DEVELOPMENT OF GIS MAPS SHOWING ASPECTS OF AVAILABILITY, SUSTAINABILITY AND VULNERABILITY OF GROUNDWATER RESOURCES, PITKIN COUNTY, COLORADO

Phase 3 of the Development of County-wide Maps for GIS-Based Groundwater Resources Evaluation, Pitkin County, Colorado

By:

Paul K.M. van der Heijde
Heath Hydrology, Inc.
Boulder, Colorado
(under subcontract with Integral Consulting Inc.)

and

Dr. Kenneth E. Kolm
Integral Consulting Inc.
Louisville, Colorado

for:

Pitkin County
Health Rivers Board and
Board of County Commissioners
Colorado

Contract No. 195-2010

November 13, 2011

Table of Contents

List of Tables

List of Figures

1.0 Introduction

Under an agreement with Pitkin County, Integral Consulting Inc. (Integral) of Louisville, Colorado, in cooperation with Heath Hydrology, Inc. (HHI) of Boulder, Colorado, was tasked to complete a series of geographic information system (GIS) maps. These maps are to be used in conjunction with the earlier developed groundwater resources evaluation procedure as planning and landuse management tools by Pitkin County. The project consists of two major elements: 1) conducting a Hydrologic and Environmental Systems Analysis (HESA) and preparing supporting GIS maps of the area covered by the watersheds of the streams tributary to the central Roaring Fork (CRFT) between the towns of Basalt and Aspen, Colorado, including the Fryingpan River, Maroon Creek, Castle Creek, Hunter Creek, Woody Creek, and the City of Aspen; and 2) integrating the results of the focused HESA and resulting GIS maps with the GIS maps developed in previous studies, providing county-wide coverage of the hydrogeology.

The project is a follow-up of previous studies performed by Hydrologic Systems Analysis, LLC in cooperation with HHI for the Crystal River and West Sopris Creek areas (CRWS; *Kolm and others, 2008*); the Middle Roaring Fork area (MRF; *Kolm and Gillson, 2004*), 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).

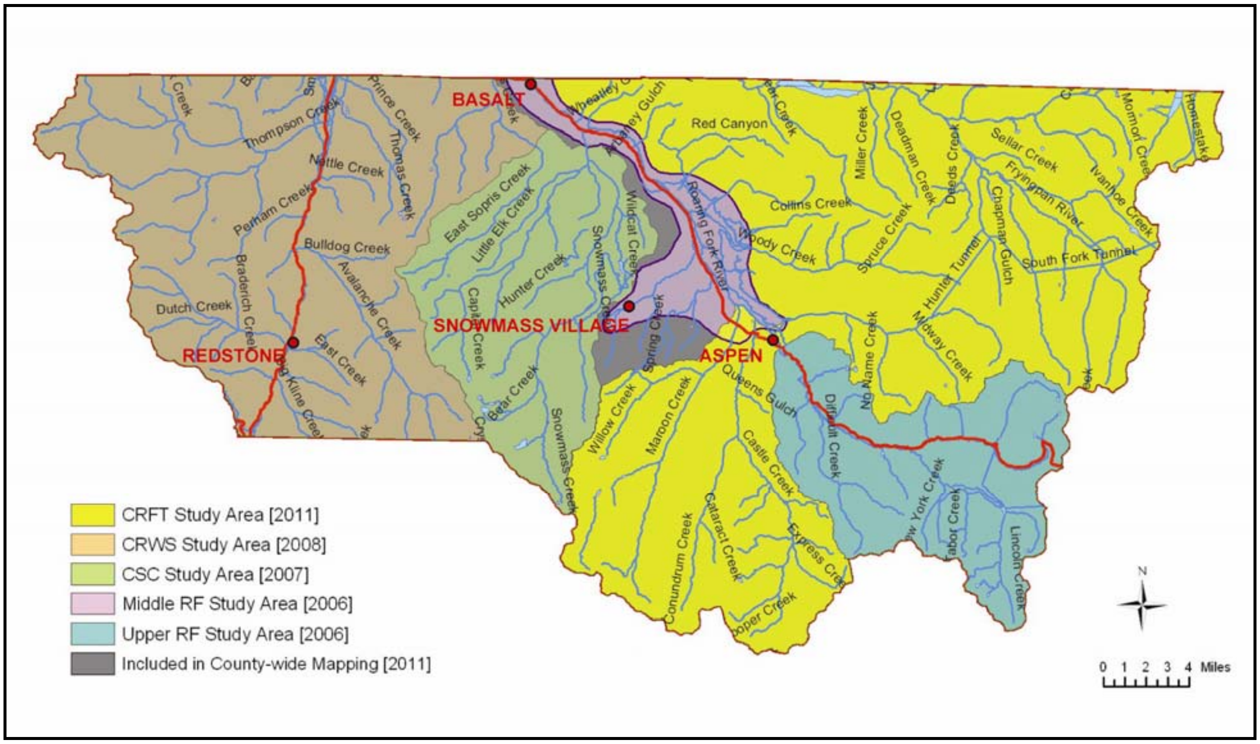

Figure 1. Location of the Central Roaring Fork Tributaries (CRFT), Crystal River and West Sopris Creek (CRWS), Capitol and Snowmass Creek (CSC), Middle Roaring Fork (MRF), and Upper Roaring Fork (URF) Study Areas, Pitkin County, Colorado.

The project consists of four phases: 1) HESA, formulating conceptual models of the groundwater systems, and developing a supporting database for the CRFT area (*Kolm and van der Heijde, 2011*); 2) developing a coherent and consistent county-wide hydrogeological nomenclature, updating the GIS maps of the MRF and URF study areas, and preparing county-wide maps and databases of the major hydrogeological units (*van der Heijde and Kolm, 2011*); 3) creating county-wide GIS maps showing aspects of groundwater availability, sustainability and vulnerability (*this report*), and production of a short outreach document describing the past and current GIS-based groundwater resources evaluation studies; and 4) presenting findings to the Board of Pitkin County Commissioners and staff, and to the public.

This report presents the terminology related to availability, sustainability, vulnerability and susceptibility of groundwater resources and a discussion of the issues encountered in the production of county-wide GIS maps addressing aspects of groundwater availability, sustainability and vulnerability.

2.0 Groundwater Availability, Sustainability and Vulnerability

In previous studies on the GIS-based groundwater resources evaluation in Pitkin County, GIS maps were designed for use in conjunction with a groundwater resources evaluation procedure to identify, among others, locations in designated areas of the county (*Kolm and van der Heijde, 2006; Kolm and others, 2007; Kolm and others, 2008*):

A. Where groundwater resources are: 1) available in reasonable, sustainable quantities, at reasonable depths; 2) available in reasonable quantities, at reasonable depths, but (potentially) not sustainable because of current landuse or future landuse changes; and 3) not available in reasonable quantities at reasonable depths.

B. Where groundwater resources are vulnerable (using a rating of high, moderate, 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 groundwater table is likely to fluctuate significantly (*e.g.*, because of snowmelt, spring runoff, or upland flood irrigation).

Objective A has two elements: 1) determining the presence or *availability* of a groundwater supply, and 2) assessing *sustainability* of an available groundwater supply. Objective B focuses on the *vulnerability* of a groundwater resource to contamination from sources at or near the ground surface. Objective C relates to the both the *availability* of a groundwater supply (is it always present despite seasonal or multi-year fluctuations of the water table?) and its *sustainability* (can it be utilized as a long-term resource despite such fluctuations?). Note that in Objective A, the sustainability of a groundwater resource is cast in terms of its vulnerability or non-sustainability as a water supply.

In earlier projects regarding availability, sustainability, and vulnerability of groundwater resources in Pitkin County (*Kolm and van der Heijde, 2006; Kolm and others, 2007; Kolm and others, 2008*), it was concluded that not enough data were available to take a quantitative approach and prepare maps identifying specific areas of resource availability and sustainability, and that vulnerability could only be assessed using a few descriptive categories (*high, moderate, low*). Issues leading to that conclusion 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 groundwater level information (except for the static water level at the time of drilling of a well); and the lack of any quantitative hydrogeological parameters for most of the county’s hydrogeologic units. Therefore, a step-wise evaluation procedure was developed to use with the conducted HESAs and with available information, collected and organized in GIS layers, to address in a qualitative manner the study objectives on a site-specific scale.

The following sections describe the terminology and mapping of groundwater resources availability, sustainability and vulnerability as presented in the county-wide GIS databases for project phase 3.

2.1 Availability and Sustainability of a Groundwater Supply

Availability of groundwater is often understood as the availability of a sufficient groundwater supply with respect to actual or anticipated demand. Such a demand may be cast in terms of average amount of water needed during a certain period (week, month, season, year, multiple years), and peak demand versus average demand. Reilly and others (*2008*) stated that: *"Although the quantities of water in a hydrologic system usually can be measured, computed, or estimated, water availability is a more elusive and multifaceted concept. Water availability is a function not only of the quantity and quality of water in a basin or aquifer system but also the physical structures, laws, regulations, and socioeconomic factors that control its demand and use."* The Ground Water Availability Interest Group of the National Ground Water Association identifies groundwater availability as *"the rate at which groundwater may be withdrawn to meet current needs without either impairing the resource or undermining its availability to meet future needs"* (*NGWA, 2011*).

The availability of a groundwater supply is a function of local hydrogeology and hydrology (*e.g.*, presence and thickness of aquifer materials, amount and type of recharge, storage capacity and permeability of aquifer materials), and geochemistry (as pertains to water quality), subject to regulatory and legal restrictions in the use of such a supply (*e.g.*, water rights and well permits). These regulatory and legal restrictions are often related to potential negative impacts exploitation of a groundwater supply may have, such as reductions in surface water flows or pumping capacity of neighboring wells, effects on groundwater-fed wetlands, and unacceptable lowering of the water table. Another aspect of availability of a water supply is the economic feasibility of its utilization. This means that the aquifer is not prohibitively deep, has enough permeability and storativity to prevent deep cones of depression, is large enough to supply the desired amount of water, and has potable water of sufficient quality. Note that sustainability is also an element of economic feasibility.

The objective of sustainable groundwater use or *sustainability* of a groundwater supply is to maintain the desired water supply for a prolonged period of time without irreversibly depleting the resource or injuring vested interests (*e.g.*, water rights) or ecological and other communal values. Note that some definitions of the term availability of groundwater include elements of sustainability. In nature, increased groundwater pumping will be balanced by a change in one or more water balance components: 1) reduction of groundwater storage, resulting in lowering of the water table; 2) reduction of evapotranspiration due to a diminishing water supply for phreatophytes and wetlands from a declining water table; 3) increase of stream bank infiltration, that is, increased recharge of the aquifer from adjacent streams and, thus, reduced in-stream flow; and 4) reduction of aquifer 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. In that case, a particular rate of pumping of the new wells will result in a new long term steady state condition in the aquifer with permanent changes to one or more of the other water balance components.

In the approach to sustainability presented in this project, 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 an unacceptable change in the water balance components. Thus, to determine sustainability in a qualitative sense, the question to be answered is: Are there significant, reliable, long-term, recharge mechanisms present? To answer that question, the following are evaluated: 1) source(s) of replenishment/ recharge; and 2) relevant human-caused conditions. 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 diversion structures; 3) irrigation return flow from agricultural areas and golf courses; 4) infiltration from OWTS (Onsite Wastewater Treatment Systems) leach fields; 5) infiltration from leaking sewer lines; and 6) recharge from infiltrating melt water from snowmaking at ski resorts.

As discussed in the previous section, availability and sustainability of a groundwater supply are deeply interwoven aspects of determining the feasibility of a groundwater resource for use as a water supply. To determine the availability and sustainability of groundwater for a particular demand requires quantification through field data collection and modeling of many of the factors described in the previous section. As such an effort goes well beyond the scope of the current project, a more descriptive approach has been taken, combining in a systematic way the information collected in previous studies, as presented in GIS databases, with the extensive field knowledge of the project team. The results are presented in sets of GIS layers and databases showing in a descriptive or qualitative manner aspects of: 1) presence and type of geologic materials that may provide a groundwater supply and their hydrogeologic characteristics; 2) potential presence of water and resource characteristics that may determine economic feasibility for use as a water supply; and 3) type of recharge.

2.1.1 Presence and Type of Geologic Materials That May Provide a Groundwater Supply and Their Hydrogeologic Characteristics

The type of geologic materials, and their hydrogeologic characteristics, present at a particular location is a major factor in determining the availability and sustainability of a groundwater resource. For the purpose of mapping these elements, two GIS layers have been developed describing hydrogeologic characteristics of potential aquifers: 1) unconsolidated quaternary deposits, and 2) bedrock units. The hydrogeologic characteristics of the major hydrogeologic units displayed in these layers, primarily in terms of type (matrix, fracture-dominated, karst, or combination of these) and magnitude of permeability (high, moderate, low), are shown in Table 1. The resulting GIS maps are shown in Figures 2 and 3. In the GIS program’s Table of Contents (Figure 4), these layers are labeled “GW: Aquifer Type - Quaternary Deposits” and “GW: Aquifer Type – Bedrock,” respectively.

Hydrogeological Unit	*Hydrogeological Unit Symbol **	*Composition*	*Hydrogeological Characteristics*	*Permeability/Storativity*
Modern alluvium	Qal	Poorly sorted riverine gravel, sand and silt deposited mainly in stream channels and floodplains in major stream valley bottoms; moderately to well bedded deposits	Generally good local phreatic aquifer with matrix based permeability; limited variations in groundwater levels; often sustained by local and sub-regional discharge to adjacent stream or directly by stream.	High matrix-permeability; high storativity
Quaternary gravels, fans & terraces	Qgf	Poorly sorted sands and gravels; pebbles and cobbles in sand to silt matrix; forms terraces above current Roaring Fork River level	Potentially good, spatially continuous phreatic aquifer with high matrix based permeability and small water table gradients; sustainability depends on local natural and/or anthropogenic recharge mechanisms; may be supported by underlying bedrock; may be prone to significant (seasonal) water table fluctuations.	High matrix-permeability; high storativity
Quaternary glacial deposits	Qm	Heterogeneous, poorly sorted deposits of boulders, gravel, sand, silt and clay	Potentially good local phreatic aquifer with variable matrix based permeability and high water table gradients; sustainability depends on local natural and/or anthropogenic recharge mechanisms; may be prone to significant water table fluctuations.	High matrix-permeability; high storativity
Quaternary colluvium and landslide deposits	Qls	Loose gravels and rock debris with mixed matrix composition (sand-clay) on valley sides, valley floors and hillslopes; deposited by gravitational processes	Potentially good, highly localized phreatic aquifer with high matrix based permeability and high water table gradients; sustainability depends on local natural and/or anthropogenic recharge mechanisms and may be dependent on underlying bedrock characteristics; may be prone to significant (seasonal) water table fluctuations.	High matrix-permeability; high storativity
Older ridge top sands and gravels	Qog	Poorly sorted sands and gravels; pebbles and cobbles in sand to silt matrix	Although having high matrix based permeability, location in topography precludes any significant groundwater presence.	High matrix-permeability; high storativity
Tertiary sedimentary basin fill deposits	Ts	Weakly indurated to unconsolidated fluvial deposits (pebbles and cobbles in a matrix of silty sand) filling the Carbondale Collapse subsidence feature and present in some adjacent areas	In the basins and valleys near the north-central boundary of county it is a good continuous, very thick aquifer with high matrix based permeability; regionally sustained by direct recharge and recharge through adjacent bedrock; significant subregional flow exiting Pitkin County to the North.	High matrix-permeability; high storativity

Table 1. Hydrogeological Characteristics of Major Hydrogeologic Units, Pitkin County, Colorado.

Hydrogeological Unit	***Hydrogeological Unit Symbol ****	***Composition***	***Hydrogeological Characteristics***	***Permeability/Storativity***
Tertiary ash-flow tuffs and basalts	Taf	Massive, fractured, bedded, well-cemented, non-welded ash-flow tuffs; some thick, vesicular, locally dense basalt	Potentially good local bedrock aquifer with fracture based permeability; sustainability depends on elevation and local recharge mechanisms.	Moderate fracture permeability; moderate storativity
Tertiary intrusive rocks	Tmi	Granodiorite and quartz monzonite; may occur as dikes and sills	Fractured crystalline system with very low matrix permeability; not a (sub-)regional aquifer; may produce locally water in concentrated fracture zones and support adjacent Quarternary aquifers. These characteristics may extend into adjacent rocks metamorphosed during the Tertiary intrusion.	Mostly low permeability, localized zones with moderate fracture permeability; low storativity
Wasatch and Ohio Creek Formations	Two	Channel sandstones and overbank siltstones and shales; conglomerate; carbonaceous shales and lignite near base	Overbank sandstones form a good aquifer system with moderate to good matrix and fracture based permeability; may be a locally good water producer; siltstones and shales are confining layers; aquifers are sustainable at moderate elevations in western part of county; outcrops are recharge areas for a regional flow to the west across county border.	Layers with very low permeability and layers with moderate matrix and fracture permeability; low to moderate storativity
Mesa Verde Group	Kmv	Interbedded sandstones and siltstones, shales and carbonaceous shales and coals	Good regional bedrock aquifer system; sandstones and coals have both moderate matrix and fracture based permeability; may locally be a good water producer; shales are confining layers; regionally sustainable aquifer at moderate elevations in western part of county; outcrops are recharge areas for regional flow to the west across county border.	Layers with very low permeability and layers with moderate matrix and fracture permeability; low to moderate storativity
Mancos Shale (undivided)	Km	Silty to sandy shale with bentonites with minor limestone- and sandstone beds; when undivided, lower section includes Ft Hays limestone (see separate section below)	Mostly aquitard with very low permeability serving as a confining layer for underlying or embedded aquifers; however, locally moderate aquifer conditions when highly fractured or in areas with sand lenses and sandy beds; sustainability highly dependent on local recharge mechanisms.	Very low permeability rock with some moderately permeable beds; low storativity

Table 1 continued. Hydrogeological Characteristics of Major Hydrogeologic Units, Pitkin County, Colorado.

Hydrogeological Unit	***Hydrogeological Unit Symbol ****	***Composition***	***Hydrogeological Characteristics***	***Permeability/Storativity***
Mancos Shale - Sandstone members	Kms	Outcrops of local or discontinuous sandstone beds in Upper Mancos Shale unit	Locally moderate aquifer conditions; sustainability highly dependent on local recharge mechanisms.	Moderate matrix and fracture permeability; moderate storativity
Mancos Shale - Fort Hays Limestone member	Kmf	Thick-bedded coarse-grained limestone	Good local or regional fractured-flow aquifer; however, generally covered by many hundreds of feet of shale except near outcrops; outcrops are recharge areas for a regional flow to the west across county border; (sub-)regionally sustainable aquifer.	Moderate fracture permeability; moderate storativity
Mancos Shale - Lower Shale unit	Kml	Silty shale with sandstone beds	Mostly very low permeability aquitard; however, locally moderate aquifer conditions when highly fractured or in areas with sand lenses and sandy beds; sustainability highly dependent on local recharge mechanisms.	Very low permeability rock with some moderately permeable beds; low storativity
Dakota Sandstone and Burro Canyon Formation	Kdb	Well indurated, medium to coarse grained quartzose sandstones in well-cemented thick beds and conglomerate with occasional siltstones and carbonaceous shale	Good regional bedrock aquifer system; sandstones have both moderate matrix and fracture based permeability; sub-regionally sustainable aquifer with recharge in outcrop areas; mostly protected by overlying Mancos Shale except for outcrop areas.	Moderate matrix and fracture permeability; moderate storativity
Morrison and Entrada Formations	Jme	Morrison Form. (Jm): Siltstones and claystones throughout with sandstones becoming more common in lower sections, and limestone near base; Entrada Form. (Je): fine-grained, well-sorted sandstones; Je overlain by Jm	Entrada is a very good, regionally sustainable aquifer with moderate to good matrix and fracture based permeability. Morrison shales are confining layers while the lower Morrison sandstones and limestone may serve as local to sub-regional aquifers with sustainability dependent on local recharge conditions.	Layers with very low permeability and layers with moderate matrix and fracture permeability; low to moderate storativity
Chinle and State Bridge Formations	TrPcs	Thin even bedded red beds of calcareous siltstone and mudstone becoming sandy near base (Chinle) unconformily on top of interbedded siltstone and sandstone becoming more clayey towards the base (State Bridge)	The Chinle Formation is a very low permeability aquitard and constitutes a major regional confining layer with respect to underlying aquifers. Local sandstone units in the Chinle and State Bridge Formation near outcrops may provide a local water source.	Very low permeability rock with some moderately permeable beds; low storativity

Table 1 continued. Hydrogeological Characteristics of Major Hydrogeologic Units, Pitkin County, Colorado.

Hydrogeological Unit	***Hydrogeological Unit Symbol ****	***Composition***	***Hydrogeological Characteristics***	***Permeability/Storativity***
Maroon and Minturn Formations	PPmm	Interbedded arkosic sandstones, silt- and mudstones, and conglomerates (Maroon); interbedded shale, siltstone, sandstone, limestone and conglomerate (Minturn/Gothic)	Arcosic sandstones, conglomerate and limestones form a tight bedrock aquifer with primarily fracture based permeability; is an aquifer where metamorphosed and well cemented. At the local scale fracture zones may provide good aquifer conditions. May sustain adjacent or overlying Quarternary aquifers.	Moderate fracture permeability; moderate storativity
Eagle Valley Formation and Eagle Valley Evaporite	Pe	Tan, reddish brown, reddish grey siltstone, gypsum and carbonate rocks. Evaporite contains anhydrite, halite, gypsum and light colored mudstone. May have intruded in higher formations.	Generally poor aquifer except where local karst and/or extensive fracturing have developed.	Moderate fracture permeability; moderate storativity
Belden Formation	Pb	Shales interbedded with limestone and dolomite and some sandstone	Mostly a very low permeability aquitard; may act as the confining unit for underlying Leadville Limestone.	Very low permeability rock with some moderately permeable beds; low storativity
Leadville Limestone	Ml	Thick-bedded massive limestone in upper part; thin- to thick-bedded dolomite in lower part; Gilman Sandstone member at the base (dolomitic sandstone to sandy dolomite)	Significant regional, fractured permeability aquifer with local karst; local aquifer conditions in fractured Gilman Sandstone; presence of extensive mining tunnels near outcrops provide significant additional fracture-zone-like permeability; interconnected and scattered nonconnected mineworking tunnels are present in the vicinity of the Leadville outcrops.	Moderate fracture and karst permeability; moderate storativity
Precambrian Granites and Gneisses	YXg	Granites and gneisses	Fractured crystalline system with very low matrix permeability; not a (sub-)regional aquifer; may produce locally water in concentrated fracture zones and support adjacent Quarternary aquifers.	Mostly low permeability, localized zones with moderate fracture permeability; low storativity

Table 1 continued. Hydrogeological Characteristics of Major Hydrogeologic Units, Pitkin County, Colorado.

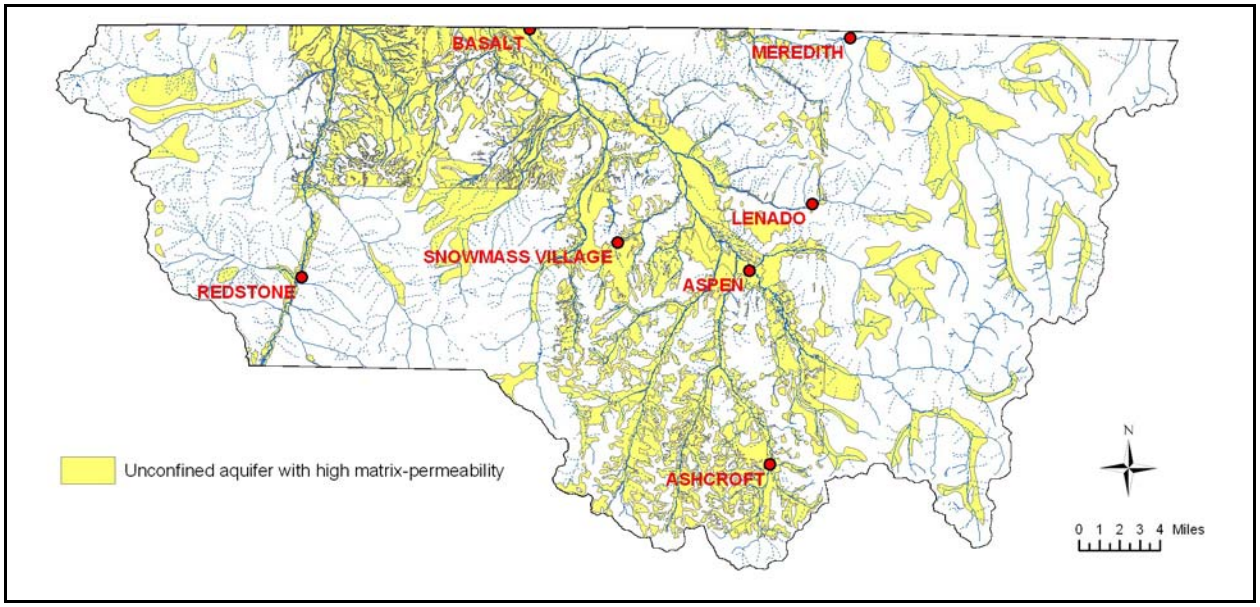

Figure 2. Map Showing Potential Groundwater Resources in Unconsolidated Quaternary Deposits Including Hydrogeological Characteristics, Pitkin County, Colorado.

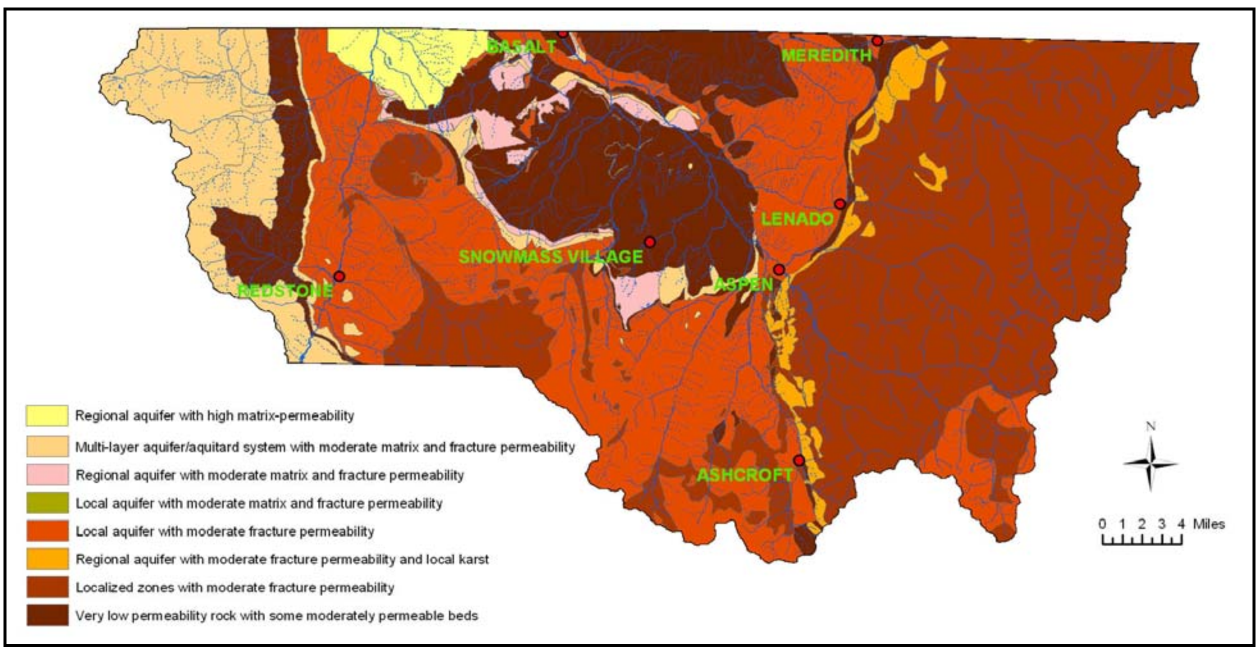

Figure 3. Map Showing Potential Groundwater Resources in Bedrock Including Hydrogeological Characteristics, Pitkin County, Colorado.

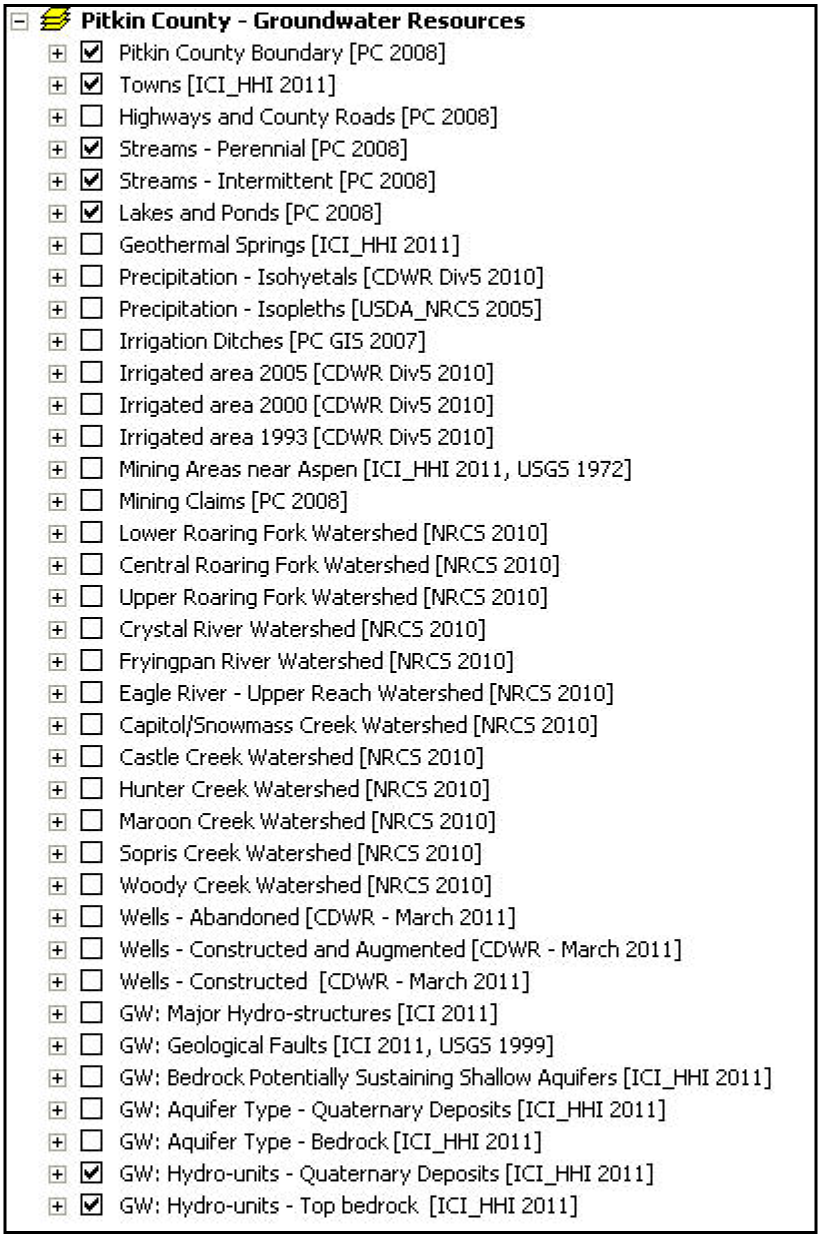

Figure 4. Table of Contents (TOC) for Arcview/ArcMap Display of County-wide Groundwater Resources GIS Maps, Pitkin County, Colorado.

2.1.2 Potential Presence of Water and Resource Characteristics That May Determine Economic Feasibility for Use as a Water Supply

In addition to the hydrogeology characteristics described in Section 2.1.1, the resource characteristics that determine economic feasibility for use as a water supply are: 1) depth to water, that is, the distance between the ground surface and the (ground-) water table; 2) the saturated thickness of the groundwater resource or aquifer, that is, the distance between the base of the aquifer and the water table; and 3) the magnitude of seasonal and multi-year variations in water table elevations. Typically, the presence of groundwater in a geologic unit is determined either directly through observation of the hydraulic head or the water table in drilled or dug wells and excavations, or indirectly through geophysical exploration. The saturated thickness of an aquifer is more complex to determine as, frequently, wells drilled in an aquifer do not reach its base and, thus, the elevation of this base cannot be directly measured. Given the clustered nature of the distribution of the wells in the county and the lack of aquifer-base-penetrating deep wells, very little information is available regarding aquifer-base elevations. Thus, often, even when the water table elevation is known, the saturated thickness can only be estimated from interpretation of other geologic information. Finally, fluctuations in water table elevations can only be measured directly in wells. However, the clustering of wells in the county limits mapping of such fluctuations on a county-wide scale. Due to the paucity of direct observations and measurements, only a qualitative description for these characteristics can be given (see Table 2). Note that when bedrock is covered by Quaternary sediments, the underlying hydrogeologic unit may sustain the overlying Quaternary aquifers, but is typically not exploited as an independent resource.

The location of these groups of hydrogeologic units in the county-wide GIS maps can be found by using the label under column "Type of Hydrogeologic Units" in Table 2 and the GIS layers "GW: Hydro-units - Quaternary Deposits" and "GW: Hydro-units - Top bedrock" (Figure 4). The hydrologeologic units have been discussed in detail in the Phase 2 report of this project (*van der Heijde and Kolm 2011*)

Type of Hydrogeologic Units	Groundwater Resource Characteristics		
	Depth to Water	Saturated Thickness	Water Table Fluctuations
Alluvium	Small [< 20 ft]	Small [10–20 ft]	Small
Unconsolidated Quaternary Units Except Alluvium	Moderate to large [20–100 ft]	Highly spatially variable [0–100 ft]	Moderate to large
Tertiary Unconsolidated Sediments	Moderate [20–50 ft]	Large [>100 ft]	Small
Bedrock Without Quaternary Cover	Moderate to large	Large [>100 ft]	Moderate to large

Table 2. Groundwater Resource Characteristics That May Determine Economic Feasibility for Use as a Water Supply, Pitkin County, Colorado.

2.1.3 Type of Recharge

The sustainability of a groundwater resource is determined by the recharge type or characteristics. The first major distinction that can be made is between natural and human sources of replenishment of utilized groundwater. Natural recharge of an aquifer includes: 1) direct recharge from precipitation; 2) recharge from losing streams; 3) recharge from underlying bedrock; and 4) recharge from adjacent groundwater basins. Human sources of replenishment include: 1) man-made water bodies (ponds, reservoirs); 2) irrigation return flow; 3) leaking irrigation ditches and diversion conduits; 4) OWTSs; 5) golf courses; and 6) snowmaking. Each of these recharge sources are characterized by specific seasonal and multi-year fluctuations.

In Pitkin County, the most significant component of recharge from precipitation is snowmelt. Typically, a portion of the melting snow seeps directly into the soil and travels to the water table. Another large segment of the melt water runs off on the ground surface as sheet flow, or in the shallow soil as interflow. A portion of this runoff may infiltrate again and contribute to groundwater recharge, sometimes called “displaced recharge.” This phenomenon occurs primarily on slopes covered with landslide or moraine materials and on the steeper parts of alluvial fans. Another important component of recharge from precipitation is net rainfall, which is precipitation minus evapotranspiration (evaporation from soil and vegetation surfaces and transpiration by vegetation). The amount of net precipitation (recharging snowmelt plus net rainfall) is highly dependent on vegetation, ground elevation, slope steepness and slope aspect, and hydrogeologic materials (soils, geomorphic materials, and bedrock). The total precipitation is included in the GIS by two layers: “Precipitation - Isohyetals” and “Precipitation – Isopleths” (Figures 4 and 5). Because of the complex factors involved, actual recharge from precipitation is highly variable spatially. For unconsolidated sediments, a first estimate is typically taken at about 10% of total precipitation; no such estimate is available for exposed bedrock. As the recharge from precipitation is climate driven, the same temporal variability (both seasonal and multi-year) of precipitation and air temperatures is observed.

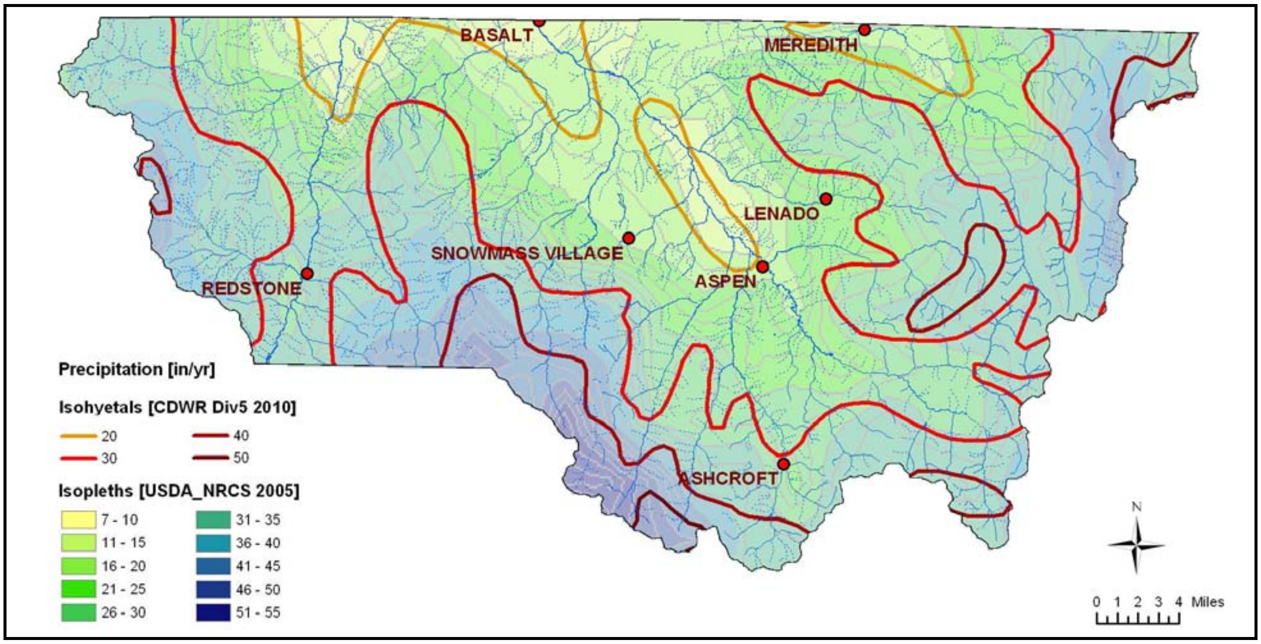

Figure 5. Map Showing Precipitation Isohyetals and Isopleths, Pitkin County, Colorado.

Locally, groundwater may be recharged by “losing” streams, that is, streams losing water to the adjacent aquifers. The groundwater recharge from such streams may be seasonal, such as during spring snowmelt, or more continuous, such as in some sections of perennial streams. When a stream is in direct contact with groundwater, the groundwater flow near the stream may be reversed during part of the year and the stream becomes a “gaining” stream. Here again, seasonal and multi-year fluctuations occur. It should be noted that a gaining stream may become a losing stream from pumping one or more nearby wells. A GIS data layer with all streams in the county, both perennial and intermittent, is available from the County GIS department (Figure 6). However, without information on groundwater levels near these streams or direct measurements of changes in instream flows (i.e., increases or decreases from upstream to downstream), it is not possible to determine if a stream is gaining or losing. In some locations, ponds and reservoirs may contribute to recharge of shallow local aquifers (Figure 6).

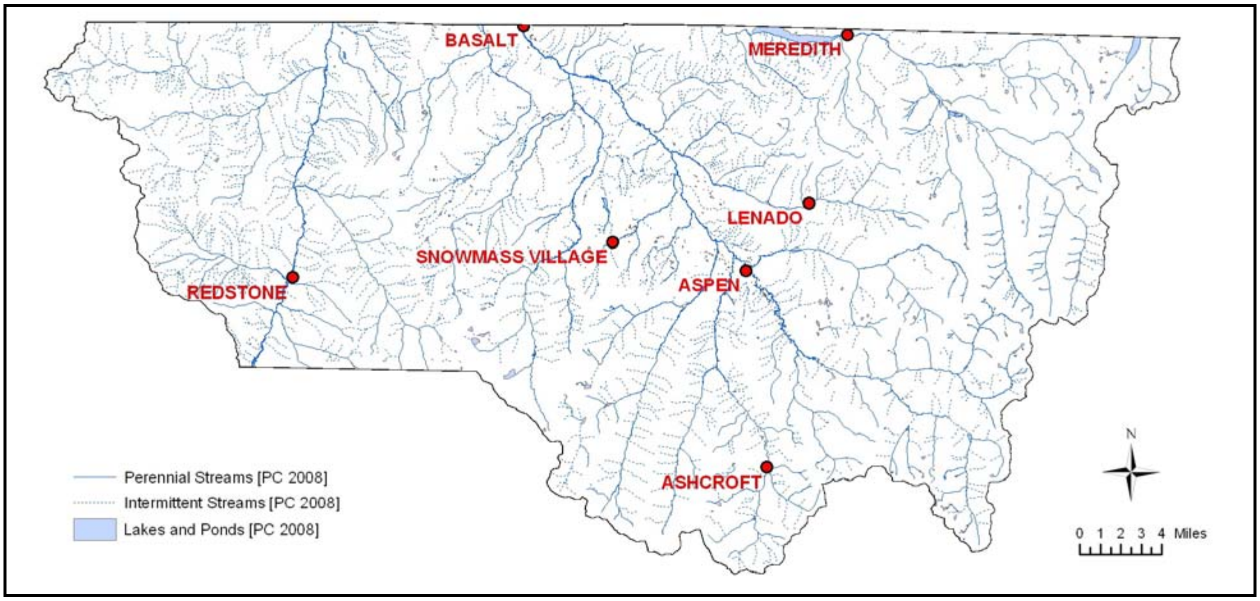

Figure 6. Map Showing Perennial and Intermittent Streams and Ponds and Reservoirs, Pitkin County, Colorado.

Many of the shallow unconsolidated aquifers overlie somewhat permeable, more regional bedrock systems. Although the permeability of these bedrock systems may be small, the large size of their recharge catchments and the long travel times between recharge and discharge areas may result in a rather continuous and reliable recharge of the supported shallow aquifer. This may occur in some of the terraces, fans, and moraine (quaternary) deposits located in the hatched area of Figure 7. Very few groundwater resources in Pitkin County are recharged from neighboring groundwater basins. Actually, the reverse is occurring as the deeper aquifers on the northern and western county borders "lose" water to regional groundwater systems.

One of the most significant human sources of groundwater recharge in Pitkin County is the irrigation return flow from agricultural lands and golf courses. Most of the water used for irrigation in the county is diverted surface water from rivers and streams and would not contribute to the groundwater resources if they were not diverted for this type of use. The temporal variability (both seasonal and multi-year) is a function of crop utilization and climatic conditions and varies in both seasonal and multi-year cycles. The GIS databases developed for this project includes layers showing the irrigated agricultural area in Pitkin County as of 1993, 2000, and 2005 (Figure 8). Note the significant decrease in irrigated agricultural areas between 1993 and 2005. Furthermore, there are an increasing number of golf courses, replacing to some extent the agricultural acreage taken out of production. It should be noted that because of the use of fertilizers and pesticides, the water quality of the irrigation return flow may be significantly altered.

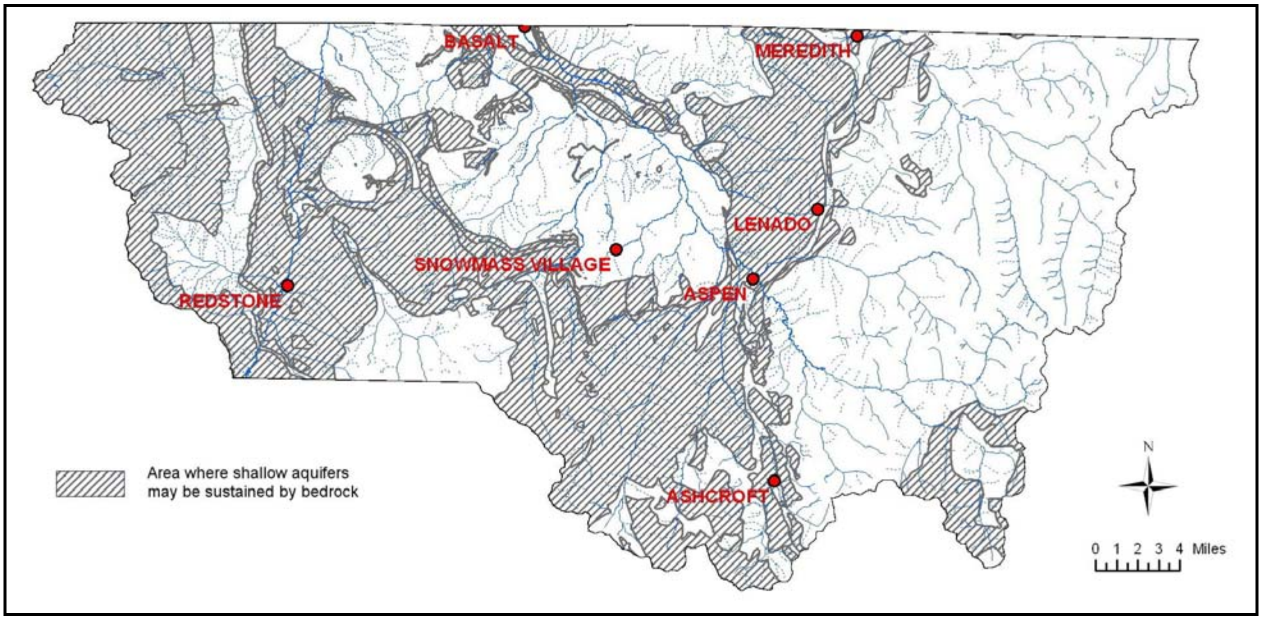

Figure 7. Map Showing Area Where Shallow Aquifers May Be Sustained by Bedrock, Pitkin County, Colorado.

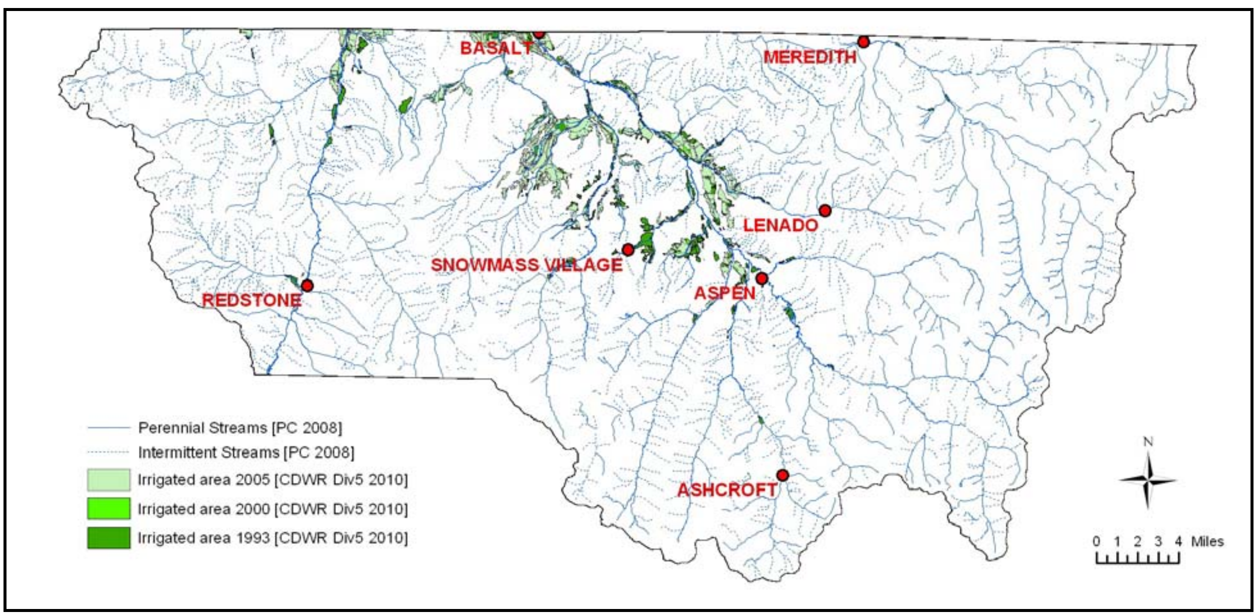

Figure 8. Map Showing Irrigated Areas in 1993, 2000, and 2005, Pitkin County, Colorado.

In many cases related to the irrigation practices on agricultural lands, a number of active and abandoned irrigation ditches and diversion conveyances are located at the lower elevations in the county, many of them unlined and leaking. In some areas, these leaking ditches may provide a large part of the recharge of the underlying groundwater. As irrigated acreage decreases and water rights shift, some of these leaking ditches and canals will become dry and the groundwater recharge function ceases. Similarly, the ditches that are used for irrigation of agricultural acreage will show the same recharge periodicity as the irrigation return flow. A GIS data layer with the ditches in the county is available from the County GIS department. However, the attribute table does not include information on operational characteristics, and some irrigation ditches may have been taken out of service at some time in the past (Figure 9).

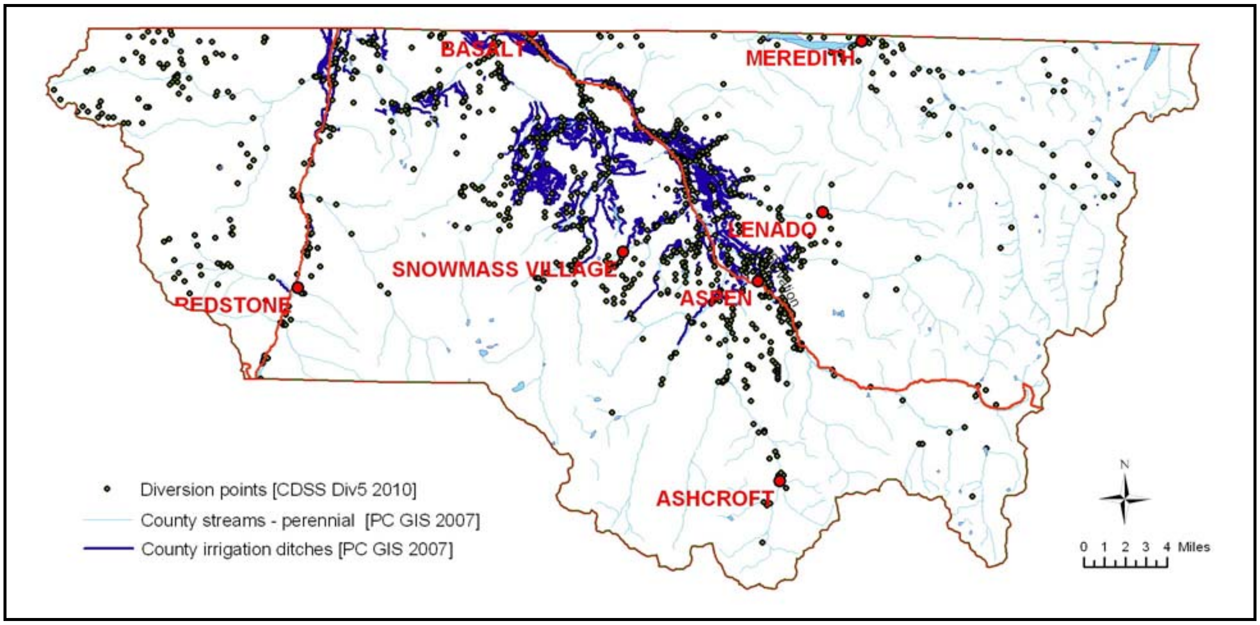

Figure 9. Map Showing Ditches and Diversion Points, Pitkin County, Colorado.

OWTSs contribute to groundwater recharge by infiltrating water from their leach fields. In flat areas, this leachate seeps down to the water table, or, if a barrier in the form of a very low-permeability layer is encountered in the unsaturated zone, may form a local perched water table. In sloping areas, the OWTS leachate may be transported in the shallow soil layers as interflow and may provide "displaced recharge." The importance of OWTS to groundwater recharge is dependent on the density of the OWTSs in a particular area, and any significant recharge from OWTSs may only occur in specific areas, such as subdivisions not connected to centralized treatment systems.

Finally, the main effect of snowmaking at the ski resorts occurs during the snow melt season. Often non-groundwater sources are used for this purpose and thus, may provide an additional source of groundwater recharge. The increased snowpack due to snowmaking will show a temporal behavior comparable with snowmelt from precipitation.

2.2 Vulnerability and Susceptibility of Groundwater Resources

Vulnerability of groundwater 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 more or less likely to occur. The concept of vulnerability has received broad attention in relation to groundwater protection, both from the research community and from the public policy and enforcement sectors (*NRC, 1993*; *van der Heijde and others, 1997*).

The term *vulnerability* is often used in the context of determining the *susceptibility* of a public water resource (*EPA, 2006; CDPHE, 2011*) and, in some instances, even used interchangeably (*NDEQ, 2011*). Susceptibility indicates how susceptible a public water supply (PWS) is to: 1) identified potential contaminant sources (PCSs), or 2) to particular contaminants that could be released from those PCSs (*EPA, 2006*). In other words, where does the water of a PWS come from, what contaminant sources potentially threaten the PWS, and what influence would the release of contaminants have on the water supply (*CDPHE, 2011*)? The 1996 Safe Drinking Water Act Amendments directed that each state develop a Source Water Assessment and Protection Program (SWAP).

In support of this legislation, EPA published various guidance documents on how to develop and conduct such state programs. One element of this guidance relates to susceptibility determination (SD) of a PWS (*EPA, 2006*). SD involves four critical factors: 1) the presence of PCSs and the likelihood that contaminants will be released from those contaminant sources; 2) the physical integrity of the well(s) or intake(s); 3) the sensitivity of the natural setting (the degree and amount of protection afforded by the natural hydrogeologic and hydrologic setting); and 4) the presence of existing or likely contamination in the source water. The term *vulnerability of a groundwater resource*, as used in this report, is equivalent to the third item, the sensitivity of the natural setting as it pertains to groundwater. Specifically, vulnerability is defined as the likelihood of a contaminant, after its release at the surface, to reach the top of the groundwater resource, which in Pitkin County is mostly equivalent to reaching the water table. In addition, the definition of vulnerability of a groundwater resource, for the purpose of this report, is extended to include subsurface anthropogenic contaminant sources, such as result from underground mining, and certain natural sources of deterioration of groundwater quality, such as result from chemical dissolution in shales. Note that, although the above discussion focuses on PWSs (both municipal and community water supply systems), vulnerability and susceptibility classifications can easily be extended to individual or private water supply systems.

The potential of contaminants to leach into a groundwater resource from the soil surface and reach water supply wells depends on many factors, including the composition, structure, texture, and permeability of soils and rock; depth to groundwater (to allow for natural attenuation and remediation in soils and the unsaturated zone); 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 (to prevent contaminants from entering the subsurface). For the purpose of this project, the main factors identified as contributing to the vulnerability of a groundwater resource are: 1) recharge rate; 2) depth to the water table; 3) presence of a significant soil layer; 4) presence and permeability of the unsaturated zone; and 5) presence of fractures near the surface. Note that parameters that are of interest in determining travel times between the location where a contaminant enters the saturated zone (*i.e.*, the aquifer) and a point of exposure (*e.g.*, a well or a stream), such as the permeability of the aquifer, are not considered in this section.

To move a contaminant through the subsurface, a driving force is needed. The main natural driving force is recharge. In case of liquid contaminants or contaminants released together with a liquid (such as OWTS leachate or oil spills), the contaminant may have an anthropogenic driving force. If an anthropogenic or recharge-related driving force is absent or present only to a small degree, the contribution to vulnerability is low. In comparison, the areas of significant natural recharge will have significant vulnerability. The distribution and magnitude of natural recharge was discussed in Section 2.1.3 of this report.

The depth to the water table (that is, the thickness of the unsaturated zone including the soil zone) is of significance in determining vulnerability, because it provides a measure of time and distance available for various natural attenuation processes to be effective. The type and effectiveness of the attenuation processes involved depend on the contaminant and the physical and biochemical characteristics of the soil and rock. A larger depth to water provides a longer time (and pathway) for the contaminant to interact with the soil and rock and, thus, contributes more to the protection of the groundwater resource than a small depth to water. As the soil zone generally is a more dynamic physical, chemical and biological environment than the deeper unsaturated rock layers, the presence, type and thickness of soil and geomorphic deposits (including their mineralogy and organic carbon content) have a major influence on the determination of vulnerability.

In the presence of a thick unsaturated zone beneath the soil zone, the vertical permeability distribution and, in the case of unconsolidated sediments, the grain size distribution, become important factors in determining groundwater vulnerability. The presence of layers with low permeability results in a slow movement of water down to the saturated zone, and the presence of rather unsorted grain sizes has a filtering function with respect to contaminating particles. Both of these characteristics contribute to a lowering of the vulnerability of the underlying groundwater. Conversely, the absence of low-permeability layers and the presence of only well-sorted grain sizes increase the vulnerability of the underlying groundwater.

Finally, one of the main contributors to the vulnerability of bedrock systems is fracture zones that extend from depth to the surface, especially in the Precambrian gneisses and granites and in the Tertiary intrusive rocks. These fractures and fracture zones may provide an almost instantaneous pathway to the groundwater. Although such zones are localized, they also tend to be the areas where groundwater may be available and accessed. These fracture zones, being often the main source of localized water supply, are also highly vulnerable.

A special mention needs to be made regarding the mining district around Aspen, especially with respect to the Leadville Formation. Here, a major concern is not only the short groundwater transport pathways provided by the mining corridors, but also the propensity of the corridors to actually serve as a source of contamination by exposing dissolvable chemicals in the host rock. This is especially an issue for those mining galleries that are below the water table. A map showing the above and below water table mining areas near Aspen have been included in the Phase 1 deliverable of this project (*Kolm and van der Heijde 2011*).

It should be noted that the presence of the Mancos Shale units, the Morrison Formation, the Chinle Formation, and the Eagle Valley Evaporites in the central and western sections of the county also are a concern with respect to water quality. These formations are known to release salts, particularly sulfates, and selenium into surface water and groundwater, thereby increasing the total dissolved solids (TDS) and decreasing the water quality.

Determining the vulnerability of groundwater at a particular site involves a quantitative assessment of a number of factors beyond the scope of and data available for this project. In general, the vulnerability of the groundwater resources in Pitkin County ranges from high to moderately high.

2.3 Vulnerability of Groundwater Due to OWTSs

One major concern of Pitkin County is the effect of increased numbers and uses of OWTSs on the groundwater system, with cascading effects on groundwater supply and quality, and ultimately surface water quality. The pathways of OWTS discharge could involve the nearby interflow system, as well as the local and subregional shallow and deep groundwater systems, and could affect nearby wells, springs, and surface water bodies (notably rivers and streams).

Pitkin County Code Title 6—Health and Safety, latest release in 2010, states the various Evaluation Criteria for the approval of OWTS construction permit applications. Two of these criteria can be evaluated during due diligence by the owner with the aid of the GIS databases and layers prepared in this project. The following criteria can be evaluated in this manner:

4a: *Adequate Water Supply*: Figure 1 through Figure 9, and Table 1 and Table 2 all supply information that would be useful for determining if a given property has an adequate water supply. The methods and approach developed by Kolm and van der Heijde in previous reports (*Kolm and van der Heijde, 2006*; *Kolm and others, 2007; Kolm and others, 2008*) should be employed (Note that an adequate water supply is required for efficient operation of the OWTS);

4d: *Setbacks from reservoirs, lakes, streams, ditches, wells, wetlands, floodplains, riparian zones*: The guidance needed for setbacks is stated in 6.28.040: Setbacks and Other Factors Affecting OWTS Siting (see Table 6.28-1). A GIS can be used to determine these setback distances by plotting the location of the proposed OWTS on the following GIS maps: 1) riparian and floodplain area; 2) wetlands maps; 3) topography showing dry gulches; 4) surface water bodies including reservoirs, lakes, rivers, streams, irrigation ditches; 5) drain tiles, piped or lined irrigation ditches; 6) dwellings; 7) drinking water supply cisterns and supply lines; 8) springs; and 9) well locations. Some of these GIS maps are available in the GIS maps and databases provided to Pitkin County with this report. GIS maps of riparian and floodplain areas, wetlands, drinking water supply infrastructure, and springs may need to be prepared separately. Topography of dry gulches may be evaluated by overlaying the digital elevation model (DEM) with the stream layer.

The regulations state that the OWTS absorption bed or trench identified on the site plan must have certain minimal horizontal distances from various features, such as wells, springs, and other bodies of water; riparian areas; and wetlands in order to be permitted. The GIS maps and databases, as described above, provide an efficient way to accomplish this, as well as an aid in the review of such permit applications.

3.0 Summary

The purpose of this Phase 3 report is to present the terminology related to availability, sustainability, vulnerability and susceptibility of groundwater resources and discuss the development and use of county-wide GIS maps showing aspects of groundwater resource availability, sustainability and vulnerability in Pitkin County, Colorado. The type of geologic materials and their hydrogeologic characteristics present at a particular location in Pitkin County is a major factor in determining the availability and sustainability of a groundwater resource. Two GIS layers were developed describing hydrogeologic characteristics of potential aquifers within the county: 1) unconsolidated quaternary deposits, and 2) bedrock units. A table was prepared of hydrogeologic characteristics of the major hydrogeologic units displayed in these GIS layers, primarily in terms of type (matrix, fracture-dominated, karst, or combination of these) and magnitude of permeability (high, moderate, low).

The sustainability of a groundwater resource in Pitkin County is determined primarily by the recharge type or characteristics, and by the water usage. Natural recharge of aquifers in Pitkin County includes: 1) direct recharge from precipitation; 2) recharge from losing streams; 3) recharge from underlying bedrock and 4) recharge from adjacent groundwater basins. Human sources of replenishment includes: 1) man-made water bodies (ponds, reservoirs); 2) irrigation return flow; 3) leaking irrigation ditches and diversion conduits; 4) OWTSs; 5) golf courses; and 6) snowmaking. Each of these recharge sources are characterized by specific seasonal and multi-year fluctuations, and GIS layers that aid in determining recharge in Pitkin County include: 1) Precipitation (isohyetals and isopleths); 2) Streams (perennial and intermittent); 3) Lakes and ponds; 4) Bedrock potentially sustaining shallow aquifers; 5) Irrigated areas (1993, 2000, 2005); and 6) Irrigation ditches. In addition, OWTSs, golf courses, and ski resorts (snowmaking) contribute to groundwater recharge locally.

Groundwater vulnerability is primarily defined in this report as the configuration of protective layers about the aquifer to protect it from contamination. In this context, most of the aquifers in Pitkin County are highly to moderately vulnerable to contamination. Special consideration should be given to groundwater supplies near areas of the Mancos Shale units (Town of Snowmass Village), the Morrison Formation, the Chinle Formation, and the Eagle Valley Evaporite, due to increased risk of natural TDS, sulfates, and selenium concentrations, and mining areas near the Leadville and Tertiary Intrusive aquifers, due to increased risk of metals concentrations and contaminants related to mining activity (Town of Aspen, for example).

A major concern of Pitkin County officials is the effect of increased numbers and uses of OWTSs on the groundwater system, with cascading effects on groundwater supply and quality, and ultimately surface water quality. This report discusses two of the evaluation criteria, adequate water supply and setbacks, that are stated in Pitkin County Code Title 6—Health and Safety, latest release in 2010, for the approval of OWTS construction permit applications. Adequate water supply and setbacks can be evaluated during due diligence by the owner or County with the aid of the GIS databases and layers prepared in this project.

4.0 References

Bredehoeft, J.D. 2006. *On Modeling Philosophies*. Ground Water, Vol. 44 (4), pp. 496-499.

CDPHE (Colorado Department of Public Health and Environment). 2011. *Source Water Assessment and Protection.* Accessed at www.dcphe.state.co.us/wq/sw/swaphom.html on 07/08/2011.

Devlin, J.F., and M. Sophocleous. 2005. *The Persistence of the Water Budget Myth and its Relationship to Sustainability*. Hydrogeology Journal, Vol. 13(4), pp. 549-554.

EPA (U.S. Environmental Protection Agency). 2006. *How-To Manual: Update and Enhance Your Local Source Water Protection Assessments.* EPA Office of Water, EPA816-K-06-004.

Kolm, K.E., and R.G. Gillson, III. 2004. *State of Ground and Surface Water in the Central Roaring Fork Valley, Pitkin County, Colorado*. Report prepared by HSA for Pitkin County Commission of County Commissioners.

Kolm, K.E., and P.K.M. van der Heijde. 2006. *Development of GIS-based Ground Water Resource Evaluation of the Upper and Middle Roaring Fork Valley Area, Pitkin County, Colorado*. Report prepared by HSA and HHI for Pitkin County Commission of County Commissioners.

Kolm, K.E., P.K.M. van der Heijde, and M. Dechesne. 2007. *GIS-based Ground Water Resources Evaluation of the Capitol and Snowmass Creek (CSC) Study Areas, Pitkin County, Colorado*. Report prepared by HSA and HHI for Pitkin County Commission of County Commissioners.

Kolm, K.E., P.K.M. van der Heijde, and M. Dechesne. 2008. *GIS-based Ground Water Resources Evaluation of the Crystal River and West Sopris Creek (CRWS) Study Area, Pitkin County, Colorado*. Report prepared by HSA and HHI for Pitkin County Commission of County Commissioners.

Kolm, K.E., and P.K.M. van der Heijde. 2011. *Hydrologic and Environmental Systems Analysis and Formulation of Conceptual Models for the Central Roaring Fork Tributaries (CRFT), Pitkin County, Colorado.* Report prepared by Integral Consulting Inc. for Pitkin County Commission of County Commissioners.

NDEQ (Nebraska Department of Environmental Quality). 2011. *Source Water Assessment program.* Downloadable from http://www.deq.state.ne.us/SurfaceW.nsf/Pages/SWAP .

NGWA (National Ground Water Association). 2011. *Ground Water Availability Interest Group.* Accessed at http://www.ngwa.org/availability/index.aspx on 07/08/2011.

NRC (National Research Council). 1993. *Ground Water Vulnerability Assessment; Predicting Relative Contamination Potential under Conditions of Uncertainty*. National Academy Press, Washington, D.C.

Reilly, T.E., K.F. Dennehy, W.M. Alley, and W.L. Cunningham. 2008. *Ground-Water Availability in the United States*. U.S. Geological Survey. Circular 1323.

Sophocleous, M. (ed.). 1998. *Perspectives on Sustainable Development of Water Resources in Kansas.* Kansas Geological Survey, Bulletin 239.

Van der Heijde, P.K.M., K.E. Kolm, H. Dawson, and M. Brooke. 1997. *Determining Water Infiltration Routes from Structures Located above Carlsbad Cavern, Carlsbad Caverns National Park, Carlsbad, New Mexico*. Report submitted to National Park Service, Fort Collins, Colorado.

Van der Heijde, P.K.M., and K.E. Kolm. 2011. *Development of County-wide Hydrogeological GIS Maps for Pitkin County, Colorado.* Report prepared by Integral Consulting Inc. for Pitkin County Commission of County Commissioners.