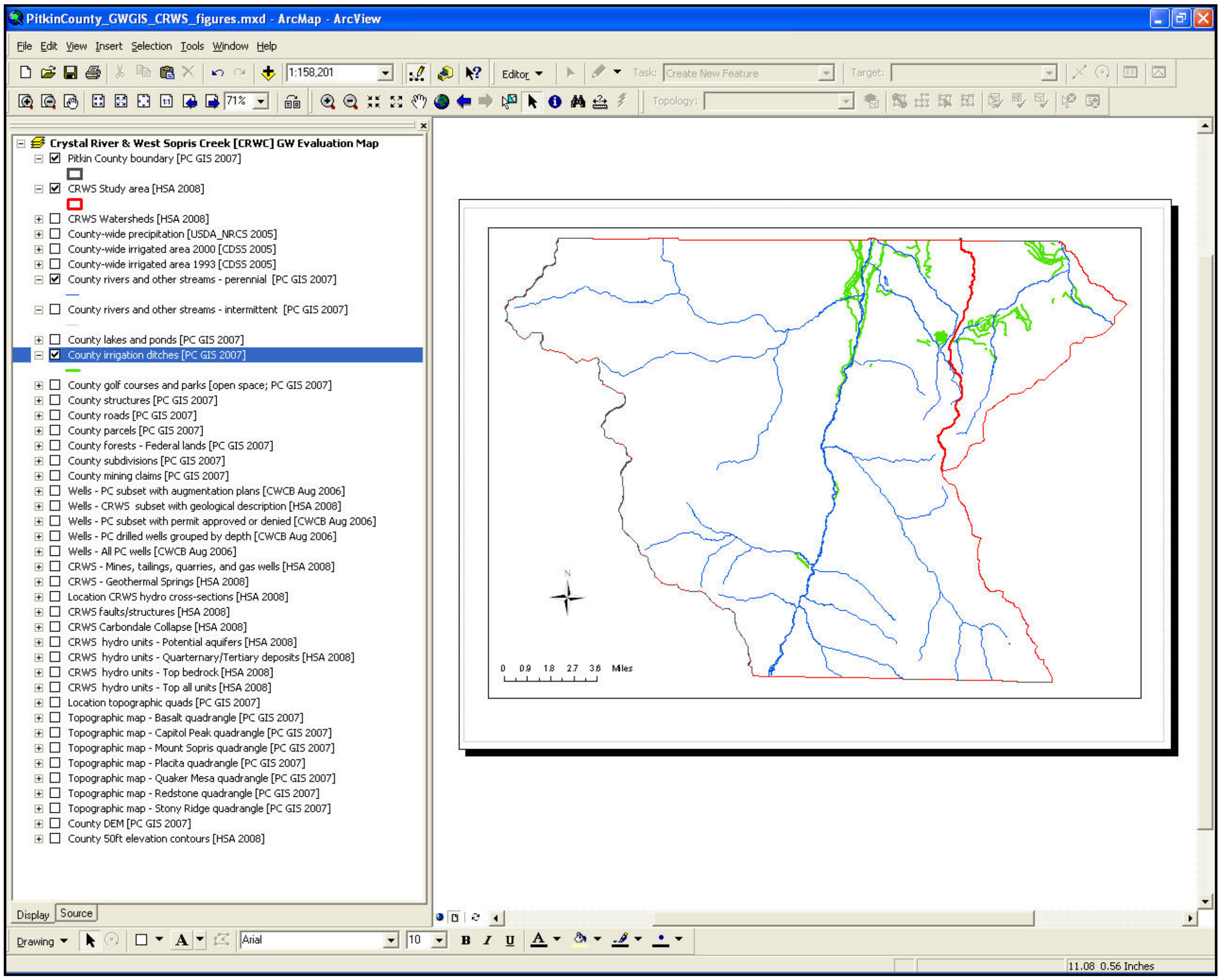


Figure 46. Detail of the Pitkin County GIS Map Showing the CRWS Study Area, the Perennial Streams Layer, and the Irrigation Ditch Layer.

provided by Pitkin County. The *HSA_PCGIS* subdirectory also contains various HSA/HHI-produced hydrogeology files (*CRWS_HydroUnits_All*, *CRWS_HydroUnits_Aquifers*, *CRWS_HydroUnits_Bedrock*, *CRWS_HydroUnits_Unconsolidated*, *CRWS_HydroUnits_cross_sections*, *CRWS_CarbondaleCollapse_polygon, and CRWS_faults_structures)*, and the file *CRWS_wellswithgeology*, containing a subset of the State well database with additional hydrogeologic information collected from well logs filed with the Colorado State Engineer Office. The HSA_PCGIS subdirectory also contains two databases: 1) point location and type of existing and historic mine sites in the study area for use in identifying anthropogenic influences (WestPitkinMines.csv); and 2) a geothermal springs set, currently containing only the location of Penny Hot Springs (WestPitkinSprings.csv). The hydrogeology layers resulted from digitizing and evaluating the 1:24,000 scale geologic quadrangle maps Basalt (*Streufert and Others, 1998*), and Mount Sopris (*Streufert, 1999*) produced by the Colorado Geological Survey, the Leadville 1^{o} x 2^{o} quadrangle geologic map (scale 1:250,000) (*Tweto, and Others, 1978*) published by the U.S. Geological Survey, and maps in the report "An Environmental and Engineering Geology Study, Eagle, Garfield, Gunnison and Pitkin Counties, Colorado" (*Olander and Others, 1974*), published by the Colorado Geological Survey. The

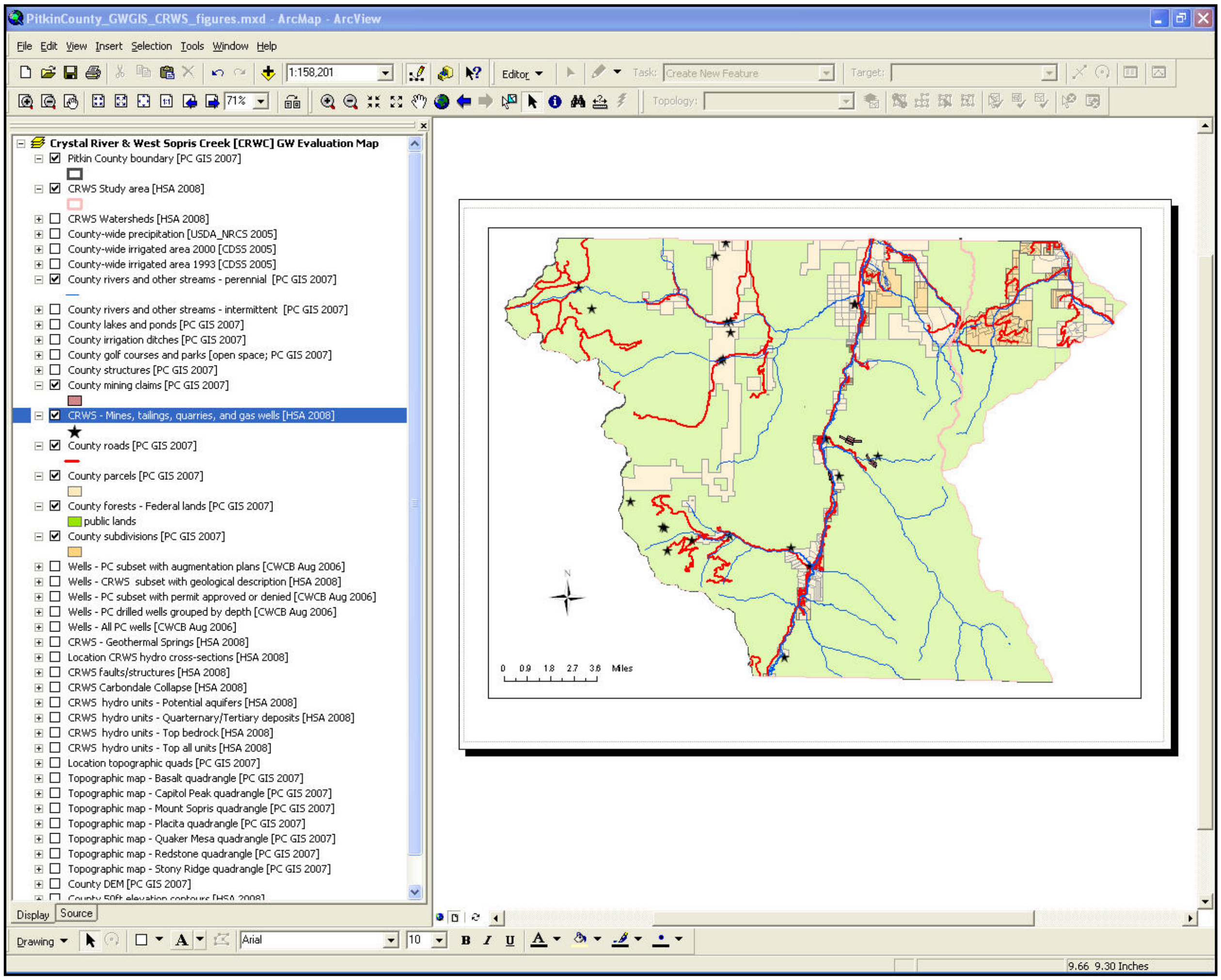


Figure 47. Detail of the Pitkin County GIS Map Showing the CRWS Study Area with Roads, Mining Claims, Current and Historic Mine and Quarry Sites, County Parcels (light yellow), Subdivisions (light brown), and Non-developable Federal Lands (green).

faults/structures layer is based on the 1:24,000 scale Basalt and Mount Sopris geologic quadrangle maps, the Leadville 1^o x 2^o quadrangle geologic map, and studies of the Carbondale Collapse structure (*Kirkham and Others, 2002*).

There are 4 hydrogeologic system layers and 2 hydro-structure layers on the GIS map (*i.e.*, "hydro units" for short): 1) layer showing the top of the hydrogeologic system with all units present (*CRWS hydro units - Top all units*) (Figure 48); 2) layer showing the Quaternary and Tertiary unconsolidated deposits only (*CRWS hydro units - Quarternary/Tertiary deposits*); 3) layer showing the bedrock units at the surface of the bedrock, *i.e.*, subcrop where overlain by unconsolidated Quarternary or Tertiary deposits, or outcrop where top bedrock is exposed (*CRWS hydro units - Top bedrock*); 4) layer showing the potential aquifer units (*CRWS hydro units - Potential aquifers*) (Figure 49); 5) layer showing linear hydro structures (*CRWS faults/structure*) (Figure 50); and 6) layer showing the Pitkin County section of the Carbondale Collapse structure (*CRWS Carbondale Collapse*) (Figure 50). All HSA/HHI produced layers are referenced as *HSA 2008*. Note that the geologic maps used for the digitizing are on different scales, the digitized maps show different levels of resolution with respect to the (hydro)geology. Part of the area not covered by the Mount Sopris and Basalt 1:24,000 geological quadrangle maps has been digitized using the Environmental and Engineering Geology Study, Eagle, Garfield, Gunnison and Pitkin Counties, Colorado" (scale 1:48,000; *Olander and Others, 1974*). The area outside the fore mentioned maps was digitized based on the Leadville 1:250,000 geologic map resulting in a less detailed coverage than the rest of the area. The faults/structures layers have been prepared by combining the faults layers of the three geological quadrangle maps and adding the manually digitized extent of the Carbondale Collapse structure. The CRWS GIS map also includes a layer showing the location of the hydrogeological cross-sections discussed in Chapter 2.

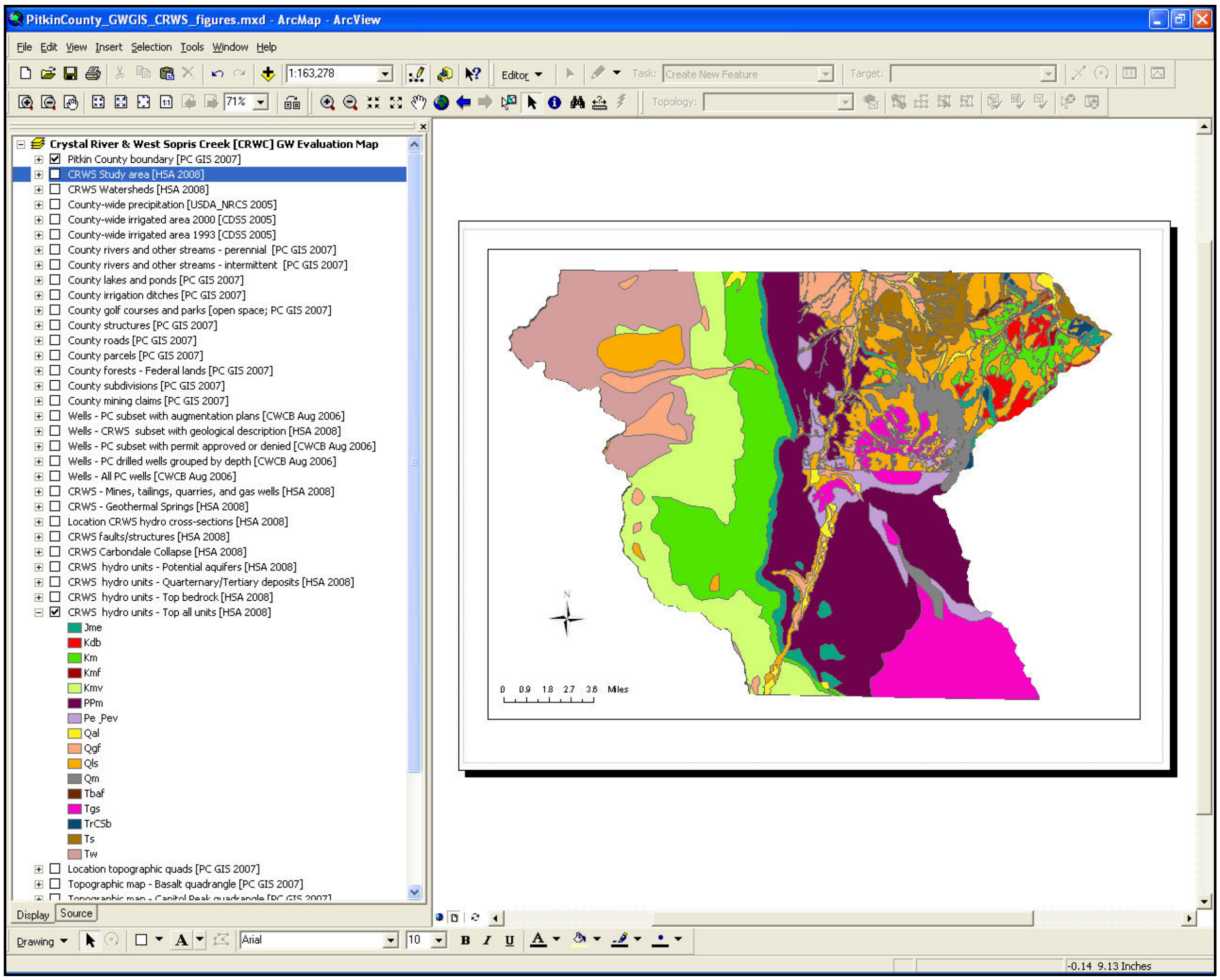


Figure 48. Detail of the Pitkin County GIS Map Showing the CRWS Study Area with *CRWS Hydro - All Units* Layer Activated. (See Chapter 2 for Explanation of Abbreviations and Details of Color Scheme).

The *Wells_DWRSC_Pitkin* subdirectory contains a subset of the August 2006 version of the state-wide well database, maintained by the State of Colorado Division of Water Resources (http://www.water.state.co.us/pubs/welldata.asp). The database subset is restricted to Pitkin County (county code 49) and includes both well permits (drilled or not) and drilled wells. The

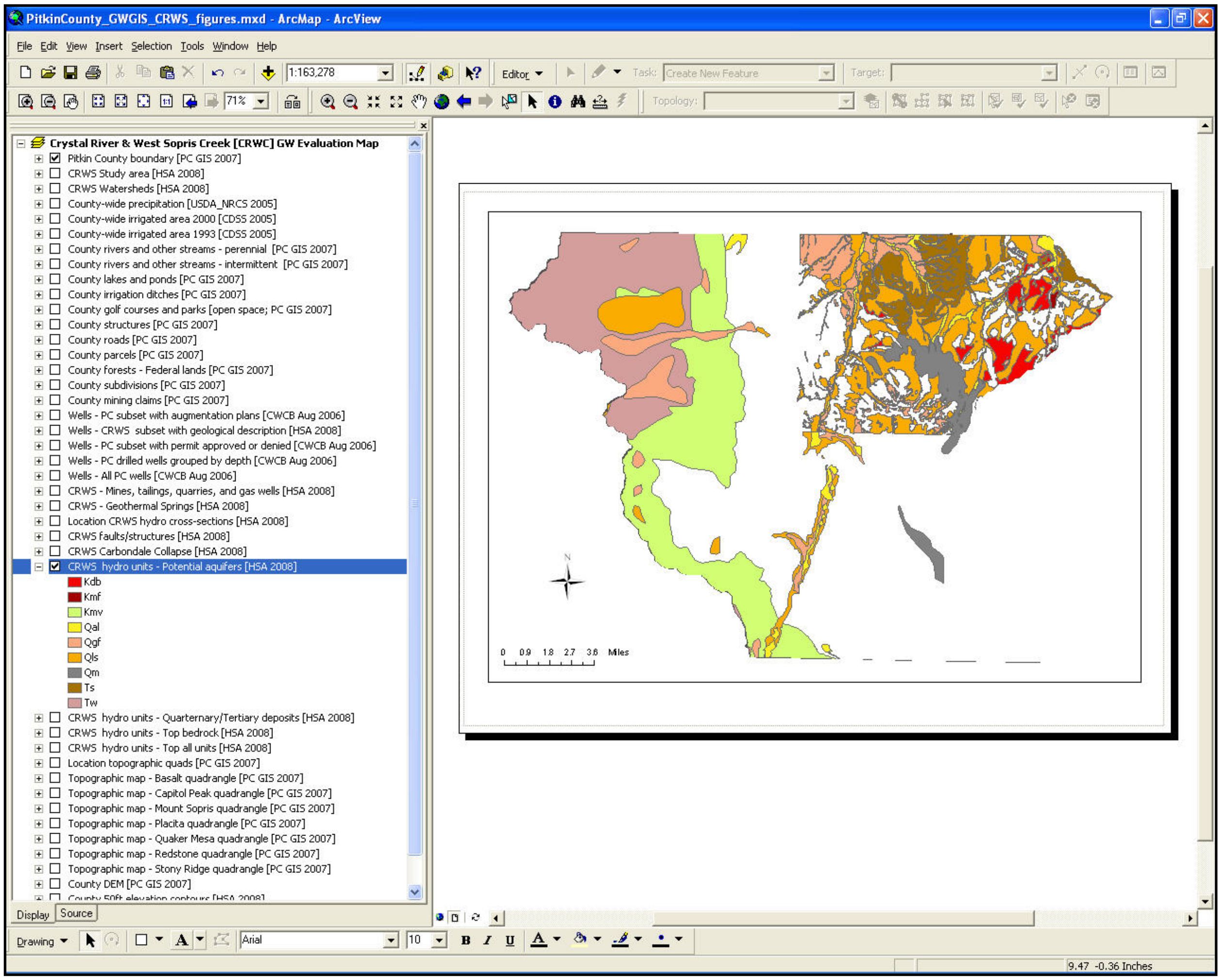


Figure 49. Detail of the Pitkin County GIS Map Showing the CRWS Study Area with *CRWS Hydro - Potential Aquifers* Layer Activated. (Note That the Maroon Formation [Not Shown] May Locally Provide a Source of Water, Especially in Areas where Geo-structures Have Increased the Permeability.)

well coordinates are transformed 'on the fly' from UTM Zone 13N, NAD 1983 to CSP/NAD83 when the *wells.dbf* file is accessed by ArcMap. The attribute table [right-click on layer in contents column and select *Open Attribute Table*) includes fields for completion date, total well depth and depth to water (water table), as well as fields containing information regarding required augmentation plans and permit status. The subdirectory also contains the file *WELLVIEW_CODES.pdf* with explanations of the fields in the wells attribute table (also included in an Appendix of this report). Layers based on these data are referenced as *CWCB Aug2006*. The state database has been used to prepare separate GIS layers to identify drilled wells grouped by depths, locations with approved drilling permits (drilled or not drilled), and wells with required augmentation (Figures 51 shows the drilled wells by depth). Note that these different well layers use the same data source-file (*wells.dbf*).

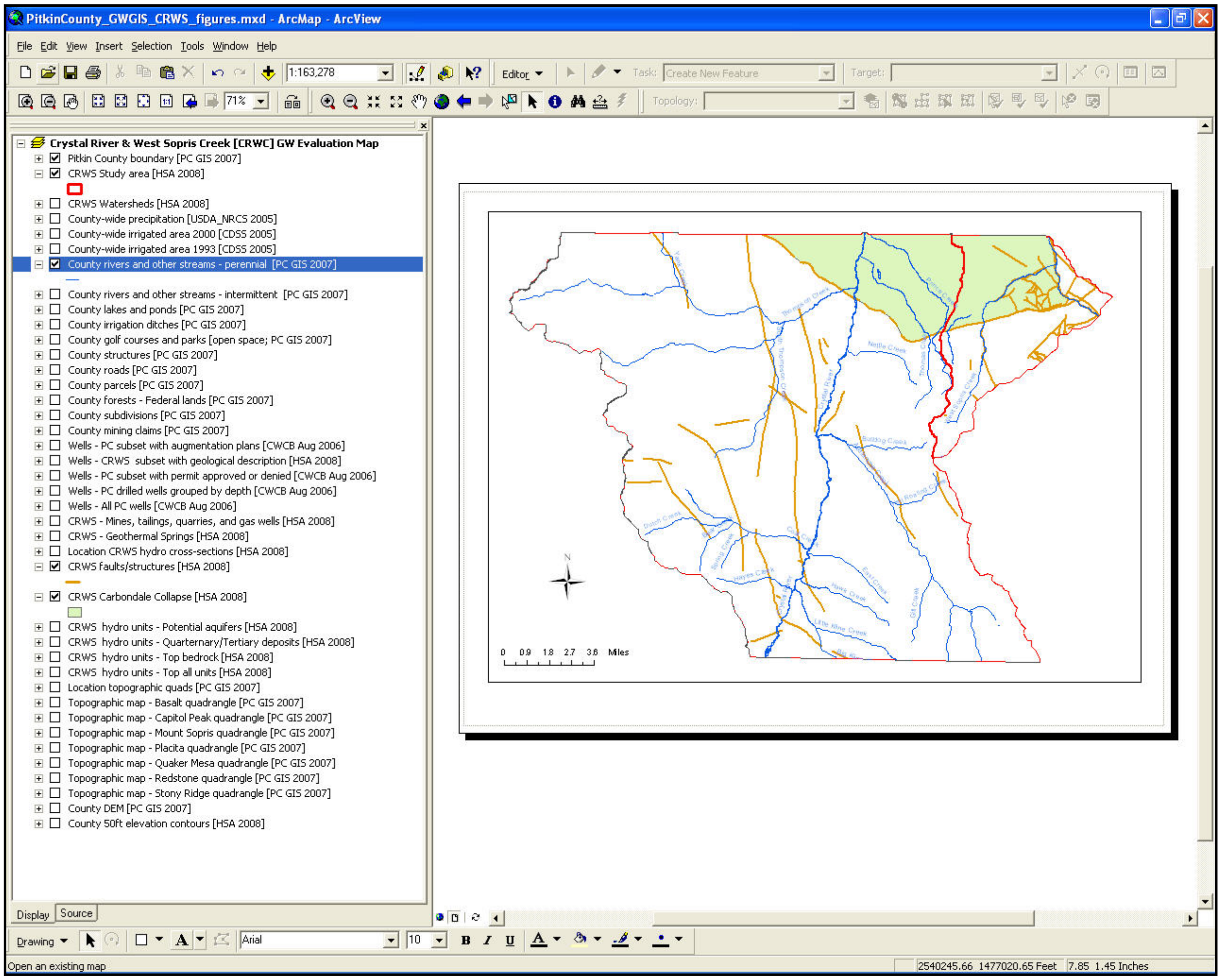


Figure 50. Detail of the Pitkin County GIS Map Showing the CRWS Study Area and the Faults/Structures and the Carbondale Collapse Layers. (The Streams Layers are Include as a Reference Layer.)

The files in the *Colorado DSS*, *Pitkin County GIS*, *NRCS Data Gateway* and *Wells_DWRCS_Pitkin* directories may require regular updating from the data source/owner/custodian. Specifically, the well database maintained by the State of Colorado is updated on a quarterly basis. An appendix to this report describes the procedure for updating the GIS files for these well data.

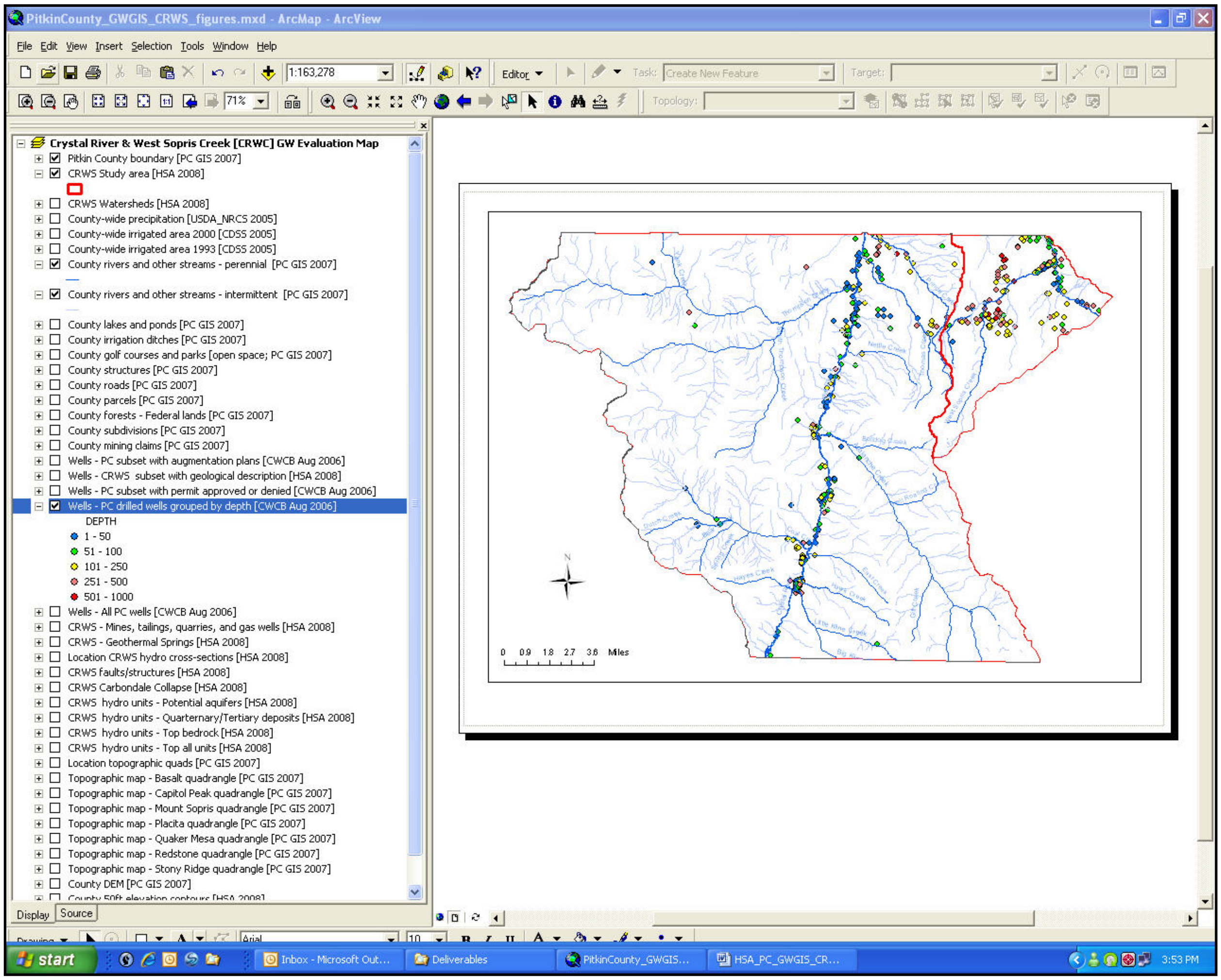


Figure 51. Detail of the Pitkin County GIS Map Showing the CRWS Study Areas and All Drilled Wells Grouped by Depth.

4. Ground Water Resources Evaluation Procedure

The complexity of the hydrogeology in CRWS 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 with respect to contamination from the surface. Specifically, the absence of detailed and up-to-date information on water table elevations and fluctuations, formation depth and thickness, aquifer matrix and fracture permeability distributions, and water budgets limits the quantitative analysis of ground water resources availability and sustainability. To achieve the project's objectives, an intuitive and flexible analysis procedure has been developed that optimally utilizes existing geo-information and the capabilities of a GIS (*Kolm and van der Heijde, 2006; Kolm and Others, 2007*). This stepwise procedure facilitates the evaluation of ground water availability, sustainability, and vulnerability on a site-specific base. The following text segment is largely taken from Kolm and others (*2007*). A summary of this procedure is included in an Appendix to this report.

At each step of the assessment procedure, notes refer to individual layers in the CRWS GIS map. For ease of reference in this chapter, each layer in the Table of Contents of the GIS map has been numbered as shown in Figure 52. To view a referenced layer in ArcMap, place a check mark in the layer's checkbox in the Table of Contents; these user-placed check marks should be removed when moving to the next step in the procedure.

It is assumed that the starting point of the assessment procedure is a permit application for development of one or more parcels in the CRWS study area. Note, that the stepwise procedure may also be used for other planning or permitting applications. Upon receipt of a permit application, the first step is to determine the precise location or platting of the selected site, and to use this location in conjunction with the hydrology and hydrogeology GIS layers to determine the presence of ground water (Objective 1a; see Chapter 1). The succeeding tasks include determining the level of ground water availability (Objective 1b; see Chapter 1), sustainability as a resource at the site (Objective 2; see Chapter 1), and vulnerability to contamination and subsequent loss of supply (Objective 3; see Chapter 1). The GIS map includes layers showing wells with augmentation requirements, approved wells (drilled or not), drilled wells, and denied permit (Objective 4). 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 by the permit applicant or other users.

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 or other low-permeability bedrock. Such potential aquifers may be in surficial material or bedrock formations. It should be noted

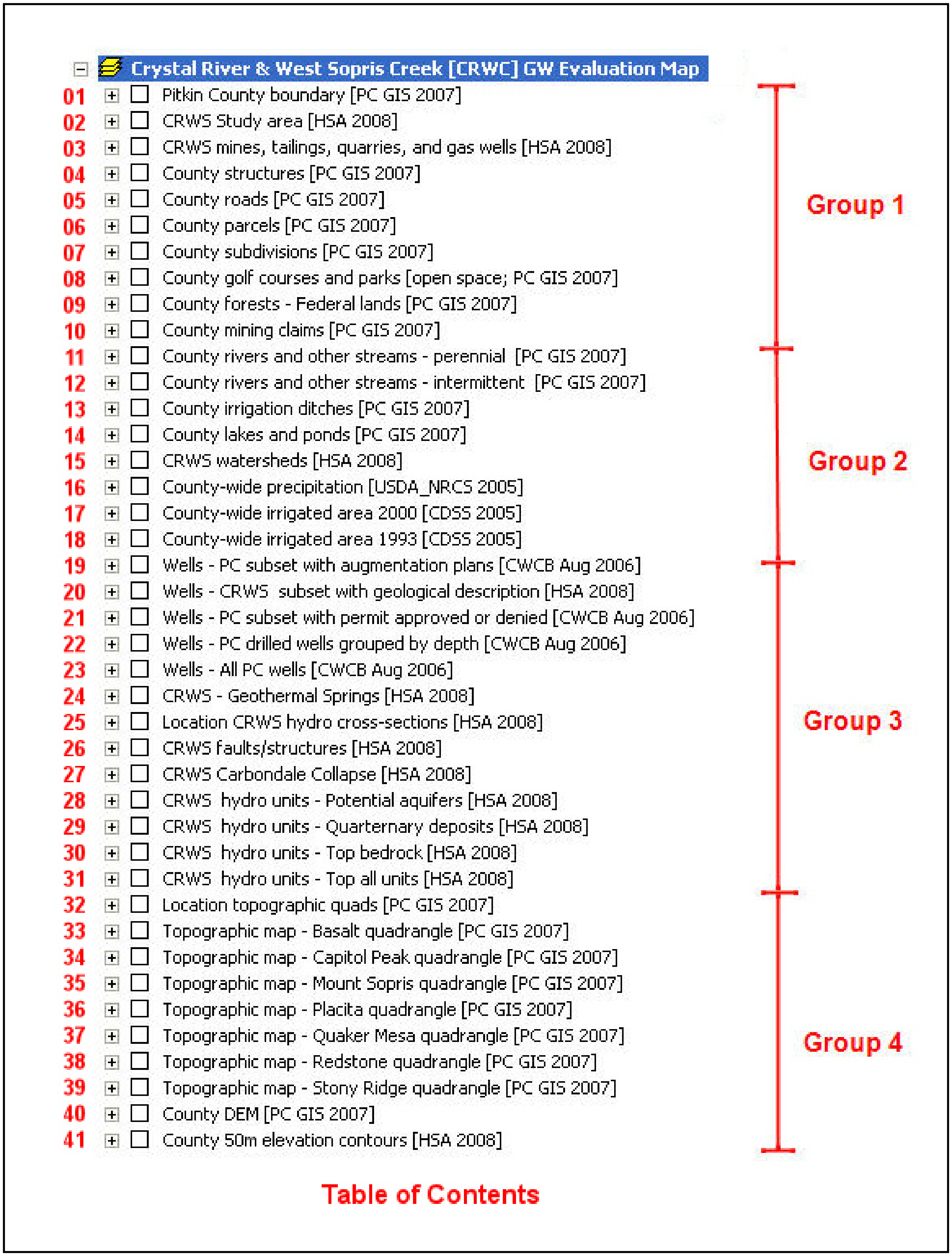


Figure 52. Annotated Table of Contents for the CRWS GIS Map.

that even in low-permeability bedrock, a source of water can be found for individual users when the presence of hydro structures, such as fracture zones in the Maroon Formation, has resulted in locally increased permeability.

4.1.1. Potential Unconfined Surficial Aquifer Material in the Study Area

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

<u>Modern Alluvium</u> (Qal). This material is primarily located in the valleys along the modern streams, *i.e.*, the Crystal River, Prince Creek, West Sopris and Sopris Creeks, and along some intermittent streams near the northern county line. These materials usually are natural aquifers that are in direct contact with and are sustained by the nearby surface water bodies. They are subject to seasonal fluctuations and changes in surface water body characteristics and use, such as spring runoff and withdrawal for irrigation. They may be recharged from seepage from higher terraces or leaking ditches, and/or from irrigation return flow. (GIS layer 29 in Figure 52; Figure 53).

<u>Terrace Gravels and Fans</u> (Qgf). This material is located above the modern stream levels on the hillslopes. Extensive areas of this material can be found in the lower Crystal River valley up to Avalanche Creek, and in the upper sections of the Thompson Creek watershed. Due to the extent of these materials in some parts of the study area and the drainage patterns present in these materials, they may provide a permanent source of water sustained by natural recharge. When present as stand-alone terraces, these materials usually are dry, but can be aquifers created and sustained by anthropogenic activity, such as leaking irrigation ditches or irrigation return flow. (GIS layer 29 in Figure 52; Figure 53).

<u>Landslides</u> (Qls). This material can be found in many places along the hillslopes in the northeast quadrant of the CRWS study area and along North Thompson Creek. These materials are primarily dry, but in areas of irrigation ditches and other anthropogenic activity, may become aquifers. They also may be seasonally of importance as a source of water. (GIS layer 29 in Figure 52; Figure 53).

<u>Moraines</u> (Qm). This material is primarily located at the northern and eastern flanks of Mount Sopris, and along the middle reach of Avalanche Creek. The moraines of the CRWS area are dry near the surface, but frequently contain natural ground water at depth, depending on connection to subsurface bedrock units, anthropogenic activities that promote recharge, or climate/precipitation input at higher elevations. (GIS layer 29 in Figure 52; Figure 53).

<u>Tertiary Sedimentary Deposits</u> (Ts). This material can be found in the northern and northeastern sections of the study area. The weakly indurated to unconsolidated fluvial deposits (pebbles and cobbles in a matrix of silty sand) have a major presence in the Carbondale evaporite collapse area near the northern county line where they are partially covered by Quarternary sediments. This unit is potentially a good local or subregional aquifer of variable thickness with significant matrix based permeability and may act in conjunction with overlying sediments as a source of water. (GIS layer 30 in Figure 52; Figure 54).

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.

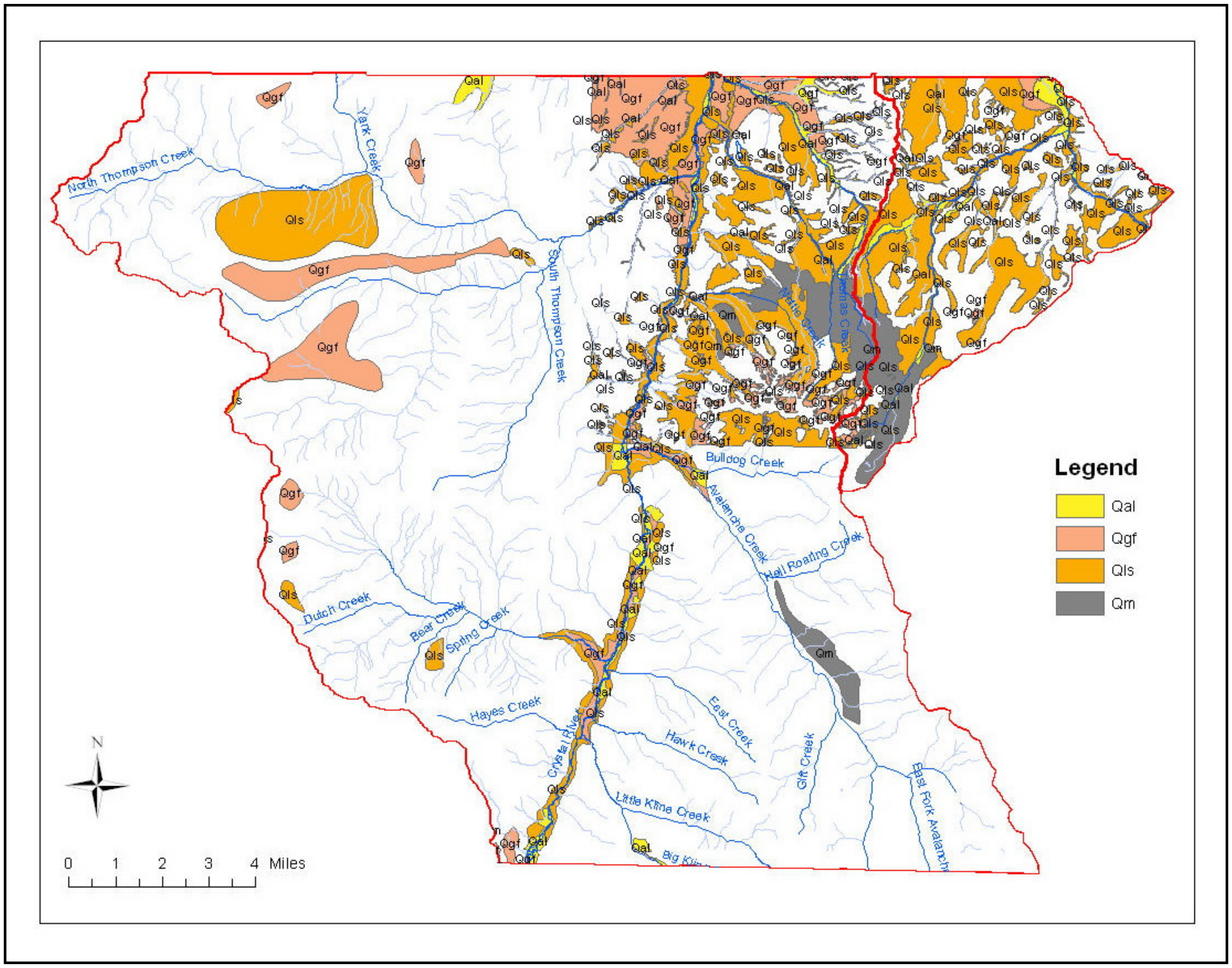


Figure 53. CRWS GIS Map Showing the Quarternary Hydro Units.

4.1.2 Potential Unconfined And Confined Bedrock Aquifer Material

The following bedrock materials may constitute aquifers in the study area (GIS layer 30 in Figure 52; Figure 54):

<u>Mount Sopris Granodiorite</u> (Tgs). These Upper Tertiary intrusive rocks are found in the vicinity of Mount Sopris and in the Elk Mountains near the upper reaches of Avalanche Creek. This unit may locally act as an unconfined, moderately permeable, fractured crystalline aquifer with local recharge.

<u>Wasatch and Ohio Creek Formation</u> (Tw). This unit consists of channel sandstones, conglomerates, overbank siltstones, claystones and shales. The conglomerates and sandstones are potentially good aquifers, both on a regional scale with matrix-based permeability and on

a local scale with fracture-based permeability. The siltstones, claystones and shales may form internal, potentially discontinuous confining layers. This unit is primarily located near the North and Middle Forks of Thompson Creek in the northwestern section of the study area.

Mesa Verde Formation (Kmv).This unit consists of interbedded sandstones and siltstones, shales, carbonaceous shales and coals and is potentially a complex of good aquifers with both matrix- (regional scale) and fracture-based (local scale) permeability. This unit is at or near the surface in a north-south stretching zone just west of the Crystal River, dipping down to the west underneath the Wasatch and Ohio Creek Formation. In the study area, this unit is a recharge zone for the regional system, and it is likely that in the outcrop area the unit contains a deep water table. Further to the west Kmv becomes a part of a confined aquifer system.

Fort Hays Member of Mancos Shale (Km). This unit consists of thick-bedded, coarse-grained limestone and may be a good local or regional fractured-flow aquifer when present. Its extent in the study area is not very well known. As it is part of the larger Mancos Shale formation, the Ft Hays unit is probably at or near the surface in a north-south stretching zone just west of the Crystal River, dipping down to the west underneath the Mesa Verde Formation. If present here, its outcrop/subcrop is a recharge zone with a deep water table. The unit may be also present in the Mancos shales directly north and northeast of Mount Sopris as it is discussed in the Basalt geological map (*Streufert and Others, 1998*). If present, its extent is more localized as the Mancos Shale in this area is disconnected from the Mancos Shale to the west. The unit is mostly confined except in the outcrop zones.

Dakota-Burro Canyon Sandstone (Kdb). This unit consists of sandstone layers 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. This unit is covered by the Mancos Shale except for outcrops and subcrops in the northeastern and eastern sections of the study area, and a small outcrop band west of the Crystal River. The (north-)eastern segment may provide a source of water although its orientation and elevation in the landscape indicates that it can only be recharged locally from precipitation. The outcrop of this unit west of the Crystal River is a recharge zone for a regional system and has a deep water table. This unit is primarily confined except in the outcrop/subcrop areas.

Morrison and Entrada Sandstones (Jme). This unit consists of poorly indurated, fine grained, well sorted sandstones, siltstones and claystones. The Entrada sandstones form a very good regional aquifer with matrix and fracture permeability. The Morrison shales are confining layers, while the lower Morrison sandstones perform as aquifers. This unit is mostly covered by the Dakota-Burro Canyon Formation and Mancos shales and thus confined, except in a small outcrop band west of the Crystal River, and in the hills east of Mount Sopris. The outcrop of this unit west of the Crystal River is a recharge zone for a regional system and has a deep water table.

Maroon and Minturn Sandstones (PPmm). This unit is characterized by grayish-red to pale-red arkosic sandstones, silt- and mudstones, and conglomerates. In the Minturn Formation these materials are interbedded with shale and limestone. Where metamorphosed and well cemented, this unit acts as crystalline rock with only local potential for significant fracture permeability. This is the situation in the study area where significant fracturing occurs along the north-south trending fault and fracture zone of the Crystal River providing increased permeability beneath and along the river. Significant secondary fracturing occurs in the surrounding hills steering ground water flow towards the river valley. In the central Crystal River area, these fractured aquifer conditions are further enhanced by the additional fracturing related to the synclinal trough. Most of the area with Maroon/Minturn sub- or outcropping is considered a recharge zone, except for stream valleys where it is in the discharge zone. The recharge zone at the higher elevations have a deep water table, while in the discharge zones the water table may reach into the sediments above it.

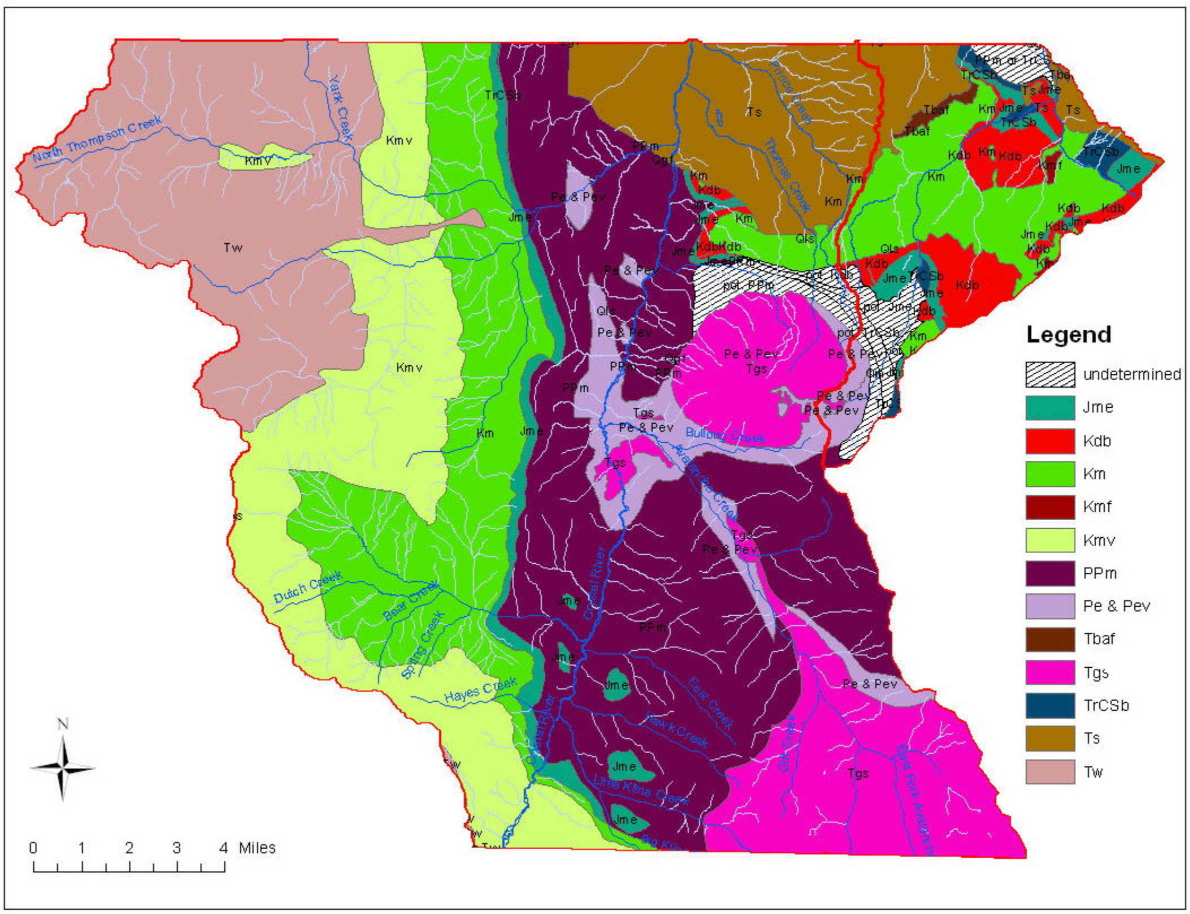


Figure 54. CRWS GIS Map Showing the Bedrock Hydro Units.
(note: the area labeled 'undetermined' is either Km or Kdb).

Note that, in general, the Mancos Shale (Km), the Morrison shales (Upper Morrison; Jme), Chinle and State Bridge Formations (TrCSb), the Eagle Valley Formation, and the Eagle Valley Evaporite are mostly low permeability units and are considered in the study area to be confining layers. The State Bridge Formation in the eastern section of the study area may contain some discontinuous sandstones providing a highly localized fractured aquifer.

4.1.3 Is the Potential Surficial Aquifer Connected/Not Connected with a Bedrock Aquifer?

If it has been determined that the site is located in an area with a potential alluvial/colluvial aquifer (Section 4.1.1), 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 impermeable shales of the Mancos, Morrison, Chinle or State-Bridge Formations, or the Eagle Valley Formation or Eagle Valley Evaporite are areas where connectivity is not likely. Areas where landslide and alluvial material overlie the Tertiairy sediment deposits, the Mt Sopris Granodiorite, the Wasatch and Ohio Creek Formation, the Mesa Verde Formation, the Fort Hays Limestone, the Dakota-Burro Canyon Sandstone, the Morrison and Entrada Sandstones, or the Maroon and Minturn Sandstones may have direct bedrock connectivity. In these connected areas, ground water may flow either upward from bedrock to unconsolidated deposits (*i.e.*, bedrock recharges unconsolidated deposits), or downward from unconsolidated deposits to bedrock (*i.e.*, unconsolidated deposits recharges bedrock).

4.1.4 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. GIS layers 19-23 (Figure 52) show the locations of the wells recorded in the state well database. The attribute table for these layers contain information with respect to depth to water table at time of drilling, screen placement, depth to well 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 (GIS layer 40 in Figure 52), the 50ft elevation contours layer (GIS layer 41 in Figure 52), or the topographic map layers (GIS layers 33-39 in Figure 52). Note, that in absence of sufficient well data, analysis of topography, vegetation, and nearby stream elevations may provide some insights with respect to nearby water table elevations.

4.2 Potential Sustainability of a Water Supply from Ground Water

This section describes the approach to accomplish objective 2: potential sustainability of a 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.

*4.2.1 Is There Direct Infiltration of Precipitation into the Alluvial/Colluvial Aquifer or the Bedrock Aquifer, and How Much***?**

Every part of the surficial 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 map (layer 16 in Figure 52). 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 and that overall precipitation increases from the north end of the study area towards the south end (see Figure 6).

4.2.2 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 is flowing for most of the year in the stretch across the aquifer, and the water table near the stream should be below stream level. GIS layers11 and 12 (Figure 52) are based on Pitkin County's waterline layer which contains, among others, a field indicating intermittent stream flow (ephemeral stream) or continuous stream flow (perennial stream). By comparing hydrogeologic unit information from layer 29 with the streams layers 11 and 12, the existence of a hydraulic connection may be assessed. When the stream is rated intermittent, additional information from filed observations may be required. There is no hydraulic connection between a stream and the aquifer when 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 simultaneously 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 (from 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.

4.2.3 Is the Saturated Alluvial/Colluvial Aquifer Connected with an Irrigation Ditch or Subject to 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 GIS layer 29 is compared with the county's ditches layer (GIS layer 13 in Figure 52). 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 of 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 (Figure 52, GIS layers 17 and 18, 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.

4.3 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 bedrock aquifers are overlain by confining units (see section 4.1.2).

All potential sedimentary aquifers shown in GIS layers 29 (Qa, Qgf, Qls, Qm) and 30 (Ts) (Figure 52) are vulnerable; natural protection is only available for bedrock aquifers underneath confining layers.

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 ISDSs, gas stations, urban runoff, and agricultural land use. However, such an analysis goes beyond the scope of this project.

5. Case History Examples

In this section, four examples are presented illustrating the step-wise approach developed for determining if ground water can provide the water supply for a given site. The general location of these sites are shown in Figure 55. Site 1 is located in the Upper Crystal River (UCR) hydrogeological subsystem; site 2 is located in the Central Crystal River (CCR) hydrogeological subsystem; site 3 is located within the Carbondale Collapse area of the Lower Crystal River (LCR) hydrogeological subsystem; and site 4 is located in the hills of the West Sopris Creek (WSC) hydrogeological subsystem. The examples illustrate the variability of drinking water supplies, with respect to availability, sustainability, and vulnerability and the influence of the highly localized hydrogeology and hydrological conditions on it. All four sites are vulnerable to ground water pollution. Note, that the map display is in 'Data View' mode (*Click View →Data View on the menu bar of the ArcMap window*). The GIS layer numbers in the following discussions refer to Figure 52.

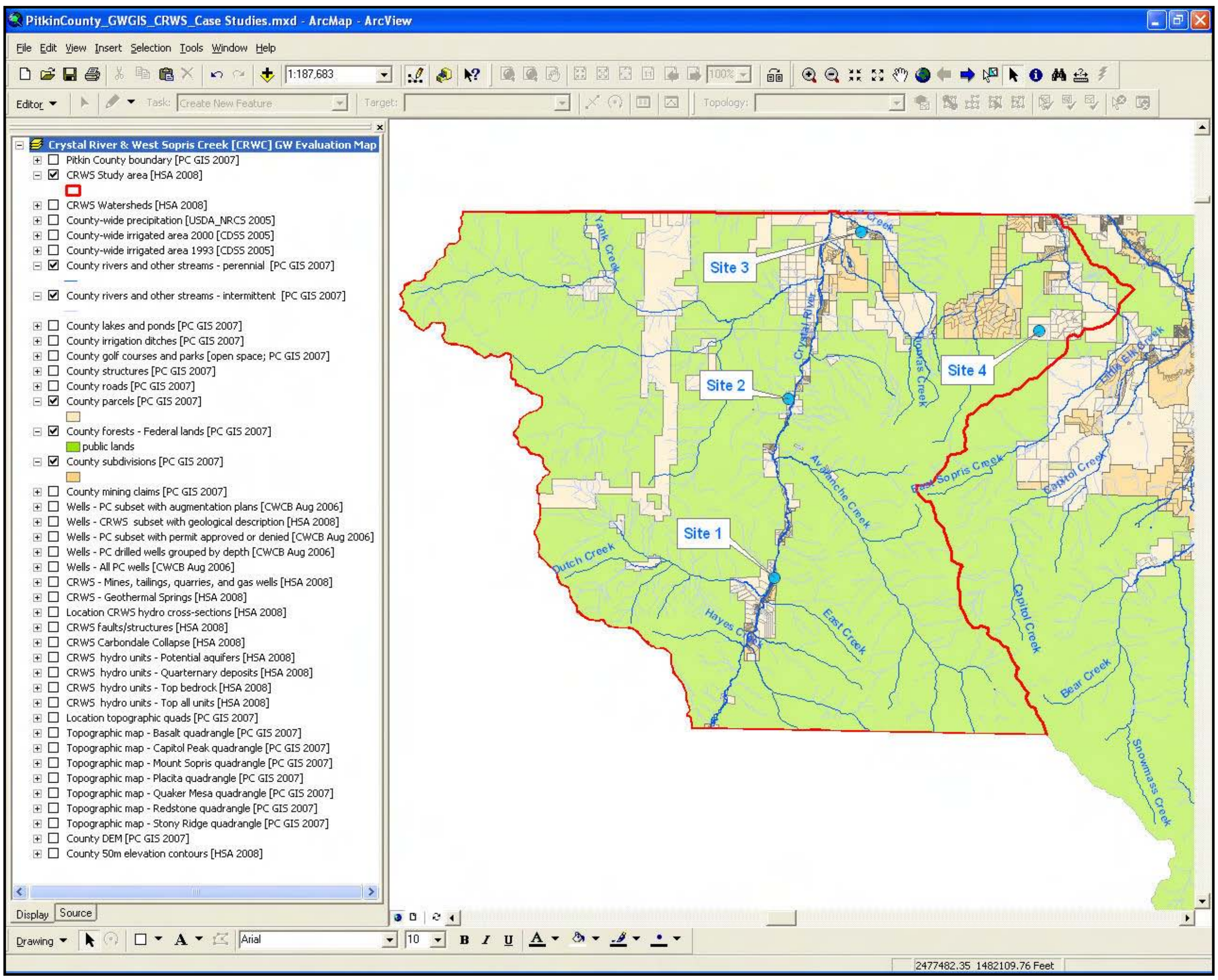


Figure 55. Location of Example Sites.

5.1 Example 1 in the Upper Crystal River Valley

5.1.1 Identify Location on GIS Map

Example 1 is a site located on parcel #272917400012 [at about (Colorado State Plane, Central Zone NAD 83) coordinate 2508882, 1499200], north of Bighorn Ridge PUD and Redstone subdivisions (blue marker dot; Figure 56). Parcel and subdivision details are found by using the *Identify* function on the menu bar and selecting the *County parcels* or *County subdivisions* layer from the layers list at the top of the *Identify Results* window (layers 06 and 07, respectively; Figure 52). The coordinates of the site can be found near the lower right hand corner of the map while moving the mouse to the location of the site (Figure 56). The streams layer and the roads layer are shown for orientation. The label feature of the subdivision layer and the streams layer are turned on to assist in identifying map features. The site is located in the valley section of the UCR hydrologic subsystem (Figure 57), and the hydrogeologic conceptual model for this area is shown in Figure 14.

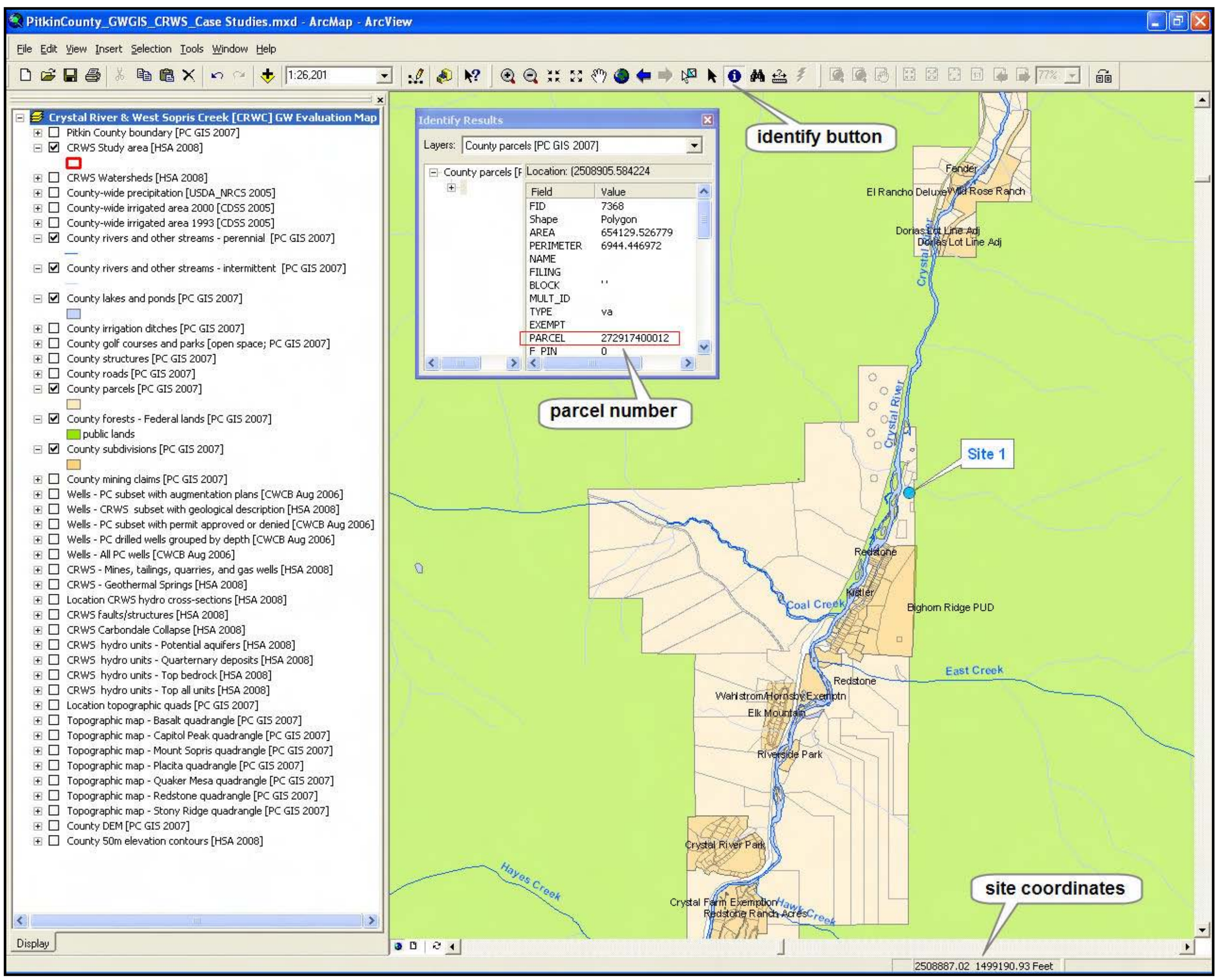


Figure 56. Locate Site 1 Using GIS Layers 06 and 07
(layers 11 and 12 [*streams*] are used for orientation).

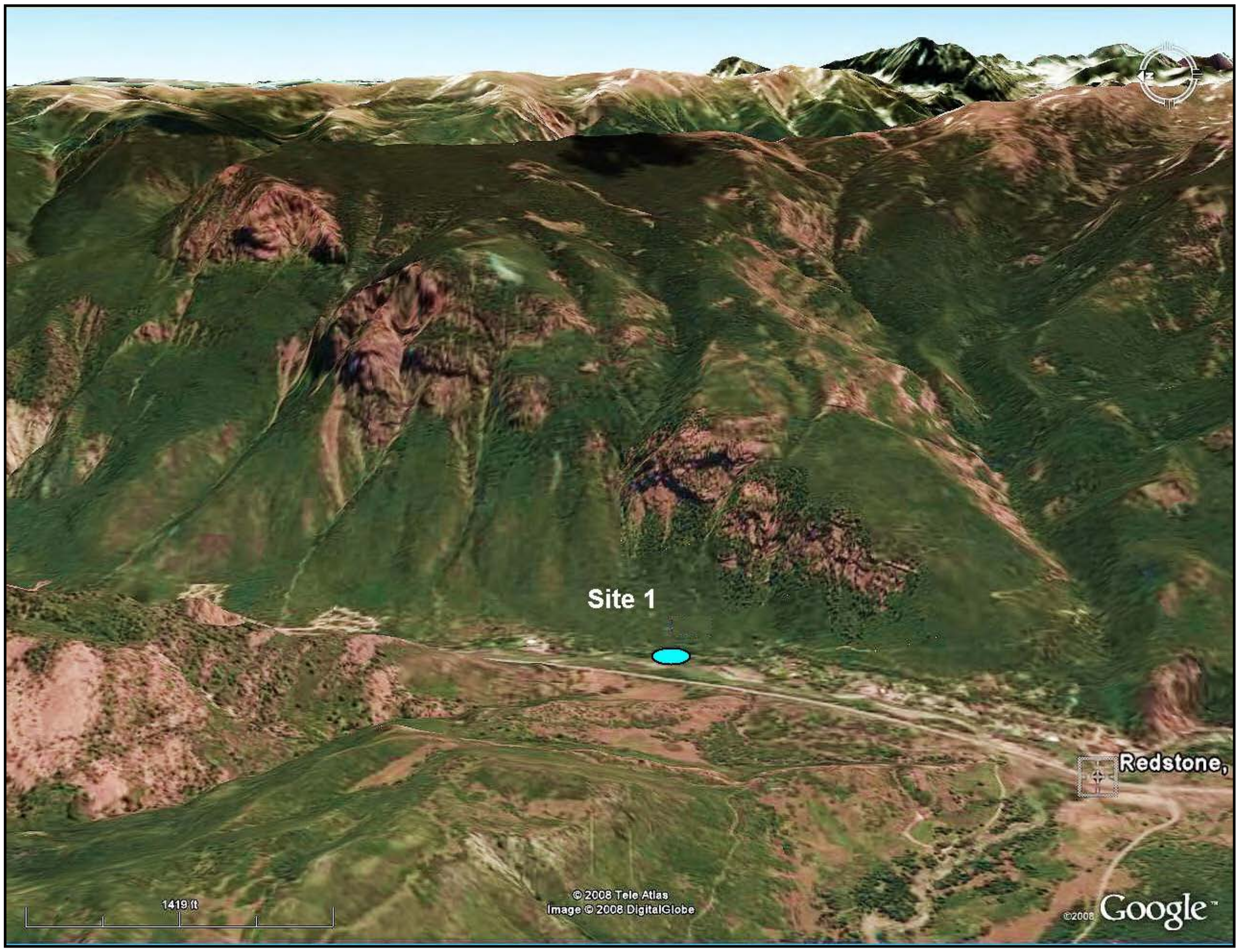


Figure 57. Google Earth View of Site 1 Looking East.

5.1.2 Determine Ground Water Availability

Using the *Identify* function on the menu bar and turning on the *Hydrounits - Potential aquifers* layer (layer 28) from the GIS map's table of contents, it is determined that the potential aquifer material is Qls (landslide deposits, colluvium; Figures 14 and 58). From using the *Identify* function for the *Hydrounits - Top bedrock* layer (layer 30), the underlying bedrock unit is determined to be PPmm (Maroon and Minturn Formations; Figure 59). From the discussion of the UCR subsystem in chapter 2 and the mapping of potential aquifer units (layer 28), it is concluded that the PPmm unit at the site is not a major aquifer. However, on a local scale, the Maroon/Minturn behaves as a fractured crystalline rock and may provide sufficient connectivity between surficial sediments and bedrock aquifer to sustain a surficial aquifer. This means that the surficial aquifer, if water bearing, is connected to and sustained by the underlying bedrock unit and that aquifer sustainability is determined both by subregional recharge at the higher elevations to the east of the site.

Further study of the topography in the vicinity of the site (layers 38, 40, 41 and Figure 57), in conjunction with the hydro units, indicates that rapid runoff from snowmelt and summer storms from the steep slopes east of the site through the intermittent stream just north of the site also recharges the surficial aquifer at the site. Note that there is no confining unit present in the vicinity of the site and that both the surficial unit and the bedrock are under unconfined conditions.

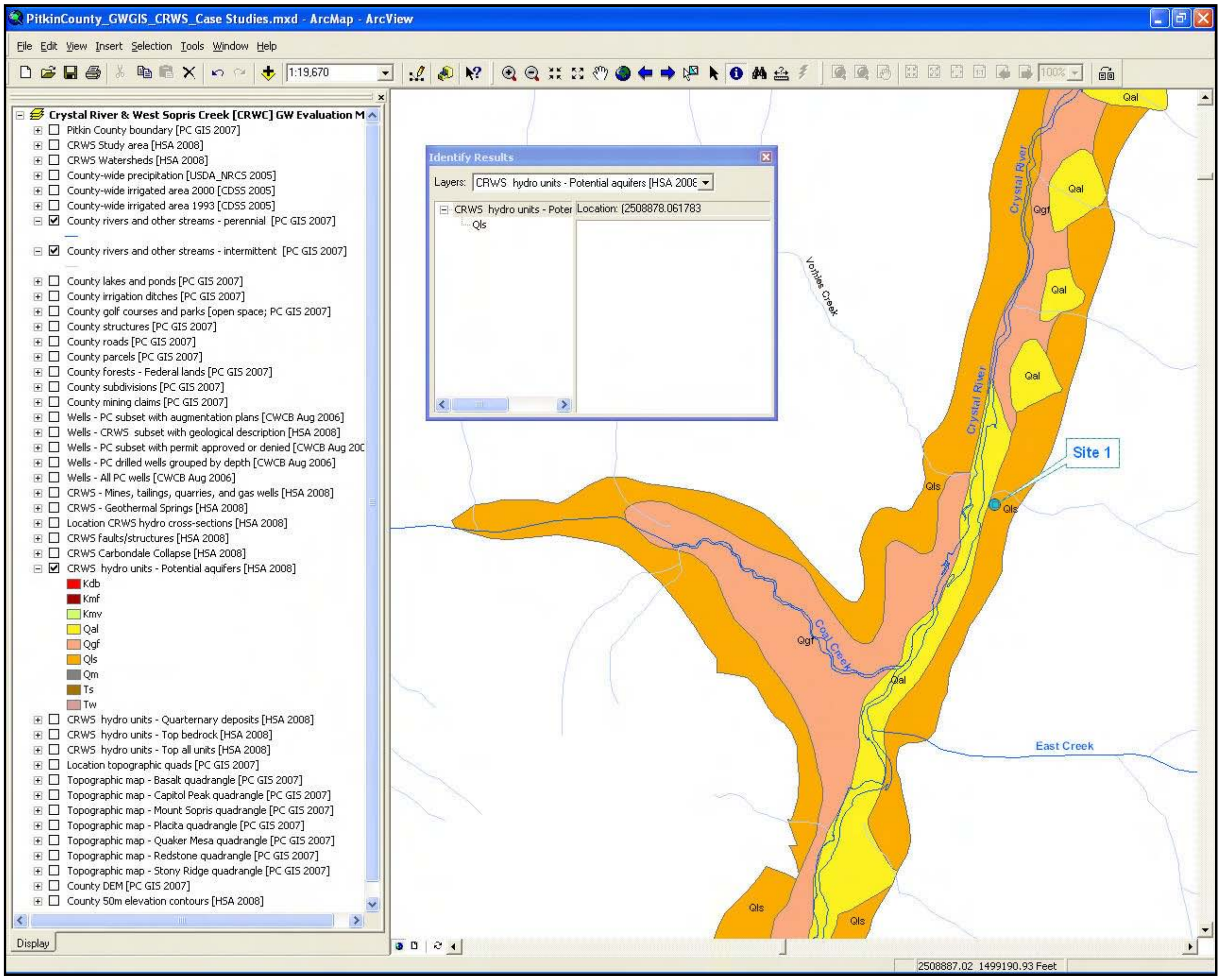


Figure 58. Determine the Potential Presence of an Unconsolidated Aquifer at Site 1 Using GIS Layer 28.

The next step is to determine if the unconsolidated material is saturated or unsaturated. This determination is made on the basis of information from nearby wells (if present), the water levels in nearby streams in conjunction with ground elevation at the site, and other landscape details.

Layer 22 (*drilled wells grouped by depth*) is turned on to identify relevant nearby wells. There is 1 well nearby that may provide relevant information (permit # 148743; Figure 60). Other wells nearby are either too shallow (permit # 95815), on the opposite side of the river (permit #54638), or to far form the site (permit # 15045). The well(s) of interest can be selected using the *Select Tool* from the *Tools* toolbar (Figure 60). From the attribute table of layer 22, well depth, depth to static water level at time of drilling, well production (gallon per minute yield), and time of year of drilling can be evaluated with respect to pre-development saturated thickness (Figure 60; see Appendix 2 for explanation of field names). To display only the subset of selected wells, use the *Selected* button next to the *Show 'All' Records* button at the bottom of the attribute table (Figure 60).

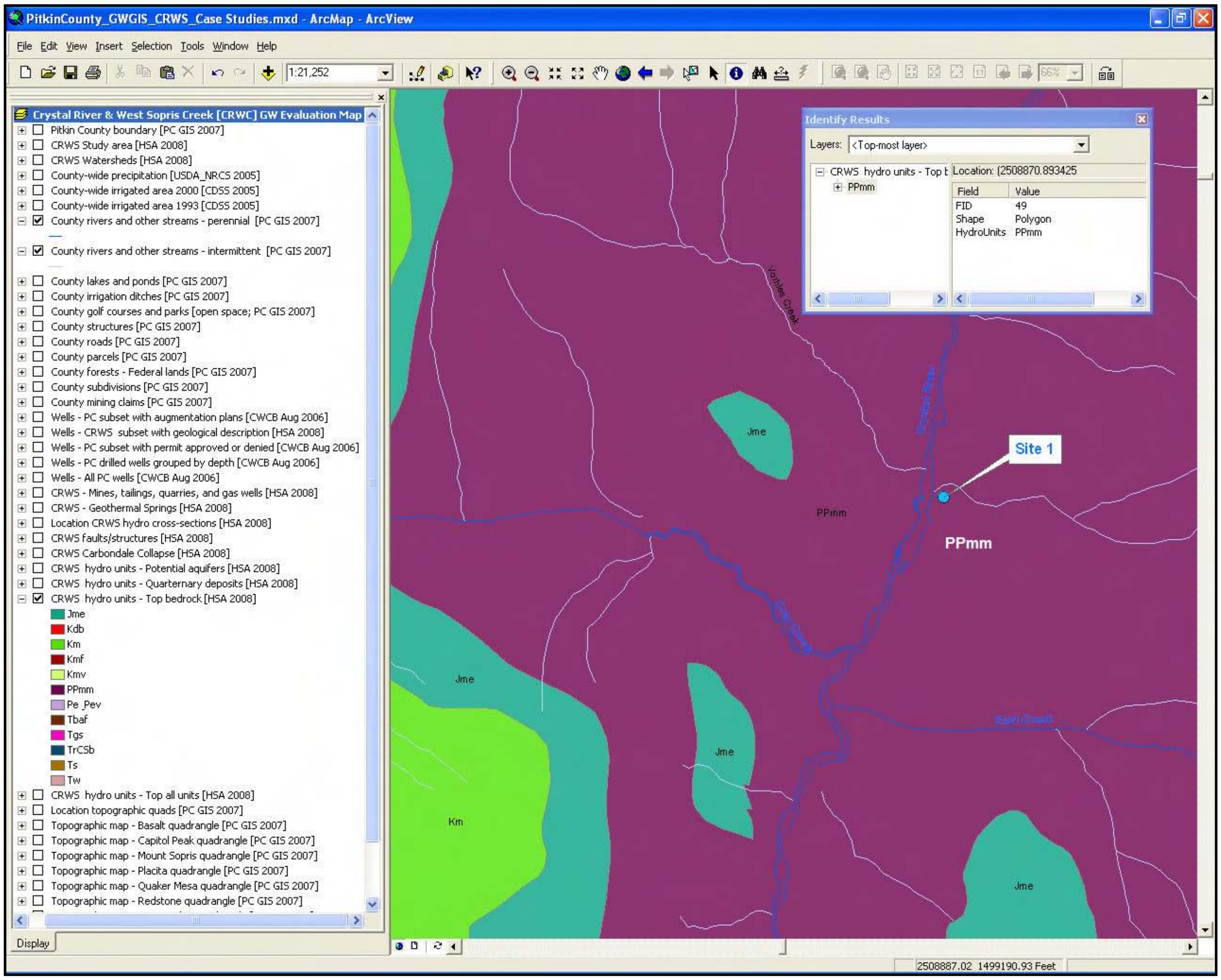


Figure 59. Determine the Hydrogeological Unit Underlying the Unconsolidated Aquifer at Site 1 Using GIS Layer 30.

From the map it appears that this well is located at the boundary between the Qls and Qal, but note that in this area, hydrogeologic mapping is based on the Environmental and Engineering Geology Study, Eagle, Garfield, Gunnison and Pitkin Counties, Colorado (scale 1:48,000; *Olander and Others*, *1974*), and may not have enough detail to make an accurate distinction between hydro units. The depth of well 148743 is 70ft with a screened interval from 39 to 54 ft. Static water level at time of drilling was 21 ft. The drilling of the well was probably halted at or near top bedrock, indicating a saturated thickness of the unconsolidated aquifer of at least 50 ft. Well yield was given as 10gpm.

5.1.3 Determine Ground Water Sustainability

The precipitation layer (layer 16) is turned on to assess the recharge potential from precipitation in the vicinity of the site. The site is located in an area that receives annually an average of about 31 inches of precipitation and has an estimated recharge ranging from 10 to 30 percent of direct recharge from precipitation per year (Figure 61). Additional recharge may occur during snowmelt as redistributed infiltration from surface runoff or interflow from higher elevations. Calculation of actual recharge amounts requires professional judgment using standard practices.

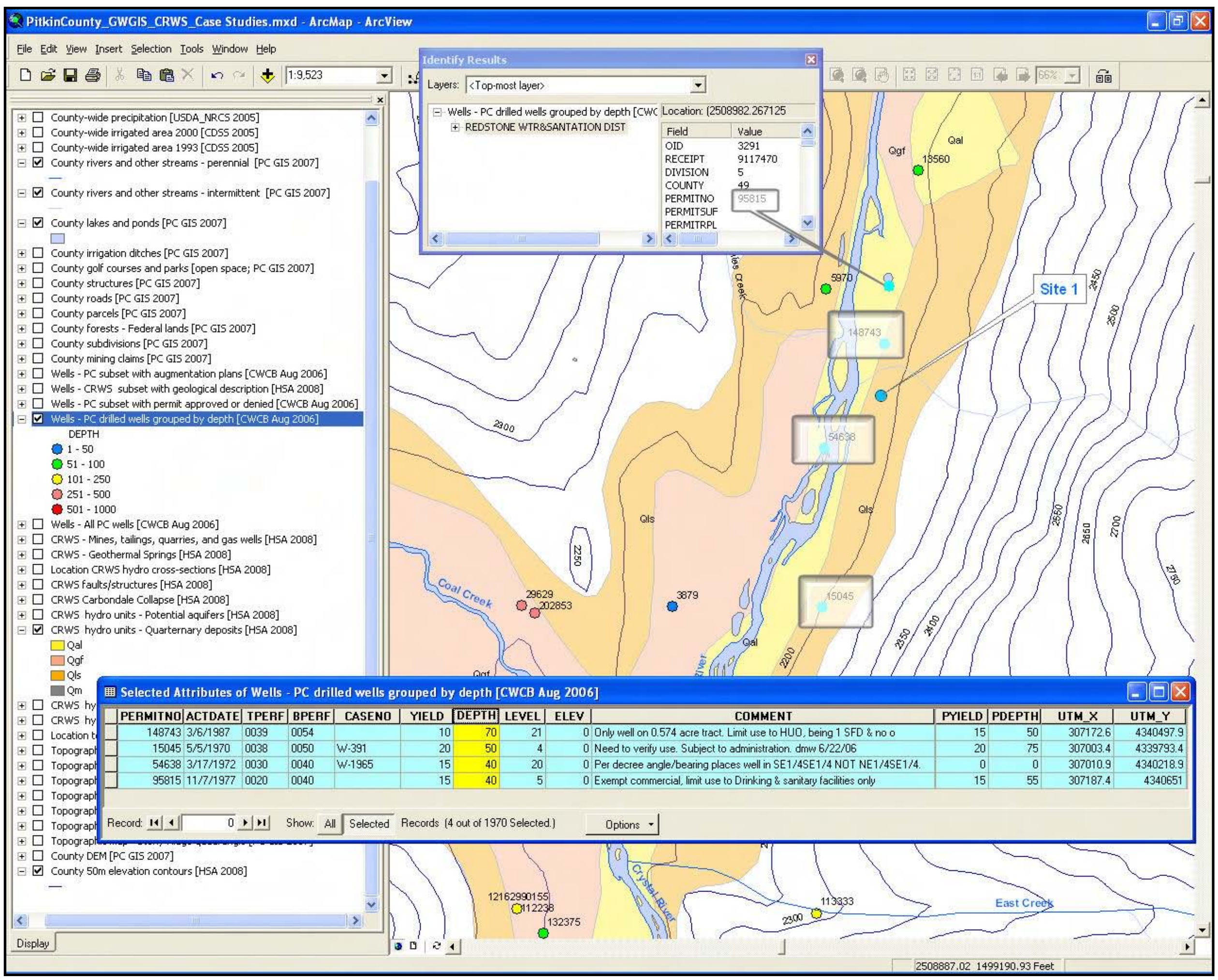


Figure 60. Identify Relevant Wells in the Vicinity of Site 1 Using GIS Layer 22.

The next step is to determine if the shallow aquifer is hydraulically connected or not-connected with a perennial stream. This step is performed to determine the potential for recharge to the aquifer from a nearby stream. First, layers 11 and 12 (*perennial and intermittent streams*) and layer 14 (*ponds*) are turned on (Figure 60). By analyzing the location of the streams in the context of the conceptual model of the UCR subsystem (Figure 14), it appears that a hydraulic connection exists between the unconsolidated materials in the vicinity of site 1 and the Crystal River.

Although little information is available with respect to ground water levels and flow direction, local topography and location and elevation of the Crystal River (Figure 60) indicate that ground water generally flows westwards to discharge into the river. The water wells near the river may have captured or new wells may capture this flow towards the river, potentially reversing local discharge to the stream and making the stream effluent (loosing) near the site.

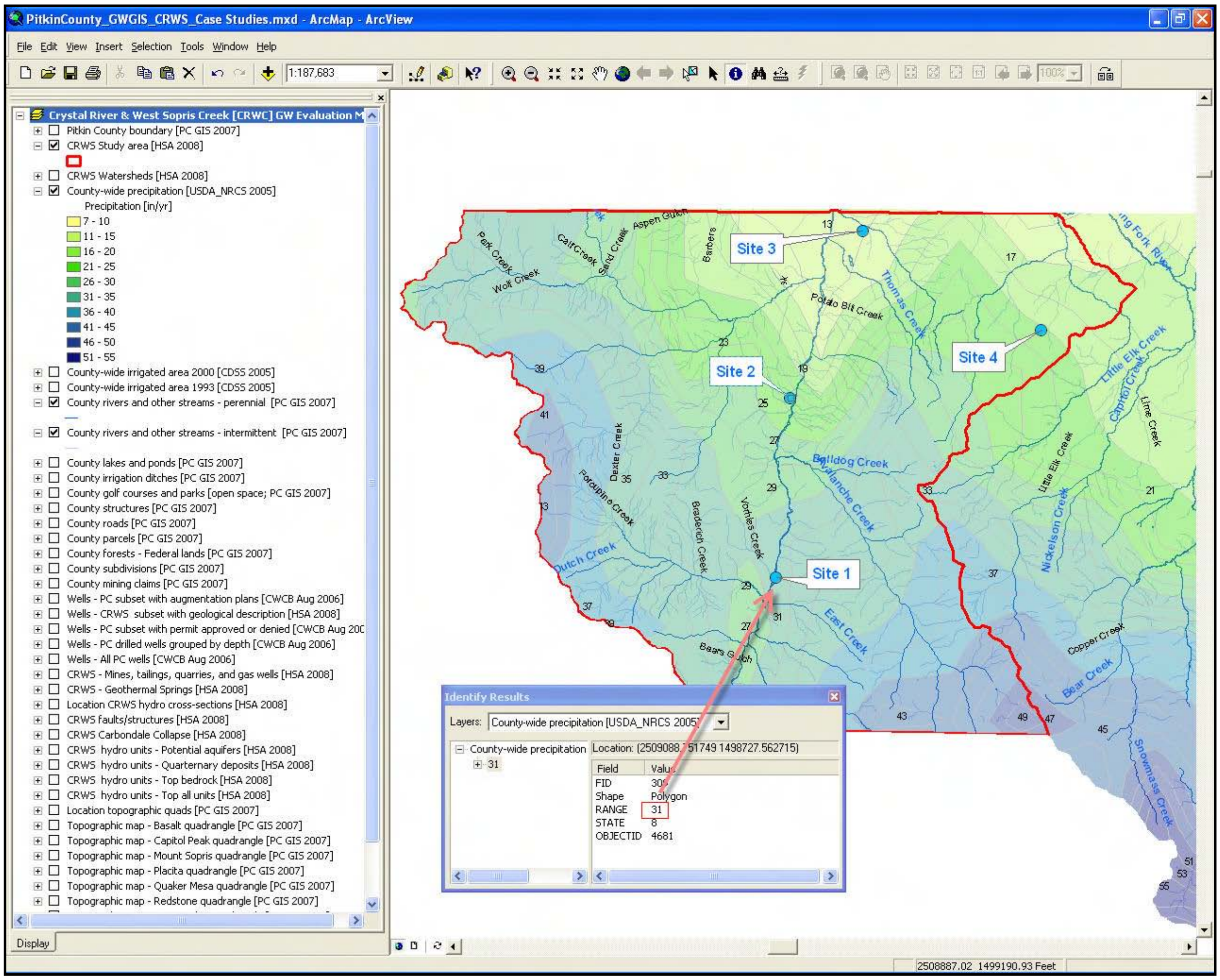


Figure 61. Determine Recharge from Precipitation in the Vicinity of Site 1 Using GIS Layer 16.

Layers 13 (*ditches*), 17 (*irrigated acreage 2000*), and 18 (*irrigated acreage 1993*) are used in conjunction with layer 29 (*surficial hydro units*) to determine if the shallow aquifer near site 1 is recharged by irrigation practices, which may not sustain a ground water supply if water uses and water-rights ownership change. Figure 61 shows that a single ditch and some irrigated areas are located to the southwest of the site, on the other side of the Crystal River. Thus, there is no irrigation return flow or ditch leakage recharging the surficial aquifer at the site.

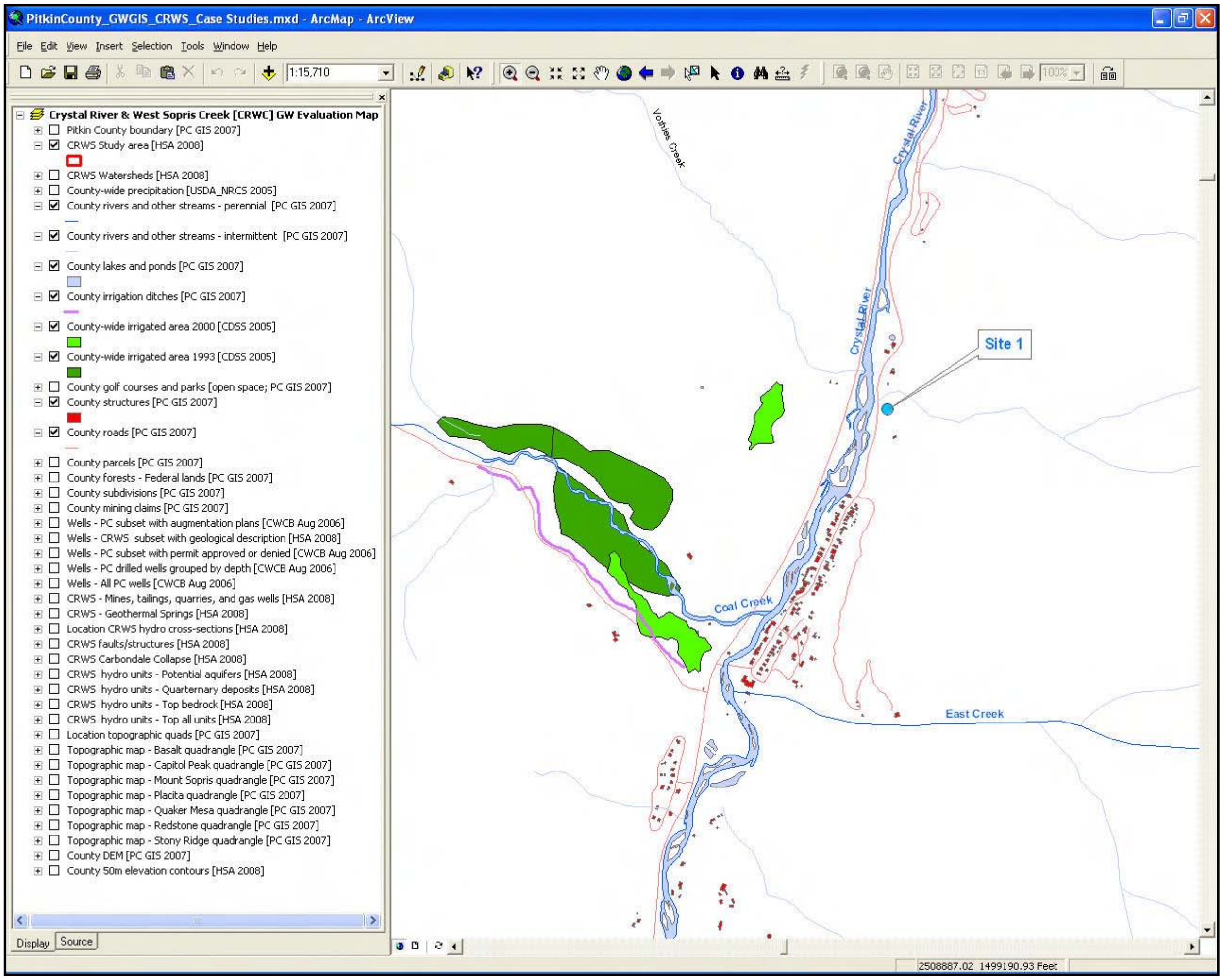


Figure 62. Determine Potential Recharge from Irrigation Return Flow and Ditch Leakage in the Vicinity of Site 1 Using GIS Layers 13, 17 and 18.
(Note, layers 4 [*structures*], 5 [*roads*] and 11 and 12 [*streams*] have been activated for orientation).

5.1.4 Determine Ground Water Vulnerability

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 with unconsolidated sediments, and bedrock aquifer outcrops or subcrops, is vulnerable to contamination from the land surface. Because the surficial aquifer and the shallow water table near site 1 is unprotected by a natural barrier, the ground water vulnerability in the area is considered high. Furthermore, wells near the Crystal River may draw stream water with a quality that is less than that of ground water recharged on the surrounding slopes. Also, this area may be particular vulnerable to contamination from neighboring ISDSs due to the hydrogeological conditions. Calculation of actual risk (both qualitatively and quantitatively) requires professional judgment using standard practices.

5.2 Example 2 in the Central Crystal River Valley

5.2.1 Identify Location on GIS Map

Example 2 is a site located on parcel #26491600004 [at about (Colorado State Plane, Central Zone NAD 83) coordinate 2511307, 1530186], south of the Crystal River Country Estates subdivision (blue marker dot; Figure 63). Parcel and subdivision details are found by using the *Identify* function on the menu bar and selecting the *County parcels* or *County subdivisions* layer from the layers list at the top of the *Identify Results* window (layers 06 and 07, respectively; Figure 52). The coordinates of the site can be found near the lower right hand corner of the map while moving the mouse to the location of the site (Figure 63). The streams layer and the roads layer are shown for orientation. The label feature of the subdivision layer and the streams layer are turned on to assist in identifying map features. The site is located on a terrace in the valley section of the CCR hydrologic subsystem (Figure 64), and the hydrogeologic conceptual model for this area is shown in Figure 18.

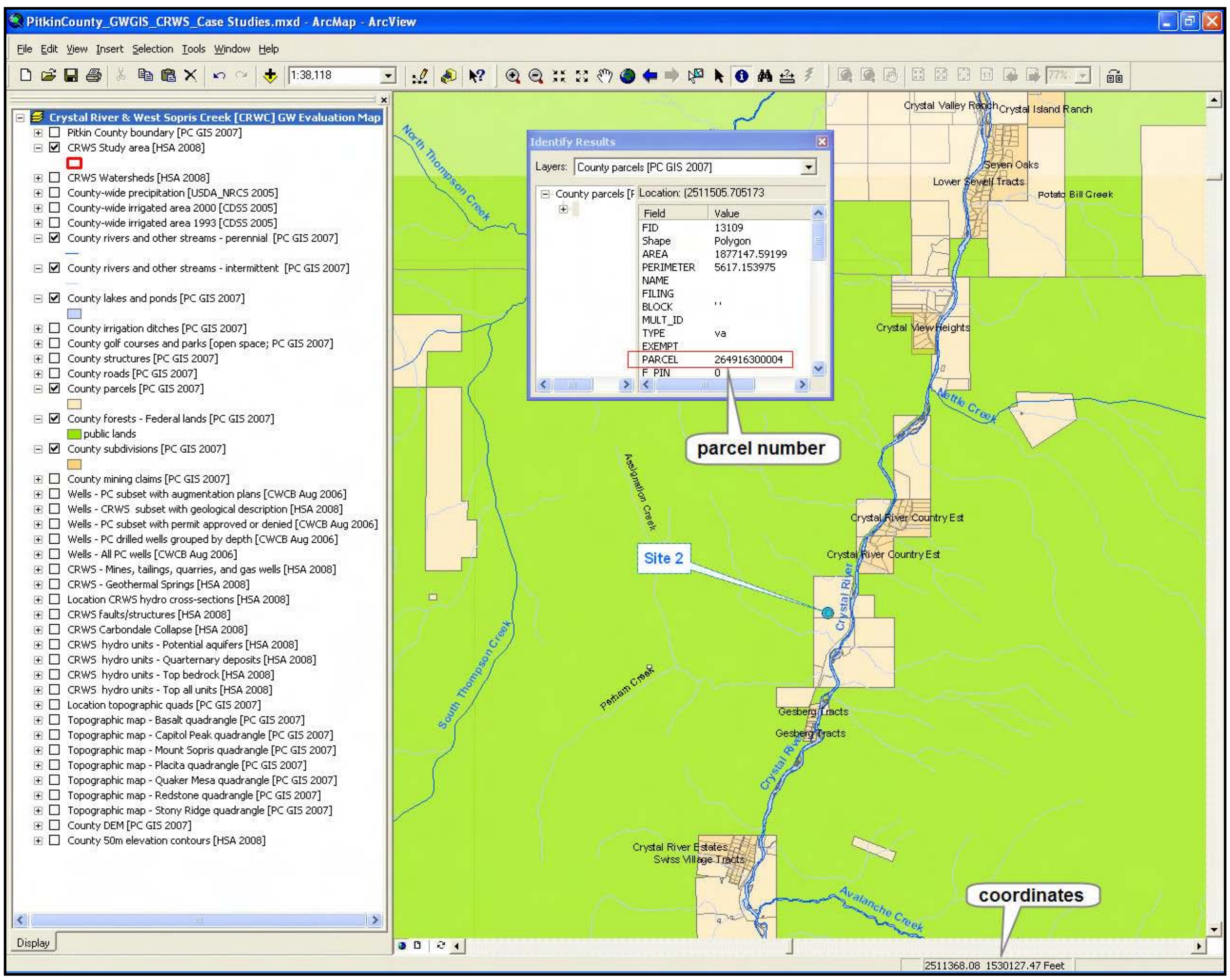


Figure 63. Locate Site 2 Using GIS Layers 06 and 07
(layers 11 and 12 [*streams*] are used for orientation).

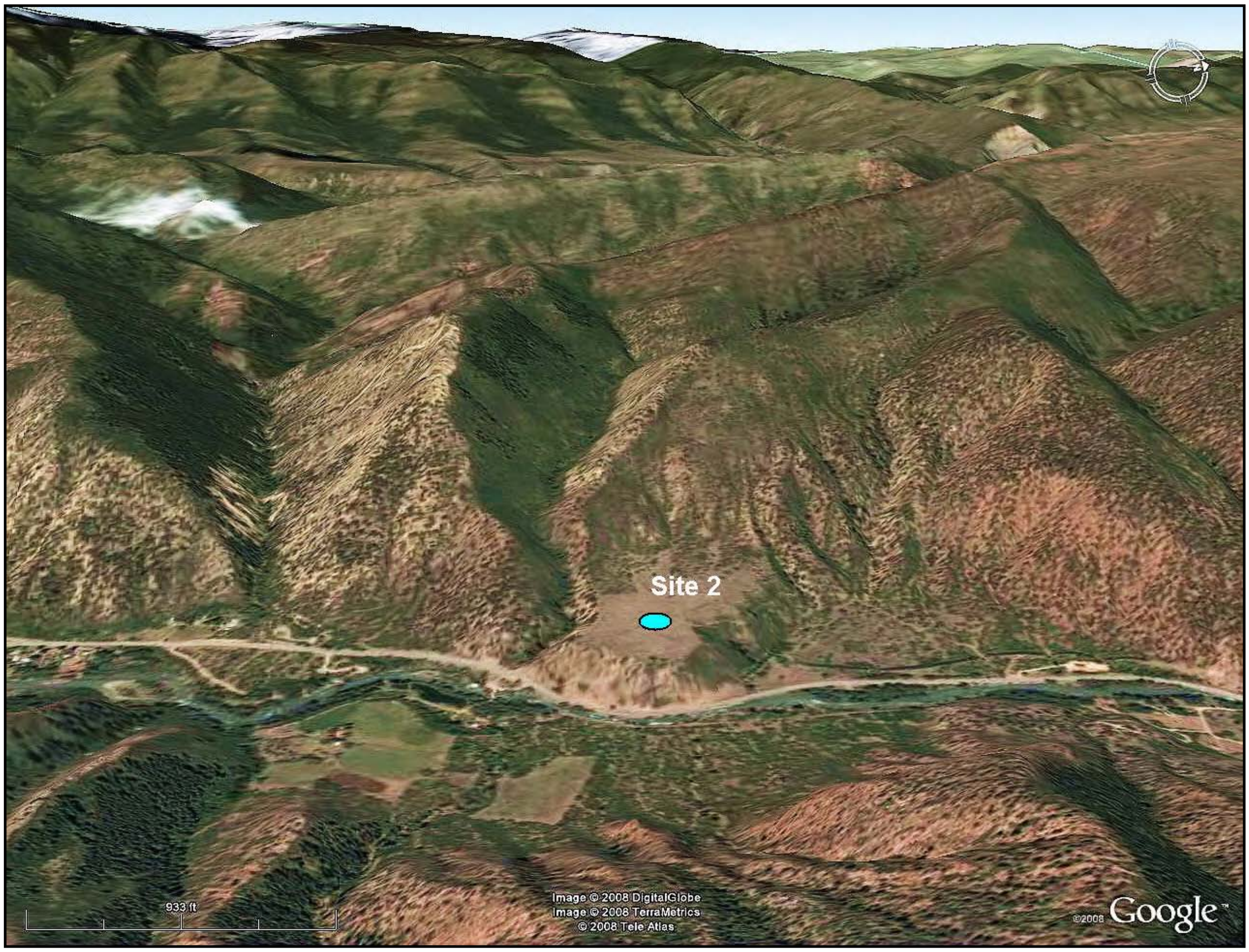


Figure 64. Google Earth View of Site 2 Looking West.

5.2.2 Determine Ground Water Availability

Using the *Identify* function on the menu bar and turning on the *Hydrounits - Potential aquifers* layer (layer 28) from the GIS map's table of contents, it is determined that the potential aquifer material is Qgf (terrace gravels, fan deposits; Figures 18 and 65). From using the *Identify* function for the *Hydrounits - Top bedrock* layer (layer 30), the underlying bedrock unit is determined to be Pe (Eagle Valley Formation; Figure 66). From the discussion of the CCR subsystem in chapter 2 and the mapping of potential aquifer units (layer 28), it is concluded that the Pe unit at the site is not an aquifer and behaves as an impermeable bedrock layer and can not sustain a surficial aquifer. This means that the sustainability of a surficial aquifer at the site, if water bearing, is doubtful.

Further study of the topography in the vicinity of the site (layers 38, 40, 41 and Figure 64), in conjunction with the hydro units, indicates that rapid runoff from snowmelt and summer storms from the hill slopes directly to the west through the intermittent streams just north and south of the site bypass the potential aquifer at the site.

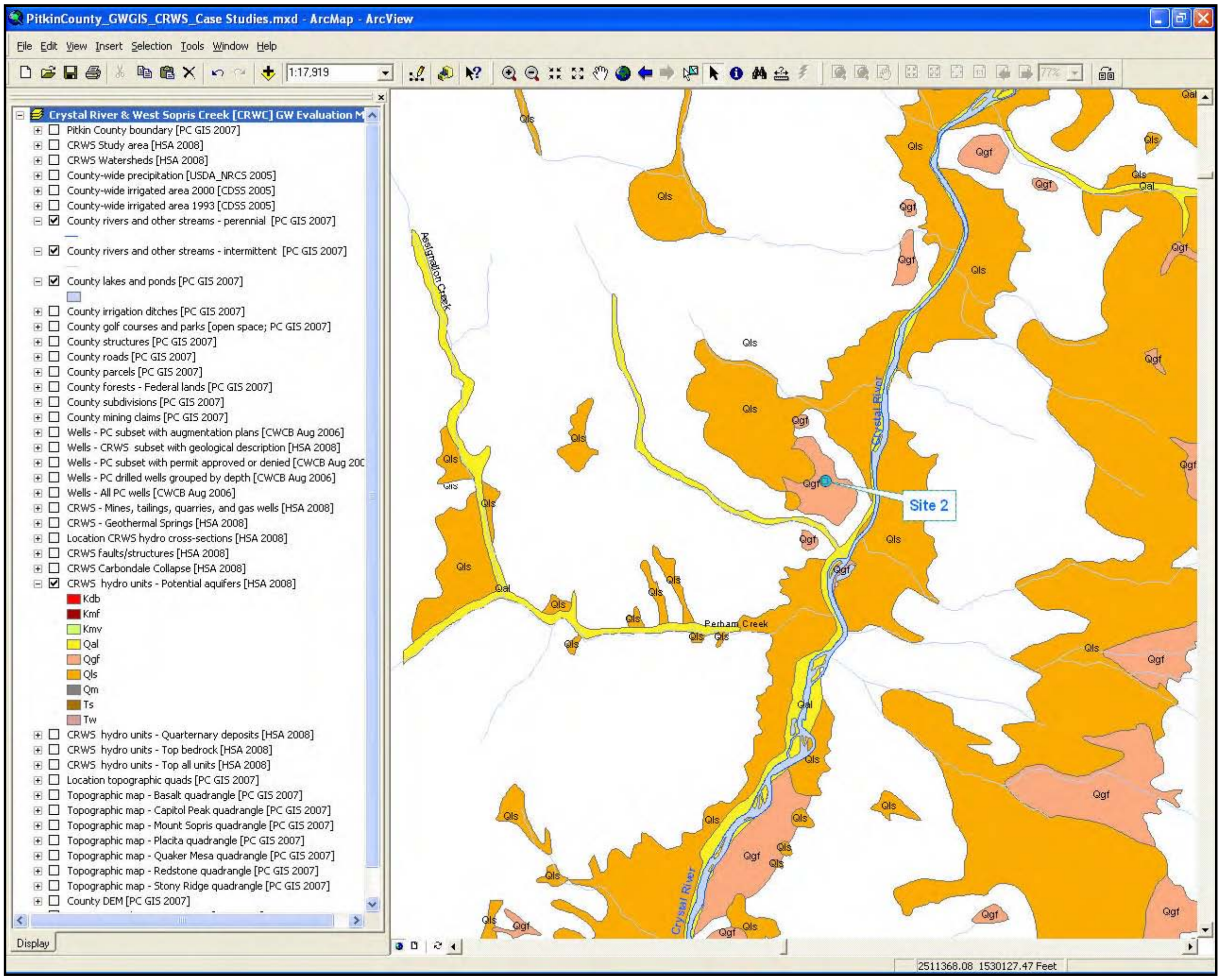


Figure 65. Determine the Potential Presence of an Unconsolidated Aquifer at Site 2 Using GIS Layer 28.

The next step is to determine if the unconsolidated material is saturated or unsaturated. This determination is made on the basis of information from nearby wells (if present), the water levels in nearby streams in conjunction with ground elevation at the site, and other landscape details.

Layer 22 (*drilled wells grouped by depth*) is turned on to identify relevant nearby wells. There are 2 wells nearby that may provide relevant information (permit # 114177 and 27490; Figure 67). Both wells are yellow-colored indicating that their depths fall in the range 101-250 ft. The wells can be selected using the *Select Tool* from the *Tools* toolbar (Figure 67). From the attribute table of layer 22, well depth, depth to static water level at time of drilling, well production (gallon per minute yield), and time of year of drilling can be evaluated with respect to pre-development saturated thickness (Figure 67; see Appendix 2 for explanation of field names). To display only the subset of selected wells, use the *Selected* button next to the *Show 'All' Records* button at the bottom of the attribute table (Figure 67).

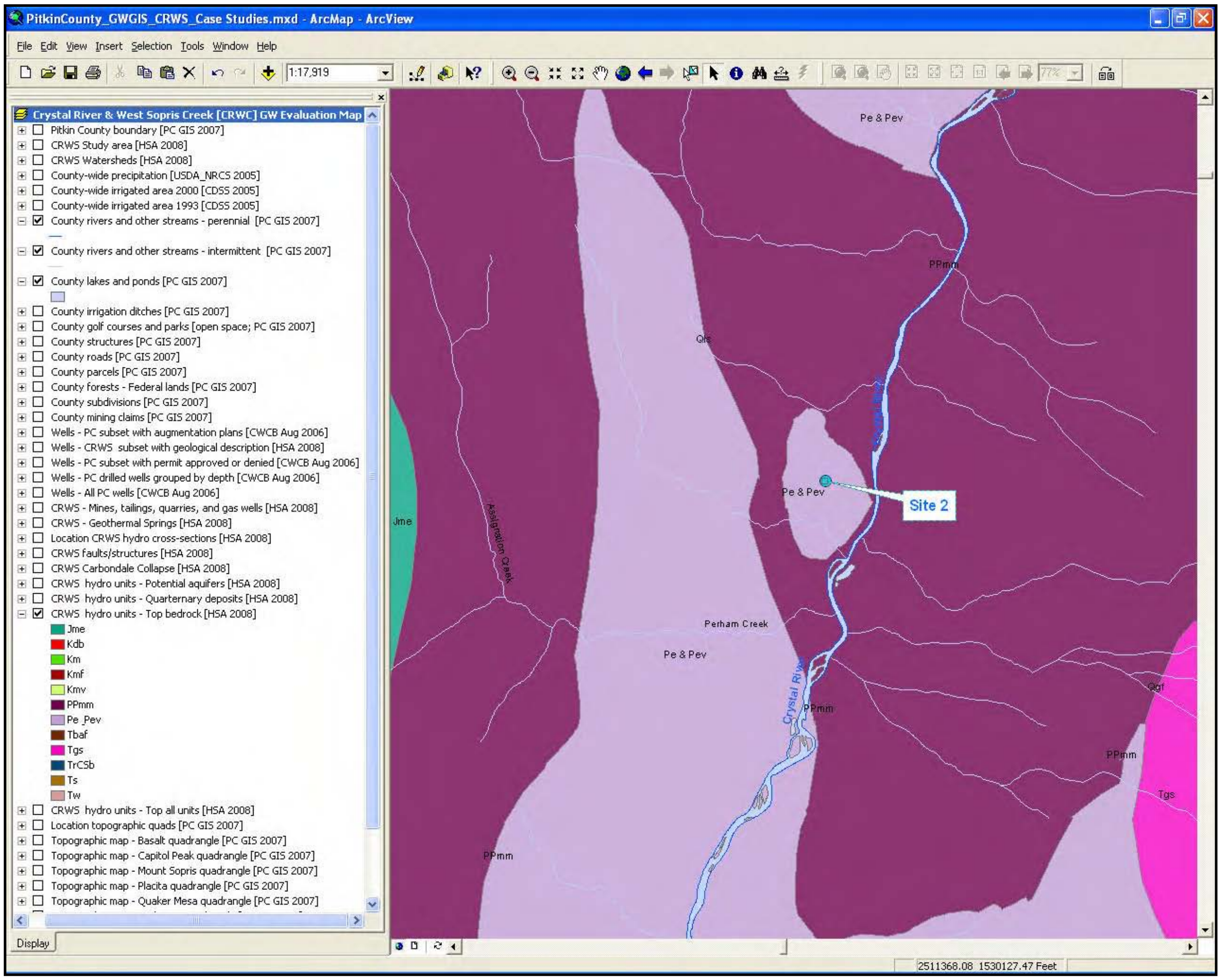


Figure 66. Determine the Hydrogeological Unit Underlying the Unconsolidated Aquifer at Site 2 Using GIS Layer 30.

From Figure 67 it appears that both wells are located in Qls and, because of their depth, probably reach into the Maroon/Minturn Formation (activate layer 30 and deactivate layer 28). The depth of well 114177 is 135ft. Ground elevation at this well is about 20ft higher than at site 2 (determined using layer 40 and the *Identify* function). There is no screened interval given, meaning that this well is probably an open non-screened bore hole in the bedrock. Static water level at time of drilling was 90ft. Yield was given as 15gpm, the maximum for *household use only* wells. The rather high yield for a bedrock well signals that the local permeability of the Maroon/Minturn unit beneath the Eagle valley Formation is enhanced by secondary fracturing, which presence is indicated by the course of the small stream directly south of the well (Figure 64). This information indicates that the Quarternary deposits were not considered reliable as a source of water.

The depth of well 27490 is 1305ft with a screened interval from 80 to 130 ft. Static water level at time of drilling was 70ft. Ground elevation at this well is about 50ft lower than at site 2. Yield for this well was given as 50gpm. The rather high yield for a bedrock well signals that the local permeability of the Maroon/Minturn unit (no Eagle Valley Formation at this location) is enhanced by secondary fracturing, which presence is indicated by the course of the small stream directly north of the well (Figure 64). Again, this information indicates that the Quarternary deposits were not considered reliable as a source of water.

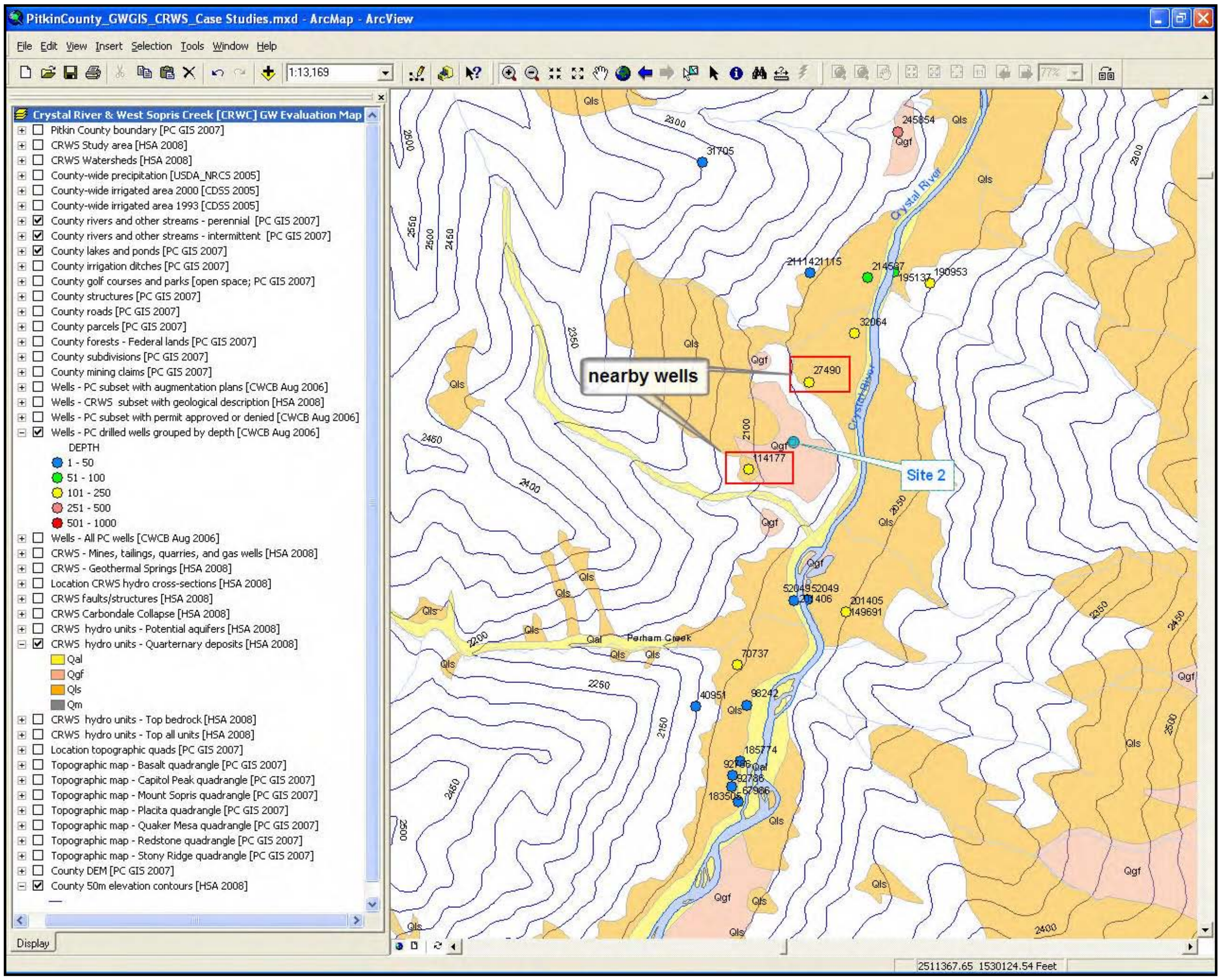


Figure 67. Identify Relevant Wells in the Vicinity of Site 2 Using GIS Layer 22.

5.2.3 Determine Ground Water Sustainability

The precipitation layer (layer 16) is turned on to assess the recharge potential from precipitation in the vicinity of the site. The site is located in an area that receives annually an average of about 23 inches of precipitation and has an estimated recharge ranging from 10 to 20 percent of direct recharge from precipitation per year (Figure 61). No additional recharge from snowmelt or summer storm runoff redistribution is expected. Calculation of actual recharge amounts requires professional judgment using standard practices.

The next step is to determine if the shallow aquifer is hydraulically connected or not-connected with a perennial stream. This step is performed to determine the potential for recharge to the aquifer from a nearby stream. First, layers 11 and 12 (*perennial and intermittent streams*) and layer 14 (*ponds*) are turned on (Figure 66). By analyzing the location of the streams in the context of the conceptual model of the CCR subsystem (Figures 18 and 64, layers 11, 12 and 41), it appears that there is no hydraulic connection between the unconsolidated materials in the vicinity of site 1 and the Crystal River, or even the intermittent streams directly north and south of the site.

Layers 13 (*ditches*), 17 (*irrigated acreage 2000*), and 18 (*irrigated acreage 1993*) are used in conjunction with layer 29 (*surficial hydro units*) to determine if the shallow aquifer near the site is recharged by irrigation practices, which may not sustain a ground water supply if water uses and water-rights ownership change. Figure 68 shows that there is a ditch located between the site and the Crystal River. However, the ditch is about 60 ft lower in elevation than the ground surface of the site (using the identify function on layer 40) and it is unlikely that, if the ditch is leaking, it would have any influence on the ground water conditions at the site. The only irrigated areas are located on the east side of the Crystal River, having no potential as irrigation return flow at the site.

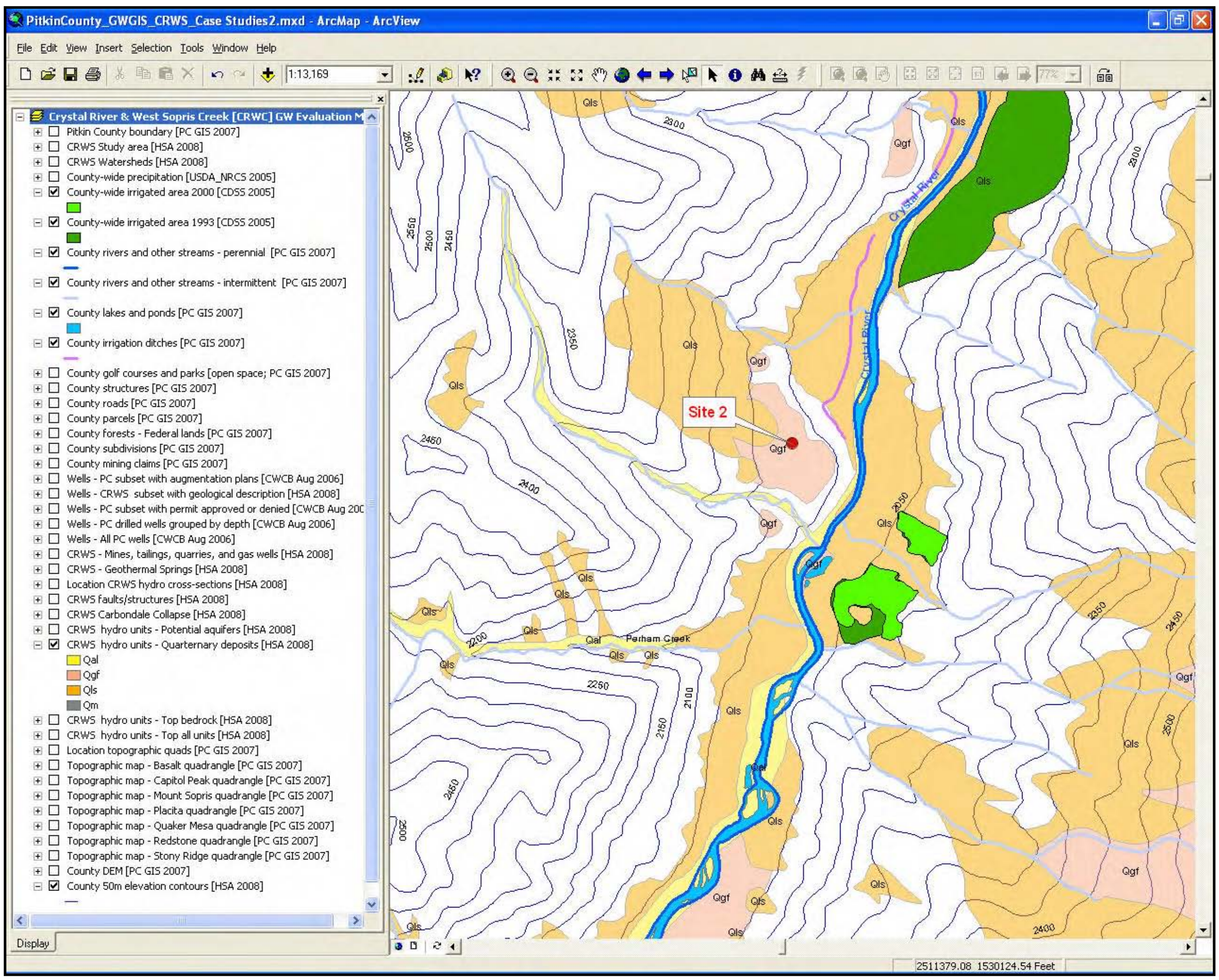


Figure 68. Determine Potential Recharge from Irrigation Return Flow and Ditch Leakage in the Vicinity of Site 2 Using GIS Layers 13, 17 and 18.

(Note, layers 11 and 12 [*streams*], 29 (*Quarternary units*) and 41 [*elevation contours*] have been activated for orientation).

5.2.4 Determine Ground Water Vulnerability

Natural protection from overlying confining units is important for maintaining natural water quality. All ground water in the area with unconsolidated sediments, and bedrock aquifer outcrops or subcrops, is vulnerable to contamination from the land surface. If an adequate supply is found in the Maroon/Minturn unit at the site in the absence of a reliable surficial aquifer, it may be somewhat protected from contamination from the surface in the direct vicinity of the site (such as from an ISDS) by the rather low permeability of the Eagle Valley Formation. However, its recharge area (*i.e.*, surrounding Maroon/Minturn unit not covered by the Eagle Valley unit) may be exposed. Therefore, the ground water vulnerability at the site is considered moderate. Calculation of actual risk (both qualitatively and quantitatively) requires professional judgment using standard practices.

5.3 Example 3 in the Lower Crystal River Valley

5.3.1 Identify Location on GIS Map

Example 3 is a site located on parcel #246314400010 [at about (Colorado State Plane, Central Zone NAD 83) coordinate 2523828, 1559000], southeast of the Stark Mesa subdivision (blue marker dot; Figure 69). Parcel and subdivision details are found by using the *Identify* function on the menu bar and selecting the *County parcels* or *County subdivisions* layer from the layers list at the top of the *Identify Results* window (layers 06 and 07, respectively; Figure 52). The coordinates of the site can be found near the lower right hand corner of the map while moving the mouse to the location of the site (Figure 69). The streams layer and the roads layer are shown for orientation. The label feature of the subdivision layer and the [perennial] streams layer are turned on to assist in identifying map features. The site is located in the LCR hydrologic subsystem (Figure 70), and the hydrogeologic conceptual model for this area is shown in Figures 21a and 21b.

5.3.2 Determine Ground Water Availability

Using the *Identify* function on the menu bar and turning on the *Hydrounits - Potential aquifers* layer (layer 28) from the GIS map's table of contents, it is determined that the potential aquifer material is Qgf (gravels and fans) in conjunction with Ts (Tertiary sediments; Figures 21b and 71). Using the *Hydrounits - Top bedrock* layer (layer 30; Figure 72), it appears that the top bedrock unit is the weakly cemented Tertiary sediments unit. Based on information given in Figure 21b and Table 1, the underlying bedrock unit is determined to be Pe (Eagle Valley Formation and Evaporites). From the discussion of the LCR subsystem in chapter 2, it is concluded that the Pe unit at the site has, in general, a low permeability and can be considered the impermeable base of the local Qgf/Ts aquifer system. This means that the Qgf unit, if water bearing, is part of a larger aquifer system that includes the underlying Ts unit . Therefore, at this site, aquifer sustainability is determined both by local recharge and subregional recharge at the higher elevations to the south of the site. As there is no confining unit present in the vicinity of the site, both the Qgf and Ts units are under unconfined conditions.

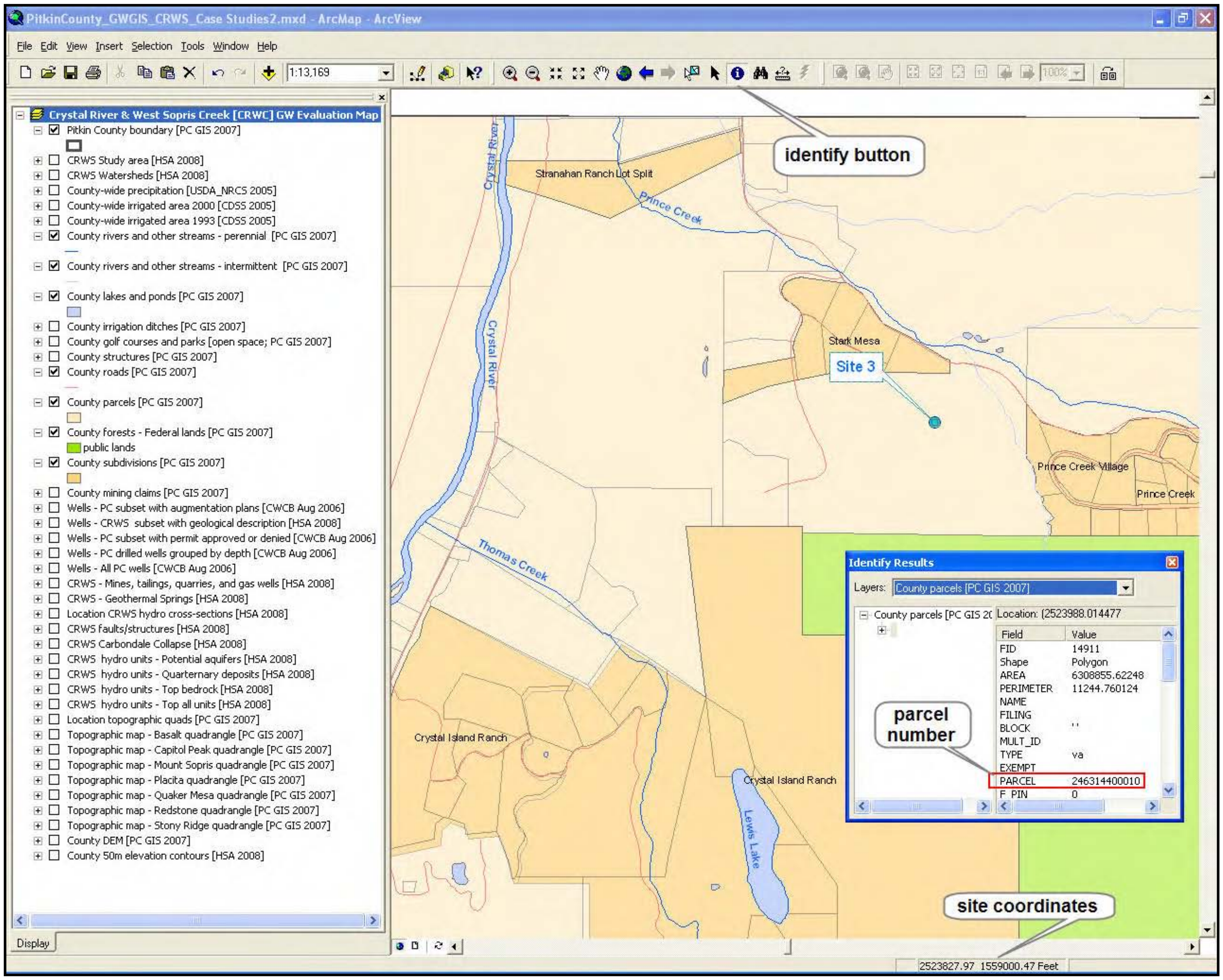


Figure 69. Locate Site 3 Using GIS Layers 06 and 07
(layers 11 and 12 [*streams*] and 5[*roads*] are used for orientation).

The next step is to determine if the unconsolidated material is saturated or unsaturated. At this site, this means that first the presence of ground water in the Qf unit needs to be determined. If there is no year-round ground water present in the Qf unit, then thw focus should be on the Ts unit for further analysis. This determination is made on the basis of information from nearby wells (if present), the water levels in nearby streams in conjunction with ground elevation at the site, and other landscape details.

Layer 22 (*drilled wells grouped by depth*) is turned on to identify relevant nearby wells. There are 7 wells nearby that may provide relevant information (permit # 165735, 35455, 161275, 246868, 51675, 149657, and 46725; Figure 73). Although these wells are some distance away from site 3, they are relevant because of their location within the local hydrogeologic system. From the attribute table of layer 22, well depth, depth to static water level at time of drilling, well production (gallon per minute yield), and time of year of drilling can be evaluated with respect to pre-development saturated thickness (Figure 73; see Appendix 2 for explanation of field names). Note that well 165735 was drilled twice, first in 1992 as a screened well with a yield of 1.8 gpm and a depth of 380 ft, and a second time, unscreened, in 1999 in a slightly different location with a yield of 3.5 gpm and a depth of 440.

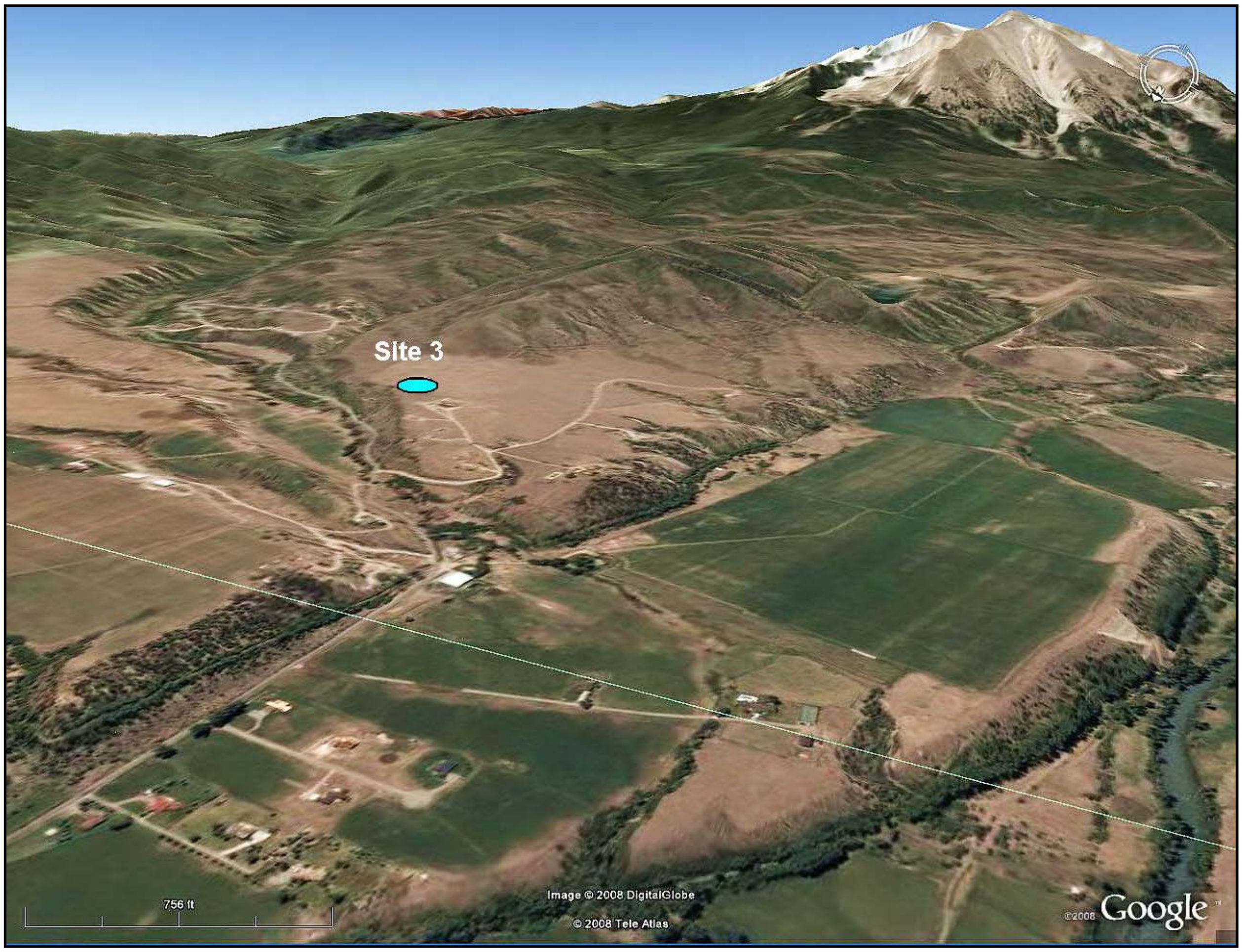


Figure 70. Google Earth View of Site 3 Looking Southeast.
(The blue line across the lower part of the figure reflects the approximate location of the northern county line).

From the map, it appears that the water table in most wells is at depths ranging from over 100 ft to more than 200 ft. The only exception is well 51675 near Prince Creek. This indicates that the water table in this area is mostly below the Qgf unit in the Ts unit. Thus, the main aquifer for site 3 is the Ts unit. Note that well 46725 was originally drilled to a depth of 335 ft and deepened in 2002 to 506 ft, probably because of diminished yield

5.3.3 Determine Ground Water Sustainability

The precipitation layer (layer 16) is turned on to assess the recharge potential from precipitation in the vicinity of the site. The site is located in an area that receives annually an average of about 13 inches of precipitation and is considered arid. This area has an estimated recharge of about 10 percent of direct recharge from precipitation per year (Figure 61). Calculation of actual recharge amounts requires professional judgment using standard practices.

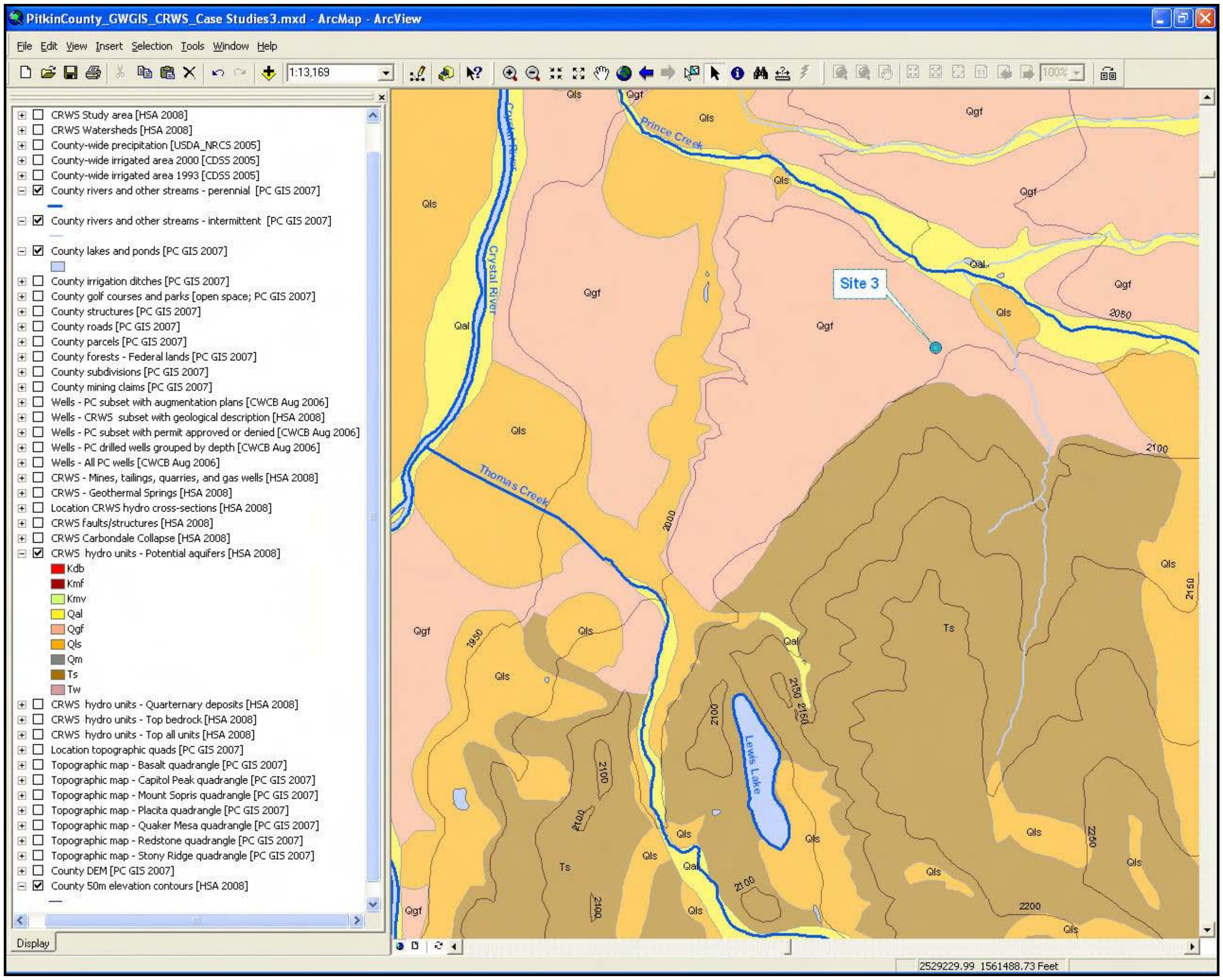


Figure 71. Determine the Potential Presence of an Unconsolidated Aquifer at Site 3 Using GIS Layer 28.

The next step is to determine if the aquifer is hydraulically connected or not-connected with a perennial stream. This step is performed to determine the potential for recharge to the aquifer from a nearby stream. First, layers 11 and 12 (*perennial and intermittent streams*) and layer 14 (*ponds*) are turned on (Figure 74). By analyzing the location of the streams in the context of the conceptual model of the LCR subsystem (Figure 21b), it appears that a hydraulic connection exists between the Tertiary sediments in the vicinity of site 1 and Prince Creek.

Further study of the topography in the vicinity of the site (layers 38, 40, 41 and Figure 71), in conjunction with the hydro units, indicates that rapid runoff from snowmelt and summer storms from the slopes of Mount Sopris will recharge the lower portions of the aquifer (the Ts unit), either directly or through infiltration from Prince Creek (Prince Creek becoming a loosing stream at lower elevations).

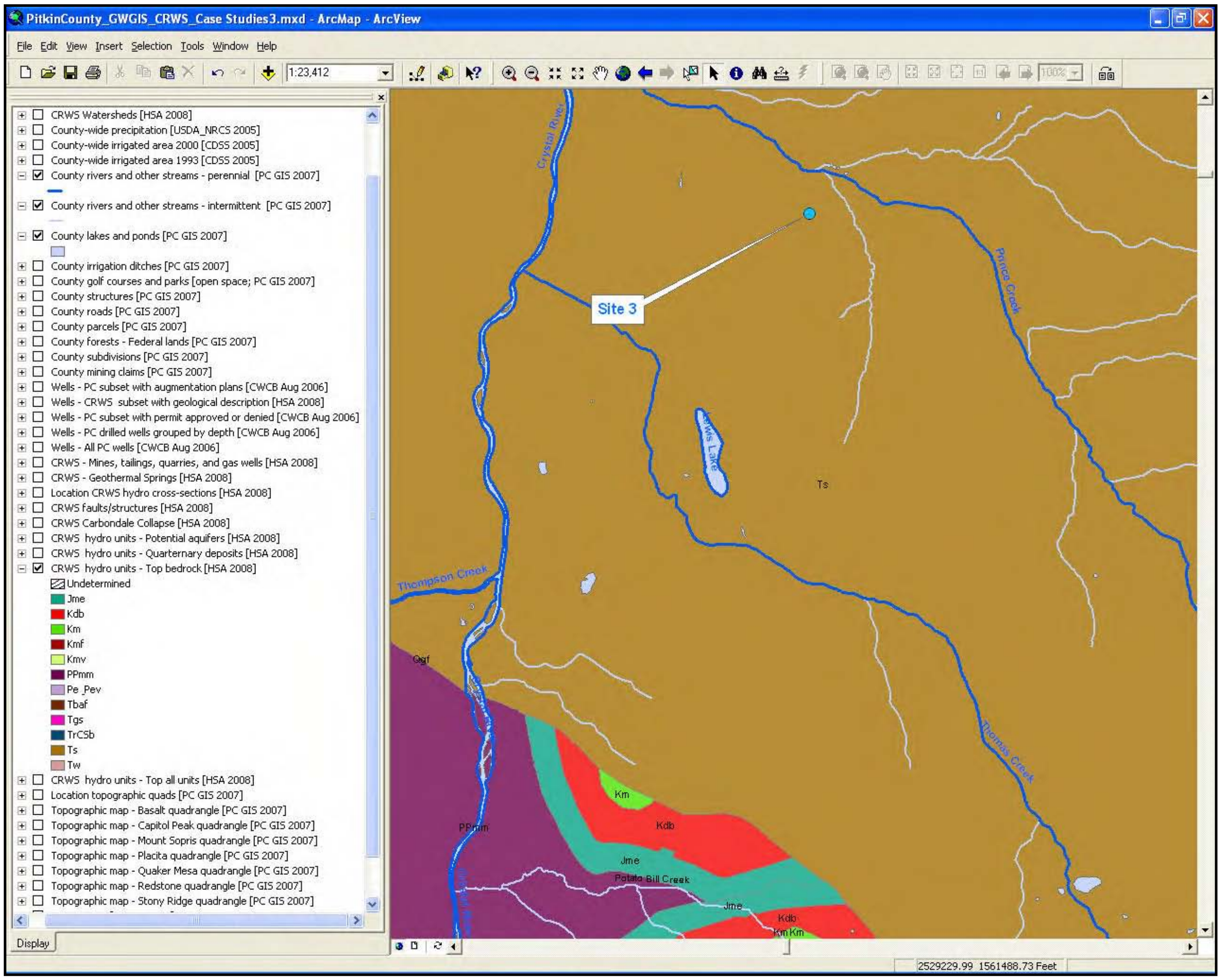


Figure 72. Determine the Hydrogeological Unit Underlying the Quarternary Unit at Site 3 Using GIS Layer 30.

Layers 13 (*ditches*), 17 (*irrigated acreage 2000*), and 18 (*irrigated acreage 1993*) are used in conjunction with layer 29 (*surficial hydro units*) to determine if the aquifer near site 3 is recharged by irrigation practices, which may not sustain a ground water supply if water uses and water-rights ownership change. Figure 74 shows an extensive network of irrigation ditches and large sections of irrigated areas. Thus, there is irrigation return flow or ditch leakage recharging the surficial aquifer is significant at the site.

5.3.4 Determine Ground Water Vulnerability

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 with unconsolidated or weakly cemented sediments is vulnerable to contamination from the land surface. As the aquifer system near site 3 is unprotected by a natural barrier, but depth to water is rather large, the ground water vulnerability in the area is considered moderately high. Another concern is the presence of extensive irrigated acreage. Irrigation return flow may be of lesser quality than native ground water due to the use of agricultural chemicals. The presence of cattle may have a negative influence on the quality of local recharge. Calculation of actual risk (both qualitatively and quantitatively) requires professional judgment using standard practices.

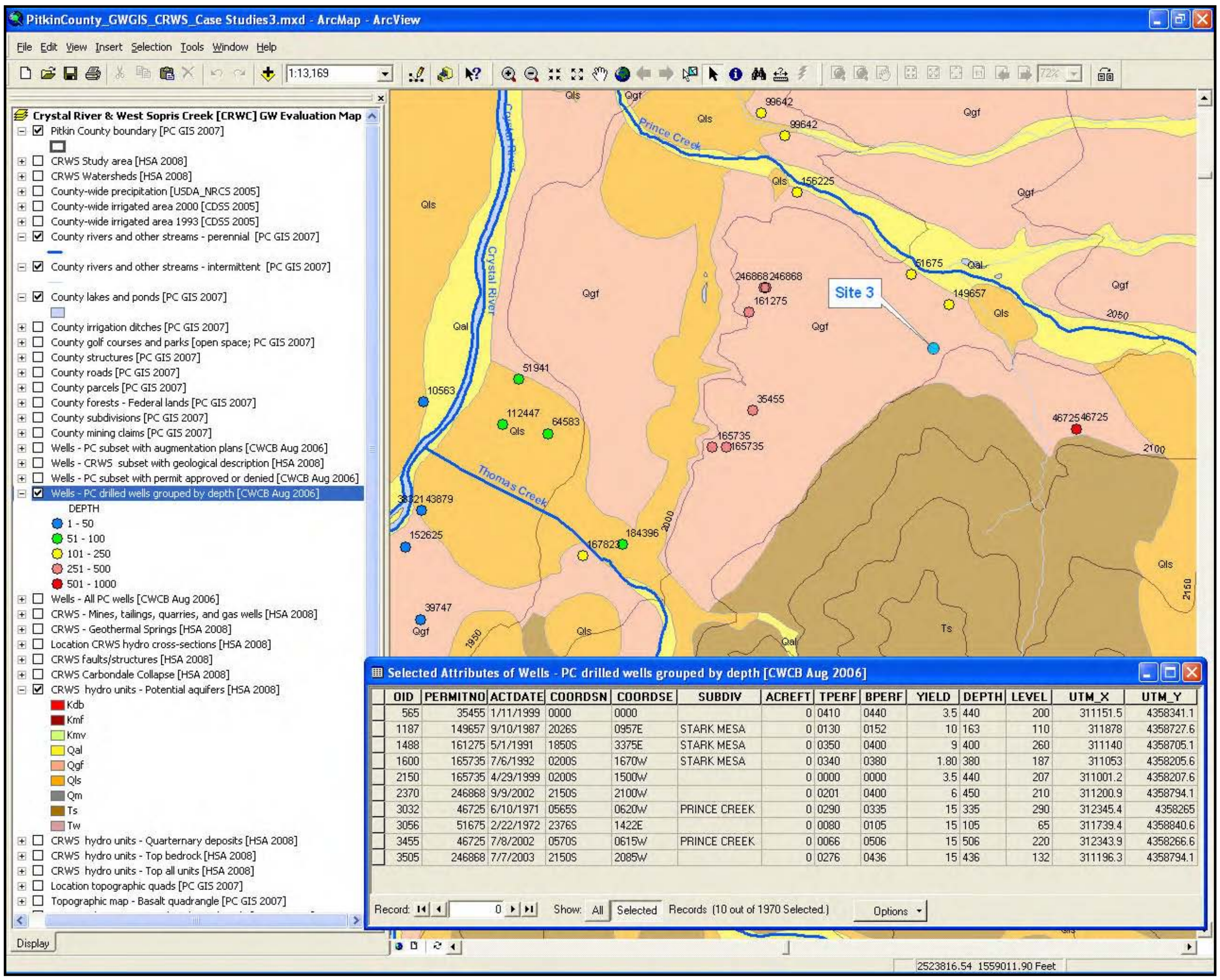


Figure 73. Identify Relevant Wells in the Vicinity of Site 3 Using GIS Layer 22.

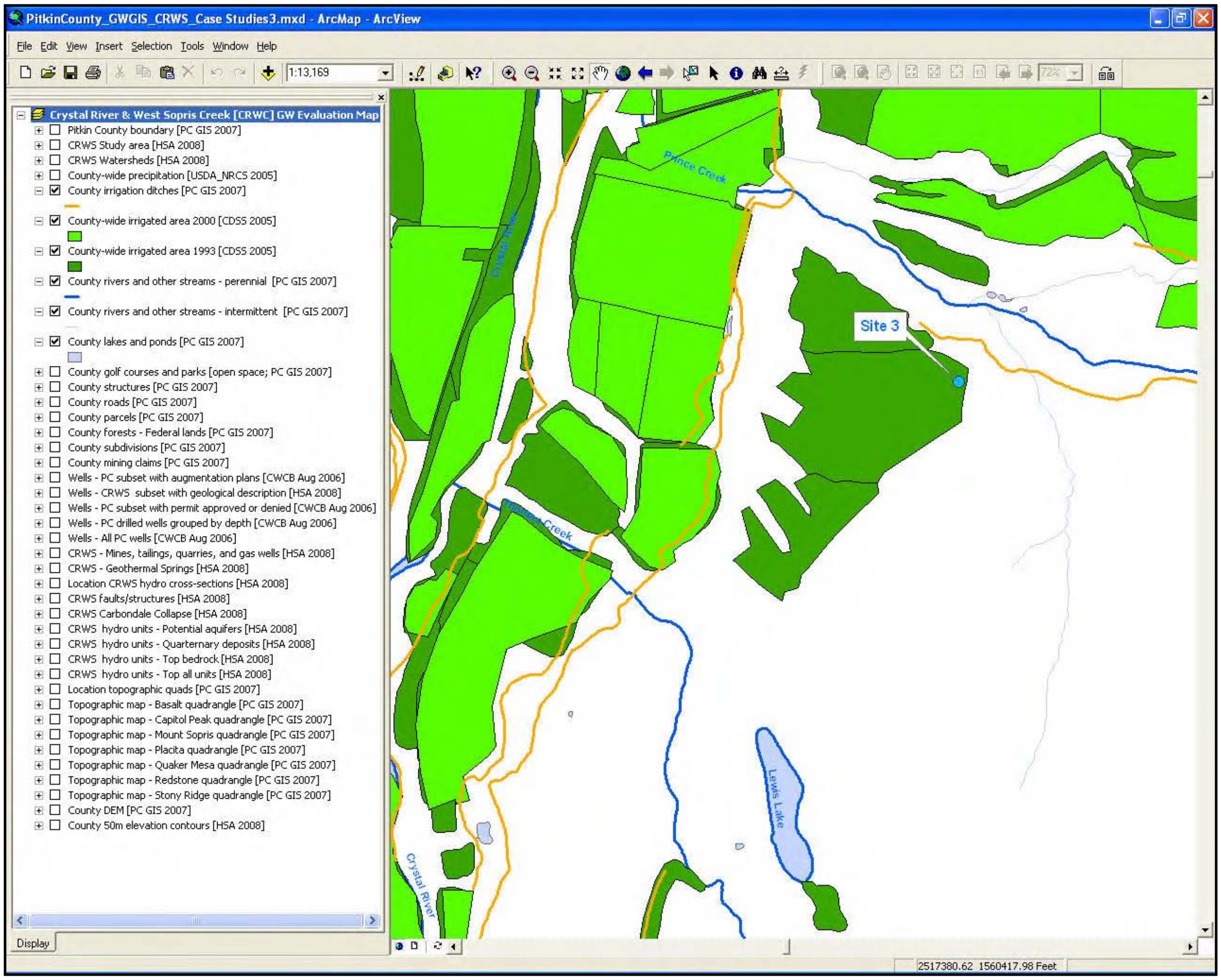


Figure 74. Determine Potential Recharge from Irrigation Return Flow and Ditch Leakage in the Vicinity of Site 3 Using GIS Layers 13, 17 and 18.

5.4 Example 4 in the West Sopris Creek Watershed

5.4.1 Identify Location on GIS Map

Example 4 is a site located on parcel #246535400011 [at about (Colorado State Plane, Central Zone NAD 83) coordinate 2554655, 1541940], east of the Sopris Mountain Ranch subdivision (blue marker dot; Figure 75). Parcel and subdivision details are found by using the *Identify* function on the menu bar and selecting the *County parcels* or *County subdivisions* layer from the layers list at the top of the *Identify Results* window (layers 06 and 07, respectively; Figure 52). The coordinates of the site can be found near the lower right hand corner of the map while moving the mouse to the location of the site (Figure 75). The streams layer and the roads layer are shown for orientation. The label feature of the subdivision layer and the [perennial] streams layer are turned on to assist in identifying map features. The site is located in the WSC hydrologic subsystem (Figure 76), and the hydrogeologic conceptual model for this area is shown in Figure 26.

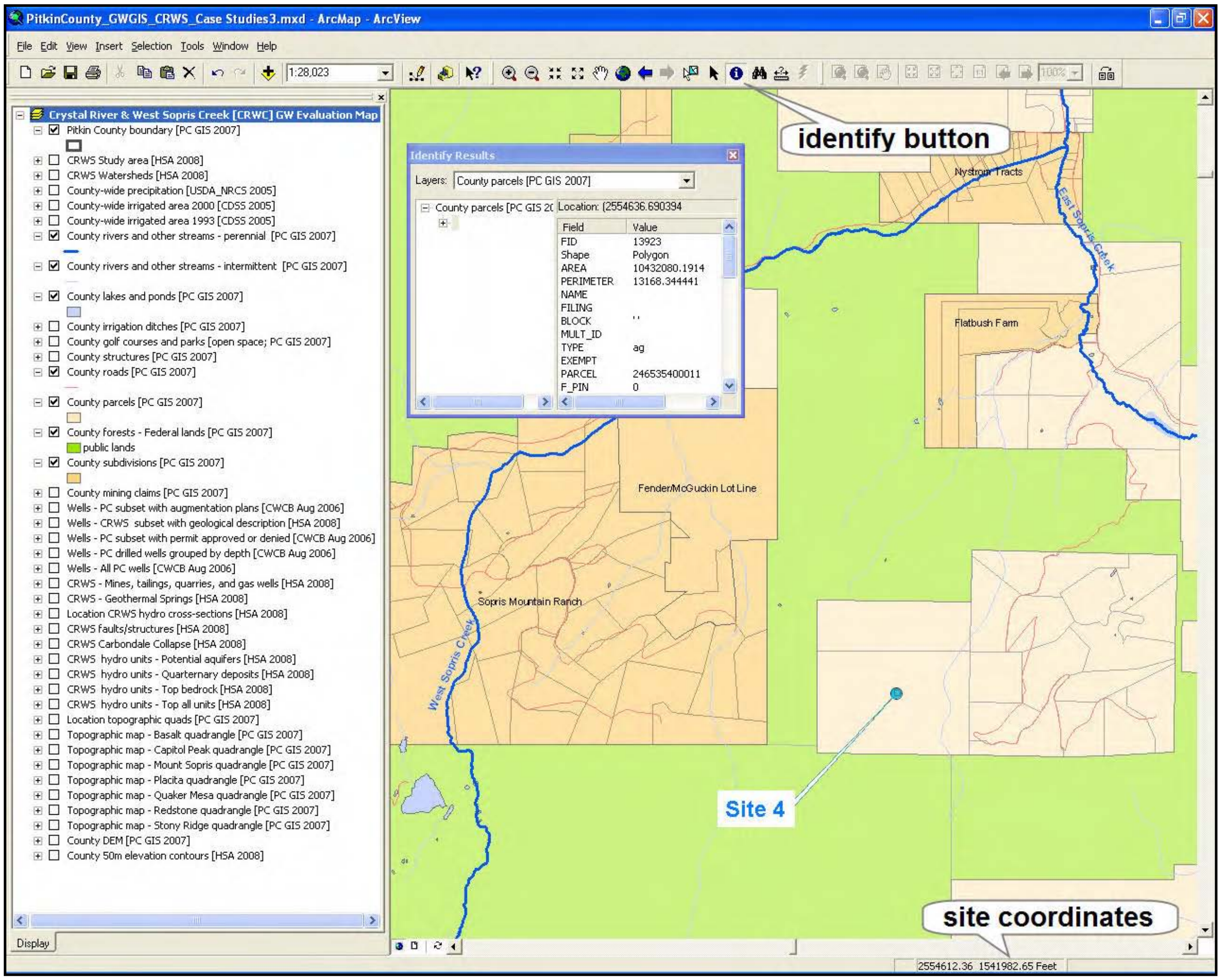


Figure 75. Locate Site 4 Using GIS Layers 06 and 07
(layers 11 and 12 [*streams*] and 5[*roads*] are used for orientation).

5.4.2 Determine Ground Water Availability

To determine if a surficial aquifer is present at the site, the *Hydrounits - Potential aquifers* layer (layer 28) from the GIS map's table of contents is turned on. Although the landslide deposits unit (Qls) and some alluvium (Qal) are located in the vicinity of the site, it is apparent that the site itself is not situated on top of potential aquifer material (Figure 77). Using the *Hydrounits - Top bedrock* layer (layer 30; Figure 78) in conjunction with the faults layer (layer 26), it appears that top bedrock is the low-permeable Mancos Shale (Km). Based on information given in Figure 26 and Table 1, the Mancos Shale is underlain by the Dakota and Burro Canyon unit (Kdb) and/or the Morrison and Entrada unit (Jme). Observing the irregularly distributed outcrops and subcrops of both units directly south of the site, it is not possible to confirm without local drilling if the Kdb unit is present at the site. This determination is important because the upper section of the Morrison and Entrada units is shale and is considered a confining layer. If the Kdb unit is present at the site, it is recharged at its sub- and outcrops to the north and the south and may be somewhat sustainable from local, natural recharge. If the Kdb unit is present at the site, it is covered by the confining Mancos Shale and is considered locally to be under confined conditions.

Figure 76. Google Earth View of Site 4 Looking North.

Layer 22 (*drilled wells grouped by depth*) is turned on to identify relevant nearby wells. There are a number of wells nearby that may provide relevant information. Of special interest are the wells with permit numbers 28062 (at about 2150ft from site 4), 225406 (at about 4150ft), and 228015 (at 4450ft) (Figure 78). Although these wells are some distance away from site 4, they are relevant because of their location within the local hydrogeologic system and their depth. From the attribute table of layer 22, well depth, depth to static water level at time of drilling, well production (gallon per minute yield), and time of year of drilling can be evaluated with respect to pre-development saturated thickness. Well 28062 has a depth of 137ft, initial depth to water of 88ft and an estimated yield of 10gpm. It is likely that this well obtains its water from the Kdb unit beneath the Mancos Shale. Well 225406 has a depth of 256ft, an initial depth to water of 137ft, and an estimated yield of 10gpm. Ground elevation at this well is less than at well 28062, but it is much deeper with a screened interval between 180ft and 258ft. It is also obtaining its water from the Kdb unit beneath the Mancos Shale. Well 228015 has a depth of 373ft, initial depth to water of 59ft, and an estimated yield of 10gpm. It is screened between 285 and 370ft. Ground elevation is about that of site 4. It is likely that this well too obtains it water from the Kdb unit. From the above information it is concluded that the principal aquifer at site 4 is the Kdb unit, likely under confined conditions.

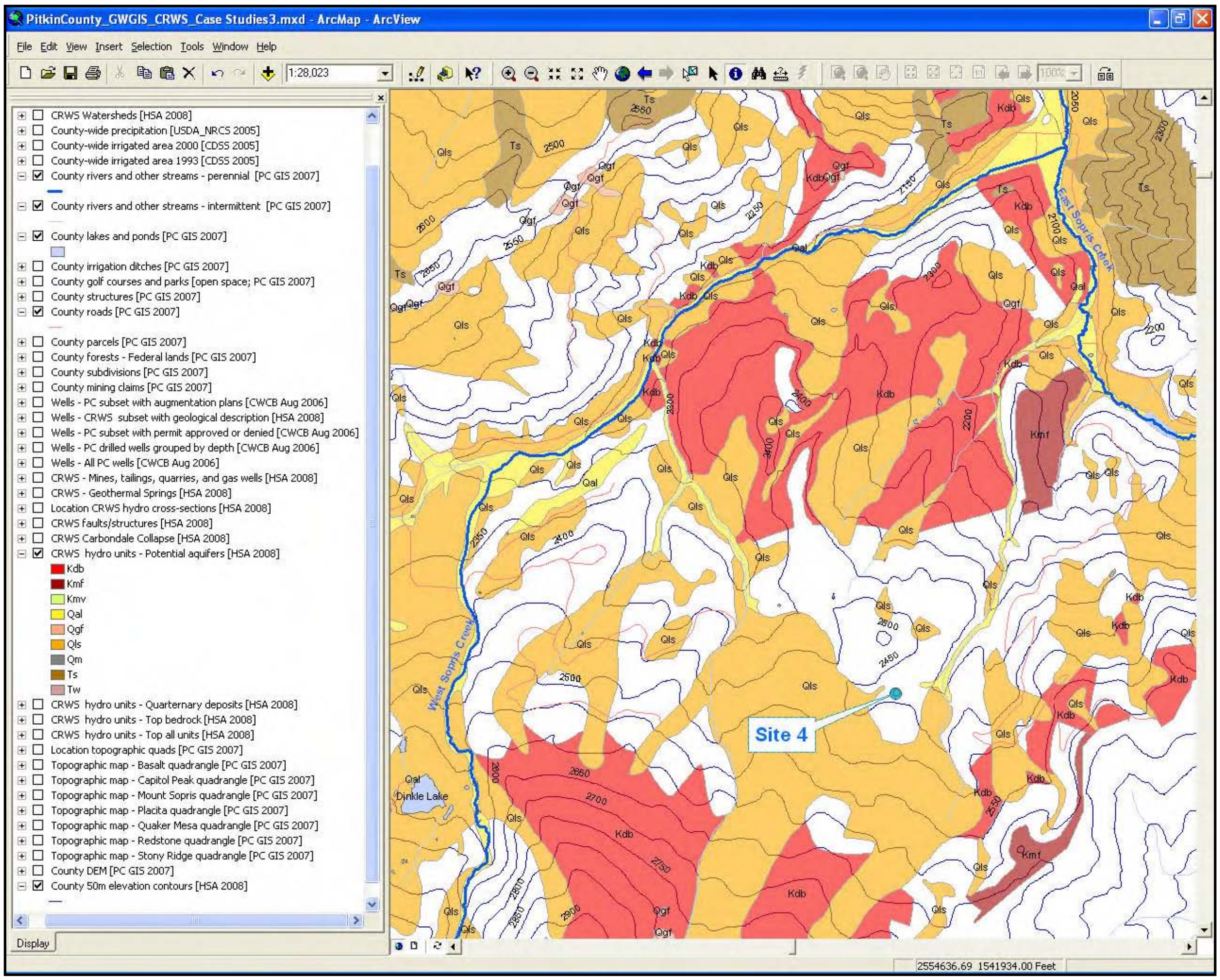


Figure 77. Determine the Potential Presence of an Unconsolidated Aquifer at Site 4 Using GIS Layer 28.

5.4.3 Determine Ground Water Sustainability

The precipitation layer (layer 16) is turned on to assess the recharge potential from precipitation in the vicinity of the site. The site is located in an area that receives annually an average of about 21 inches of precipitation and has an estimated recharge ranging from 10 to 20 percent of direct recharge from precipitation per year (Figure 61). Calculation of actual recharge amounts requires professional judgment using standard practices.

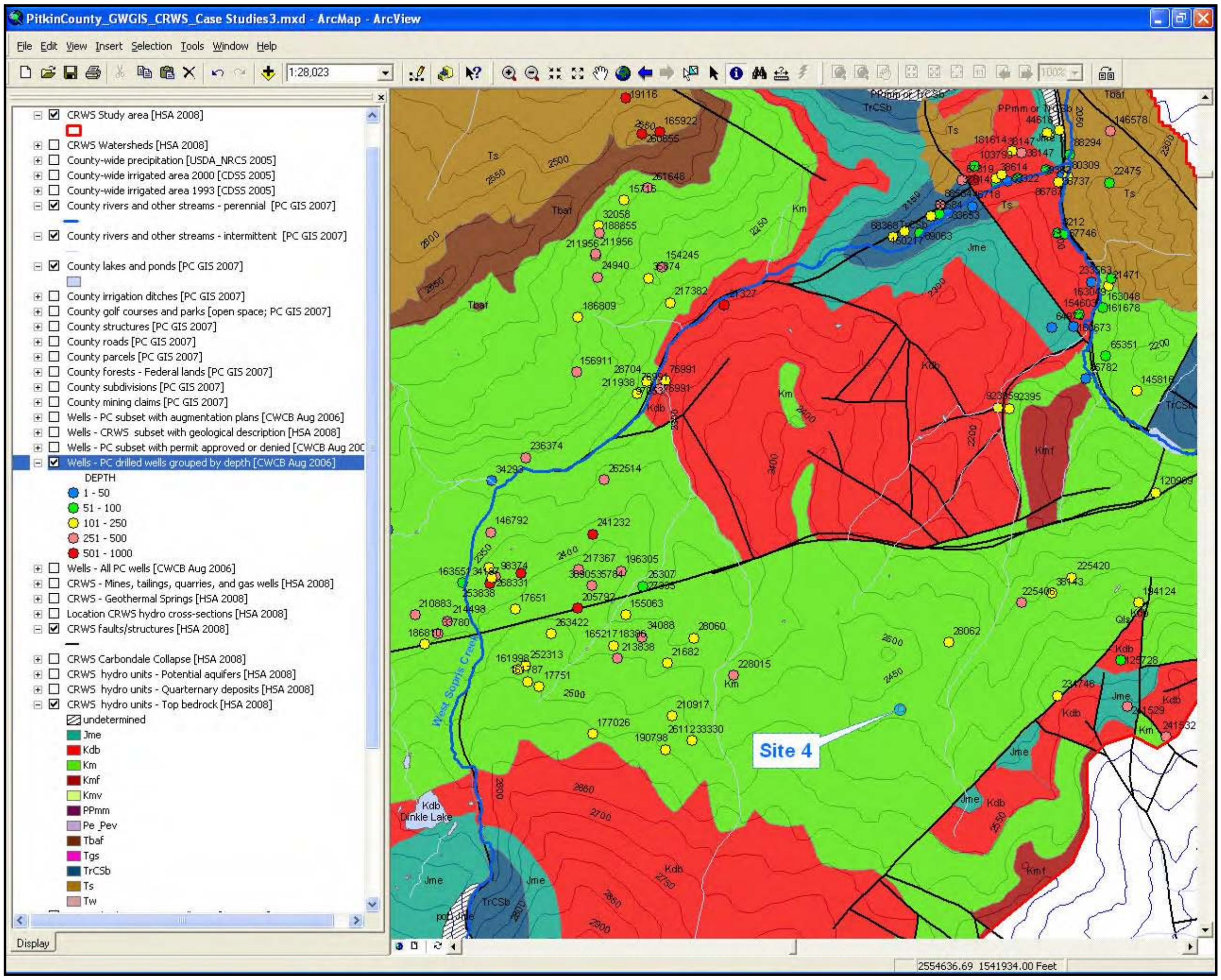


Figure 78. Determine Bedrock Aquifers at Site 4 Using GIS Layers 30 and 26.
The Figure Also Shows Wells Layer 22, Elevation Contours (Layer 41) and Various Water Layers.

The next step is to determine if the aquifer is hydraulically connected or not-connected with a perennial stream. This step is performed to determine the potential for recharge to the aquifer from a nearby stream. First, layers 11 and 12 (*perennial and intermittent streams*) and layer 14 (*ponds*) are turned on (Figure 79). By analyzing the location of the streams in the context of the conceptual model of the WSC subsystem (Figure 26), it appears that there is no hydraulic connection with nearby streams.

Layers 13 (*ditches*), 17 (*irrigated acreage 2000*), and 18 (*irrigated acreage 1993*) are used in conjunction with layer 29 (*surficial hydro units*) to determine if the aquifer near site 4 is recharged by irrigation practices, which may not sustain a ground water supply if water uses and water-rights ownership change. Figure 79 shows that irrigated lands and related irrigation ditches occur at lower elevations to the north of the site near West Sopris Creek. None of these irrigated lands or ditches effect the recharge conditions at site 4. Thus, there is no irrigation return flow or ditch leakage recharging the aquifer at the site and the only recharge occurs in the Kdb aquifer sub- and outcrops to the north and south of the site.

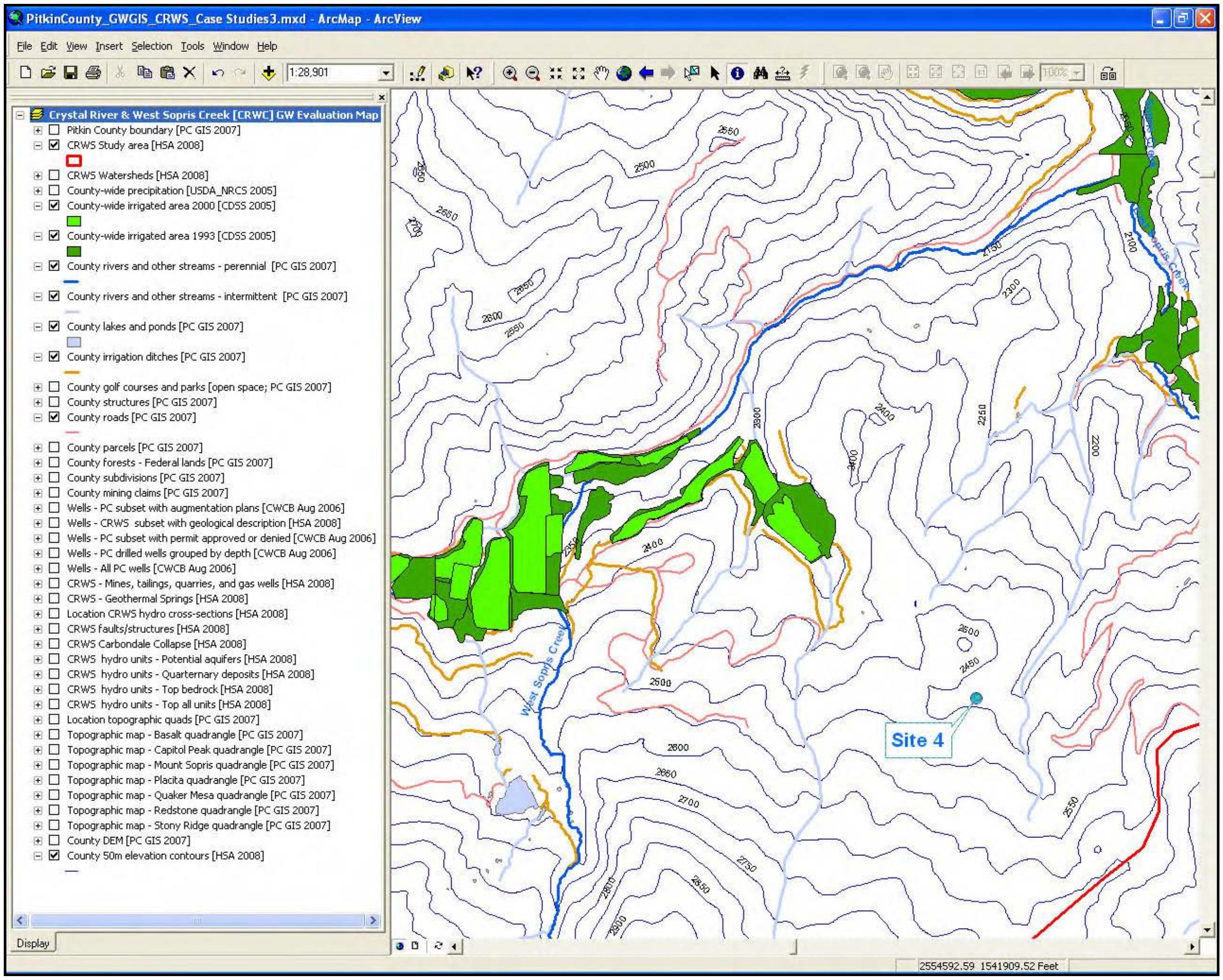


Figure 79. Determine Potential Recharge from Irrigation Return Flow and Ditch Leakage in the Vicinity of Site 4 Using GIS Layers 13, 17 and 18.

5.4.4 Determine Ground Water Vulnerability

Natural protection from overlying confining units is important for maintaining natural water quality. The site is in an area with an extensive Mancos Shale that serves as a protective layer on top of the aquifer, but near unprotected recharging sub- and outcrops. Therefore, its vulnerability is rated moderate.

6. 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 a GIS map 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 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, upland flood irrigation, and drought); and 3) the vulnerability of the resources to contamination. In addition, the GIS map provides information with respect to wells for which augmentation is required, and shows well applications approved (*i.e.*, permitted wells, drilled or not drilled) or denied, and wells actually drilled. Note that availability and sustainability should be judged in relation to well yield requirements, presence of other resource usages, ecological requirements, water right issues, and physical constraints, such as limitations on drawdown.

Key elements in this project are the adaptation of the step-wise ground water resources evaluation procedure developed in a previous HSA/HHI study for Pitkin County, as well as the hydrologic systems analysis and the formulation of conceptual models for the study area. The GIS map and supporting data bases focus the non-public lands area of the Crystal River and West Sopris Creek watersheds. The incorporated data bases include delineated hydrogeological units created by HSA/HHI, as well as data bases from Pitkin County, the Colorado Division of Water Resources/Colorado Water Conservation Board, and the Natural Resources Conservation Survey (USDA).

Based on field work and hydrologic systems analysis, five general conceptual models are identified within the regional scale context of the CRSC area: 1) Upper Crystal River (UCR) Subsystem near Redstone, CO; 2) Central Crystal River (CCR) Subsystem; 3) Lower Crystal River (LCR) Subsystem including the Carbondale Collapse; 4) West Sopris Creek (WSC) Subsystem; and 5) the Thompson and Coal Creek (TCC) Subsystem. Each of the five subsystems has a unique set of natural system parameters defining recharge and discharge, ground water levels and fluctuations, ground water flow velocities and direction, and ground water storage. In addition, important anthropogenic hydrologic system parameters include ground water recharge from irrigation and irrigation ditches, and ground water discharge from wells. If water rights and allocations should change for these ditches, the hydrodynamics of the Quaternary glacial and alluvial aquifers would change, and water supplies from ground water may decline or vanish.

Four case history examples are presented to illustrate the analysis procedure, using the GIS map and data bases provided with this report. Site 1 is located in the Upper Crystal River (UCR) hydrogeological subsystem; site 2 is located in the Central Crystal River (CCR) hydrogeological subsystem, site 3 is located within the Carbondale Collapse area of the Lower Crystal River (LCR) hydrogeological subsystem, and site 4 is located in the hills of the West

Sopris Creek (WSC) hydrogeological subsystem. The examples show the existing uncertainties in evaluating local ground water resources due to data limitations, and illustrate the variability of drinking water supplies, in availability, sustainability, and vulnerability, dependent on the local hydrogeology and hydrological system. All four sites are vulnerable to ground water pollution, albeit not at the same level. The examples demonstrate the utility and advantages of the GIS-based analysis procedure and its advantages over simple, one-layer paper maps showing, for example, some general ground water characteristics, and 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 section 2 of this report, as well as in the CSC, MRF and URF reports by Kolm and Others (*2007*), Kolm and van der Heijde (*2006*), and Kolm and Gillson (*2004*). 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 Upper Roaring Fork Drainage area has a complete HSA, but lacks the delineation and digitalization of hydrogeologic units. 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 has a complete HSA, and most of the GIS data base development and evaluation is completed. The region is complex due to the presence of shallow aquifers of various types (moraines, landslide deposits, outwash plains, alluvium), and a complex, faulted bedrock system. The hydrologic parameters for the Snowmass and Capitol Creek areas would need to be evaluated as these were not assessed in-depth as part of the present study. The priority for this work is low compared with the assessment needs of other areas.

The Crystal River area has a complete HSA, and most of the GIS data base development and evaluation is completed. The region is complex due to some urbanization, shallow aquifers of various types (moraines, outwash plains, alluvium), and a complex, faulted bedrock system. 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 low 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.

GIS database evaluation can be enhanced by the development of custom tools in ArcToolbox. The stepwise approach of the ground water resources assessment procedure can be maintained, but the extensive use of the information toolbar can be eliminated by predefining layer selections of importance for each of the 10 steps of the procedure.

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Appendix 1

Climate Data for Basalt and Redstone Stations, Colorado

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

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	37.7	42.6	50.5	59.2	69.9	78.5	86.6	83.8	75.1	63.0	49.4	36.9	61.1
Average Min. Temperature (F)	7.4	12.2	19.7	25.6	34.4	40.0	46.9	45.4	36.4	25.8	18.7	10.0	26.9
Average (Mean) Temperature (F)	22.4	27.8	35.1	42.5	52.1	59.3	66.7	64.6	55.8	44.4	34.0	23.4	44.0
Average Total Precipitation (in.)	0.84	0.79	0.58	1.35	1.02	1.73	1.14	1.99	1.96	1.57	0.80	1.32	15.10
Average Total Snow Fall (in.)	15.2	12.0	6.3	3.4	0.0	0.0	0.0	0.0	0.6	5.2	5.7	17.9	66.3
Average Snow Depth (in.)	7	3	1	0	0	0	0	0	0	0	0	4	1

Table A.1.1. Monthly Climate Summary for Basalt, Colorado [station 050514] for period 7/1/1965 to 5/31/1972.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	38.0	43.8	53.4	61.2	68.8	81.2	86.7	85.0	75.2	66.3	45.0	32.9	61.6
Average Min. Temperature (F)	11.8	16.0	23.4	30.7	35.5	43.9	48.9	46.4	36.3	30.3	17.7	8.7	29.2
Average Total Precipitation (in.)	0.88	0.94	0.77	1.15	0.96	0.59	0.46	1.64	1.80	1.04	1.32	2.00	13.54

Table A.1.2. Monthly Climate Summary for Basalt, Colorado [station 050514] for period 1/1/1971 to 12/31/2000.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	33.1	36.2	42.7	51.1	60.5	71.8	76.4	74.6	67.0	55.3	39.2	31.5	53.3
Average Min. Temperature (F)	7.7	11.5	17.3	24.5	31.9	39.4	44.2	43.8	36.7	38.0	17.5	9.0	26.0
Average (Mean) Temperature {F)	20.5	23.9	30.0	37.8	46.2	55.6	60.3	59.2	51.8	41.7	28.3	20.2	39.6
Average Total Precipitation (in.)	1.78	2.41	3.09	2.04	2.30	1.48	2.23	1.67	2.98	3.02	2.64	2.03	27.66
Average Total Snow Fall (in.)	26.0	29.9	32.4	12.1	5.3	0.5	0.0	0.0	0.5	6.9	26.4	29.5	169.4
Average Snow Depth (in.)	21	16	5	1	0	0	0	0	0	0	3	11	5

Table A.1.3. Monthly Climate Summary for Redstone, Colorado [station 056970] for period 6/1/1979 to 6/30/1994.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	32.7	36.9	43.0	31.1	60.5	71.9	76.5	74.4	66.9	55.4	39.2	32.3	53.5
Average Min. Temperature (F)	7.7	11.8	17.5	24.3	32.0	39.2	44.2	43.4	36.6	27.9	17.1	9.5	26.0
Average Total Precipitation (in.)	1.96	2.68	2.89	2.16	2.44	1.51	1.94	1.99	3.00	3.15	2.77	2.25	28.72

Table A.1.4. Monthly Climate Summary for Redstone, Colorado [station 056970] for period 1/1/1971 to 12/31/2000.

Appendix A2

Data Fields of the Colorado Division of Water Resources Wells Database.

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

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:

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	*Description*
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 geothermal.
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.

Appendix 3.

Update Procedures for GIS Databases.

The GIS map for use with the ground water resources assessment procedure links to five groups of databases: 1) CDSS (Colorado Decision Support System) irrigated acreage databases; 2) HSA_PCGIS hydrogeological databases prepared by HSA/HHI; 3) NRCS (Natural resources Conservation Service) precipitation database; 4) Pitkin County GIS geographic and hydrological databases; and 5) the DWRSC (Colorado Division of Water Resources) wells database.

The CDSS databases contain the irrigated acreage information and may occasionally be updated when new surveys of irrigated acreage become available. CDSS database information can be found at: http://165.127.23.116/website/cdss/ or the CDSS website at: http://cdss.state.co.us/DNN/default.aspx.

The HSA_PCGIS hydrogeological databases are "as-is" and are not expected to be updated on a regular basis. For more information contact: pvdh@heath-hydrology.com.

Information regarding the NRCS precipitation database can be found at the NRCS Data Gateway: http://datagateway.nrcs.usda.gov/GatewayHome.html.

For information regarding the Pitkin County GIS databases contact the City of Aspen/Pitkin County GIS Department at: gis@ci.aspen.co.us.

The CDWR wells database is updated on a quarterly basis. See: http://water.state.co.us/pubs/welldata.asp. To update the GIS well database included with this report use the following procedure:

Step 1. Obtain the latest edition of the quarterly updated state well database from the Colorado Division of Water Resources for Pitkin County (county code 49).

Step 2. Delete the old 'well.dbf' file from the 'Wells_DWRSC_Pitkin' subdirectory of the CRC ground water GIS file set and copy the 'well.dbf' file from the CDWR-provided disk to the 'Wells_DWRSC_Pitkin' subdirectory. Make sure that the name in the target directory is 'well.dbf'.

Step 3. Modify the reference in the CWCB well layers in the GIS Table of Contents to reflect the date of the new well data.

Note: Some wells, identified in the CDWS well database with the Pitkin County code 49, lie outside the county boundary. This is caused by either incorrect coordinates in the database, or that no coordinates were provided to the state. In the latter case, UTM coordinates are shown as zero's. In the CSC GIS map, this latter issue is addressed by automatically excluding these zero-value coordinates using the *Definition Query* function of the wells' *Layer Properties* windows.

Appendix 4

Stepwise Approach to Assessing Ground Water Availability, Sustainability, and Vulnerability in the Crystal River and West Sopris/Sopris Creek Study Area, Pitkin County, Colorado.

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.

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

Step 1. Start ARCMAP™ (ESRI®, Redlands, California) and load the CSC GIS map [*file: PitkinCounty_GWGIS_CSC.mxd*].

Step 2. Determine the precise location or platting of the selected site. This site should be plotted on the GIS map using the appropriate layers in the GIS (*e.g.*, using site coordinates or location information on streams, roads, parcels, etc.).

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.

Step 3. Determine the potential unconfined surficial aquifer material at the site.

Step 4. Determine potential unconfined and confined bedrock aquifer material at site.

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.

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 nearby wells based on distance to site of interest and comparable hydrogeology and combine with layers identified as relevant in steps 3 through 5. Using the accompanying attribute table for the drilled well layer, well depth, depth to static water level at time of drilling, well production (gal per minute yield), and time of year of drilling can be found and a judgement be made with respect to pre-development saturated thickness. 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 map. 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 waterline layer 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, or the information resulting from steps 3-6, with the county's streams layer, 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 subject to return flow of irrigation water. This step is performed to determine recharge to the aquifer from 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, or the information resulting from steps 3-6, is combined with the county's ditches layer. The potential effect of the return flow of irrigated acreage on recharge can be evaluated by plotting the site of interest on the 2000 or 1993 irrigated acreage layer. 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 with unconsolidated sediments, and bedrock aquifer outcrops is vulnerable; natural protection is only available in areas with confining layers overlying bedrock aquifers. Calculation of actual risk (both qualitatively and quantitatively) requires professional judgment using standard practices.