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.

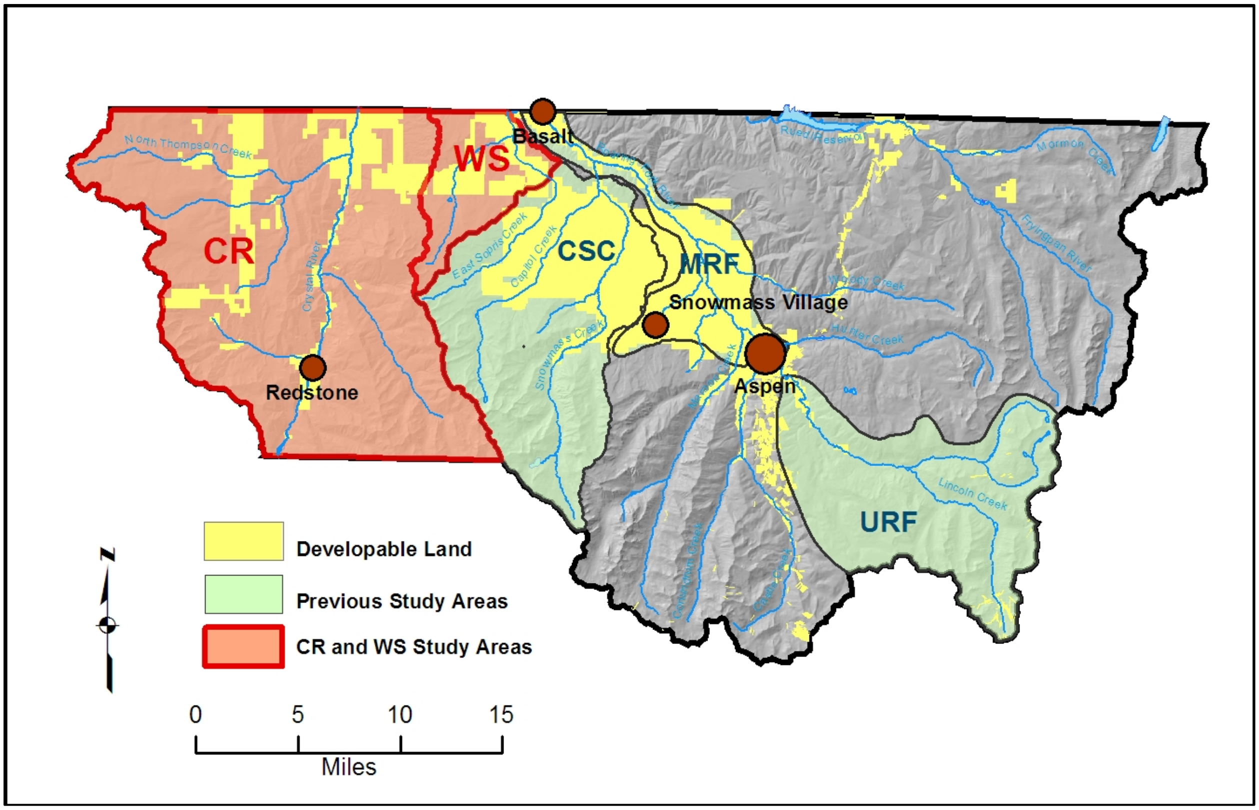

Figure 1. Location of the Crystal River and West Sopris Creek (CRWS), Capitol and Snowmass Creek (CSC), Middle Roaring Fork (MRF), and Upper Roaring Fork (URF) Study Areas, Pitkin County, Colorado.

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.

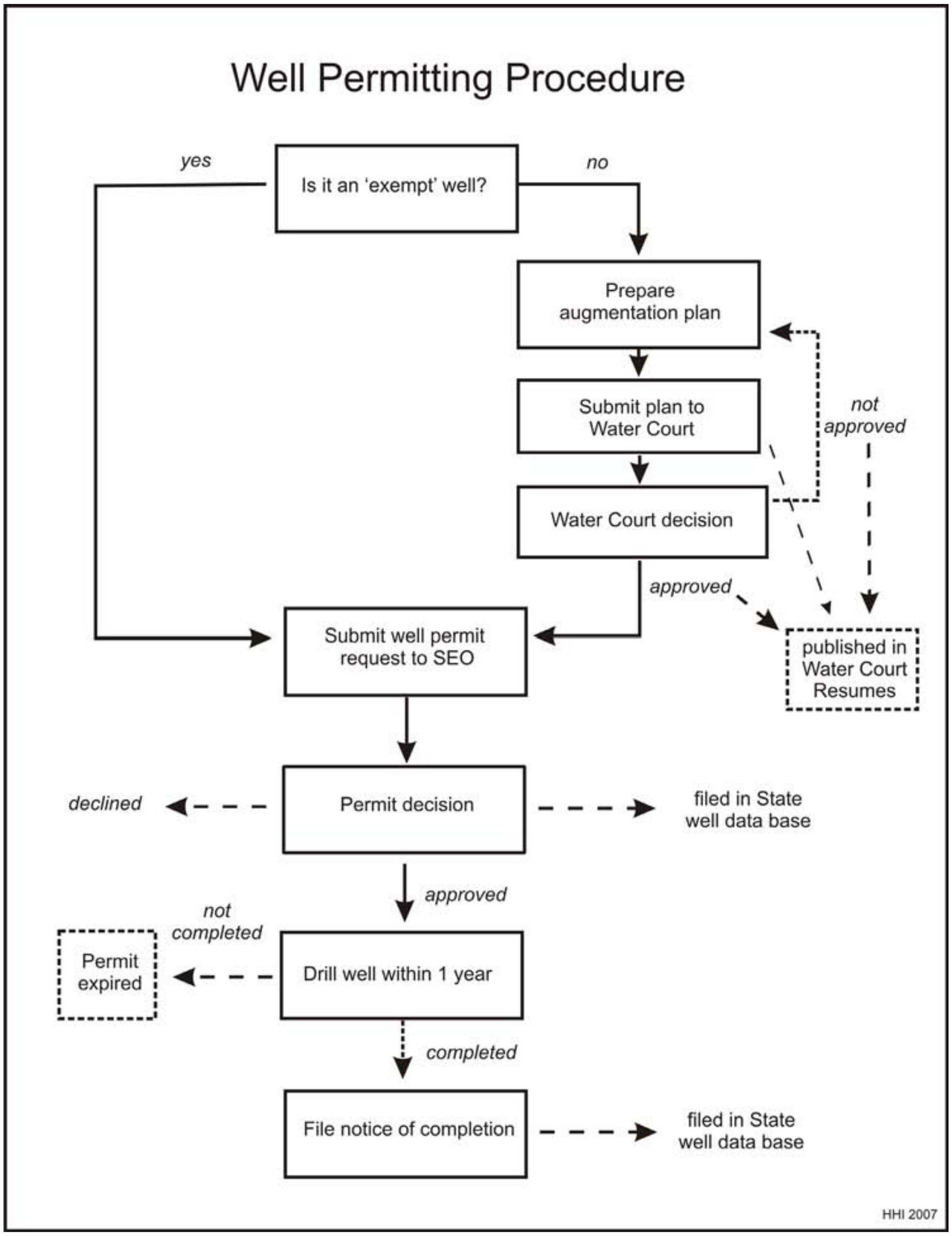

Figure 2. Flow Chart of Well Permitting Procedure (from: *Kolm and Others, 2007*).