

CLASSIFICATION OF AQUIFERS

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Preface

This dissertation contains three papers describing an approach to classifying aquifers and groundwater systems. The three papers bring together the development of a basin scale groundwater classification system that integrates the literature, data gathering, and data analysis and testing. The classification system is a comprehensive method designed to improve interdisciplinary communication and standardize how groundwater systems are compared in watersheds across in the west and potentially beyond.

The first paper, *An Aquifer Classification System for Watershed Managers in the Intermontane West* was submitted to the Journal of American Water Resources Association (AWRA) in fall 2008. The paper was revised following the recommendations of the peer reviewers and my dissertation committee and resubmitted in December 2009. A longer version of the AWRA paper is contained in this dissertation. The first paper provides the foundation used to develop the proposed aquifer classification system. It includes technical aspects of the classification method, and the proposed mapping approach. A simplified case study is included in the first paper to demonstrate how the classification system is applied.

The second paper, *Application of a Visual, Symbol, and Tabular Based Groundwater Classification System for the Lower Ruby Valley Watershed, Southwest Montana* is a case study that illustrates how the classification system is applied. Both deep and shallow aquifer systems are addressed. The third paper, *Application of an Aquifer Classification Methodology to Three*

Western Watersheds: Case Studies of the Truckee Watershed, California; Paradise Valley Watershed, Nevada; and the lower Boulder – Longmont Watershed, Colorado provides three additional examples of how the classification system can be applied to a wide range of hydrologic conditions typical of western groundwater basins. The third paper outlines the data and analysis needed to classify aquifers based on data derived from previous hydrogeological studies. It presents maps that allow for the comparison of groundwater systems in contrasting watershed settings. The broad applicability of the methodology is promoted.

Together, the three papers describe a method for comparing and contrasting aquifer properties and systems needed by watershed managers. It is argued that the proposed methodology is needed to assist managers and planner in understanding the role of aquifers in watersheds as well as for the broad multi-basin comparison of aquifer data . The classification method does not replace current standard practices traditionally used to assess or characterize aquifers and groundwater systems. However, it does provide a standard methodology by which existing and new hydrogeologic data can be organized, easily communicated, and broadly compared on a watershed scale of 1:100,000 to 1:250,000. It is believed this classification system will promote an improved technical understanding between groundwater professionals and natural resource managers. Three appendices are included in this dissertation in hard copy and electronic form. The appendices provide supporting information for the three papers.

Paper Number 1

An Aquifer Classification System and GIS-Based Analysis Tool for Watershed

Managers in the Intermontane West

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Abstract

Aquifers and groundwater systems can be classified using a variety of independent methods to characterize geologic and hydraulic properties, the degree of connection with surface water, and geochemical conditions. In light of a growing global demand for water associated with population growth, land development, and the expected effects of climate change, a standardized approach for classifying groundwater systems at the watershed scale is needed. To this end, a comprehensive classification system is developed that combines recognized methods and new approaches into one system. The purpose of this approach is to provide groundwater professionals, policy makers, and watershed managers with a widely applicable classification system that reduces sometimes cumbersome complex groundwater databases and analyses to straightforward graphical representations. The proposed classification system uses basin geology, aquifer productivity, threats and impacts posed by humans, water quality, and the degree of groundwater/surface water exchange as classification criteria. The approach is based on literature values, reference databases, and basic hydrologic and hydrogeologic principles. The proposed classification system treats data set completeness as a variable and includes

a tiered assessment protocol that depends on the quality and quantity of data. In addition, it assembles and catalogs groundwater information using a consistent set of nomenclature. It is designed to analyze and display results using Geographical Information System (GIS) mapping tools, while standardizing descriptions of groundwater conditions and to support resource managers as they make land use decisions at the watershed scale.

Key Terms: Hydrogeology, groundwater management, watersheds, watershed management, geographical information systems, rivers / streams, surface water / groundwater connection, and land use.

1.0 Introduction

Ideally, every land use decision should consider of the source(s) of water necessary to sustain the management decision, in addition to considering its economic, environmental, and social costs (Van de Wetering 2007). Unfortunately, in light of growing water demands associated with population growth, development, and the expected effects of climate change, this seems to rarely be the case (Alley et al. 2002, Daughton 2004, and Jury and Vaux 2005). Clearly, the world faces growing water supply and availability challenges. In the arid and semi-arid areas of the western U.S., demands for water will increase competition among agricultural, municipal, industrial, and ecological water users (Watson et al. 1998, Loáiciga 2000, Loáiciga et al. 2000, Field et al. 2007, and Kundzewicz et al. 2007). Furthermore, groundwater is no longer regarded as an independent natural resource; groundwater provides as little as 90 percent of perennial

stream flow in basins dominated by low permeability materials to more than 90 percent in highly porous and permeable settings (Winter et al. 1998). The exchange between surface water and groundwater at multiple scales is considered to be a critical process that underpins the ecological systems associated with surface water (Naiman et al. 1992, Stanford and Ward 1992, Gibert et al. 1997, Edwards 1998, and Hancock et al. 2005). In cases where watershed scale groundwater conditions are either inadequately characterized or descriptions are overly complex, planners and managers are more likely to miss key concerns and make poor decisions. In an effort to provide managers a logical and well organized set of water resource data, a unifying method by which groundwater conditions can be incorporated into watershed management and land use planning for water-limited basins that are common throughout western North America is proposed (Kendy 2003 and Carter et al. 2007).

The proposed methodology summarizes hydrogeologic and hydrologic datasets and indices is capable of describing both simple and complex groundwater systems in watershed settings. The methodology classifies and maps aquifers at the watershed scale using as key components the geological setting, productivity, threats and impacts posed by humans, groundwater quality, and the degree of groundwater/surface water exchange. The proposed methodology also uses a tiered watershed groundwater classification approach that is based on an evaluation of the quantity and quality of available data, organizing descriptions of basin scale groundwater conditions both graphically and descriptively. A nomenclatural scheme is developed for the primary purpose of facilitating communication among scientists, professionals, managers, and citizens. The

nomenclature is based on well supported classification ranges and principles useful to organize, compare, and contrast aquifers.

1.1 Background

Groundwater classifications have been developed at various scales, however, rarely at the watershed scale. Most often groundwater systems have been classified by describing overall properties of geologic materials or lumping earth materials in units with similar hydrogeologic properties. Meinzer (1923 and 1942) published some of the earliest tabulated hydraulic properties of sediments and rocks related to grain size, porosity, rock interstitial geometries at the pore scale, and specific yield. Meinzer (1923) developed descriptions of regional groundwater flow systems and water producing regions of the U.S., as well as a classification of spring discharge (Meinzer 1927).

Tolman's (1937) classic text book *Ground Water* classified the occurrence and distribution of subsurface water into saturated and unsaturated zones. In the saturated zone, groundwater was classified as free water, confined water, and fixed groundwater, or connate water. Tolman identified perched groundwater as water that is part of the unsaturated zone. Tolman also classified the geologic characteristics of artesian aquifers identifying them as stratiform, high pressure, fracture and joints, solution cavities and lava tunnels, or alluvial cones and fans. Tolman (1937), Thomas (1951) and Todd (1959) mapped and described groundwater occurrence in the U.S. within the general regions identified by Meinzer (1923), although Thomas combined some of 21 provinces into 10 regions where differences were minor. Characterization of groundwater resources of the

U.S. was later expanded by Todd (1983) and Heath (1984). They described the general characteristics and productivity of major groundwater production regions of the U.S.

Heath (1984) classified transmissivity of major aquifers into four categories from very small (less than $25 \text{ m}^2/\text{day}$) to very large (greater than $2,500 \text{ m}^2/\text{day}$), based on reported literature values and common ranges of transmissivity. Other classifications by Heath included porosity, recharge, composition, and components of the primary aquifer systems. He also tabulated common ranges for hydraulic conductivity and well yield, but published no specific classification categories for groundwater regions of the U.S. Bear (1972) apportioned hydraulic conductivity values into classifications for aquifers and non aquifers. He proposed classifying aquifers on a qualitative scale ranging from good to poor aquifers, and classifying relative permeability of groundwater systems on a scale ranging from pervious, semi-pervious, to impervious. Todd's (1983) compendium of 20 papers describing groundwater regions of the U.S. exemplifies the techniques and methods typically used for mapping and characterizing aquifers and groundwater systems. The format describing groundwater resources in Todd's work provides similar information for each region, however, each region has unique characteristics and reporting methods for describing, mapping aquifers, and categorizing breaks in hydrogeologic data. Heath (1984) and Todd (1983) produced useful summaries for characterizing aquifers based on regional assessments, although the scale they examined is comparatively large (i.e., 1:1,000,000 or more vs. 1:100,000 often used at the basin or watershed scales).

Hubbert published *The Theory of Ground-Water Motion* in 1940 which modernized the understanding of groundwater flow dynamics by using electrical theory as an analogy for groundwater movement. While not a classification, his work provides an essential cornerstone for the mathematical solutions we use today to characterize groundwater movement.

Todd (1959 and 1980) grouped water bearing units into aquifers and non-aquifers (aquitards, aquifuges and aquicludes) and groundwater basins comprised of one large aquifer or several connected and interrelated aquifers. Lohman et al. (1972) defined an aquifer as "a formation, group of formations, or a part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs." Such water bearing units are classified as unconfined (water table as the upper surface), confined (over- and underlain by confining beds which allow the water within the aquifer to gain hydrostatic pressure), and perched (saturated zone located in the vadose zone) (Freeze and Cherry 1979). Poland et al. (1972) provided similar definitions including that of aquifer systems, aquicludes, and aquitards among other terms. His work focused on characterizing land subsidence triggered by fluid withdrawal. Maxey (1964) grouped earth materials with similar hydrogeologic properties into hydrostratigraphic units. He provided a method to translate and generalize local features into a more lumped classification. For example, the High Plains and Alluvial Valley Aquifer hydrostratigraphic unit in Kansas is composed of multiple layers of Quaternary and Neogene-water producing units that share similar water producing capability.

Using mathematical models, Toth (1962 and 1963) developed a groundwater flow system classification with local, intermediate, and regional flow systems. Conceptually, Toth's systems originate from a recharge area and end at a discharge area associated with springs, rivers, lakes or an ocean. Short distances between recharge and discharge areas, as well as variable flow and water quality differences at discharge sites, distinguish local flow systems from intermediate and regional flow systems. Winter (2001) classified landscapes into Fundamental Hydrologic Landscape Units (FHLU) where characteristic groundwater conditions were associated with uplands, valley sides and lowlands (Figure 1). Winter's classification concepts are in part adapted and expanded for the classification system proposed in this paper.

In addition to the approach of classifying groundwater systems by their physical properties and flow characteristics, other classification methods are developed herein that use water supply potential, water quality, and the potential to contaminate groundwater systems as criteria. Groundwater development potential and vulnerability classifications are developed using a scoring methodology by Kreye et al. (1998) and Berardinucci and Ronneseth (2002). Their work is adapted here for classifying aquifers in terms of aerial coverage, the relative capacity of aquifers vs. demand, and aquifer vulnerability to contamination. EPA's DRASTIC model classifies aquifer vulnerability and was specifically developed to assess aquifer contamination potential (Aller et al. 1987). While DRASTIC is not used in this classification system, it provides for a more focused evaluation of aquifer vulnerability in cases where general classification of aquifer vulnerability is insufficient.

Water quality is classified from good to poor using several groundwater classification approaches (e.g., Walker 2001, Lowe et al. 2002, and Texas Natural Resource Conservation Commission 2003.) The U.S. Clean Water Act of 1977 requires groundwater quality be classified. In most states these classifications are based solely on specific conductance. In terms of more detailed chemical classification methods, Back (1961) developed mapping techniques for hydrochemical facies, an approach to differentiate groundwater quality based on cation and anion chemistry and the percent thereof in groundwater. A similar approach is proposed in this paper wherein specific conductance and common ion chemistry together are used to classify groundwater quality, along with other criteria.

Recent groundwater system classification efforts include work by Hibbs and Darling (2005) and Anning and Konieczhi (2005) who used a physiographic groundwater classification and the flow characteristics of alluvial basins in Southwest U.S. and Mexico. These classification efforts focus on differences within a specific geographic area and are not necessarily applicable in other geographic areas. The State of California Department of Water Resources (2003) and the State of Colorado (Topper et al. 2003) developed a system that classifies groundwater geographically by groundwater basin or regional aquifer system.

Domenico (1972) was probably one of the earliest to suggest the important role groundwater plays in watersheds, including its importance to ecologic systems. Research

in ecohydrology has described groundwater dependence ecosystems (GDE) and the river-groundwater exchange process (Hayaskhi and Rosenberry 2002, Boulton and Hancock 2005; Danielopol et al. 2003, 2004, and 2006; and Eamus and Froend 2006).

In spite of these advances in classifying a wide range of conditions that are commonly found in groundwater systems and aquifers, there exist no unifying methods for watershed settings or approaches that are linked explicitly to land use planning. The following provides the approach and methods used to develop such a classification system. The proposed classification scheme presented below is designed to integrate methods described in the literature with new approaches that ultimately support watershed management and land use planning.

2.0 Approach

A hierarchical approach is proposed for organizing, presenting, and describing groundwater conditions for watershed management applications. It applies a standardized nomenclature, new mapping techniques, and a three tiered methodology. This approach was loosely modeled after the classification system for natural rivers developed by Rosgen (1994 and 1996). Rosgen's morphological and four-tiered approach brought together existing stream metrics and uses a robust database of hydrologic information and morphological classifications to support his system improving communication amongst scientists and managers. Like the classification system developed by Rosgen (1994, 1996), the proposed groundwater classification system is supported by a database in which published values are used to define general characteristics of groundwater systems.

By analogy with Rosgen's stream classification scheme, the proposed groundwater classification scheme is designed to be useful for planners and managers who are not necessarily hydrologists by training (e.g., Simon et al., 2007), helping them categorize and compare types of streams, or in this case aquifers (Juracek and Fitzpatrick 2003). In addition, a tiered approach is adapted from Rosgen's methodology to define the level of assessment and quality of data collected to complete the classification process. Additional criteria are also adapted from other published classification systems to describe basic groundwater quality and depth to groundwater, and an approach is proposed to classify the degree of groundwater/surface water exchange.

Lastly, a new mapping procedure that provides a graphical summation of watershed groundwater data is presented and applied using GIS applications. The proposed mapping procedure is not intended to replace text, figures, maps, and tables in comprehensive groundwater reports, but rather provide a practical graphical application that groundwater professionals and watershed specialists can use to illustrate groundwater conditions. The mapping is also designed to assist managers in determining the relative importance of groundwater as a natural resource and to allow for comparisons of watershed scale groundwater resources when prepared by properly trained professionals.

2.1. Methods

Five fundamental components (steps) were selected as the principal parameters needed to classify basin scale hydrogeologic systems (Figure 2). These include the following:

- Step 1. Geologic framework
- Step 2. Aquifer properties and basin hydrostratigraphy

- Step 3. Anthropogenic changes associated with land use, management impacts, or threats to groundwater supplies
- Step 4. Groundwater quality and vulnerability
- Step 5. Degree of connection between groundwater and surface water and depth to groundwater

The selection of these five components and steps ensures that the classification scheme incorporates the typical type of information assessed by groundwater professionals as well as the type of information needed by land use planners and watershed managers to support planning objectives. Further, it is recognized that the availability of compiled hydrogeological is likely to vary from watershed to watershed. As a consequence, a tiered classification approach is proposed that is based on the completeness of the available hydrogeologic data.

2.1.1 Level of assessment

Prior to initiating the five steps, groundwater system classification begins with the characterization of the physical system, including its geology, groundwater hydraulics, surface water resources, and in some cases wetland vegetation and aquatic biology (Figures 2 and 3). Specific field assessment procedures are not described in this paper, rather, and the reader is directed to standard texts and references. A three-tiered inventory approach for classifying basin groundwater systems is proposed (Table 1). Tier 1 assessments are completed using readily available data typically from local, state, and federal data services (Table 1). Tier 2 and Tier 3 assessments rely on more extensive information typically collected from project specific groundwater studies. In general, the higher the tier designation the more robust the data set and its analyses.

2.1.2 Geologic framework (Step 1)

The geologic framework of a watershed ideally is described in the context of the local and regional lithologic and depositional history. Miall (2000) and Davis (1983) provide good summaries for basin analysis methods and basin depositional models. Igneous and metamorphic petrology also can dominate western watersheds, along with complex structural settings, and must be evaluated to assess the geologic framework. The goal of the geological framework analysis is to identify potential hydrostratigraphic units and the likely physical conditions that affect groundwater occurrence, flow conditions, and aquifer properties (Maxey 1964; Domenico 1972).

Typically, for mountainous west landscapes, groundwater systems can be described as the bedrock mountain groundwater system (upland), alluvial fan groundwater system (valley side), and fluvial plain groundwater system (lowland) (Winter 2001). The proposed geologic classification codes are based on alluvial basins and watersheds of the intermontane west have common geomorphic and geologic features that control groundwater movement, water production, and water quality (Table 2).

2.1.3 Aquifer properties and basin hydrostratigraphy (Step 2)

Once the geological framework has been assessed, the next step is to identify potential aquifer systems and likely groundwater boundaries and properties. This step generally involves development of a conceptual basin scale model of the hydrogeology including defining hydrostratigraphic units and groundwater system boundaries (Anderson and Woessner 1992). Cross sections and fence diagrams are often used to depict both general

and unique physical and hydrological conditions in these settings, and groundwater potentiometric data should be compiled and mapped to interpret flow directions.

Aquifer productivity and hydraulic properties of groundwater systems compiled from available site specific literature, concurrent studies, or from general hydrogeologic references. They include: porosity (n), specific yield (S_y), storage coefficient (S), hydraulic conductivity (K), transmissivity (T), thickness of the aquifer (b), and cross-sectional area perpendicular to flow (A) for calculating groundwater flow (Q). A water balance computation and a surface water routing analysis (e.g., surface flow loss and gain, irrigation water use, etc.) also are useful to characterize basin surface water and groundwater exchange, aquifer properties, and recharge/discharge relationships (Winter 1981 and National Research Council 2004).

The narrative and numerical standards developed in Tables 3 and 4 are based on an analysis of aquifer property datasets and summaries gathered from regional aquifer studies prepared by the U.S. Geological Survey and other published sources (Table 5). A large body of literature was reviewed and data tabulated to identify empirical (Table 3) and numerical ranges of aquifer productivity (Table 4). While the database used was not complete, it was coupled with the work by Heath (1984) and Bear (1972) and is considered adequate to support the developmental work presented here. Heath (1984) recognized four ranges of transmissivity for groundwater regions of the U.S. ranging from very small ($<25 \text{ m}^2/\text{day}$), small ($25 \text{ to } 250 \text{ m}^2/\text{day}$), moderate ($250 \text{ to } 2500 \text{ m}^2/\text{day}$), and large ($>2,500 \text{ m}^2/\text{day}$). Bear (1972) developed a classification of hydraulic

conductivity for good aquifers (0.3 to 30,000 m/day), poor aquifers (.003 to <.3 m/day), and non-aquifers (<.003 m/day) as well as ranges for pervious (30 to 30,000 m/day), semi-pervious (0.003 to <30 m/day), and impervious (<0.003 m/day) groundwater systems. The classification ranges set by Heath and Bear are similar to the transmissivity and hydraulic conductivity classifications of low, intermediate, and high aquifer productivity developed in this work. Johnson (1967) classified values of specific yield based on grain size and is adapted to support flow classes in Table 4. The classification of flow capacity presented in the works of Geldon (2003), Anderson et al. (1999), Frost and Smith (1959), Berardinucci and Ronneseth (2002), and Kontis et al. (2004) was also reviewed. Although their suggested ranges were developed for a specific groundwater flow system and geographic areas studied in the west, they may not represent all hydrogeologic settings in the west.

Over 20,000 individual observations were compiled into one data set (see map in Appendix A, Figure A4 for regional spatial coverage). The general geographical location, geological parent material, and aquifer types were tabulated in the database but not used to separate findings by region as done by Heath (1984) and Todd (1983). The data compiled from the literature were separated into five subsets for analysis. The subsets are: all data; reported low range and upper range published in regional summaries; western basins; and individual wells. Box and whisker plots were prepared as well as summary tables to determine the 25th and 75th quartiles, maximum and minimum values, mean, median, standard deviation, and confidence intervals for mean values. Grouping these data into lower and upper range plots of aquifer properties provided a reasonable

approach to separate ranges used to define high and low productivity. A graphical analysis using box and whisker plots (Appendix A electronic database), and a direct comparison of Heath's (1984) and Bear's (1972) common hydraulic characteristics for groundwater systems, approximate ranges of aquifer productivity for low, intermediate, and high flow groundwater systems is developed (see Appendix A Figures A1, A2, and A3). The ranges for high, intermediate, and low productivity systems span a difference of two orders of magnitude in the range of values for specific capacity, hydraulic conductivity, transmissivity, and variable ranges of specific yield, storage coefficient, and gradient (Table 4). The results were rounded to whole numbers using English units and then converted to metric units system (Tables 3 and 4).

The narrative classification (Table 3) based on empirical criteria for productivity and numerical classification (Table 4) are used together to classify aquifers. It is suggested that the most emphasis should be placed on using the narrative classification as the definitive factor for selecting the final productivity classification. While some aquifers may have much less production potential than others, locally systems classified as having moderate and low production potential may be used as water supplies or be important sources of discharge to surface water/aquatic receptors. In addition to classifying aquifer production capacity (Tables 3 and 4), aquifer size and relative aquifer capacity vs. productivity (Table 6) can also be used in the overall aquifer classification process. This is achieved by mapping the aerial extent of aquifers and comparing groundwater availability with groundwater use as outlined in Table 6 and described by Kreye et al. 1998 and Berardinucci and Ronneseth 2002.

2.1.4 Anthropogenic changes (Step 3)

Water levels in groundwater systems naturally change in response to precipitation infiltration and groundwater discharge (Alley et al. 2002). In developed areas, water use may exacerbate natural water level fluctuations and in cases of over use may eventually limit the availability of basin groundwater (Naumburg et al. 2005). Impacts to groundwater resources resulting from changes in water levels can result in dewatering of groundwater supplies, saltwater intrusion along coast lines, and land subsidence in areas with extremely high groundwater use (Poland et. al. 1972). Unplanned dewatering reduces groundwater storage, alters exchanges between groundwater and surface water, and may lead to groundwater flow direction reversals. Artificial recharge from water routing or irrigation may result in creating groundwater systems that may not be sustainable if water management is changed in the future.

A database is developed that can be used to characterize the general range of anthropogenic water level changes from moderate to extreme using regional studies where water level impacts are reported. Published works used to develop the water level database describe artificial recharge or over pumping impacts from various locations across the U.S. at 3,000 wells (Gutentag et al. 1984, Risser 1988, Lyke and Brockman 1990, Bertoldi et al. 1991, McFarland and Ryals 1991, Frenzel and Kaehler 1992, Harrill and Preissler 1994, Mason 1998, Wilkins 1998, Ryder and Ardis 2002 ,and Payne and Magruder 2004). The vast majority of water level data gathered are for groundwater systems located in areas in central California, New Mexico, Texas, Nevada, North Carolina, Utah, Oregon, Montana, and the states underlain by the Ogallala Aquifer. The

25th and 75th quartiles were used to partition impacts in terms of total change measured and mean annual change based on a ten years of periodic water level measurements (see Appendix A electronic database). The results were tabulated into a spreadsheet and box and whisker graphical analyses were used to partition aquifer dewatering and artificial recharge ranges into none, moderate, and extreme (Table 7). Like the aquifer productivity classification range, dewatering and artificial recharge ranges are provided as a general guide, and narrative criteria in Table 6 should be used in concert with numeric breaks to properly classify dewatering and artificial recharge impacts to basin groundwater levels.

High yield (e.g., productive) aquifers may be located in settings where recharge is substantially less than the amount of water that can be routinely pumped for beneficial use, as in the Basin and Range province in the western U.S. where many productive groundwater systems are located within hydraulically-closed basins (Prudic and Herman 1996). Pumping large amounts of groundwater from this type of basin has resulted in significant dewatering (Prudic and Herman 1996). Provision for classifying recharge limited settings is described in Table 7.

2.1.5 Groundwater quality and vulnerability (Step 4)

Classification of groundwater quality and vulnerability were determined as follows: First, in the U.S. each state is required to classify groundwater in terms of human consumption and beneficial use as defined in the amended Clean Water Act of 1977. Commonly, specific conductance is used to classify general groundwater quality as good to poor (Table 8). However, an expanded classification of groundwater quality is presented here in terms of the dominant cation and anion chemistry, presence of recognized pollutants,

and implied vulnerability. Back (1961) developed mapping techniques for hydrochemical facies to differentiate groundwater quality based on cation and anion chemistry and the percent thereof in groundwater. A similar but simpler approach is proposed in this paper where specific conductance and common ion chemistry together are used to classify groundwater quality, along with other criteria for describing groundwater contamination. When sufficient general ion chemistry data are available the dominant water type can be determined (Piper et al. 1953 and Freeze and Cherry 1979). To this end, a nomenclature for water type is added to the general water quality classification as a subgroup and is used here to characterize the palatability, beneficial use, and geologic source of groundwater. Beyond general water quality, the third element used to classify the basin groundwater quality is the presence or absence of contaminants above federal drinking water standards (Table 9).

The fourth element is vulnerability. The classification developed by Kreye et al. (1998) and Berardinucci and Ronneseth (2002) is adapted here to qualitatively gauge aquifer contamination vulnerability under low, moderate, and high risk categories. The vulnerability of an aquifer to contamination from surface sources is broadly and qualitatively based on thickness and extent of geologic materials overlying aquifers, depth to water or top of confined aquifers, aquifer permeability, lithology, and land use unless a more quantitative assessment is completed (Table 10). A more rigorous assessment of vulnerability is recommended in urban settings where groundwater is used for drinking water. Examples of quantitative and more complex vulnerability assessment protocols are available from Aller et al. (1987), Kreye et al. (1998), Berardinucci and

Ronneseth (2002), Vrba and Zoporozec (1994), and the Ireland Department of Environment and Local Government et al. (1999).

2.1.6 Groundwater/surface water exchange & depth to groundwater (Step 5)

The primary purpose of this classification component is to characterize if streams are losing surface water or gaining groundwater and if there is seasonal variability. The criteria used to classify groundwater/surface water exchange are depth to groundwater, the direction and magnitude of hydraulic gradients, relative amount of aquifer exchange with surface water bodies, and the presence or absence of ecological indicators associated with the shallow groundwater (Winter et al. 1998, Winter 1999, Hayashi and Rosenberry 2002, and Hancock et al. 2005, and Eamus and Froend 2006). These parameters characterize groundwater/surface water connections to wetlands, riparian, and lacustrine environments.

Depth to groundwater

Classifying depth to groundwater is somewhat arbitrary. For example, shallow groundwater is defined as ranging from less than 0.33m (1 foot) (US Army Corps of Engineers 1987) to 30 m (100 feet) (USGS 1999) below ground surface. Descriptions from the literature and professional judgment were used to design criteria that classify depth to groundwater. This work establishes a classification using four depths: very shallow (*vs*), shallow (*s*), proximal (*p*), and deep (*d*) groundwater settings (Table 11). In addition, consideration must also be given to the length of time groundwater remains at or above the specified elevations (Table 11). Based on a literature review, a depth of less than 2 meters is used to distinguish “very shallow” or near-surface groundwater from “shallow” groundwater (US Army Corps of Engineers 1987). Plant root systems,

including wetland plant species, often tap the water table at this depth and groundwater is likely to discharge to adjacent surface bodies (Payne and Magruder 2004). Wetlands and riverine ecology are more commonly linked to groundwater and/or surface water resources when the water table is classified as very shallow (Moore and Rhoades 1966, Corps of Engineers 1987, Hayashi and Rosenberry 2002, and Hancock et al. 2005).

Groundwater occurring at depths 2 m and less than 7 m are classified as shallow groundwater. Some trees, shrubs, and herbaceous plants are able to utilize groundwater at this depth (Candell et al. 1996), but obligate wetland plant species commonly do not tap the water table in this depth range (US Corps of Engineers 1987), and discharge to surface water is less likely.

Clearly, many areas have depths to groundwater exceeding 7 m. Depths of groundwater 7 m and less than 33 m are classified as proximal and class *d* is used to indicate that the water table is deep meaning it is 30 m or more below ground surface (USGS 1999). The depth to groundwater is designated for unconfined aquifer conditions as noted in Table 11; however, the depth to the top of confined and semi-confined aquifers can also be used in this classification analysis and should be considered if there is a direct groundwater connection with surface water resources. Very deep groundwater, much deeper than 33m, may be important information for some groundwater settings, especially for water supply development. Table 11 provides a method to classify these settings and the discussion section includes more information on very deep groundwater systems.

Groundwater and surface water exchange

Recharge and discharge classes in Table 12 are used to partition estimates of groundwater discharge (D) contributions to wetlands, streams, rivers, and lakes (minor to significant). This condition is classified as a percent of available stream flow gained from groundwater (Table 12). In some cases, surface water resources may recharge shallow aquifers. In these situations the analysis is similar but reversed where losing streams are recognized using an “R” indication for aquifers that receive a minor to significant amount of recharge from surface water features. This condition is classified as a percent of available stream flow lost to groundwater (Table 12) for a given stream reach. Ranges for D and R are determined for <25 percent, 25 to 50 percent, >50 to 75 percent, and >75 percent stream flow. If there are sufficient data to provide a more accurate range (e.g., R equals 5 to 10 percent or R5-10) or a specific percentage (e.g., D35), these percentages can be used instead of the quartiles in Table 12. Synoptic surface water flow data coupled with in-channel or near-channel groundwater/surface water elevation data provide information needed to further characterize groundwater/surface water exchange (Winter et al. 1998). In cases where an aquifer is distal from surface water or wetlands and a clear connection between recharge and discharge is not determined, the R and D subclasses should be left blank. In this case, additional data should be collected to complete an analysis of groundwater/surface water connection, as time and budgets permit. In cases in which a surface water body is steady and neither gaining groundwater nor recharging the groundwater system, “R/D” is used.

It is recognized that the groundwater/surface water classification may change spatially and temporally and groundwater/surface water characterization should be adjusted to reflect major shifts in this exchange (Winter et al. 1998). Figure 4 shows an example whereby sufficient data are available for the groundwater/surface water classification to be adjusted in a fluvial plain aquifer (lowland) in which variable groundwater/surface water connections are recognized down slope. Seasonal classification intervals can be used if significant variability is evident. In some cases average annual recharge/discharge relationships between groundwater and surface water can be used instead of seasonal rates if data quality objectives for watershed or land use planning are met using annual relationships for depth to groundwater or the variability in water level change is insignificant.

2.1.7. Other considerations: shallow and deep aquifer systems

Classification of aquifers must include the ability to differentiate three dimensional groundwater conditions in multiple basin aquifer systems. For example, an alluvial fan or fluvial plain setting may include deeper water bearing units that exhibit very different flow conditions, spatial coverage, or geology. In some cases deep water-bearing units may be important components of the watershed groundwater system. Such conditions may result in defining upper, intermediate, or lower water bearing units as commonly done when formulating a three dimensional groundwater flow system of a complex basin (Anderson and Woessner 1992). Groundwater professionals have used layered conceptual models for many years to illustrate primary water bearing units and aquifers of interest at large and small scales. Examples are provided by Maxey (1964), Woodward et al. (1998), Wilkins (1998), and Payne and Magruder (2004).

Multiple aquifer systems can be depicted in plan and cross-sectional views to show aquifer classification results across the entire system. The more robust the hydrogeologic and deep well data, the more practical it is to develop detailed horizontal and vertical aquifer classification profiles of watersheds.

2.1.8. Other considerations: completing a water balance analysis

A water balance should be used to evaluate the recharge and discharge relationships in watershed settings (Winter 1981 and Reeves and Woessner 2003). The National Research Council (NRC) (2004) presented a number of simple and complex methods to estimate basin components of recharge and discharge. The NRC also recommends using these techniques to develop an overall water balance and water routing model to define groundwater and surface water interaction and the contribution of groundwater to baseflow. The criteria in Table 12 classifies the relative groundwater contribution as quartiles of flow contributions into or out of surface water bodies and wetlands. The classification criteria for differentiating groundwater/surface water connections are limited because more than one aquifer can be connected to surface water features. Annual aquifer discharge is likely to be variable depending upon the season and surface conditions. Furthermore, deep aquifers may provide recharge to overlying aquifers, and/or there may be distal hydrostratigraphic units that supply water to aquifers which have a direct connection to surface water (Winter et al., 2003). Nonetheless, an attempt should be made to assign the relative percentage of groundwater exchanges with surface water as either recharge (R) or discharge (D) in cases where aquifers are near rivers, streams, lakes, or wetlands.

In summary, a water balance is useful to describe sources and sinks of water in watersheds including precipitation, evapotranspiration, infiltration, surface flow losses and gains, and groundwater recharge and discharge. Synoptic measurement of surface water flows in streams, rivers, diversions, canals, as well as general water use data are used to characterize the connection between groundwater and surface water because they provide the means to account for groundwater discharge and surface water recharge in riverine systems.

3.0 Results - Application of Aquifer Classification

This section outlines the proposed means for organizing and tabulating groundwater classification (Figure 1, Table 1 and Appendix A). The assessment data and field observations may be averaged over the entire aquifer or to sub-areas within aquifers as data allow, or reported on a well by well basis. The groundwater classification scheme presented here is most useful when summarizing aquifer characteristics and linking the results to more detailed information contained in project reports. In addition, the classification provides site managers with a detailed and relatively inexpensive tool for comparing and contrasting aquifers. Below is the proposed order for classifying groundwater systems as well as two hypothetical examples using the classification codes:

Class order:	Steps 1 and 2: Productivity class, geologic framework, and aquifer capacity and size criteria.
	Step 3: Anthropogenic impact from dewatering / artificial recharge.
	Step 4: General water quality based on specific conductance, major ions, contaminants, and vulnerability.

Step 5: Depth to groundwater and groundwater/surface water exchange.

Additional information: Level of analysis.

Example classification codes for groundwater systems that are characterized by limited to complex data sets:

Typical use: *Class B F_{pm} , vsD25 – Tier 2*

(An intermediate flow potential aquifer in a fluvial plain meandering stream or river setting, groundwater is very shallow (<6m,) and a Tier 2 study was completed to classify this aquifer.)

Complex use: *Class B+ A_f iiib, I_D , Type 1 $CaHCO_3/m$, v , sv/M , pR25 – Tier 3*

(A high-intermediate flow potential aquifer in an alluvial fan setting. There is relatively high demand for available groundwater, the aquifer is 5 to 25 km² in area, and there are moderate dewatering issues. Groundwater quality is generally good as a type 1 calcium-bicarbonate water, but one or more metals and volatile organic compounds exceed federal drinking water standards. Groundwater vulnerability is moderate and depth to groundwater is proximal at 7 to 30 meter below ground surface. A Tier 3 study was completed to classify this aquifer.)

Mapping the aquifer characteristics provides a visually appealing and concise way to represent tabular data. Selecting the mapping method depends upon the desired level of analysis, scale, spatial and temporal data coverage, and budgetary limitations. Figure 5 illustrates the proposed mapping system for aquifer classification. Dashed lines and

question marks are used to show inferred classifications and groundwater flow direction. Figures 6 through 8 and Table 13 illustrate classification results for the Upper Beaverhead Basin aquifer of southwestern Montana. A Tier 3 level groundwater study was completed on the shallow alluvium and fluvial basin fill deposits by Uthman and Beck (1998). Their study and references provide an example of the type and level of information needed to classify basin fill groundwater systems and identify specific aquifers. Their work presented a water balance as well as synoptic flow monitoring data. The adjacent upland areas next to the basin fill sediments are also classified (Figure 8) but because there are limited data for classifying groundwater in the upland and bedrock areas, the results are considered a Tier 1 level analysis (Table 13). Large scale maps can be prepared for reporting purposes to illustrate detailed information as well as tabulated results in a format similar to that used on geological maps. The tabulated results should be included on the classification maps to provide written and color coded detailed information.

GIS mapping tools should be used to display classification results. Tabular classification can be attributed to each aquifer from spreadsheets or relational databases to allow the end user to view mapped information with aquifer specific tabular information. The use of GIS software is recommended to initially map watershed and groundwater system boundaries and other components as GIS layers, such as the geology. Groundwater systems should be assigned colors or geologic patterns to assist reviewers (Figure 8). Once aquifers are mapped in GIS and detailed tabular data are attributed to each aquifer,

they can be overlaid with management GIS layers such as municipal water systems, proposed developments, and surface water restoration projects for analysis.

The aquifer mapping process is repeated for each depth interval representing upper, intermediate, and lower aquifers in vertical cross section. Aquifers are assigned colors or geologic patterns to differentiate them, and dashed lines are used to divide aquifers into smaller units, if appropriate, with solid lines separating conceptualized aquifer boundaries.

4.0 Discussion - aquifer classification

Watershed planners and natural resource managers will benefit from a groundwater classification scheme that standardizes an approach for describing watershed scale groundwater resources (Passarella and Caputo 2006; Petts et al. 2006). The aquifer classification system described here is intended to provide government agencies, natural resource planners, land use planners, and conservation organizations with a methodology that is useful for describing basin-scale water resources and planning needed for mitigating impacts to natural resources.

This classification scheme includes five primary criteria or steps to differentiate aquifers: 1) geological framework, 2) aquifer properties, 3) threats and impacts posed by humans, 4) groundwater quality, and 5) the degree of groundwater/surface water exchange. From a reporting and mapping perspective, the classification scheme provides a way for natural resource planners to consistently analyze and compare watershed scale groundwater

resources (at a scale of 1:100,000 to 1:250,000) using visual and geographic aids, such as GIS mapping techniques.

In terms of the mapping the aquifer boundaries, the use of GIS software is instrumental in delineating aquifer boundaries. Once mapped, the aquifer layers can be overlain with other natural resource layers (e.g., soil, hydrography, geology, groundwater contamination plumes, etc), existing infrastructure (e.g., roads, cities, sewer lines, fuel pipelines, water supply lines, irrigation land use, water supply wells, etc.), and proposed developments or new land uses (e.g., subdivisions, irrigation projects, gravel operations, dams, etc.).

The ability to overlay GIS layers of aquifers and groundwater conditions provides the end user with a powerful tool to help integrate groundwater resource data into natural resource planning efforts. Most digital groundwater data are derived from accessing point files associated with wells. Although this data is useful for some purposes, for planning exercises on a landscape scale, aquifer characteristics generally have to be interpreted by groundwater professionals in order to be useful by others. By consistently mapping and compiling point data to develop aquifer delineation maps and using GIS to display the results, this approach provides the means to incorporate local point data directly into the characterization of regional GW conditions.

The proposed mapping techniques are not meant to replace the text, figures, maps, and tables in groundwater reports. Further, the classification and mapping does not replace

focused objectives and having qualified professionals involved in the analysis. The classification system is intended to enhance typical reporting. Users are provided a graphical approach to illustrate the relative importance of groundwater as a developable resource, while also identifying where groundwater and surface water interactions are likely to be present. While aquifer classification provides a framework through which to discuss and ask questions regarding groundwater and connected resources, the comprehensive studies used to develop the classification results are the primary source information that ultimately characterize groundwater conditions and serve as predictive assessments.

The mapping approach in Figure 5 is the simplest of approaches to illustrate the classification results and can be drawn using most software drawing utilities. There are other mapping approaches that could be applied that would improve the usability and comprehension of the classification results (Figure 9). A software extension could be written specifically for mapping aquifer classification results, such as an *ESRI ArcGIS 9.x* extension, which would allow users to quickly post classification results on aquifer delineation maps. Development of such a software extension would be desirable as the classification system evolves beyond its current state.

This aquifer classification system differs from previous attempts to classify aquifers and organize watershed scale groundwater data. The proposed classification system offers the end user a reproducible and comprehensive classification framework that has the flexibility to incorporate variations in the quantity of data through the Tier 1 through Tier

3 assessment approach. In cases where data are limited, a partial classification can be completed and later expanded as new data become available. The classification is also different because it combines a number of techniques that together are useful to consistently compare, contrast, and map aquifers in watershed settings. Further, the classification scheme is viewed as a method that allows groundwater professionals and watershed specialists to more easily and consistently compare basin scale groundwater systems across large regions. It provides users with a graphical approach towards determining the relative importance of groundwater as a developable resource, while identifying situations in which groundwater and surface water interactions are likely to occur.

Clearly, the spreadsheet aquifer productivity and water level impact database developed to support this classification scheme can be improved upon with the addition of more data and statistical analysis. It would be desirable to have agencies such as the USGS and state water and geological surveys evaluate this system more fully and refine data bases and improve the GIS approach used to display data. Similar to open-ware software, through professional research and development, it may be possible to enhance this classification system making it more planning and management friendly. In addition, there are some classification criteria that need further development, such as defining ‘very deep’ groundwater. At this time, a numeric depth for very deep groundwater is not developed and as an example, it could be developed in the future to aid planning and groundwater development projects. Similarly, the size of ‘very large’ aquifers could be developed.

Within the professional community, most groundwater professionals have exercised a fairly high level of freedom in technical reporting and interpretation of hydrologic data. From an applied perspective, all aquifers will not fit exactly into the numerical and narrative classification criteria described in this paper. There will be exceptions where some aquifers exhibit unique properties falling outside of the norm and crossing classification criteria boundaries. For example, a moderate hydraulic conductivity aquifer (Class B) may be associated with an exceptionally thick saturated zone resulting in a system with a high transmissivity (Class A). For the purposes outlined in this paper, the numerical breaks are considered approximate ranges, yet until a national or international database of well data is compiled and analyzed, the divisions proposed here represent an initial attempt at building a comprehensive and unified aquifer classification framework for a range of aquifers. Whereas the category limits are approximate, we contend that when used with the narrative classification criteria (Table 3) the combined approach is reasonable as a first step. More peer-reviewed research may improve this attempt at aquifer classification and could be used to refine the numerical framework. Efforts need to include a broad review of aquifer conditions vs. those that target small areas.

Further, classifying aquifers is not an either/or process, meaning that site-specific conditions may warrant selecting some classification criteria in favor of others. A weight of evidence analysis (Weed 2005) and professional judgment should be used to select classification criteria when aquifers exhibit criteria that span multiple classifications with the goal of aiding land use planning and watershed management decision-making (e.g., the end user of hydrogeologic data). To this end, a national database of aquifer

characteristics would benefit future water resource studies, groundwater classification systems, and ecosystem conservation activities. The Commission on Geosciences, Environmental and Resources (2000) also has advocated development of a central database repository for credible sources of groundwater data. They state that once assembled, these data have value far beyond their immediate use for a specific study. They recognize that there is uncertainty as to how to coalesce the many reporting formats, mapping techniques, databases, and units into a single national database for groundwater systems.

The connection between groundwater and surface water is of great interest to western land use planners and watershed managers. For example, at discharge points groundwater may feed surface water systems and native fisheries. In some cases, groundwater can be the sole source of seasonal water to a cold-water salmonid fishery. This is the case in southwestern Montana where valley bottom sloughs form in the fluvial plain and discharge to the rivers systems (D100 systems) (Payne and Magruder 2004). A major change in water management upstream will likely impact groundwater discharge in these sloughs. These types of surface water flow and groundwater characteristics are recognized as important to natural resource managers.

Lastly, the spatial and temporal distribution of data sets for western basins may dictate the level to which basin scale groundwater system classification will prove useful. The presented classification system employs levels of assessment for groundwater classification ranging from Tier 1 through Tier 3. In cases where the classification results

are based on data of limited quality or coverage, the results should be considered a Tier 1 level analysis and subject to change as additional data are collected and ultimately result in a Tier III analysis if the project warrants.

5.0 Summary and Conclusions

Basin scale groundwater systems are complex systems in that they are linked to surface water features, and provide water for municipal, residential, agriculture, and industrial use. Traditionally, large scale groundwater investigations have not been reported in the context of a groundwater classification system. The classification scheme presented in this paper is designed to provide important aquifer indices that are needed for those working in disciplines involving land use, ecosystem conservation, and watershed management. Classification indices include five primary criteria including: 1) geological framework, 2) aquifer properties, 3) threats and impacts posed by humans, 4) groundwater quality, and 5) the proportion of surface water gained or lost to groundwater to classify watershed scale groundwater systems. A water balance is also needed.

Communication among professionals concerning interactions between groundwater and surface water is challenging as in many jurisdictions because the two resources are treated as separate entities. Therefore, there is a need to improve communication amongst those studying groundwater resources, land use, and watershed and riverine systems. The aquifer classification scheme presented here is an initial step in improving communication by presenting a comprehensive water resource database application that applies a standard set of criteria describing basin scale groundwater systems.

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Table 1. A three tier assessment hierarchy for aquifer classification.

Class	Description	Data Collection Summary	Data Quality Objective
Tier 1	Semi-Quantitative	Tier 1 assessments generally rely on available local, state, and federal data sources for groundwater classification. These assessments rely on limited new data as budgets allow and are aimed at generating large-scale aquifer classification mapping units.	Broad groundwater system analysis and aquifer classification. Results are useful for baseline analysis, limited planning, and data gap identification.
Tier 2	Quantitative	Tier 2 assessments are quantitative hydrogeologic assessments that require characterization of groundwater and surface water resources. Tier 2 assessments use existing data and new data from monitoring wells, aquifer tests, groundwater age dating, geophysical surveys, stream flow measurements, wetland surveys, and water quality monitoring, etc.	A detailed groundwater system analysis and aquifer classification that expands baseline data. Results are useful for planning needs and characterizing suspected groundwater issues or needs.
Tier 3	Quantitative Coupled with Predictive Modeling	Tier 3 assessments are quantitative assessments coupled with predictive modeling. Results can be used to address specific aquifer or watershed issues. These assessments use the data sets generated from Tier 1 and Tier 2 assessments and groundwater modeling approaches. Tier 3 level analysis is typically aimed at understanding complex watershed/groundwater relationships including groundwater quality, quantity, or interaction with surface water, and end products typically support groundwater management and protection.	Tier 2 objectives and development of a predictive tool useful for comprehensive planning.

Table 2. Geological framework for aquifers associated with common sedimentary/bedrock systems of the intermontane west.

<u>Geologic Framework/Depositional /Classification</u>	<u>Mapping Code</u>
Alluvium	A _x
Colluvium	C _x
Alluvial fan	A _{fx}
Fluvial plain meandering	F _{pm}
Fluvial plain braided	F _{pb}
Fluvial plain older terrace	F _{pt}
Volcanic unconsolidated	V _u
Glacial till	G _t
Glacial outwash	G _o
Glacial moraine	G _m
Lacustrine/Playa	L
Eolian	E _x
Debris flow / Landslide	D _{fx}
Bedrock ⁺	B _x
Undifferentiated	U _x

Notes: An 'x' is included on the end of the mapping codes as an option to indicate local lithology changes. ⁺A large number of consolidated volcanic (e.g., basalt, breccia, tuff, etc.) and bedrock formations (granite, sandstone, quartzite, gneiss, etc.) are possible. Identifying the type of bedrock can be included in the classification nomenclature as an abbreviation (e.g., B_{ss} (sandstone), B_v (volcanic undifferentiated), B_{bst} (basalt), and B_{ls} (limestone)). Only competent bedrock is included in this category. Unconsolidated and semi-consolidated materials should be included in the sedimentary codes in Table 2.

Table 3. Narrative description and indicators for classification of high, moderate, and low production aquifers.

Class	Flow Class Potential^a	Aquifer Flow (Q) Narrative Description Test
A	high flow	High flow aquifers provide water for large scale irrigation and municipal water supplies and the aquifers have little or no drawdown when stressed from pumping. Well placement for large municipal or irrigation water supplies is routine because of the availability of groundwater. These aquifers are an excellent source of domestic well water. These aquifers may also provide significant groundwater discharge to large streams and rivers.
B	intermediate flow	Intermediate flow aquifers provide water for irrigation and municipal water supplies. However, well placement may be challenging in order to develop a desired flow rate, drawdown in production wells may be significant, exceeding more than 50 percent of the available drawdown, and wells are often carefully designed and placed to maximize well efficiency. These aquifers are usually a good source of domestic well water. These aquifers may also provide significant groundwater discharge to small and moderate size streams and rivers.
C	low flow	Low flow aquifers are generally not used for irrigation or municipal water supplies. These aquifers may be used for domestic groundwater supplies but locating wells may be difficult or may not achieve the desired minimum flow rate. These aquifers have limited groundwater discharge potential except for very small streams and wetlands.
L_f	Limited or no flow	Generally not used for any type of water supply and provide little or no groundwater discharge to surface water.

Notes:

L = aquatard

^aAquifer flow potential is dependent on the geometry of the aquifer as well as the hydraulic properties in Table 4. Quantitative partitions are not proposed for this reason but described as narrative classification criteria.

Table 4. Hydraulic indicators for classification of high, intermediate, and low production aquifers^q.

Class	Flow Class Potential*	SpC	K^a	T^b	Sy^c	S^d	i^e
A	high flow (entire range)	>58	>76	>2300	0.12 to 0.35	variable	variable
A-	low high flow	>58 to 580	>76 to 760	>2300 to 23000			
A+	very high flow	>580 to 5800	>760 to 7600	>23000 to 230000			
A++	extremely high flow	>5800	>7600	>230000			
B	intermediate flow (entire range)	0.6 to 58	0.8 to 76	23 to 2300	0.10 to 0.35	variable	variable
B+	high intermediate flow	>6 to 58	>7 to 76	>230 to 2300			
B-	low intermediate flow	0.6 to 6	0.8 to 7	23 to 230			
C	low flow (entire range)	<0.6 to 0.01	<0.8 to 0.01	<23 to 0.23	0.02 to 0.12	variable	variable
C+	very low flow	<0.6 to 0.06	<0.8 to 0.1	<23 to 2.3			
C-	extremely low flow	<0.06 to 0.01	<0.1 to 0.01	<2.3 to 0.23			
L	Limited or no flow	<0.01	<0.01	<0.23	<0.02	variable	variable

Notes:

SpC = Specific capacity (liters/minute per meter of drawdown)

K = hydraulic conductivity (m/day)

T = transmissivity (m²/day)

Sy = specific yield in unconfined aquifers

S = storage coefficient for confined and semi-confined aquifers

i = gradient

L = aquitard

^aSupported by Bear (1972)^bSupported by Health (1984)^cAdapted from Johnson (1967) based on grain size analysis and relative hydraulic conductivity. Due to the overlap of Sy for aquifer classification, Sy alone cannot be used to partition aquifer flow potential but Sy can help partition classifications with other data, such as K and T.^dThere is insufficient data available to partition storage (S) into high, intermediate, and low flow aquifers. In addition, the available data are highly variable. Professional judgment should be used to determine if S is commensurate with aquifer flow potential. As of gradient, this parameter is also highly variable and professional judgment should also be used to determine if gradient (i) is commensurate with aquifer flow potential.^eNumerical values in this table provide an indication of the potential aquifer production/yield. The ranges in this table should be compared to the narrative aquifer flow criteria in Table 3 to classify aquifers as low, intermediate, or high flow systems.

Table 5. Literature cited and geographic location for aquifer productivity data^a.

Source	Geographic Location
Anderson 1995	South-Central Arizona and Parts of Adjacent States
Anderson et al. 1999	SNAKE RIVER PLAIN Aquifer, Idaho
Angeroth 2002	Pinal Creek Basin near Globe, Arizona
Bertoldi et al. 1991	Central Valley, California
Bredehoeft and Farvolden 1963	Intermontane Basins of Northern Nevada
Frenzel and Kaehler, C.A., 1992	Mesilla Basin, New Mexico and Texas
Geldon et al. 2002	Upper Colorado, New Mexico, Utah, and Wyoming
Geldon 2003	Yucca Mountain, Nevada
Gutentag et al. 1984	High Plains Aquifer of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming
Harlow and Lecain 1993	Southwestern Virginia
Harrill and Preissler 1994	Western Nevada
Heath 1984	The entire U.S.
Hollyday and Hileman 1996	Valley and Ridge Physiographic Province Eastern and Southeastern United States
Johnson et al. 1968	Central California
Knotis et al. 2004	Glaciated Northwest U.S.
Lindholm 1996	Idaho and Eastern Oregon
Lyke and Brockman 1990	Onslow and Jones Counties, North Carolina
Mason 1998	Southwestern Utah
Maurer 2002	Douglas County, Nevada
Maurer and Berger 1997	West-Central Nevada
Maurer and Thodal 2000	Western Nevada
McFarland and Ryals 1991	South-Central Oregon
Payne and Magruder 2004	Southwest Montana
Plume 1996	Great Basin Region of Nevada, Utah, and Adjacent States
Pope et al. 1999	Southwest Montana
Risser 1988	White Sands Missile Range, New Mexico
Ryder and Ardis 2002	Texas Gulf Coast
Slagle 1988	Northwestern Montana
Steele et al. 2002	Western Nebraska
Swain et al. 2004	Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States
Thomas et al. 1989	Lander County, Nevada
Uthman and Beck 1998	Southwest Montana
Vaccaro 1992	Washington, Oregon, and Idaho
Vaccaro et al. 1998	Puget Sound, Washington and British Columbia
Wilkins 1998	Parts of Colorado, New Mexico, and Texas
Woodward et al. 1998	Oregon and Washington

Notes: ^aSee Appendix A Figure A4 for general location of study areas.

Table 6. Classification of aquifer capacity vs. productivity and geographic coverage of aquifers^a.

Classification	Mapping Code	Narrative Description
Heavy	i	At or near capacity for demand or biologic need compared to productivity A small or moderate groundwater development could significantly impact those already using groundwater for a water supply or there are riverine or lacustrine systems dependant on groundwater to sustain biologic resources. With additional development, there will be significant impacts to existing beneficial uses because the groundwater water supply is over-allocated and/or the connected water resources are highly sensitive to decreased groundwater discharge.
Moderate	ii	Demand or biologic need is moderate compared to productivity A very large or several large groundwater development projects could impact those already using groundwater and/or riverine or lacustrine systems are at least partially dependant on groundwater to sustain biologic resources. With additional significant groundwater development, existing beneficial uses could be impacted because the groundwater water supply is at least partially allocated and/or the connected water resources are somewhat sensitive to decreased groundwater discharge.
Light	iii	Far from capacity for demand or biologic need compared to productivity The groundwater system is not commonly used as a water supply or there is additional allocation possible without realizing any negative impacts on existing water users. The riverine and lacustrine systems are not dependent or have a very limited dependence on groundwater discharge. Additional groundwater development will not likely impact water users or connected ecologic systems.

Classification	Mapping Code	Relative Area
Small aquifer area	a	< 5km ² (<1.5 mi ²)
Intermediate aquifer area	b	>5km ² to 25 km ² (>1.5 mi ² to 8 mi ²)
Large aquifer area	c	>25 km ² (>8 mi ²)

Notes: ^aAdapted from Kreye et al. (1998) and Berardinccis and Ronneseth (2002).

Table 7. Numeric and narrative hydraulic classification for anthropogenic impacts.

Map Code	Classification & Narrative	Total Water Level Change (m)^a	Average Annual change (m/year)^b
I_{Am}	Extreme artificial recharge <i>Long-term recharge water may create aquifers or shallow hydrostratigraphic layers that may be utilized for beneficial use.</i>	>3	>0.1
I_A	Moderate artificial recharge <i>A noticeable long-term increase in water level in aquifer, but the increase may not necessarily be enough to create water bearing units that can be utilized for beneficial use.</i>	>1 to 3	>0.01 to 0.1
None	Unaltered/minor impacts	-2 to 1	-0.1 to 0.01
I_D	Moderate dewatering <i>A noticeable long-term decrease in water level in aquifer but it may not necessarily be enough impact beneficial use but could if it continues.</i>	<-2 to -20	<-0.1 to -0.6
I_{Dm}	Extreme dewatering <i>Long-term water withdrawals are severe enough in aquifer that wells may need to be deepened in order to sustain beneficial use.</i>	<-20	<-0.6

Notes: ^aProductive aquifers may be located in settings where recharge is substantially less than the amount of water that can be routinely pumped for beneficial use. These aquifers are given an additional “X” classification indicating they can be or are being mined.

^bBased on ten years of record.

Table 8. General groundwater quality classification.

Criteria	Good <i>Type 1^a(T1)</i>	Limited <i>Type 2^a(T2)</i>	Poor <i>Type 3^a(T3)</i>	Very Poor <i>Type 4^a(T4)</i>
Specific conductance ^b (SC) (microsiemens per cm at 25° C)	<1,000 ^c	1,000 to <2,500	2,500 to 15,000	>15,000
Use as public/private water supplies	Yes ^d	Typically not useful - marginally useful according to the CWA	No if SC is > 7,000 (it is rare to use water that is >2,500)	No
Use for irrigation	Yes ^d	Yes, typically	Yes, marginally useful	No
Use for commercial and industrial	Yes ^d	Yes, marginally useful	Yes, marginally useful	Some uses
Use for wildlife/livestock/aquatic life/phreatophytes	Yes	Yes, marginally useful	Yes, marginally useful	No

Notes:

^aCommon ion chemistry and dominant anion: (Cl, HCO₃, SO₄, other) and cation: (Na & K, Ca, Mg, other) should be included with general water quality classification if sufficient water quality data are available. "T1_{CaHCO₃}" would be an example classification for groundwater when combining the classification based on specific conductance and the dominant ion chemistry. Adapted from Freeze and Cherry (1979) and Piper et al. (1953).

^bAdapted from the State of Montana Administrative Rules 17.30.1011. Depending on the state, substitutes for local/state required specific conductance linked to the State/Federal Clean Water Act classification criteria can be used as necessary.

^cAn "e" modifier may be used with Type 1 water quality classification if the SC is below 250 suggesting excellent water quality is present: eT1.

^dWith little or no treatment.

CWA = Clean Water Act

Table 9. Types of contaminants and classification codes.

<u>Contaminant</u>	<u>Mapping Code*</u>
Fuel related contaminants	f
Metals	m
Nutrients	n
Pathogen / biological	p
PCB	pcb
Radiological	r
Semi-volatile organic compounds	sv
Volatile organic compounds	v
Other organic	xo
Other inorganic	xi
Other biological	xb

Notes: *The contaminant classification code in this table is added to the classification criteria in Table 8 that is known to have metal, nutrient, volatile organic compounds or other contaminants above federal drinking water standards for human consumption.

Table 10. Classification of aquifers based on vulnerability to contamination.*

H (High Vulnerability): Highly vulnerable to contamination from surface sources. H aquifers have little natural protection against contamination introduced at the ground surface (e.g., shallow permeable aquifers in urban settings). Existing land uses or future additional developments, which may introduce a contaminant to the land surface, should initiate measures to protect against introducing contaminants. H aquifers should be given first priority for the implementation of quality protection measures. Often the water table is shallow or very shallow (see Table 11), hydraulic conductivity is moderate to high, and it is an unconfined setting.

M (Moderate Vulnerability): Moderately vulnerable to contamination from surface sources. M aquifers have limited natural protection against contamination introduced at the ground surface (e.g., limited low permeability layers overlying aquifers or a deeper water table compared to H aquifers in mixed land use settings). Degree of natural protection may vary across an aquifer. Existing land uses or future additional developments that could introduce a contaminant to the land surface should initiate measures to protect against introducing contaminants. M aquifers should be given priority over L aquifers when it comes to implementing quality protection measures. In proximal or deep water table (see Table 11), there is a moderate to low hydraulic conductivity, and a moderate degree of confinement where leaky conditions may be present.

L (Low Vulnerability): Generally not considered very vulnerable to contamination from surface sources. L aquifers are more protected against contamination introduced at the ground surface (extensive confining layers or very deep groundwater in rural settings). L aquifers have the lowest vulnerability rating and are the least likely to become contaminated. A rating of L does not imply that all L aquifers are immune to contamination. All aquifers are vulnerable to contamination to a certain degree, especially if there are exposed portions of the underlying aquifer or if the land-use activity breaks through the overlying confining layer. Often the water table is deep (see Table 11), the hydraulic conductivity is low and there is a high degree of confinement.

Notes: *Adapted from Kreye et al. (1998) and Berardinucci and Ronneseth (2002). Berardinucci and Ronneseth (2002) provide additional information for classifying aquifer vulnerability in terms of depth to the water table, permeability, thickness and extent of confining sediments, porosity, and land use and should be consulted for applied vulnerability assessments.

Table 11. Depth to groundwater classes for unconfined aquifers^a.

Criteria	<i>vs</i> (very shallow)	<i>s</i> (shallow)	<i>p</i> (proximal)	<i>d</i> (deep)
Depth to water (m)^b	<2 ^c	2 to <7 ^d	7 to <30	>30
Strong GW/SW connection	very common	fairly common	uncommon	very uncommon
Water table gradient	variable	variable	variable	variable

Notes:

^a Confined aquifers and underlying deeper aquifers are assumed to have occasional or no direct connection to surface water. However, these aquifers may discharge to unconfined aquifers that have critical surface water connections. In settings where groundwater may be much deeper than 30 m and is considered significant for planning, classification of depth can include an indicator on the classification to approximate first groundwater is greater than a given depth (e.g., $d_{>200}$).

^b Water tables < 0.33 m below ground surface for more than 14 days/year are likely a wetland.

^c High points must be maintained, on average, 14 days/year.

^d Low point can be > 7 m deep during the non-growing season.

Adapted from US Army Corps of Engineers (1987), Payne and Magruder (2004), and U.S. Geological Survey (1999).

Table 12. Groundwater/surface water exchange classes for unconfined aquifers near surface water features^a.

Gaining Streams/stream reaches^b – Percent surface water flow gained from groundwater^c	Percent	Class
Low contribution	<25%	D25
Moderate contribution	25% - 50%	D50
High contribution	>50% - 75%	D75
Very high contribution	>75%	D100
Losing Streams/stream reaches^b – Percent surface water flow lost to groundwater^c	Percent	Class
Low contribution	<25%	R25
Moderate contribution	25% - 50%	R50
High contribution	>50% - 75%	R75
Very high contribution	>75%	R100

Notes:

^aFor streams / rivers with no significant loss or gain, ‘**R/D**’ can be used to indicate steady conditions along a stream reach (e.g., no significant surface water flow loss or groundwater gain measured in study).

^bIn cases where surface water features have exchange with more than one aquifer, the classification effort should be completed for each aquifer and/or each surface water feature or stream reach (as appropriate for site specific conditions and project objectives).

^c An actual percentage or range vs. the quartile range listed may be used with sufficient flow data and to show variability. **R** represents the percent stream flow lost along a reach to groundwater and **D** represents the percent stream flow gained along a reach from groundwater.

Table 13. Upper Beaverhead Basin aquifer classification summary (See also Figure 8)

Aquifer Name	Map Color	Flow Potential	Geologic Framework	Significance and Size	Impacts	Water Quality & Vulnerability	Groundwater / Surface water Connection	Level of Analysis and comments
Quaternary Fluvial Plain Beaverhead River		B+ / A-	F _{pm}	i c	None	Type 1 CaHCO ₃ H	<i>s</i> to <i>sD25</i> - near the Beaverhead River at Dillon	Tier 3: Beaverhead River gains groundwater on lower reach.
Quaternary Fluvial Plain Blacktail Deer Creek		B	F _{pm}	ii c	None	Type 1 CaHCO ₃ M	<i>d</i> to <i>vsD25</i> near confluence with the Beaverhead River	Tier 3. Blacktail Deer Creek loses water along most it length.
Quaternary Fluvial Plain Rattlesnake Creek		B	F _{pm}	ii b	None	Type 1 CaHCO ₃ M	<i>d</i> to <i>s</i>	Tier 3: Rattlesnake Creek loses water along most it length.
Quaternary Alluvial Fan		B-	A _f	iii c	None	Type 1 CaHCO ₃ / CaSO ₄ M	<i>d</i>	Tier 3: fan aquifers interface with lower Tertiary units.
Quaternary Glacial Outwash		B-?	G _o	iii c	ND	Type 1 CaHCO ₃ H / L	<i>S</i>	Tier 1: limited data.
Quaternary Landslide		C or B?	D _f	iii b	ND	Type 1? M?	<i>d</i> ?	Tier 1: very limited data.
Tertiary Bozeman & Volcanics (undifferentiated)		C+ to B	A _u / V _u	iii c	ND	Type 1 CaHCO ₃ M / L	<i>d</i> ?	Tier 1. a thick sequence of gravel, fines, and volcanics.
Bedrock Undifferentiated		C / B	B _u	iii c	ND	Type 1? M	<i>d</i> ?	Tier 1: very limited data.

ND = No data.

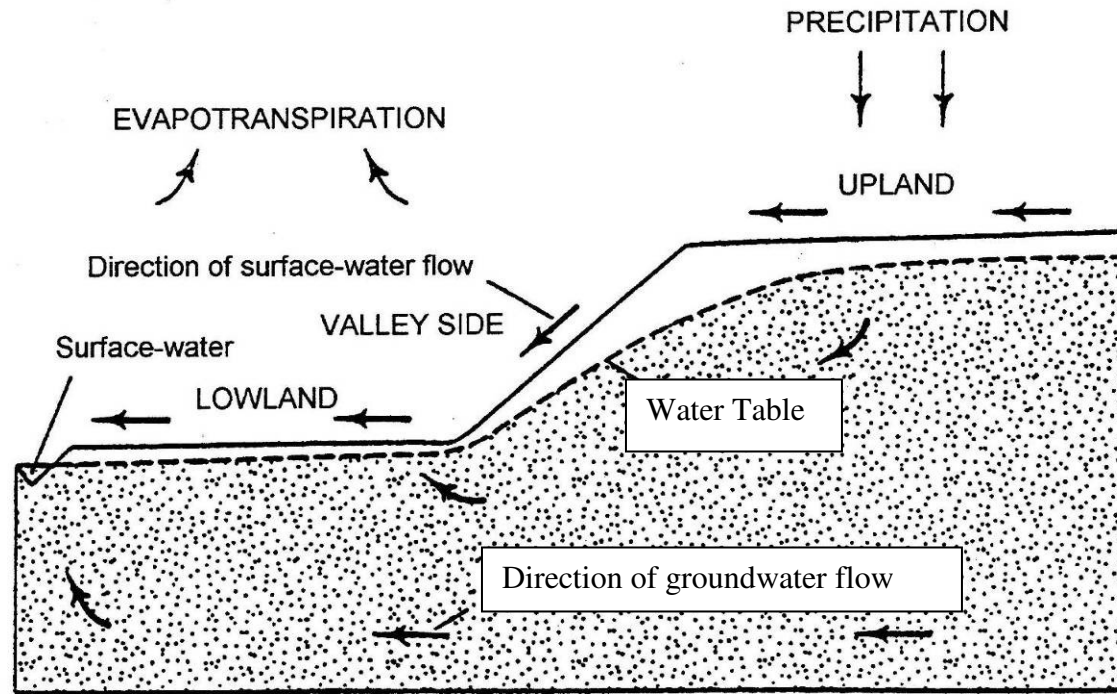


Figure 1. The Fundamental Hydrologic Landscape Unit (FHLU). Source: Winter 2001.

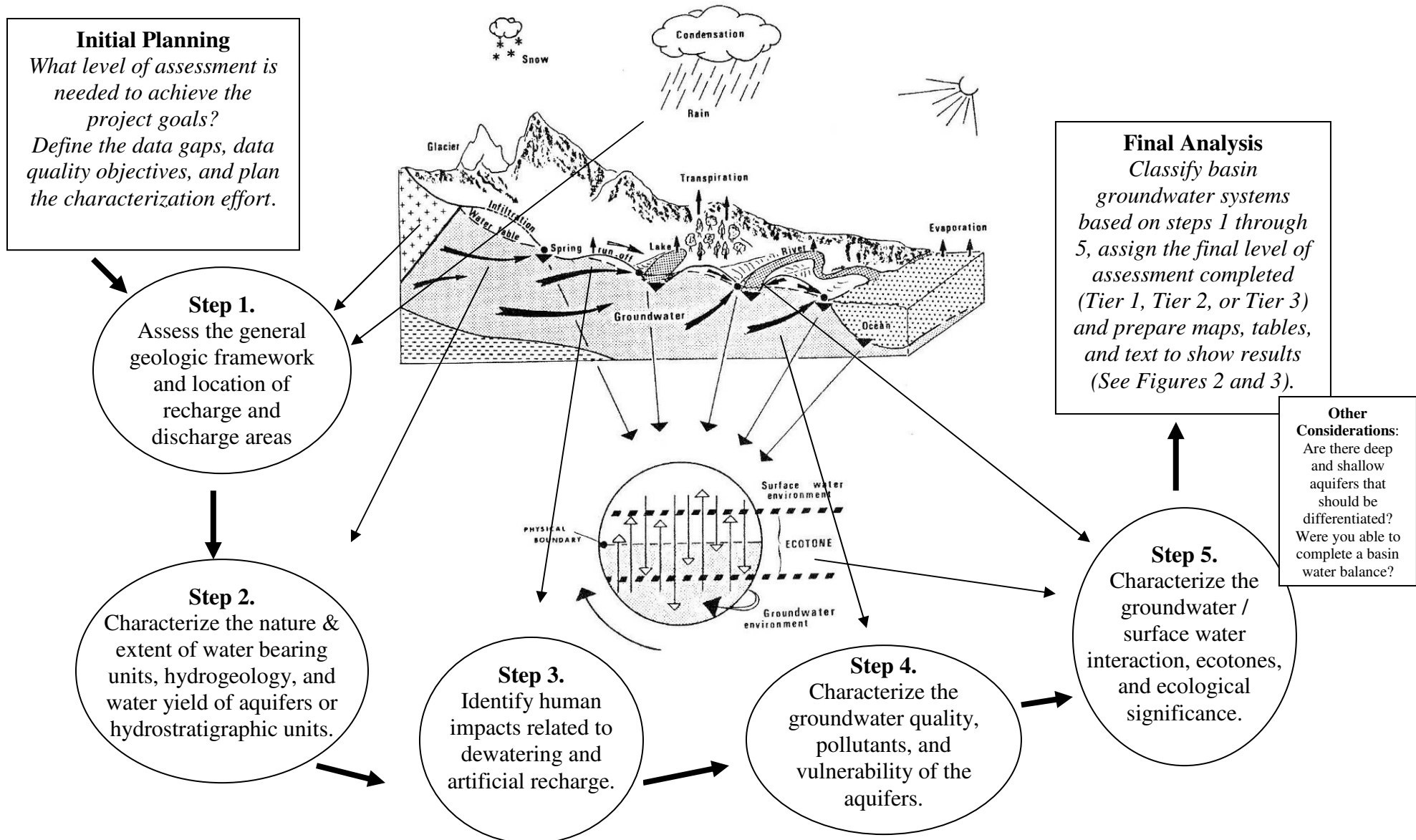


Figure 2. The basic components and steps proposed to classify basin groundwater systems and a diagrammatic explanation of groundwater/surface water ecotones in the mountain and plains landscapes (adapted from Gibert 1991).

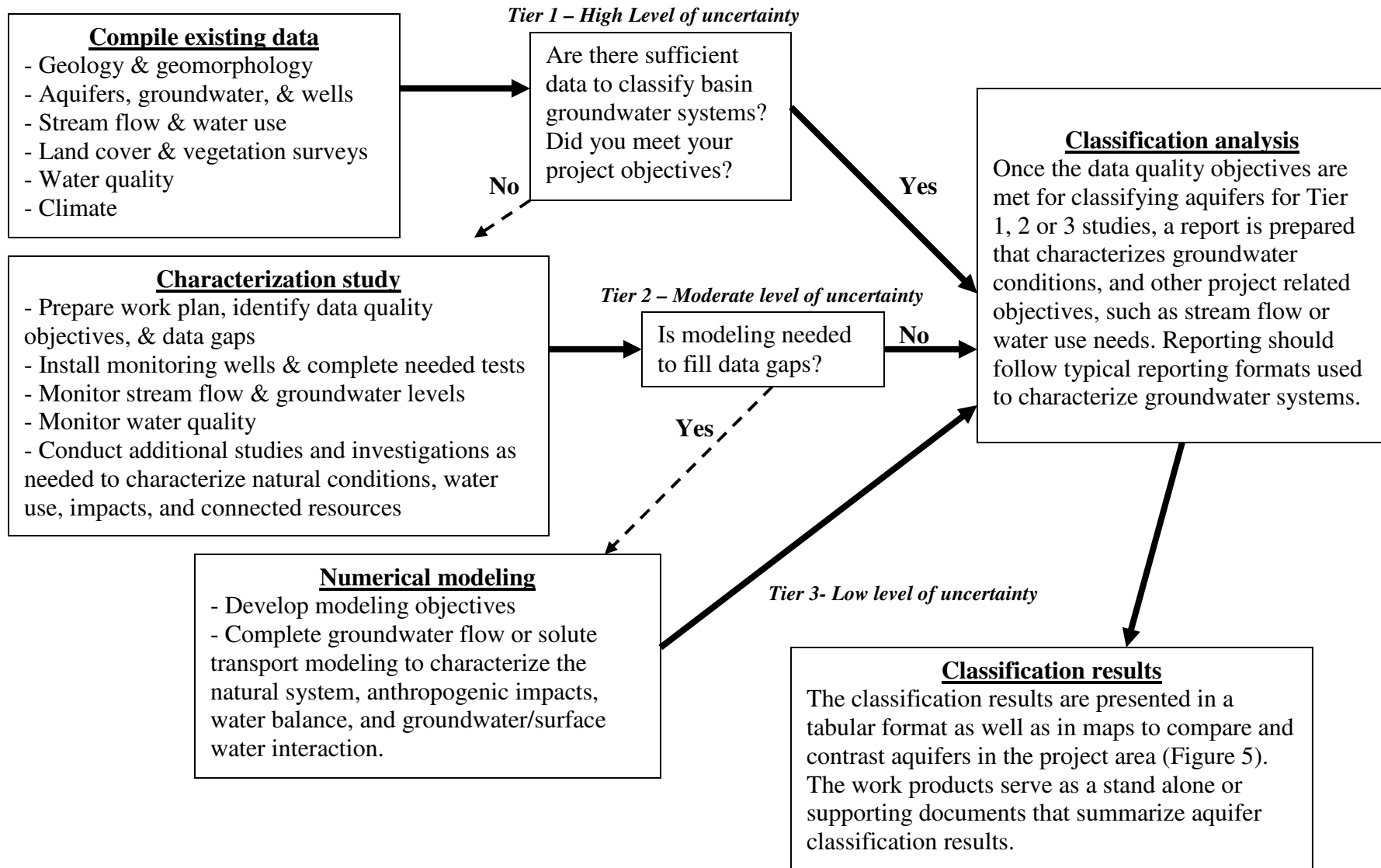


Figure 3. The progression of Tier 1 through 3 assessment procedures and types of data required to classify aquifers. Project budgets, schedules, and other factors may limit classification efforts to Tier 1 or 2 studies which have a lower level of reliability compared to Tier 3 studies.

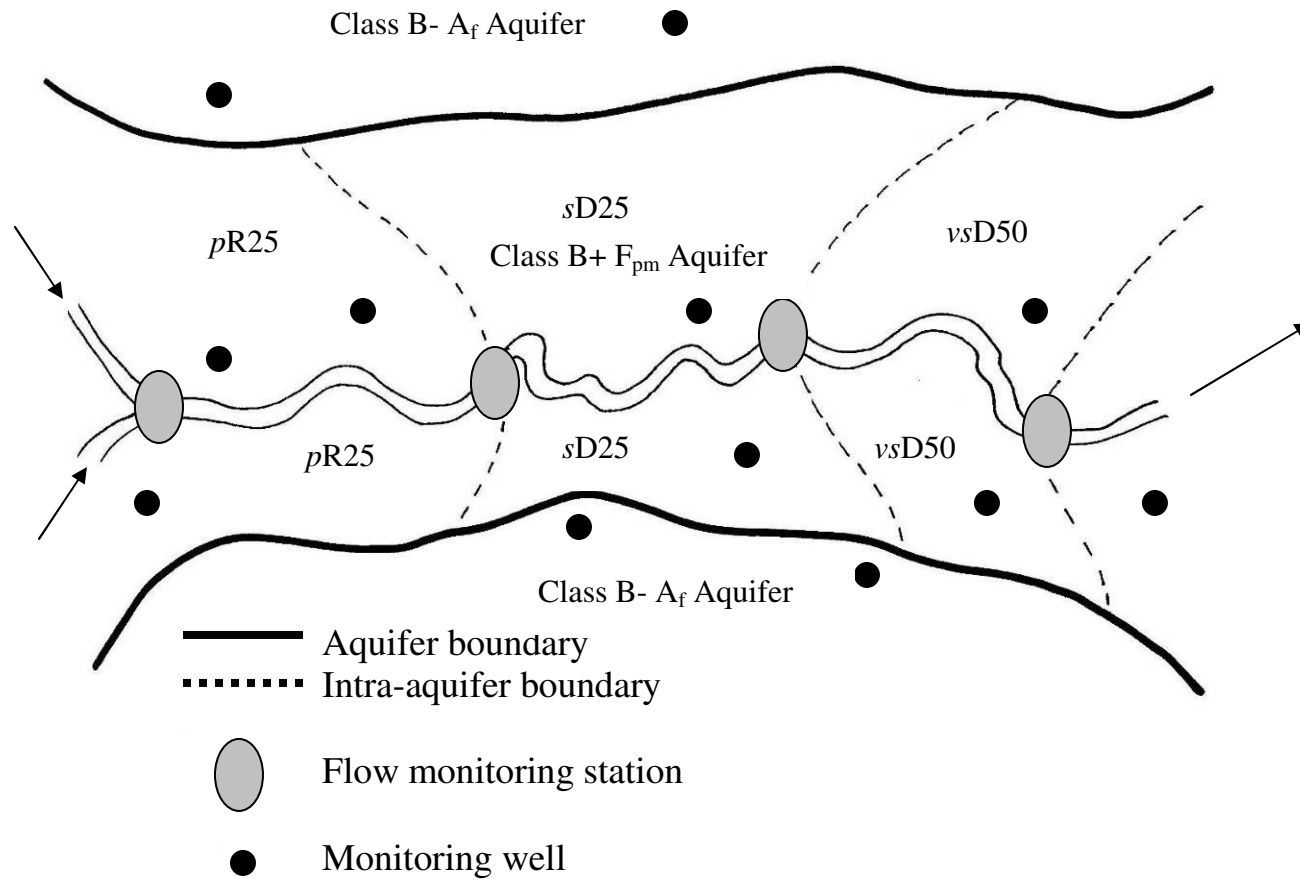


Figure 4. A diagrammatic example of aquifer classification along a fluvial plain aquifer and meandering river reach with variable groundwater/surface water connection and depth to the water table.

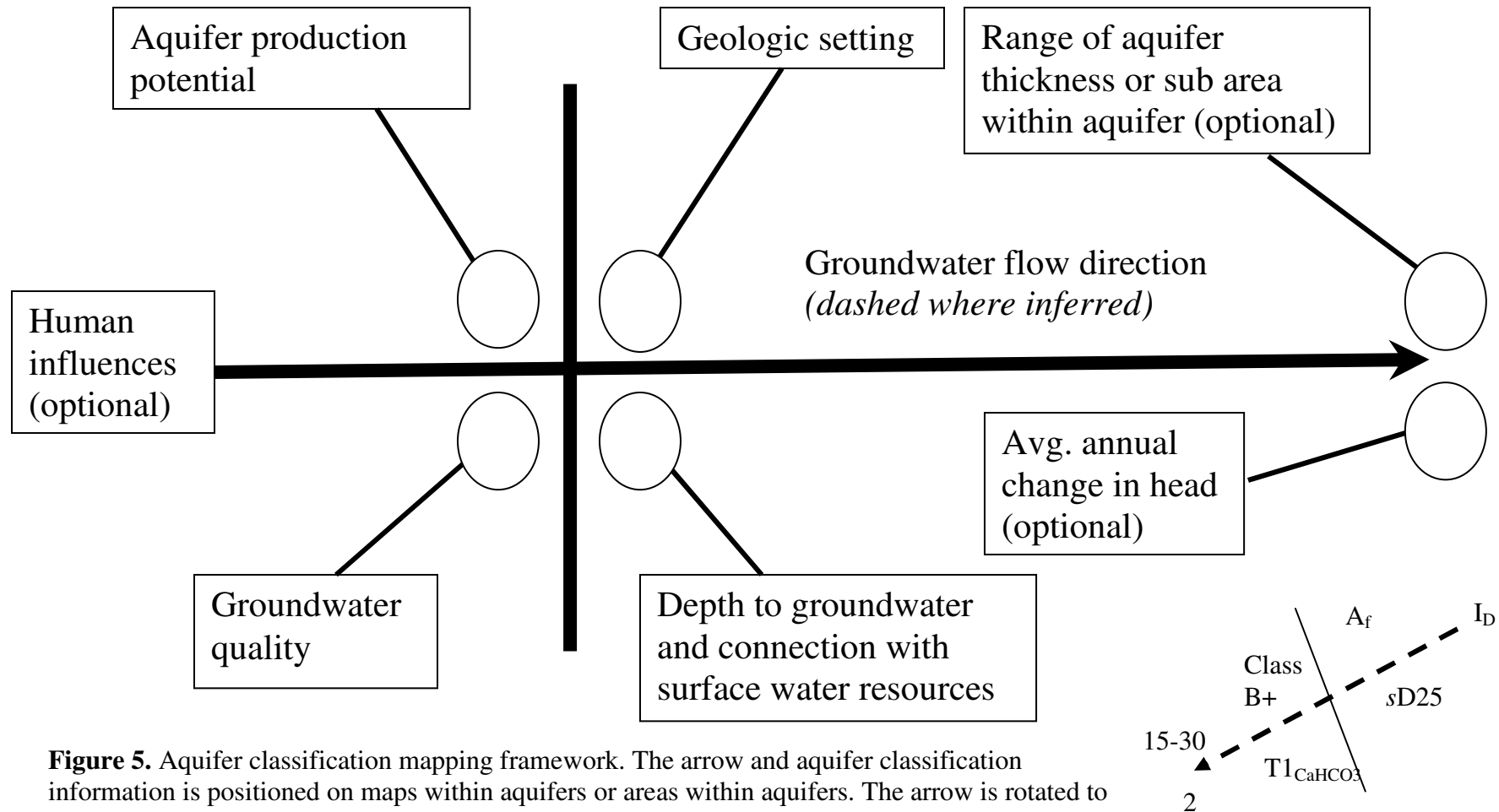


Figure 5. Aquifer classification mapping framework. The arrow and aquifer classification information is positioned on maps within aquifers or areas within aquifers. The arrow is rotated to indicate general groundwater flow direction in 360 degrees with aquifer production, geologic setting, groundwater quality and depth to groundwater positioned in the same general position as shown below, similar to how a north arrow rotates around a compass. Aquifer class should be positioned in the upper right quadrant (or left quadrant, depending on the arrow direction). An example for applying the aquifer classification arrow is shown in the lower right portion of the figure. All numbers are in meters.

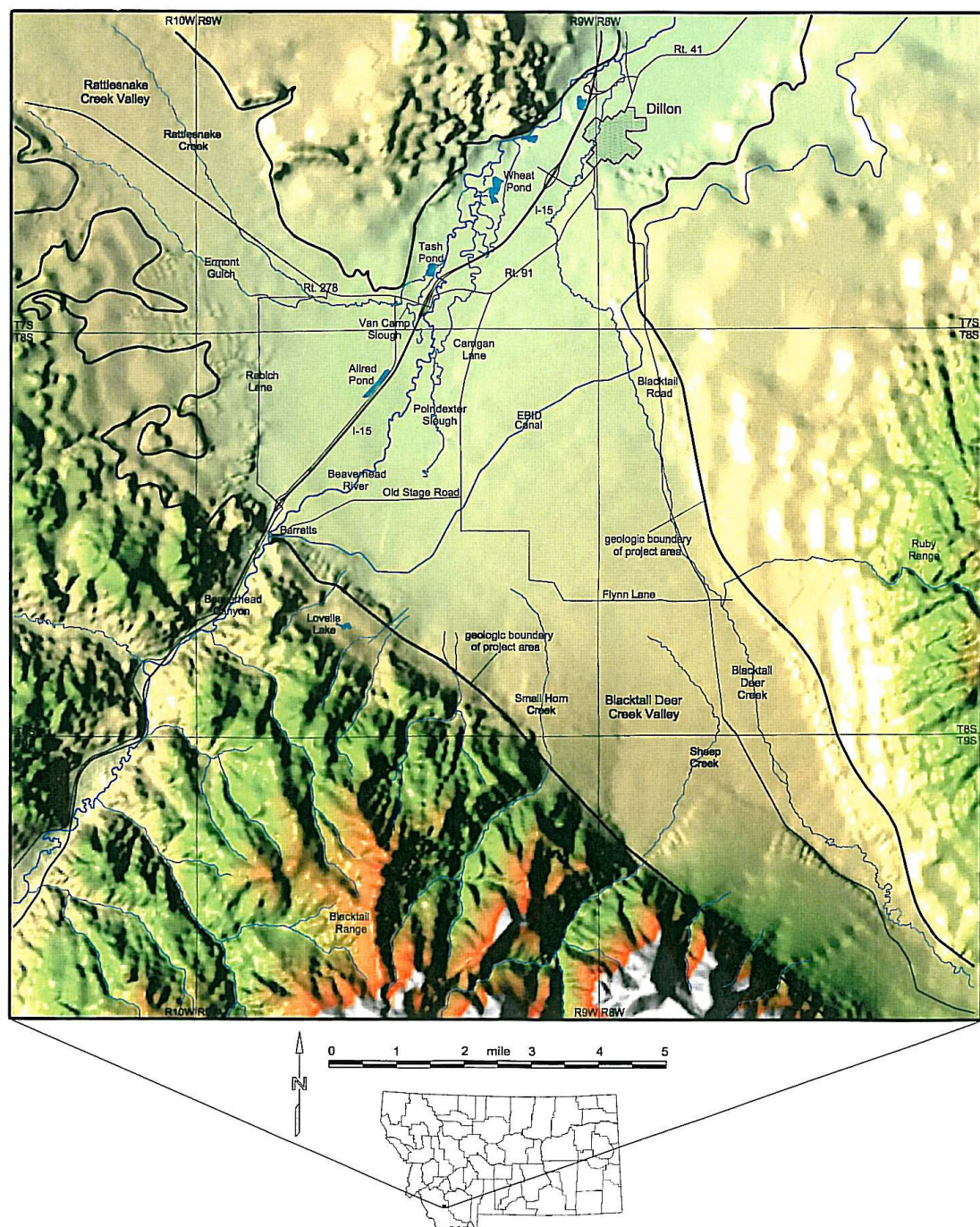


Figure 6. Project location map of the Upper Beaverhead Basin, Beaverhead County, Montana (adapted from Uthman and Beck 1998). The boundary line delineates the basin fill sediments.

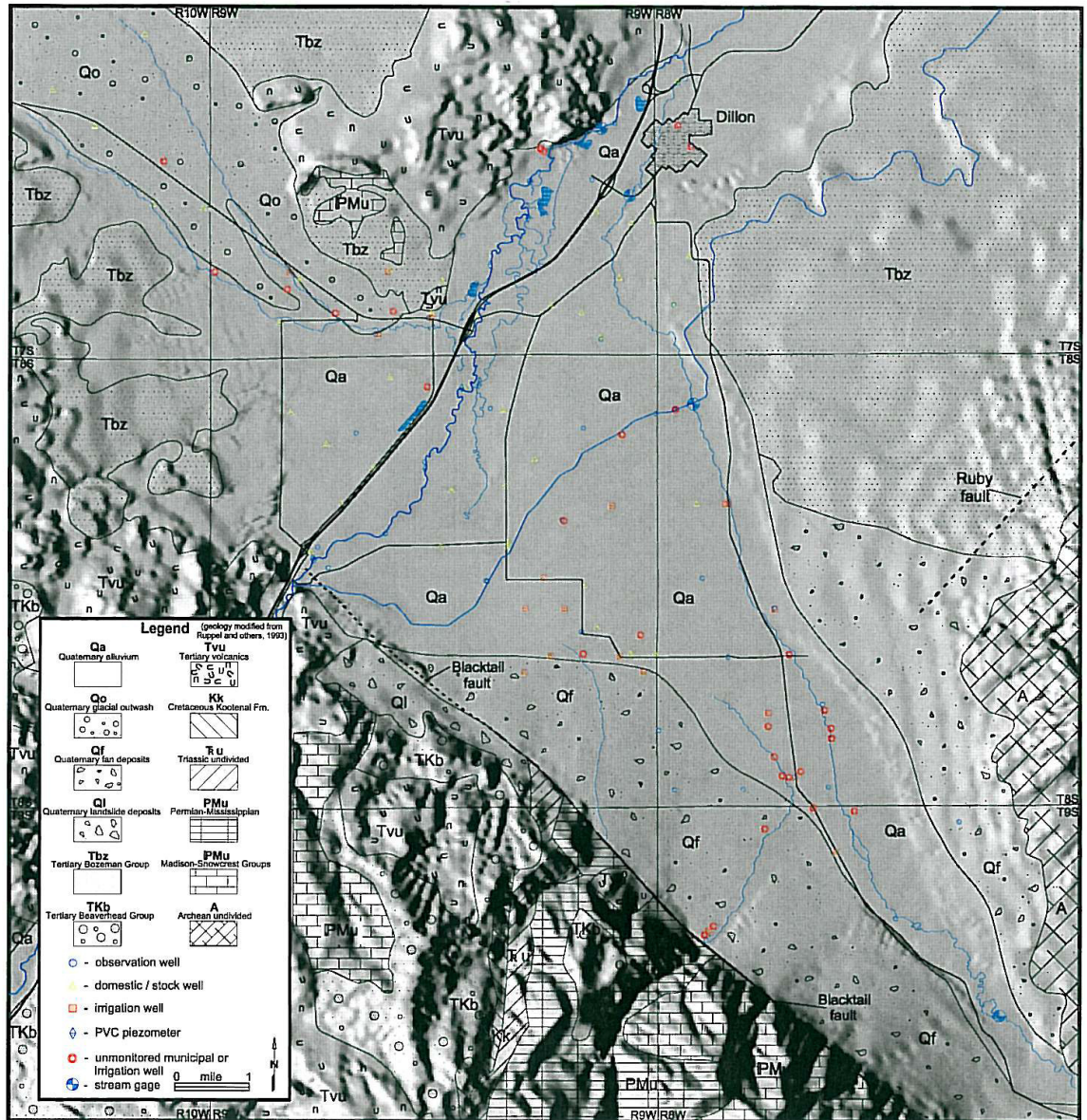
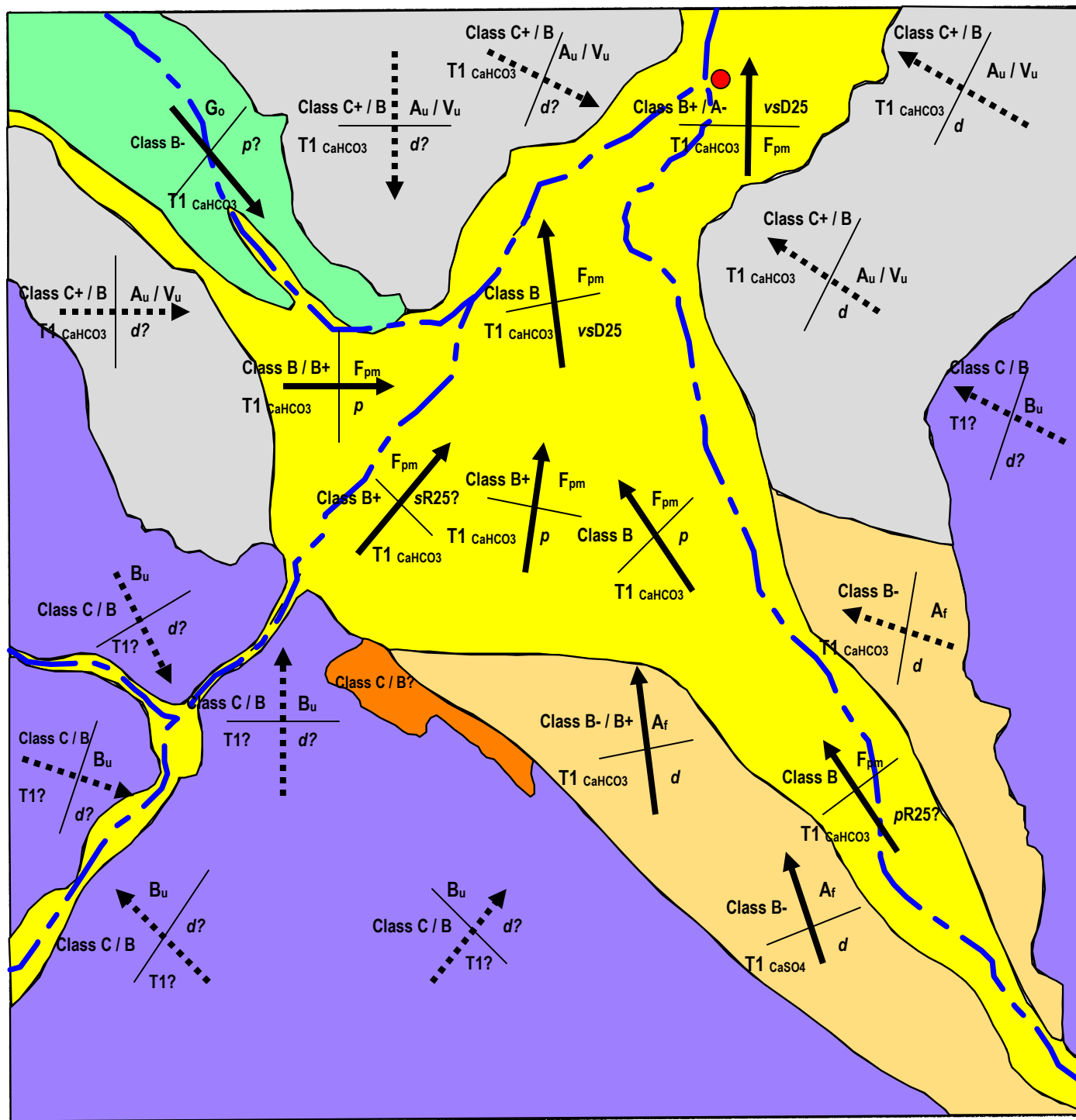
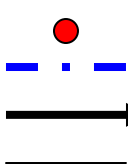


Figure 7. Generalized geology of the Upper Beaverhead Basin (adapted from Uthman and Beck 1998 and Ruppel et al. 1993).



0 Scale 6 miles

North



Dillon, Montana

River or Stream

Groundwater flow direction

Aquifer boundary

General GW flow
Direction Dashed = inferred

Geology

Aquifer Class

Water Quality

Depth to GW and SW exchange (if known)

Figure 8. Upper Beaverhead Basin aquifer classification (see Tables 1 and 13 and Figure 5 for additional aquifer classification information).

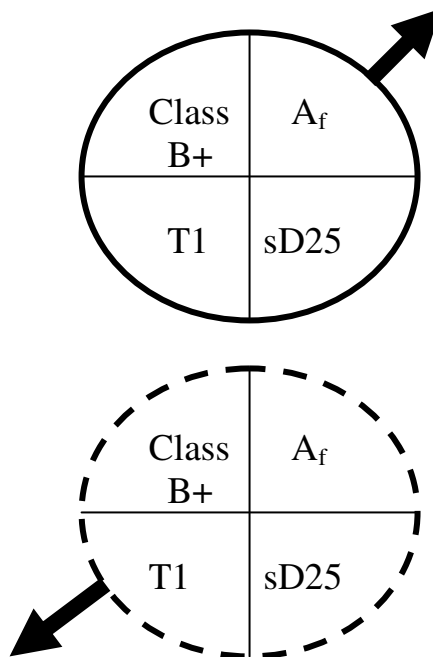


Figure 9. This figure shows an alternative mapping approach for classification results. Other configurations are possible. A dashed circle is used to indicate uncertainty in the classification results. Each quadrant shows the same information as in Figure 5. (Adapted from AWRA peer review of this paper)

Appendix A. Recommended contents, description, and examples for tabulating groundwater classification results.

Groundwater Classification Criteria	Description	Sample Code and/or Classification
Name of aquifers	Each aquifer that is being classified should be named. In cases where areas within aquifers are classified separately because of changes in productivity, water quality, or connection with surface resources they too can be named as suborders within aquifers depending on the scale and utility. The name should reflect the existing name or a broad geologic setting and general location. Other modifiers should also be used to differentiate aquifers or areas within aquifers if supported. Maps should be used to locate the project area and show aquifer boundaries.	- Beaverhead fan aquifer - Blacktail Range bedrock aquifer - Beaverhead River Floodplain aquifer - Beaverhead River Older Terrace aquifer - Tertiary unconsolidated aquifer
Aquifer productivity and hydraulic properties	Aquifer productivity is linked to the production classes in Tables 3 and 4. Supporting information should be tabulated as well as the general class to show max, min, and median production values for specific capacity (SpC), hydraulic conductivity (K), transmissivity (T), and specific yield (Sy), as examples. The aquifer properties will range depending on the number of wells and the quality of data may be variable. Professional judgment should be used to determine which measure, such as the median or 95 th percentile, should be used to classify aquifer production. In some cases, especially for Tier 1 assessments, some parameters may be inadequately quantified and have to be estimated based on literature values.	Class B+ High intermediate flow SpC (min, max, median) 3, 42, 25 (liters/minute/m drawdown) K (min, max, median) 2, 80, 55 (m/day) T (min, max, median) 450, 9400, 6200 (m²/day) Sy (estimated) 0.15
Aquifer thickness, annual head change, and related properties	These data are useful for aquifer analysis and should be mapped as part of classifying aquifer. Other hydraulic parameters can also be tabulated such as gradient or average linear groundwater velocity to help describe the aquifer.	Aquifer thickness: 15 to 30 m Typical annual head change: 2 m

Groundwater Classification Criteria	Description	Sample Code and/or Classification
Geologic framework	The geologic framework is the classification nomenclature in Table 2. The geologic framework should be consistent with the aquifer name. To illustrate how to classify the geologic setting, the aquifer names above are used to generate the geologic setting tabulated on the right.	A_{fa} (alluvial fan arid) B_{ls} (bedrock - limestone) F_p (fluvial plain) F_{pt} (fluvial plain older terrace) U_u (undifferentiated unconsolidated)
Aquifer productivity significance and size	Aquifer productivity significance is a narrative test based on an analysis of the aquifer system that compares the general productivity with how much demand or biologic need there is for the groundwater. This is a site specific classification that is based on professional judgment and analysis of the available data. In terms of aquifer coverage, the spatial horizontal boundaries of the aquifer being classified needs to be characterized and compared to the size criteria in Table 6.	iiib Light demand and intermediate size aquifer <i>Sample narrative:</i> demand for groundwater from this intermediate size aquifer is low because it is located in a rural setting with relatively few domestic and large irrigation water supply wells. Compared to the size and production of the aquifer, demand is low.
Dewatering and artificial recharge impacts	This classification criterion outlines the hydraulic impacts in aquifers associated with artificial recharge or groundwater depletion and is further defined in Table 7. The utility of head data will vary depending on the number of wells measured, duration, and the quality of the data. Professional judgment should be used to determine which measure, such as the median or 95 th percentile, serves as the best overall approach for classifying hydraulic impacts.	I_D Moderate dewatering Total head change max, min, median: +0.3, -31, -14.3 m (10 year record) Average Annual head change min, max, median +0.02, -0.68, -0.5 m (10 year record)

Groundwater Classification Criteria	Description	Sample Code and/or Classification
General groundwater quality	This classification provides the general water quality based on specific conductance and common ion chemistry. Professional judgment should be used to determine general water quality based on the information in Table 8 and review of common ion chemistry for groundwater quality. The dominant anion and cation chemistry should be selected to characterize the water.	T3 (ion chemistry not available), or Type 3 water T1 _{CaHCO₃} , or Type 1 calcium bicarbonate water T2 _{MgSO₄} , Type 2 magnesium sulfate water or T1 _{CaHCO₃ and some MgSO₄} Type 1 mixed ion water
Water quality impacts	In cases where there are water quality impacts from anthropogenic sources, a classification code is used to indicate the type of pollutant (see Table 9). Water quality impacts should be included in aquifer classifications when the groundwater quality impacts affect beneficial use of the water (meaning there is a regulatory action likely or underway) and it a significant portion of this aquifer. In general, these classification codes are most likely to be used in areas where toxic waste or fuel sites are located.	m,f,v m (metals), or f (fuel related contaminants) v (volatile organic compounds)
Aquifer vulnerability	For Tier 1 assessments, aquifer vulnerability is a narrative classification based on an analysis of the aquifer system that considers the depth to groundwater, overlying lithology separating the aquifer from surface contaminants, aquifer use and production, and land use (see Table 10). This analysis is site specific and must be based on professional judgment and a weight of evidence analysis. For Tier 2 and 3 analyses, more quantitative methods should be used to gage aquifer vulnerability and in cases where budgets allow, a more comprehensive analysis should be used gauge aquifer vulnerability.	H High vulnerability <i>Sample narrative:</i> High vulnerability because depth to groundwater is less than 7m in a moderate production sand and gravel aquifer over which an urban setting is located. The aquifer is currently used as the primary water supply for the municipality and commercial land use, such as dry cleaners and fuel storage facilities are

Groundwater Classification Criteria	Description	Sample Code and/or Classification
		present, which threaten groundwater quality.
Depth to groundwater and groundwater/surface water connection	This aquifer classification criterion identifies the general depth to groundwater and overall connection aquifers have with significant streams, rivers, lakes or wetlands within the aquifer boundary. Combined depth to groundwater and groundwater/surface water connection is likely the most difficult criteria to quantify because adequate stream flow data and water level data are needed to make a clear distinction between classes of aquifer discharge to surface resources. In cases where there is insufficient data for selecting subclasses related to flow contribution, this part of the criteria can be ignored and refined later as more data becomes available. Seasonal analysis may lead to multiple classifications for groundwater/surface water connection classes and they should be classified if significant. In addition, specific water bodies may have different groundwater/surface water connections in the same general area and they should be classified separately if the variance is significant and more detailed classification is necessary for data quality objectives (see Tables 11 and 12).	<i>vs</i> Very shallow depth to groundwater – insufficient data to quantify connection with surface water <i>sD25</i> Shallow depth to groundwater with 0 to 25 percent of surface water flow coming from groundwater <i>pR25 to pD25</i> Proximal depth to groundwater with a variable connection to surface water) <i>d</i> Deep aquifer with no nearby contribution to surface water) <i>vsD90-95 Spring Creek</i> Very shallow aquifer with very strong hydraulic contribution to Spring Creek
Level of assessment	The level of assessment should be included in aquifer classification results. The higher the level of assessment the more data are integrated into the classification (see Table 1).	Tier 1, Tier 2, and Tier 3

Groundwater Classification Criteria	Description	Sample Code and/or Classification
Full classification using the codes	The result of the tabulated aquifer classification is the complete set of classes, nomenclature, and codes. These results should be mapped spatially, in profile, and temporally to complete the aquifer classification process (see Figure 5 and 8).	Beaverhead Fluvial Plain Aquifer (coded from Figure 8 and Table 12) Class B+/A- (F _p) ic T1 _{CaHCO₃} / H vsD25 (Dillon area) Tier 3

Figure A1. Box and Whisker Plot of Specific Capacity Datasets. Dashed lines identify high, intermediate, and low flow potential aquifers. The bottom line identifies aquatards.

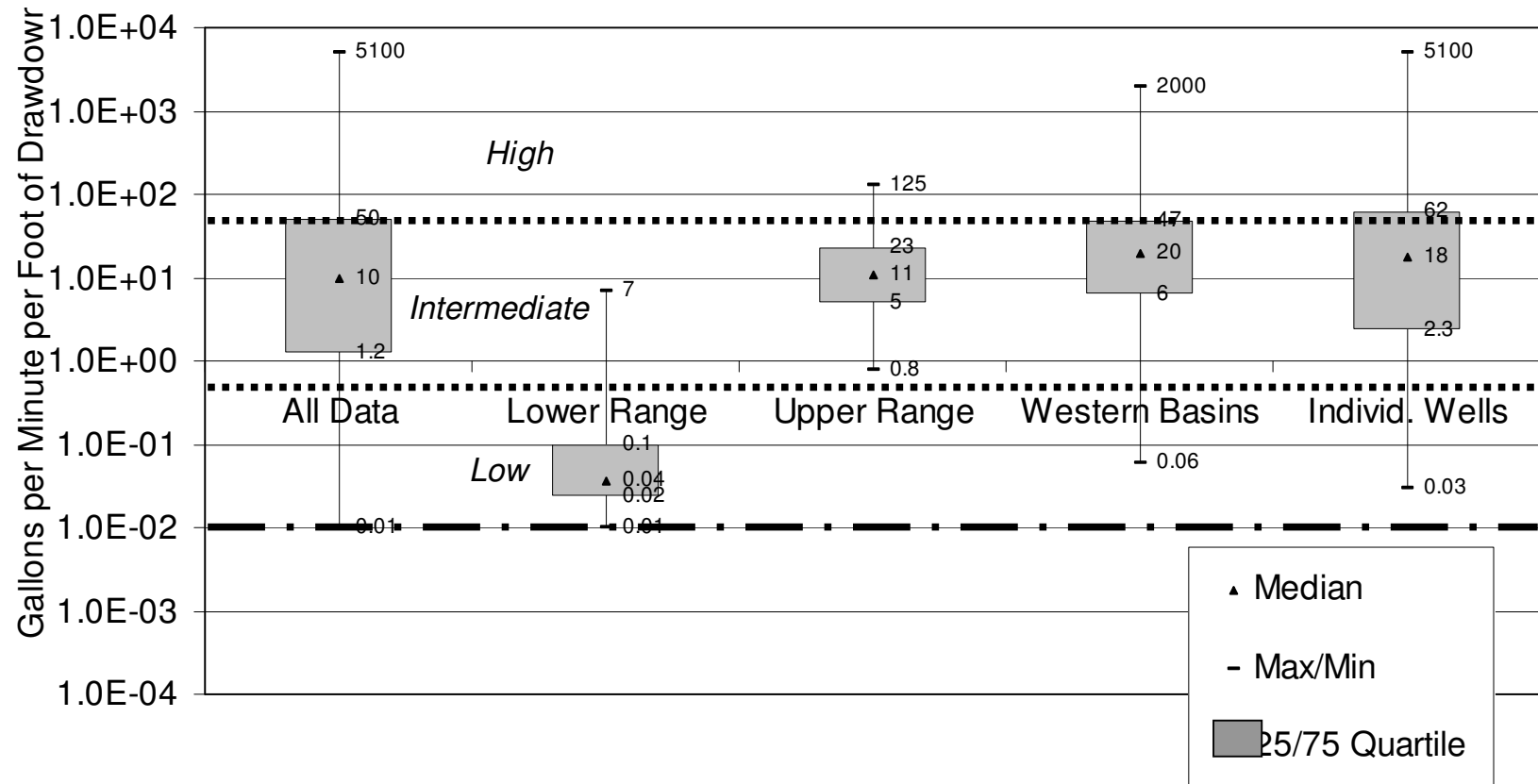


Figure A2. Box and Whisker Plot of Hydraulic Conductivity Datasets. Dashed lines identify high, intermediate, and low flow potential aquifers. The bottom line identifies aquatards.

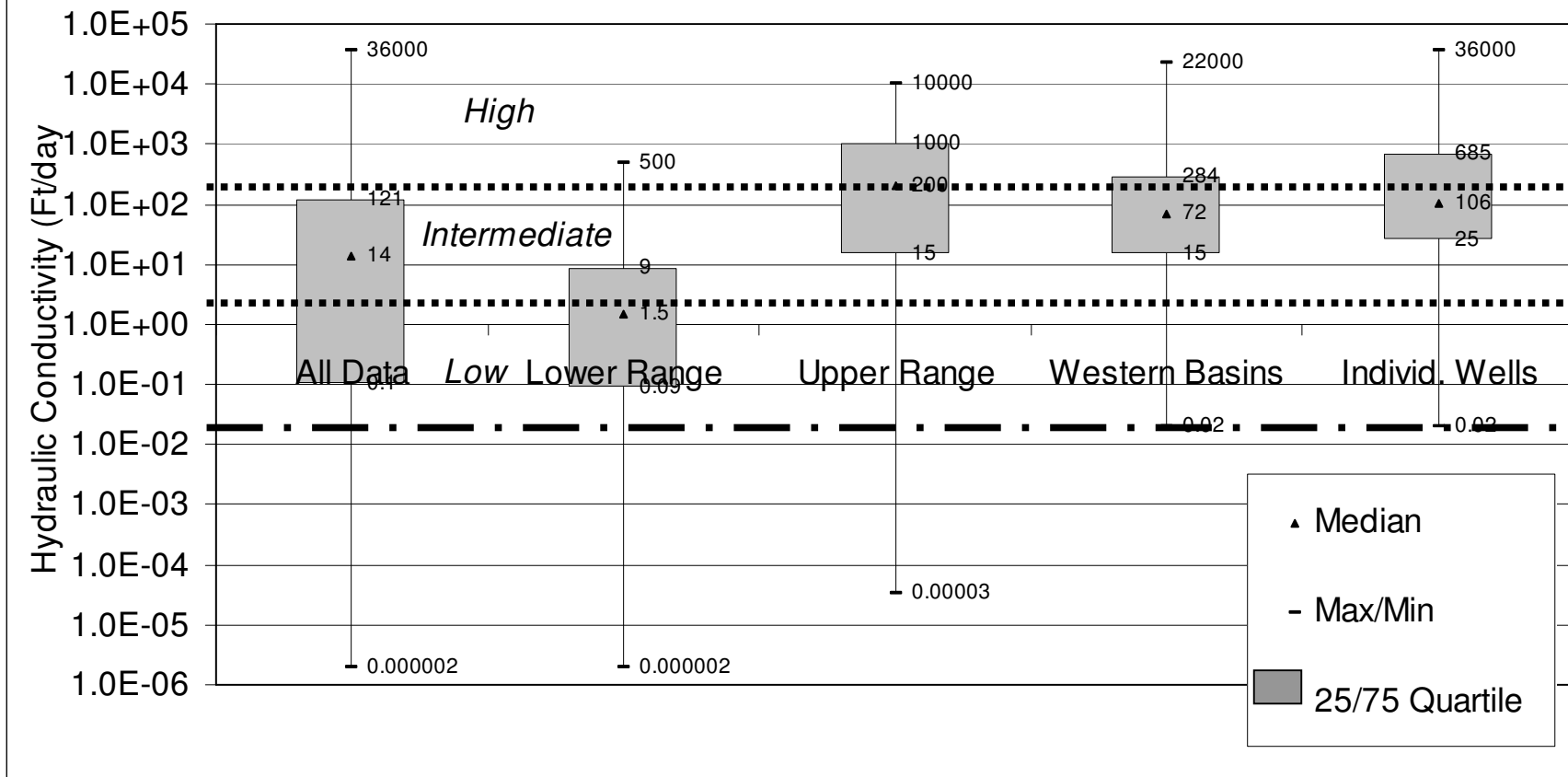


Figure A3. Box and Whisker Plot of Transmissivity Datasets. Dashed lines identify high, intermediate, and low flow potential aquifers. The bottom line identifies aquatards.

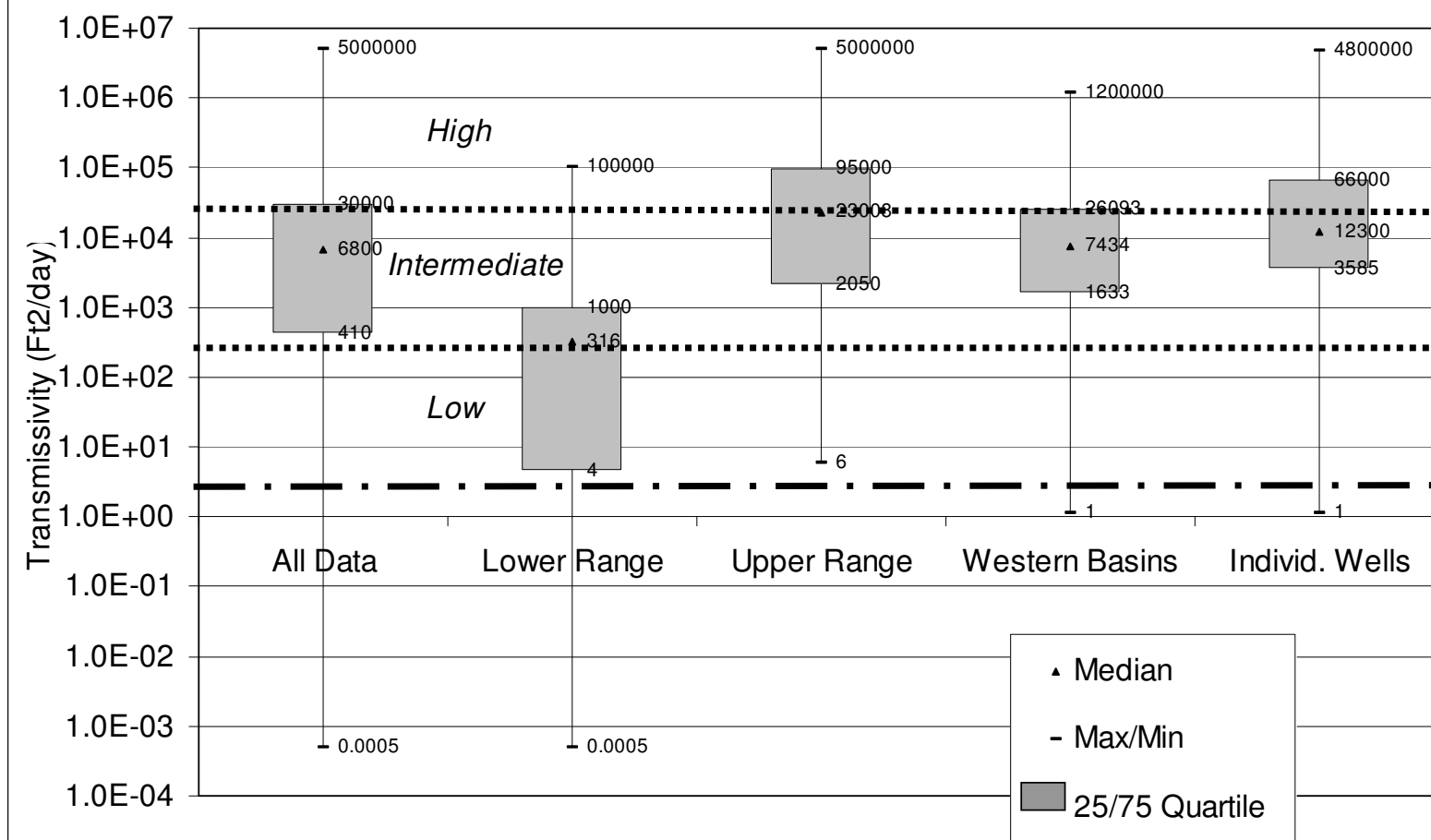
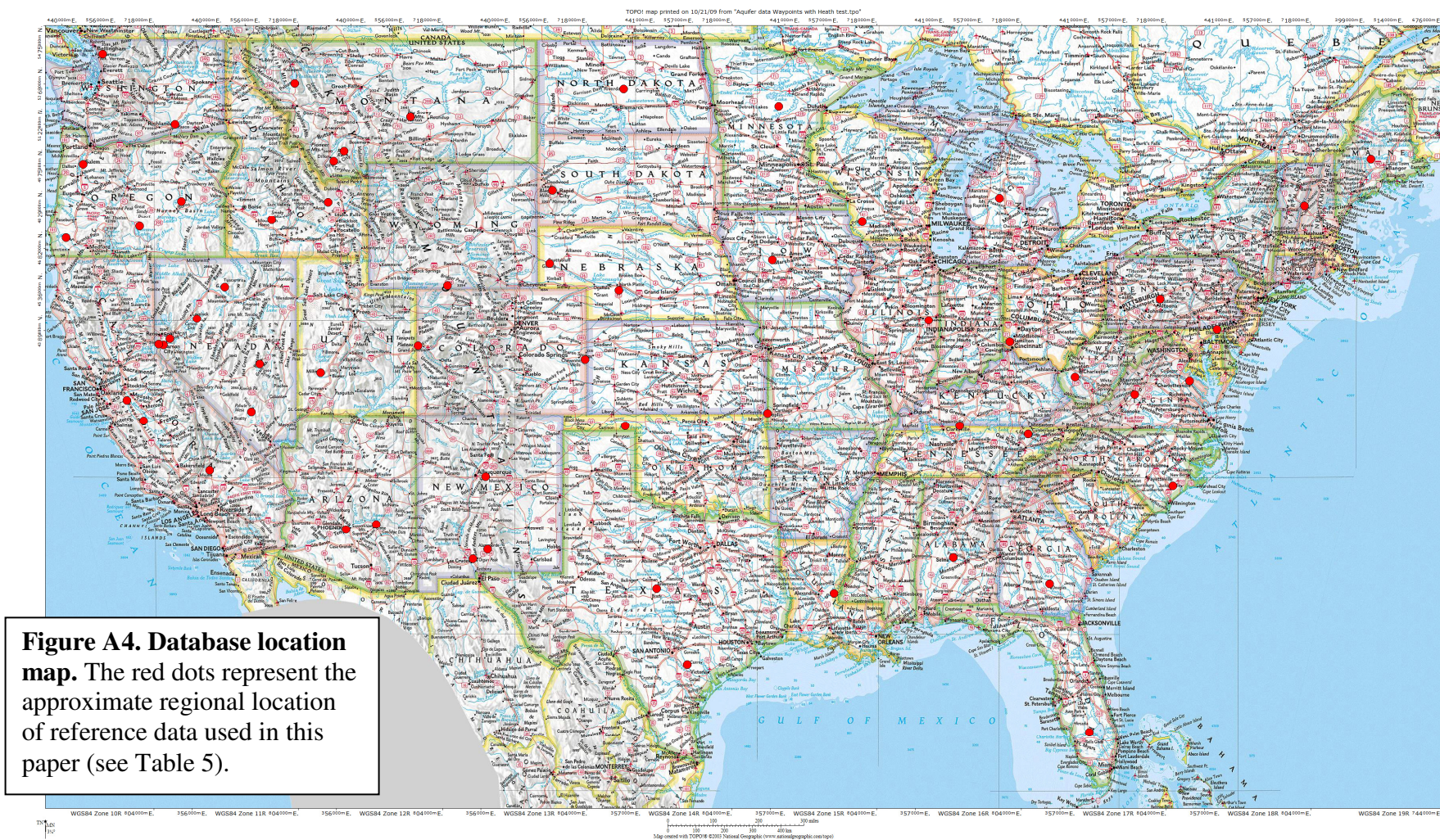


Figure A4. Database Location Map (See enclosed CD-rom for electronic data).



**Application of a Visual, Symbol and Tabular Based Groundwater Classification
System for the Lower Ruby Valley Watershed, Southwest Montana**

by Scott M. Payne, Ian Magruder, and William W. Woessner*

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Abstract

Watershed scale classification of groundwater conditions allows for a full synthesis of landscape hydrology and a platform supporting local and regional water resources management decisions. The application of the tiered basin scale groundwater classification proposed by Payne and Woessner (2010) is illustrated using a case study of the 300,000 acre Lower Ruby Valley watershed of southwestern Montana. Datasets included existing and newly collected information on the geologic setting, groundwater flow direction, aquifer productivity, water quality, anthropogenic water level impacts, depth to groundwater, and the degree of connection between groundwater and surface water. Results are described in summary tables and maps providing seamless digital overlays prepared using geographical information system (GIS) software, and map symbols representing groundwater conditions. This work illustrates how the classification system is used to assemble, analyze and display large scale watershed groundwater data. The classification system is designed to provide scientists and managers with a uniform tool with which to describe the groundwater conditions in watershed settings.

Key Terms: Case study, groundwater classification system, hydrogeology, watershed, groundwater management, watershed management, geographical information systems, rivers/streams, surface water/groundwater connection, and land use.

1.0 Introduction

As the demand for water to support domestic, municipal and agricultural use increases, and forecasts of alterations in water supplies as a result of global warming are formed, natural resource planners will need new tools to assist them in evaluating how to distribute limited water resources and evaluate economic, environmental, and social costs (Watson et al. 1998, Loáiciga 2000, and Loáiciga et al. 2000, Alley et al. 2002, Daughton 2004, Jury and Vaux 2005, Field et al. 2007, Kundzewicz et al. 2007, and Van de Wetering 2007). Most watershed to basin scale hydrological analyses focus on surface water hydrology and land use with only limited analyses of groundwater conditions (Yaffee et al. 1996). In addition, it is common that the varying levels of perspectives and knowledge of watershed scale hydrology by citizens, scientists and planners can hinder clear communications needed to formulate successful management plans (Jury and Vaux 2005). These realizations prompted an attempt at developing a standardized groundwater classification method at the watershed scale (Payne and Woessner, 2010). The result is a classification approach designed to facilitate communication amongst water users and developers, and to support the formulation of effective watershed and land use planning (Carter et al. 2007 and Kendy 2003).

In this work, the Payne and Woessner (2010) tiered basin scale groundwater classification methodology is illustrated by its application to a mountain bounded watershed in western Montana. The method classifies and maps the watershed scale geological setting, aquifer productivity, groundwater quality, depth to groundwater, and the degree of groundwater/surface water exchange (Figure 1). The use of the classification to both graphically and descriptively organize descriptions of groundwater conditions is presented. The methodology is designed to standardize nomenclature, mapping techniques, and it supplements but not replaces the text, figures, maps, and tables commonly included in watershed to basin scale hydrogeological reports (Prudic and Herman 1996, Rowe and Allender 2000, Thodal 1997, and Payne and Magruder 2004).

1.1 Study site conditions

The lower Ruby Valley Watershed is about 300,000 acres in size and located in southwest Montana (Figure 2). The regional geologic setting is associated with the northeastern edge of the basin and range geologic province (USGS 2004). The basin fill sediments are fluvial deposits of the Ruby River along with alluvial fans, debris flows, and volcanic deposits on the flanks of the local mountain ranges. The mountainous uplands rise over 5,000 feet above the valley floor and three mountain ranges, the Tobacco Root, Greenhorn, and Ruby Mountains bound the north, east, and south sides of the valley, respectively. Climate in the valley bottom is semi-arid (Magruder 2006) with an annual precipitation range from 11 inches per year in the valley to 26 inches per year in the uplands using the PRISM annual precipitation GIS coverage (Oregon Climate

Services 1998 and Magruder and Payne 2008). The valley has a mean annual temperature of 41.5 degrees Fahrenheit, ranging from a mean of 20 degrees in the winter to 62 degrees in the summer (Payne and Magruder 2004). Agriculture in the valley floor includes the production of cattle, grass hay, alfalfa, and some isolated grain crops. The majority of crop production relies seasonal irrigation with snow melt dominated surface water from the Ruby River, which has a mean annual flow of 180 cubic feet per second (cfs) at Ruby Reservoir (USGS station number 06019500 period 1938 - 2008) and tributary streams as well as water storage from Ruby Reservoir (Plate B1).

Four small towns are located in the Lower Ruby Valley including Twin Bridges, Sheridan, and Alder. The fourth town, Virginia City, is located near the headwaters of Alder Creek, which is a large tributary stream that has a 25 cfs mean annual flow (Payne and Magruder 2004) that flows into the Ruby River near the town of Alder. Several thousand people live the Lower Ruby Valley, mostly in the valley bottom. The mountainous headwaters are undeveloped with limited or no access and sparse hydrogeologic data (Magruder 2006).

Long term management of water resources in the Lower Ruby Valley requires an understanding of how changes in land and water use will affect water resources and sustainability (Magruder and Payne 2008). Figure 3 shows the watershed scale groundwater balance components. Past water management in the Ruby Valley focused primarily on surface water components in the local water balance with the objective of conservation the Ruby River aquatic ecosystem (Payne and Magruder 2004). This

approach ignores the role groundwater plays in sustaining stream flow, fisheries, and riparian corridors, key components of the aquatic ecosystems, and a critical factor in comprehensive water management in the watershed.

The Ruby Valley groundwater system is comprised of multiple bedrock-bounded aquifers which discharge groundwater to springs, streams, and the Ruby River (Payne and Magruder 2004). Geologically, aquifers are separated into bedrock, alluvial fan, undifferentiated Tertiary benches, and fluvial valley aquifers (Payne and Magruder 2004 and Ruppel et al. 1993). The surrounding bedrock aquifer is a low production aquifer system covering a large area of the project area and serves as a recharge source for the basin fill sediments. The basin fill sediments, while covering a smaller area compared to the bedrock system, is divided into nine aquifer systems with varying aquifer productivity characteristics (Magruder and Payne 2008). The change in annual water table elevation is typically ten feet or less (Payne and Magruder 2004) and groundwater flow direction is from topographically higher areas towards the Ruby River floodplain. Groundwater quality is generally good to excellent with mostly calcium bicarbonate type water chemistry and isolated areas of magnesium sulfate water chemistry and elevated nitrogen concentrations (Payne and Magruder 2004).

Irrigation water supplies the majority of recharge to the valley groundwater system in the project area (Magruder and Payne 2008). The irrigation recharge and mountain mass recharge result in significant discharge of groundwater to valley streams, springs, and wetlands in the Ruby River fluvial plain (Magruder 2006 and Magruder and Payne 2008).

Groundwater also sustains stream and river aquatic habitats and fisheries, riparian and wetland ecosystems, including abundant wildlife and waterfowl. Specifically, groundwater discharge provides late summer and early fall baseflow to valley streams when surface water irrigation withdrawals are high and critical baseflow is naturally low during the late summer through winter months (Magruder and Payne 2008). Groundwater is withdrawn from valley aquifers and used for irrigation, and as the sole source of domestic and municipal supplies.

The Ruby Valley Conservation District (RVCD) and the Ruby Watershed Council (RWC) recognized the value and importance of characterizing, understanding and developing a long term watershed scale plan that protects and maintains the current quality and quantity of the groundwater and surface water resources of the Ruby Valley. In 2004, a planning document, the Lower Ruby Valley Groundwater Management Plan (LRVGMP), was prepared that included an initial attempt at classifying watershed scale groundwater resources (Payne and Magruder 2004).

In 2005, the Ruby Groundwater/Surface Water Interaction Modeling Project (Magruder and Payne 2008) was initiated. It used the available water resource data collected under the LRVGMP, addressing data gaps in field measurements, and created a predictive computer model of the Ruby Valley groundwater system and more closely examined groundwater influenced surface water flow in basin fill sediments. Field and modeling analyses were used to refine the basin water balance and identify key processes driving exchange of groundwater with surface water, as well as providing an analysis of focused

project objectives related to future land use, irrigation efficiency improvements, and water supply.

2.0 Methods

This paper illustrates the application of the proposed watershed scale groundwater classification developed by Payne and Woessner (2010). Five fundamental components (steps) were selected as the principal parameters needed to classify basin scale hydrogeologic systems (Figures 1 and 3). These include the following:

- Step 1. Geologic framework
- Step 2. Aquifer properties and basin hydrostratigraphy
- Step 3. Anthropogenic changes associated with land use, management impacts, or threats to groundwater supplies
- Step 4. Groundwater quality and vulnerability
- Step 5. Degree of connection between groundwater and surface water and depth to groundwater

The classification process is initiated by compiling datasets and using classification criteria that describe groundwater systems working through each of the five steps (Figure 1 and Tables 1 and 2) (Payne and Woessner 2010). The classification scheme is intended to broadly describe groundwater conditions and not replace detailed studies or reports.

The method includes a three-tiered hierarchy designed to indicate if sparse or detailed datasets are available to classify watershed scale groundwater conditions (Table 2). Tier 1 assessments are completed using sparse datasets, such as data derived from state or

federal databases, with Tier 2 and Tier 3 assessments relying on more extensive information involving progressively more extensive project scale water level measurements, aquifer testing, water quality sampling, surface water studies, geologic mapping, irrigation infrastructure studies, and computer modeling, as examples. The assignment of a tier level to a basin scale groundwater classification effort is somewhat subjective, however, general guidelines are recommended.

For this work, Tier 1 and 2, and later a Tier 3, level assessments were completed in the Lower Ruby Valley (Table 2). The 2004 LRVGMP is considered a Tier 2 analysis. It incorporated compilation of existing local, state, and federal databases and focused field studies were completed to characterize groundwater and surface water conditions (Payne and Magruder 2004).

The Ruby Groundwater/Surface Water Interaction Modeling Project (Magruder and Payne 2008) was derived as an extension of the Tier 2 study and represents a Tier 3 level assessment as it incorporated field studies that filled data gaps in the Tier 2 level assessment and numerical groundwater flow modeling was completed to refine water budget analyses. The development of Tier 2 and Tier 3 level assessments for watershed scale groundwater classification and the mapping technique developed by Payne and Woessner (2010) is used to summarize the project assessment data and provide a mapping approach representing spatial tabular data (Figure 4).

2.1 Level of assessment

The following is summary of methodology used to develop the tiered datasets and basin scale classification for the lower Ruby Valley. The first study targeted compilation of existing literature, reports, maps, water level, climate, soils information, land cover information, geologic reports and maps, aquifer testing data, groundwater quality data, aerial photography, and geophysical data for the valley to characterize subsurface conditions. Compilation of existing data included completing interviews with experts familiar with the local natural resources. Sources of information included the Montana Bureau of Mines and Geology (MBMG), US Geological Survey (USGS), Montana Department of Natural Resources and Conservation (DNRC), US Forest Service (USFS), Natural Resource Conservation Service (NRCS), local and county governments, private corporations and various Internet data retrieval sources as referenced in Payne and Magruder (2004). For surface conditions, stream flow data, Ruby Reservoir storage and flows, irrigation infrastructure and surface water use information, climate, and water rights information were compiled. This information, coupled with a site visit and professional judgment, is the type of data used to support a Tier 1 level assessment.

However, additional datasets were developed and analyzed to expand this work to a Tier 2 and 3 level assessments including field investigations (hydrogeologic characterization) and later numerical flow modeling. These datasets provided the basis for assigning hydrogeological mapping units and classification symbols on the final basin scale maps. Table 3 identifies the datasets compiled for the Tier 1 through 3 assessments. A summary of the data for the Tier 1 and 2 and Tier 3 assessments follow. Standard hydrological and

hydrogeologic methodologies and analyses techniques (e.g. surface water and land use: Smoot and Novak 1968, Rantz et al. 1982, Driscoll 1986, Sauer and Myer 1992, Fetter 1994, Fulford et al. 1994, Hansen et al. 1995, and Miall 2000) were applied and are referenced in the detailed reports (Payne and Magruder 2004 and Magruder and Payne 2008).

2.2 Tier 1 and 2 assessment (steps 1 through 5)

Multiple surface and subsurface field investigations were completed in the Lower Ruby Valley project area to complete the Tier 1 and 2 assessments. The purpose of the subsurface investigation work was to characterize the geology and groundwater conditions of unconsolidated basin fill sediments composed alluvial fans, terraces, and fluvial/floodplain deposits. Methods described by Driscoll (1986), Fetter (1994), and Miall (2000) were used to support the subsurface investigation and the reader is expected to have a working knowledge of applied studies in geology/sedimentation, hydrogeology, and geophysics. The surface investigation for the Tier 1 and 2 assessments focused on the Ruby River, tributary streams, irrigation water conveyance and infrastructure, and vegetation/cropping in the Lower Ruby Valley. Methods by Fulford et al. (1994), Rantz et al. (1982), Sauer and Myer (1992), Smoot and Novak (1968), and Hansen et al. (1995) were used to support the surface investigation and the reader is expected to have a working knowledge of applied studies in hydrology, soils, agriculture, and vegetation surveys. The following is a summary of the surface and subsurface investigations in Table 3 completed for the Tier 1 and 2 assessments.

Aerial assessment: Landsat images were gathered to map irrigated lands and compared with field mapping results and GIS layers available from Montana's Natural Resource Information System (NRIS). The aerial assessment included reviewing the 1995 digital orthophotoquads, privately flown aerial photography, and aerial photography on file at the RVCD. The aerial assessment helped the project team become more familiar with project area, agricultural cropping, irrigation water use, physiographic features of the project area, and areas of the project area that could not be accessed.

Water Well Inventory: The subsurface investigation targeted characterization of the geologic conditions and groundwater conditions at depth. Several hundred domestic water wells on file with the MBMG and DNRC for the Lower Ruby Valley were compiled for project area and 80 wells were selected for monitoring based on an evaluation of long term landowner access, well use, location, well depth, well construction and availability/quality of the well log.

Well log and geologic analyses: Wells logs, surface geology and geologic literature were studied in the Lower Ruby Valley to develop a watershed scale conceptual geologic model of the watershed (Figure 5). Cross sections were developed and aerial gravity data flown for the project area were processed to estimate depth of the basin fill sediments and develop an understanding of the geologic controls on groundwater.

Monitoring water level and depth to groundwater analysis: Water levels were measured monthly or seasonally in all 80 wells as well as collected continuously in selected wells

representing the primary aquifers. Depth to groundwater was mapped using surface elevation data, depth to groundwater, and vegetation as an indicator, as described by Vereiskii and Vostokova (1966), to help determine depth to groundwater in areas with no wells (Figure 6). Hydrographs of wells monitored for this project as well as long term water level data collected by the MBMG were used to evaluate water level changes annually and compare hydrographs with climate and irrigation data. Groundwater flow direction was determined using a digital elevation model and ArcGIS 9.3 software to approximate monitoring well elevation and water level data to estimate the potentiometric surface (Figure 7).

Aquifer testing: Aquifer testing included data analysis for 20 aquifer pumping tests or slug tests and comparison of results with literature values. Aquifer testing was completed on existing wells because no funding was available for installation of new monitoring wells, although some public information for aquifer testing data was available from past studies for municipalities and mining projects.

Groundwater quality: Groundwater quality was tested and included gathering existing groundwater quality data from Madison County and the USGS. Field testing included collecting screening level data using field meters (pH, temperature, specific conductance) and use of HACH field testing strips for general water quality including nitrate, ammonia, and phosphate for all 80 wells (Figure 8). Based on the screening data (including quality control samples), nine wells sites were selected for quarterly common ion, nutrient, and trace metals sampling and analysis. Laboratory groundwater quality

analyses were analyzed by the MBMG for the primary aquifers in the project area and used to compare and support field screening data.

Measurement of river/stream flows, continuous stage, and staff gauges: A surface water monitoring network was setup using existing sites and new sites to characterize river and stream flow in the project area (Figure 9). Surface flow measurements and flows based on staff gauges/recorders with flow rated curves were collected seasonally over two field seasons for spring, summer, fall, and a limited number of winter flows. Flows were collected following standard USGS flow measuring techniques and where possible collected synoptically in sequence during dry, stable weather patterns to characterize groundwater and surface water exchange using stream flow loss and gain data.

Ditch/Canal flows: The lower Ruby Valley irrigation canals and ditches were mapped and developed into a GIS shape file (Figure 9). Flow measurements on selected ditch and canal reaches were measured synoptically to assess flow loss and gains between take out points. About 23 miles or 16 percent of the 145 miles of ditches and canals were assessed in the valley. The ditch and canal flow loss and gain results were used to estimate the overall influence of irrigation water conveyance on the valley groundwater system.

Vegetation, hydric soils, and irrigation mapping: The irrigated acres in the project area were mapped to assess the type of irrigation system in each field (flood, hand line, wheel line, or pivot) (Figure 10) as well as cropping patterns. Mapping the type of irrigation system for each field was used to assign efficiency estimates for different types of

irrigation practices which were needed to support modeling and water budget analyses. The type of surface vegetation was mapped along with soils data and water level data from wells to help determine depth to groundwater (Figure 11).

2.3 Tier 3 assessment (steps 1 through 5)

The Tier 1 and 2 assessments provided a foundation for which to complete aquifer classification work in the Lower Ruby Valley. However, there were several data gaps noted in the LRVGMP related to groundwater/surface water exchange, project area water balance, and aquifer properties that were not fully answered. A Tier 3 level assessment was completed to fill these data gaps and the following is summary of the data compilation, data collection, and analysis completed for the Tier 3 aquifer classification assessment as summarized in Table 3.

Compilation and Analysis of existing data

Most of the available information for the project area was compiled under the Tier 2 assessment and an update of the existing data was completed to ensure the most recent data were included in the assessment, including additional interviews with experts familiar with the local natural resources as described earlier.

Field Investigation and Numerical Modeling

A focused field investigation was required to support the Tier 3 assessment and numerical groundwater flow modeling. Specifically, surface flow measurements were needed in the Ruby River to estimate groundwater/surface water exchange, which also

was needed for aquifer classification and developing calibration targets for the flow model. Synoptic flow monitoring was completed on selected reaches to estimate surface water gains and losses in the Ruby River. Existing groundwater data, collected under the Tier 2 assessment, was sufficient to support the Tier 3 assessment and no additional groundwater data were collected to complete the groundwater flow modeling.

Numerical groundwater flow and surface water interaction modeling

The numerical groundwater flow model completed for the Tier 3 assessment simulates transient groundwater flow and the interaction between groundwater and streams, rivers, and irrigation canals and ditches. The model was designed to simulate broad implications of large-scale water management changes in the valley and methods by Anderson and Woessner (1992) were applied. The results presented by Magruder and Payne (2008) simulate how changes in irrigation water use and efficiency as well as the occurrence of increased groundwater development could affect flows in the Ruby River and other hydrologic features associated with the primary tributaries and Ruby River floodplain, such as groundwater fed sloughs. The modeling results provide a Tier 3 level assessment and support aquifer classification maps presented in the next section.

Data from the LRVGMP and additional stream flow collected as part of the Tier 3 assessment were used to support the groundwater flow modeling. Visual MODFLOW Version 4.2 from Waterloo Hydrogeologic, Inc. was used for all modeling. MODFLOW (Harbaugh et al., 2000) is one of the most widely used groundwater flow codes in the world and has been in public use since 1988. The Streamflow-Routing Package (STR1)

provided for MODFLOW by USGS (Prudic, 1989) was used with Visual MODFLOW to simulate seepage and flow in all natural surface water features. There are many examples of successful applications of MODFLOW similar to the use for this project. For example, Uthman and Beck (1998) use MODFLOW to evaluate the potential impacts of increased groundwater withdrawals, drought, and irrigation efficiency changes in the upper Beaverhead basin. McAda and Barroll (2002) use MODFLOW to quantify groundwater and surface water interactions in the Middle Rio Grande Basin of New Mexico. Prudic and Herman (1996) use MODFLOW combined with the STR1 package to simulate the effects of groundwater development in the Paradise Valley of Nevada.

Magurder and Payne (2008) describe the data used to parameterize the model, model time discretization, calibration, validation, the current water balance, and parameter sensitivity, which is beyond the scope of this paper. The model was parameterized and calibrated to the existing conditions and data available from the period April of 2002 through June of 2003 (Figures 12 and 13).

2.4 GIS mapping and spatial analysis (Tier 1 through 3)

Data for the Tier 1 through 3 assessments were input into ESRI ArcGIS 9.3 GIS software for mapping and analysis. Using ArcGIS 9.3, project data such as aquifer delineation, stream flows, water levels, depth to groundwater, irrigation systems could be viewed using the software and provide an ideal long term database for future monitoring, supporting future assessments or planning for watershed management, and preparing graphic displays.

2.5 Formulating the aquifer classification

Aquifer classification in the Lower Ruby Valley was completed using ArcGIS 9.3 to prepare aquifer delineation maps and setup digital layers for mapping aquifers. The mapping analysis included setting up layers showing geology, topography, hydrography, aerial photography, hill-shading/digital elevation, soils, cities/towns, roads, and other layers to aid mapping and overlaying of aquifer classification results. The primary sources of the digital information used to map aquifers in the three watersheds are Ruppel et al (1993) with other less important sources of digital information available from USGS, state, or private digital data clearinghouses. Datasets supporting classification work focused on the geologic framework, groundwater flow direction, aquifer productivity, water quality, water level trends over time, depth to groundwater, and the degree of connection between groundwater and surface water on major surface water features (Payne and Woessner 2010). The geological framework analysis was used to identify potential hydrostratigraphic units and geologic conditions that affect groundwater occurrence, flow, and aquifer properties (Maxey 1964 and Domenico 1972). Aquifers and groundwater systems, aquifer boundaries, aquifer productivity, and groundwater flow direction were identified using datasets developed for the LRVGMP and groundwater/surface water modeling report (Payne and Magruder 2004 and Magruder and Payne 2008). In addition, aquifer size and relative aquifer capacity vs. productivity were assessed by mapping the aerial extent of aquifers and qualitatively comparing groundwater availability with groundwater use as described by Kreye et al. (1998) and Berardinucci and Ronneseth (2002).

For groundwater quality, four central themes were assessed and they included general water quality based on specific conductance, the dominate cation-anion water chemistry, presence of pollutants, and aquifer vulnerability. Lastly, groundwater/surface water exchange was assessed on major surface water features and classified to complete the analysis, which included assessing depth to groundwater, the slope of the ground surface compared to the water table, the direction and magnitude of hydraulic vertical gradients, relative amount of groundwater exchange with surface water, and the presence or absence of field indicators in shallow groundwater system (Winter et al. 1998, Winter 1999, Eamus and Froend 2006, and Hayashi and Rosenberry 2002, and Hancock et al. 2005).

Mapping the classification results is equally as important as tabulating results and selecting the mapping method for a study area depends upon the desired level of analysis, scale, spatial and temporal data coverage, and budgetary limitations (Payne and Woessner 2010). For the Lower Ruby Watershed, large scale maps were prepared showing aquifer classification results for the shallow and deep aquifer systems and included tabular summaries of the mapping units to summarize findings, similar to how geological maps are supported. Payne and Woessner (2010) describe the mapping approach and the importance of summarizing mapping results in tables. Generally, each aquifer is assigned a color or geologic pattern and dashed lines are used to divide aquifers into smaller units, if appropriate, with solid lines separating aquifer boundaries.

3.0 Results

Within the basin fill sediments of the project area, the groundwater system is comprised of numerous aquifers and areas where groundwater discharges to springs, sloughs, streams, and the Ruby River. Plates B1 and B2 in Appendix B show the aquifer classification results for the Ruby basin shallow and deep aquifer systems. Page two of the plates summarizes aquifer classification results for the valley and mountain bedrock aquifer systems. The mapping and classification separates the basin aquifers into bedrock, alluvial fan, undifferentiated Tertiary benches or fans, and fluvial valley aquifers. The surrounding bedrock aquifer is assumed to have an overall low flow potential, which covers the largest portion of the project area. Because of its size, the bedrock aquifer is also an important source of groundwater recharge into the basin fill sediments, although recharge from irrigation (and water storage) is the largest single source of recharge to the basin fill sediments (based on groundwater modeling and water budget analysis (Magruder and Payne 2008 and Magruder 2006)). While data from wells located on the fringe of the bedrock aquifer system suggest that bedrock is a low flow fracture controlled aquifer system, flow data from at least one large spring supports basin limestone aquifers, and also possibly other bedrock formations, may yield larger quantities of groundwater in isolated circumstances.

3.1 Shallow basin fill aquifer

The shallow basin fill sediments, while covering a smaller area compared to the bedrock aquifer system, are divided into four primary aquifer systems and ten sub-aquifers of varying configurations and productivity. Most aquifers in the project are moderate

production systems (Class B) capable of providing adequate water for individual households (e.g., less than 35 gallons per minute as defined by State of Montana Department of Natural Resources and Conservation Water Right Bureau) and larger flows for irrigation use if wells are properly sited and designed in areas such as the Sheridan Fan or Ruby floodplain aquifer (Appendix B).

The change in annual water table elevation is typically ten feet or less (Payne and Magruder 2004) and groundwater flow direction is from topographically higher areas towards or parallel to the Ruby River floodplain. Depth to groundwater is mostly proximal to very shallow (Table 1 and Payne and Woessner 2010) in the valley and deep in the mountainous area, greater than 100 feet. However, in the narrow stream valleys in the mountains depth to groundwater may be proximal, shallow, or very shallow (Table 1) based on field observations and vegetation surveys using techniques by Vereiskii and Vostokova (1966). Without monitoring wells or synoptic flow data, depth to groundwater is not easily determined in the mountainous area and overall the depth to groundwater and flow direction is deep as inferred on the maps in Appendix B.

The mountain uplands serve as the primarily recharge areas with the valley bottoms as groundwater discharge areas and a detailed water balance for the basin fill sediments is described in Magruder and Payne (2008). In the downgradient portion of the valley, the Ruby River fluvial aquifer is noted for having significant groundwater discharge into the Ruby River where groundwater plays a significant role in sustaining the fishery and aquatic life in the Ruby River and sloughs (Payne and Magruder 2004, and Magruder and

Payne 2008). As an example, the natural and irrigation groundwater return flows in the lower end of the valley sustains Leonard Slough (Plate B1 and Figure 14) and other groundwater fed sloughs that are critical for sustaining flow in the Ruby River during periods of low flow in the late summer, providing primary spawning habitat for brown trout in the fall since the natural tributaries have fish passage issues or they are completely dewatered. Moderate to significant groundwater return flows are noted along the Ruby River floodplain aquifer, although conditions can reverse creating a complex relationship between groundwater and surface water. Other irrigation return flows are noted on the Sheridan Bench, Tobacco Root Fan, and West Bench aquifers as mapped in Appendix B.

Groundwater is generally good to excellent quality for most beneficial purposes (Type 1) and calcium bicarbonate type chemistry with isolated areas of magnesium sulfate chemistry in the lower reaches of the valley. Also, there are some areas with elevated nitrate concentrations identified in domestic water supplies (Figure 8 and Appendix B).

3.2 Deep basin fill aquifer

The second aquifer delineation map in Appendix B (Plate B2) shows the deep aquifer system. The deep system is mapped as undifferentiated tertiary sediments, underlying the alluvial fan and fluvial deposits of the shallow aquifer system. This aquifer system also has shallow groundwater producing units that are mapped on the shallow aquifer delineation map where these sediments are exposed on the valley margins. There is very little data to characterize the Tertiary sediments at depth as compared to the shallow

aquifer and much less is known about the deep system because most water supply needs are met by developing shallow groundwater. A few irrigation and municipal supply wells have penetrated the deep aquifer system and provide limited information useful to model the deep sediments and classify aquifers.

Geologically the undifferentiated tertiary sediment are composed of unconsolidated to semi-consolidated volcanic deposits, alluvial deposits, debris flow, and other units (Ruppel et al. 1993) and it is hundreds to several thousand feet thick. Overall, the valley bottom has relatively thick alluvial basin fill sediments and near the center of the valley the sediments are estimated to range from 1,500 to 3,000 feet thick based on aerial gravity data (Payne and Magruder 2004).

Deep aquifer productivity is generally low to moderate and the aquifer system is capable of producing relatively large flows from supply wells, even though hydraulic conductivity is generally low. High production rates are possible because the sediments are laterally extensive and hundreds of feet thick, providing adequate transmissivity for moderate to high well yields. However, because of the geologic variability in the deep sediments, any production well completed in the deep aquifer system must be carefully designed to exploit production zones and produce large flows. On the valley sides, the Tertiary sediments are thinner and therefore considered low productivity because the sediments have lower transmissivity (Appendix B).

The change in annual water table elevation is typically ten feet or less (Payne and Magruder 2004), although there is poor data coverage to assess water level change across the entire aquifer system, and groundwater flow direction is from topographically higher areas towards to the Ruby River floodplain. Depth to groundwater is deep (Table 1 and Payne and Woessner 2010), however, confined conditions as well as wells tapping the deep groundwater system can result in the potentiometric head rising above water producing units from artisan pressure. In addition, some areas of very shallow to proximal depth groundwater are mapped on the valley margin on the shallow aquifer system map for undifferentiated Tertiary sediments. The same bedrock aquifer system connects with the deep basin aquifer system as described above for the shallow basin fill aquifer and the mountain uplands serve as the primarily recharge areas with the valley basin fill sediments as groundwater discharge areas. A detailed water balance for the basin fill sediments is described in Magruder and Payne (2008) and modeling results describe the relationship between deep and shallow groundwater exchange. Lastly, water quality is overall good for most purposes in the deep aquifer (Type 1) and is calcium bicarbonate type water chemistry, similar to the shallow aquifers.

3.3 Unique aquifer classification features

Unique groundwater features of the Ruby Valley noted during the aquifer classification effort include Silver Springs located on the northeastern flank of the Ruby Mountains, which based on work by Payne and Magruder (2004), is believed to be groundwater discharge from local limestone formations associated with the Ruby Mountains. The spring flows about 15,000 gallons per minute or 20 cubic feet second into the Ruby River

(Figure 9). Upturned karst formations of the Madison Group are likely recharged by loosing streams and precipitation within the Ruby Mountain Range, which geologically concentrate flow to this location (Figure 15).

Important features of the study area also include the surface water irrigation system and its impact on ground cover. Water stored in Ruby reservoir during the non-irrigation season is routed along the edges of the basin fill sediments in the spring, summer, and early fall irrigation season. The water is applied to grass and alfalfa fields as well as normal runoff water from the Ruby River and tributaries. Inefficiencies associated with the complex irrigation system raise the groundwater table and result in a much moister ecosystem than what would naturally be present in the valley, such as what is currently observed in the upper Ruby Valley where no stored irrigation water use is applied. The result is the formation of wetlands and riparian plant communities that normally would be dominated by sage brush and other semi-arid vegetation. The wetlands and riparian communities provide habitat for wildlife that otherwise would be absent, providing a challenging water management issue for natural resource planners.

Another special feature in the project area includes placer workings in Alder Gulch where historically dredges removed the entire stream valley bottom in search of gold. The impact of the placer mining was complete obliteration of the original stream channel, shallow geology, and loss of nearly all fines and organic soils. The result is several miles of mine spoils comprised of rounded cobbles and boulders. The placer deposits block the original stream channel in many places and because the fines are removed, groundwater

moves in and out of the placer spoils creating a complex back and forth exchange of groundwater and surface water along the impacted reach.

4.0 Discussion

Aquifer delineation and classification maps for the Lower Ruby Valley Watershed provide a general overview of the watershed-scale deep and shallow groundwater conditions in the watershed. Sparse data coverage in the mountainous bedrock aquifer system yield Tier 1 level classification results in these areas, however Tier 3 level analysis is supported in the basin fill sediments based on data collected in groundwater studies and modeling completed by Payne and Magruder (2004), Magruder (2006), and Magruder and Payne (2008).

The classification results do not replace the field work, groundwater characterization, and groundwater/surface water modeling work for the Lower Ruby Valley Watershed.

Rather, the results provide a new visual approach to presenting watershed-scale planning information and outline general relationships between groundwater and surface water in the watershed. This approach to basin scale groundwater classification is partly formulated on the observations that watershed managers and land use planners without groundwater expertise often find it challenging to understand and sort through pertinent groundwater information that would prove useful for planning, conservation, and management of natural resources. The classification maps and summary tables are designed to meet this need by summarizing vital information in detailed groundwater studies. The classification results can be used as stand alone work products to aid

planners and watershed managers in understanding complex groundwater conditions, depending on the planning needs, or as supplements to existing groundwater reports. Conceptually, this is similar to how geologic maps are developed and used to support planning, development, and conservation projects. If more detailed information is needed to support planning or conservation work, the detailed studies are reviewed.

In addition to helping planners and watershed managers, the graphical and tabulated results are designed to provide groundwater professionals a standardized approach for comparing watershed-scale groundwater conditions. For example, groundwater production potential can be compared using the Class A through C classification framework from one aquifer to another in the Lower Ruby Watershed or anywhere aquifer classification results are available. The classification system is designed to assist groundwater professionals spatially summarize complex groundwater conditions and communicate general groundwater conditions associated with proposed developments, water resource supply assessments, environmental impact assessments, and the exchange between groundwater and surface water. Lastly, the classification and accompanying tabular and visualization tools are intended to allow groundwater professionals unfamiliar with local groundwater conditions quickly gain a basic understanding of the watershed groundwater conditions, identify data gaps, and identify past water resource studies.

GIS layers of groundwater classification results in the Lower Ruby Watershed provides a tool to aid end users by summarizing completed analyses and providing graphical displays useful to make generalizations regarding groundwater conditions. Further, the

use of GIS software was instrumental in delineating aquifer boundaries in the Ruby Watershed. The tabulated classification results can be included as attributes for each of the primary aquifers using ArcGIS 9.3 software and those who have a rudimentary understanding of viewing shapefiles can select aquifers to review tabulated summaries of classification results (e.g., the information shown on page 2 of the maps in Appendix B). Once mapped, the aquifer layers can be overlain with other natural resource layers, existing infrastructure, and proposed developments or new land uses, providing the end user with a powerful tool to integrate groundwater resource data into other natural resource planning efforts.

One key requirement for any classification system is that it must be reproducible by trained professionals. Results of the classification effort for this watershed were prepared by individuals with detailed knowledge of the local groundwater conditions as well as the classification methodology. The placement of arrows, for example, showing groundwater flow direction and aquifer properties is based on having a firm understanding of the local groundwater conditions and management issues facing local government officials and planners. Groundwater professionals classifying aquifers in watershed without this type of intimate project knowledge will be able to classify aquifer similarly as described in Payne et al. (2009), but there may be subtle differences in how the aquifers are mapped, how local planning issues are addressed, and how the groundwater conditions are summarized. The overall classification results should be similar as long as they are completed by trained groundwater professionals, the effort follows the method developed by Payne and Woessner (2010), and the same studies and reference materials are used.

From efficiency and applied standpoints, there is benefit by having trained groundwater professionals familiar with the local groundwater conditions leading the classification effort. Along these same lines there is a variable level of uncertainty in the classification results from attempting to summarize complex groundwater and surface water datasets on one map or from limited data coverage within watershed scale project areas. These limitations will give rise to potential differences in mapping, scale-dependent uncertainty, and for considering localized focused objectives, the classification maps should be used to highlight conditions that may require an in depth assessment or a detailed review of available data.

The mapping system and summary table provide useful information for general planning and groundwater discussions in the Ruby Valley. The results are specifically useful to the county planning department, local conservation groups and agencies and developers interested in development and conservation projects. In addition to local benefits, state government agencies, such as the MDRNC, also benefit from the aquifer classification maps and summary tables as well as the detailed groundwater analyses and reports. From an applied perspective, questions concerning the relationship of groundwater with other natural resources may not be obvious to end users and the classification results are designed to efficiently summarize groundwater conditions on two maps and two tables for deep and shallow aquifers, and provide a basis for which questions relevant to planning, management, or conservation efforts can be considered.

Lastly, in preparing the aquifer delineation maps for the Ruby Valley, the map scale, conservation issues, and end user were considered to decide what information was included on the maps and tables, balancing the needs of clarity, scale, and utility, similar to how different scale geologic maps are prepared. The amount of detail on the aquifer classification maps is purposely limited to ensure the maps are simple, yet informative, and the summary tables are brief to ensure they do not replace detailed studies but help lead the end user to them if necessary.

5.0 Conclusions

This case study describes the data collection and methods used to complete a Tier 1 through 3 level aquifer classification analyses in the Lower Ruby Valley watershed. The case study serves as an example for the technical scope of work, analysis, and type of data needed to classify groundwater conditions in an intermontane watershed. The Lower Ruby Valley aquifer classification results serve as a planning tool and mapping system for local watershed managers and land use planners in Ruby Watershed to broadly and consistently compare five primary aquifers and exchange between groundwater and surface water. The classification results include development of GIS shapefiles that delineate and tabulate aquifer classification results that are useful to merge with other GIS natural resource and infrastructure layers typically used to support planning and conservation efforts. While significant financial resources and time were invested to complete the Tier 3 study and aquifer classification maps, the detailed analysis coupled with the classification results are valuable baseline information and useful to support short and long term natural resource planning, stream management work, conservation of

aquatic resources, and supporting future comparison of groundwater conditions in the lower Ruby Valley watershed.

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Table 1. Summary of aquifer classification codes and descriptions* (adapted from Payne and Woessner 2010).

Geologic Framework (2)	Alluvium (A _x) Colluvium (C _x) Alluvial fan (A _{fx}), Fluvial plain meandering (F _{pm}) Fluvial plain braided (F _{pb}) Fluvial plain older terrace (F _{pt}) Volcanic unconsolidated (V _u) Glacial till (G _t) Glacial outwash (G _o) Glacial moraine (G _m) Lacustrian/Playa (L) Eolian (E _x) Debris flow / Landslide (D _{fx}) Bedrock (B _x) Undifferentiated (U _x)			
Flow Class Potential (3, 4)	(Class A) high flow potential (A-, A+, A++)	(Class B) intermediate flow potential (B-, B+)	(Class C) low flow potential (C-, C+)	(Class L _f) limited or no flow potential
Aquifer Capacity vs. Productivity (6)	(i) heavy <i>aquifer is at or near capacity</i>	(ii) moderate <i>significant increases in water use could impact capacity</i>	(iii) light <i>aquifer is far from capacity</i>	
Aquifer Size (6)	(a) small < 5km ²	(b) intermediate 5-25 km ²	(c) large >25 km ²	
Hydraulic Impact (7)	(I _{Am}) extreme artificial recharge	(I _A) moderate artificial recharge	(I _D) moderate dewatering	(I _{Dm}) extreme dewatering
General Water Quality (8)	(T1) Type 1	(T2) Type 2	(T3) Type 3	(T4) Type 4
Ion Chemistry (8)	(Ca, Na, Si, Mg, etc.) dominant cations		(HCO3, SO4, Cl, etc.) dominant anions	
Pollutants (9)	Fuel related contaminants (f) Metals (m) Nutrients (n) Pathogen / biological (p) PCB (pcb) Radiological (r) Semi-volatile organic compounds (sv) Volatile organic compounds (v) Other organic (xo) Other inorganic (xi) Other biological (xb)			
Vulnerability (10)	(H) high vulnerability	(M) moderate vulnerability	(L) low vulnerability	
Depth to groundwater (11)	(vs) very shallow <2m	(s) shallow 2 to <7m	(p) proximal 7 to <30m	(d) deep > 30m
Groundwater / Surface Water Exchange (12)	D (Groundwater discharges to surface water, % flow) (D1-100 or D25, D50, D75, D100)		R (Surface recharges to aquifer, % loss) (R1-100 or R25, R50, R75, R100)	
Level of Assessment (1)	Tier 1	Tier 2	Tier 3	

*Numeric classes, special conditions, and narrative descriptions and framework are described in Payne and Woessner (2010) in Tables 1 through 12. The appropriate table is indicated in the left column in parentheses.

Table 2. A three tier assessment hierarchy for aquifer classification.

Class	Description	Data Collection Summary	Data Quality Objective
Tier 1	Semi-Quantitative	Tier 1 assessments generally rely on available local, state, and federal data sources for groundwater classification. These assessments rely on limited new data as budgets allow and are aimed at generating large-scale aquifer classification mapping units.	Broad groundwater system analysis and aquifer classification. Results are useful for baseline analysis, limited planning, and data gap identification.
Tier 2	Quantitative	Tier 2 assessments are quantitative hydrogeologic assessments that require characterization of groundwater and surface water resources. Tier 2 assessments use existing data and new data from monitoring wells, aquifer tests, groundwater age dating, geophysical surveys, stream flow measurements, wetland surveys, and water quality monitoring, etc.	A detailed groundwater system analysis and aquifer classification that expands baseline data. Results are useful for planning needs and characterizing suspected groundwater issues or needs.
Tier 3	Quantitative Coupled with Predictive Modeling	Tier 3 assessments are quantitative assessments coupled with predictive modeling. Results can be used to address specific aquifer or watershed issues. These assessments use the datasets generated from Tier 1 and Tier 2 assessments and groundwater modeling approaches. Tier 3 level analysis is typically aimed at understanding complex watershed/groundwater relationships including groundwater quality, quantity, or interaction with surface water, and end products typically support groundwater management and protection.	Tier 2 objectives and development of a predictive tool useful for comprehensive planning.

Table 3. Datasets collected for the Tier 1 through 3 Assessments Lower Ruby Valley Groundwater Classification. The Tier 1 and 2 assessments were completed simultaneously in 2004. The Tier 3 assessment was completed in 2008.

Dataset	Tier 1	Tier 2	Tier 3	Comments
Compilation of existing data	Yes	Completed in Tier 1	Completed in Tier 1 and updated for Tier 3	Local, state, and federal databases and reports were gathered and reviewed for useful data
Aerial assessment	Yes	Completed in Tier 1	Completed in Tier 1 and updated for Tier 3	Recent to historic aerial photography was assessed
Water well inventory	Yes	Completed in Tier 1	Completed in Tier 1 and updated for Tier 3	Existing wells were used from state databases -- no new wells were drilled for the assessments
Well log, geologic, and geophysical analysis	Yes	Completed in Tier 1	Completed in Tier 1 and updated for Tier 3	Well logs from existing wells, information from geologic maps/reports, and aerial gravity data were assessed to characterize the geologic framework
Collect monitoring water level and depth to groundwater data	NA	Yes	Completed in Tier 2	80 wells were selected for seasonal water level monitoring with selected wells fitted with data loggers for continuous data
Collect aquifer productivity data	NA	Yes	Completed in Tier 2	Pumping and slugs tests were completed to characterize aquifer productivity
Collect Groundwater Quality Data	NA	Yes	Completed in Tier 2	Common ions, metals, and a suite of nutrients were analyzed seasonally to assess water quality
Measure river/stream flows, continuous stage, and staff gauges	NA	Yes	Completed in Tier 2 and expanded in Tier 3	Monthly, seasonal and synoptic surface water flow / stage was measured to prepare hydrographs

Dataset	Tier 1	Tier 2	Tier 3	Comments
Measure ditch/canal flows	NA	Yes	Completed in Tier 2 and expanded for Tier 3	Synoptic streams flows were collected to measure irrigation system delivery efficiency
Vegetation, hydric soils, and irrigation system mapping	NA	Yes	Completed in Tier 2	Wetland and riparian vegetation along with soils were mapped to identify shallow groundwater and cross referenced to irrigated field mapping
GIS mapping and spatial analysis	Yes	Completed in Tier 1	Completed in Tier 1 and updated for Tier 3	Multiple layers of natural resource GIS layers were used to map aquifers, geology, soils, depth to groundwater, vegetation, and other natural features and resources
Numerical groundwater flow and surface water interaction modeling	NA	NA	Yes	The numerical groundwater flow model completed for the Tier 3 assessment simulated transient groundwater flow and the interaction between groundwater and streams, rivers, and irrigation canals and ditches.

Notes: Not Assessed

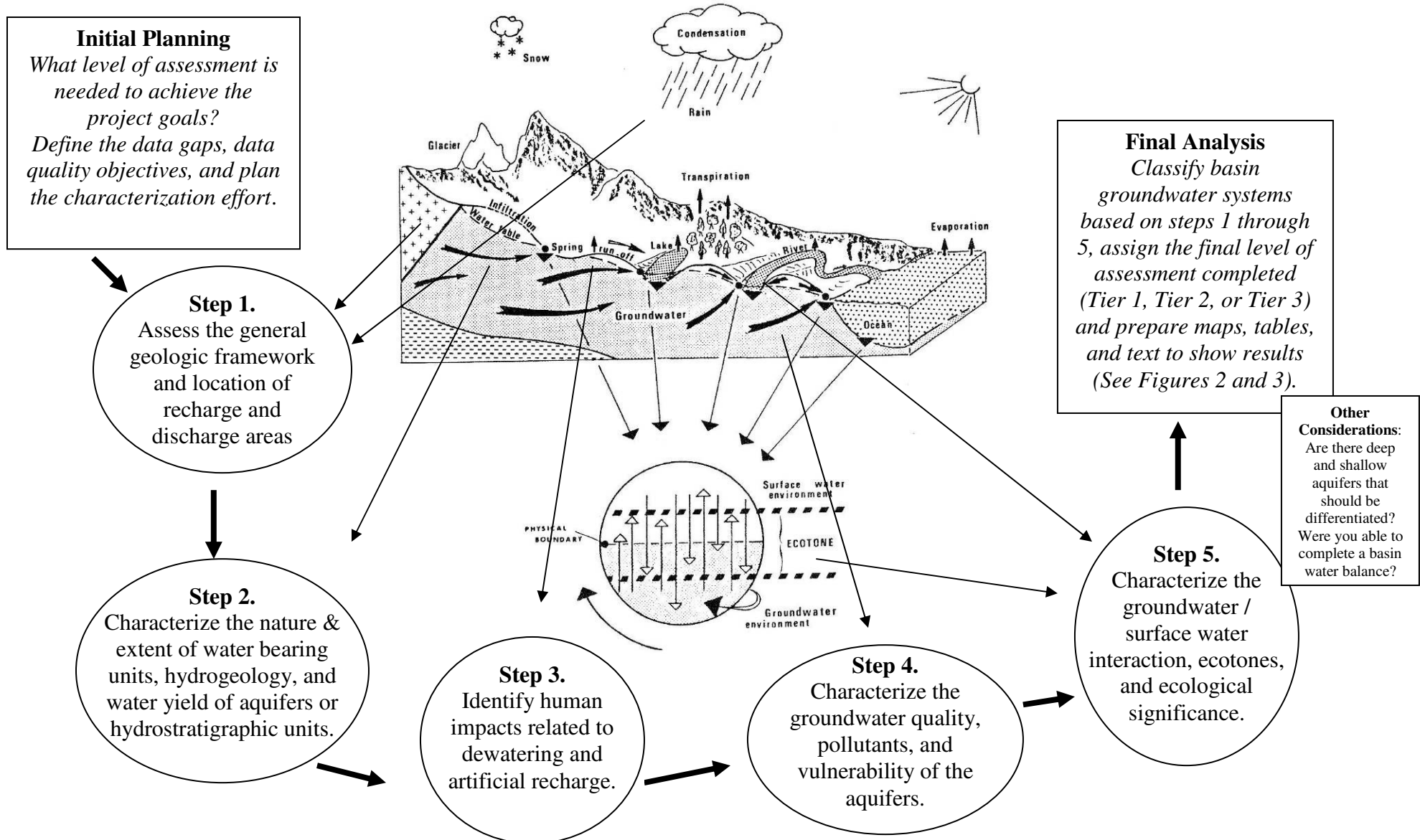


Figure 1. The basic components and steps proposed to classify basin groundwater systems and a diagrammatic explanation of groundwater/surface water ecotones in the mountain and plains landscapes (adapted from Gibert 1991). 113

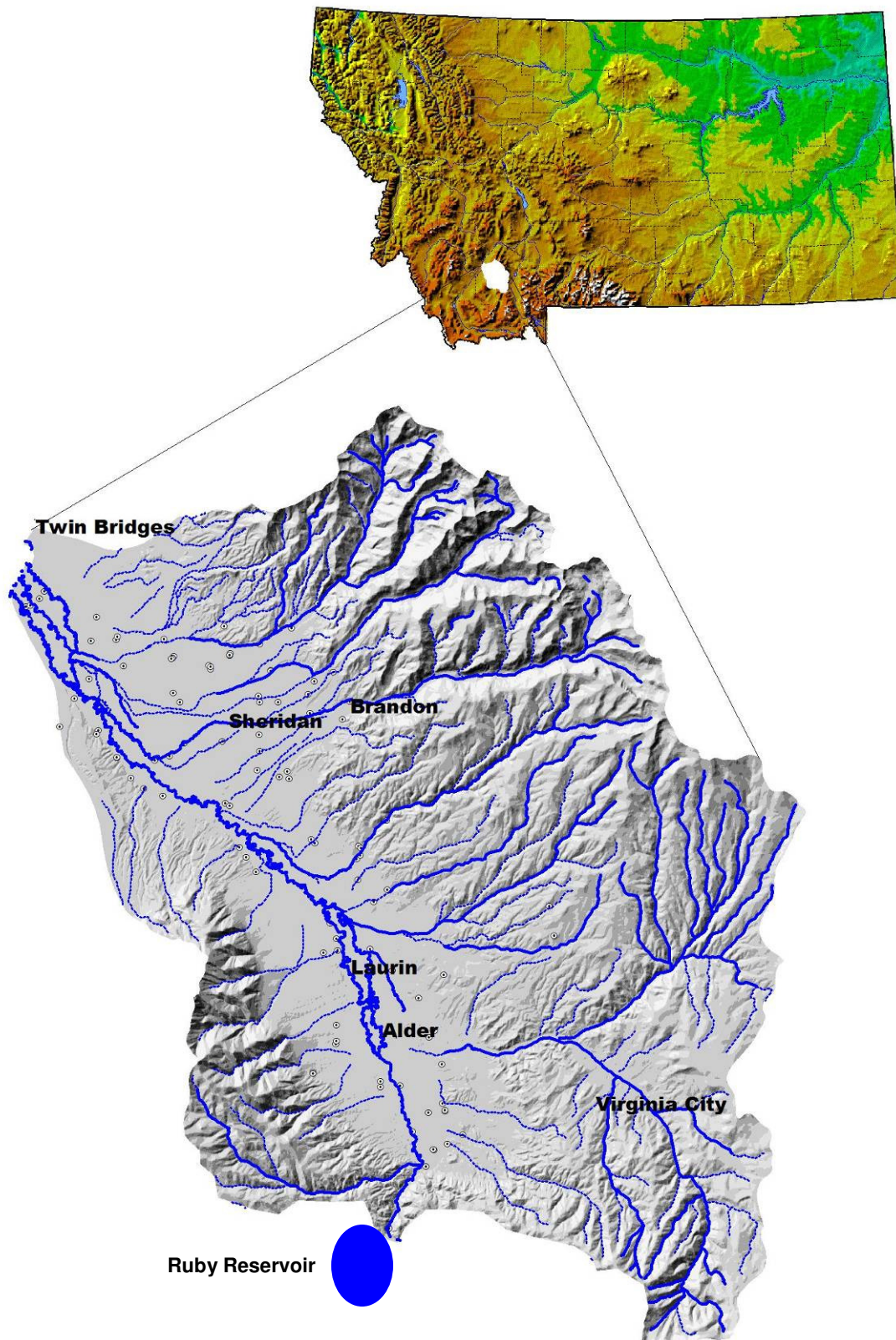


Figure 2. Location map for the Lower Ruby Valley study area.

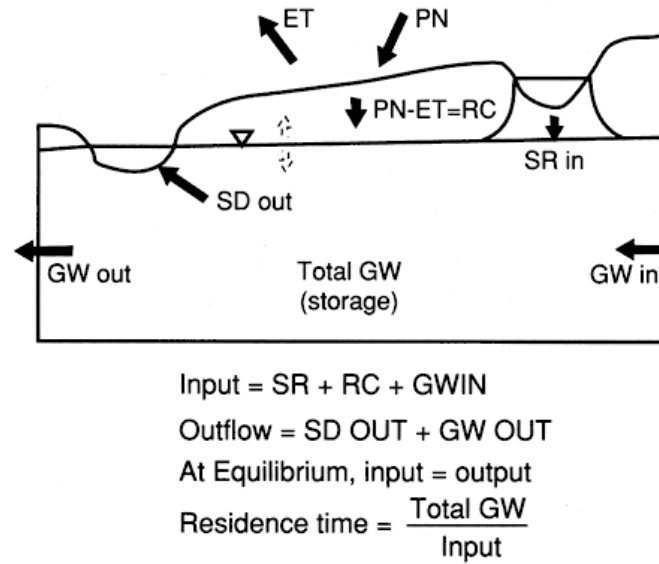


Figure 3. A large-scale schematic depiction of a basin scale groundwater budget. ET = evapotranspiration, PN = precipitation, RC = recharge, SR = stream recharge, SD = stream discharge, GW = ground water. Adapted from Kansas Geological Survey (2005).

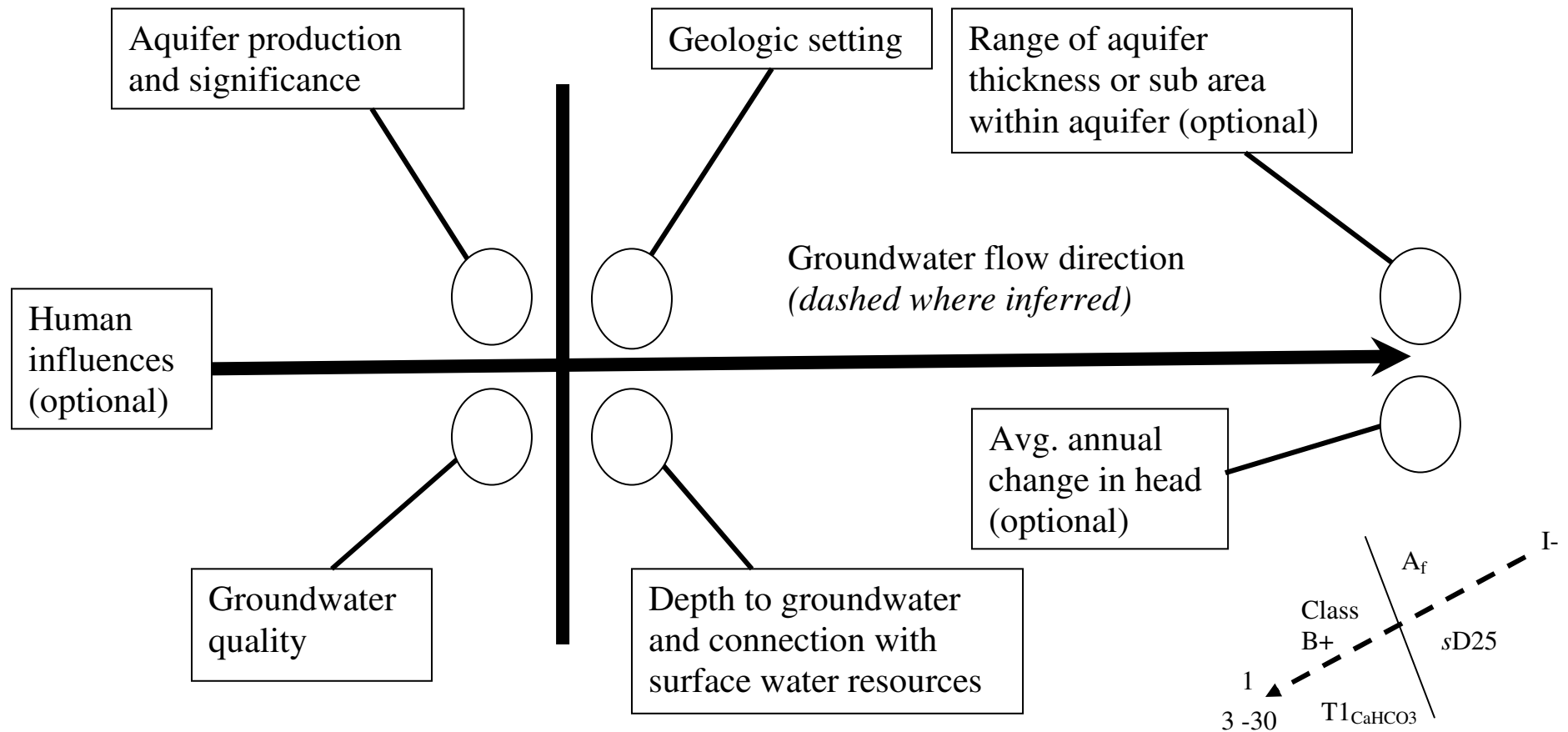
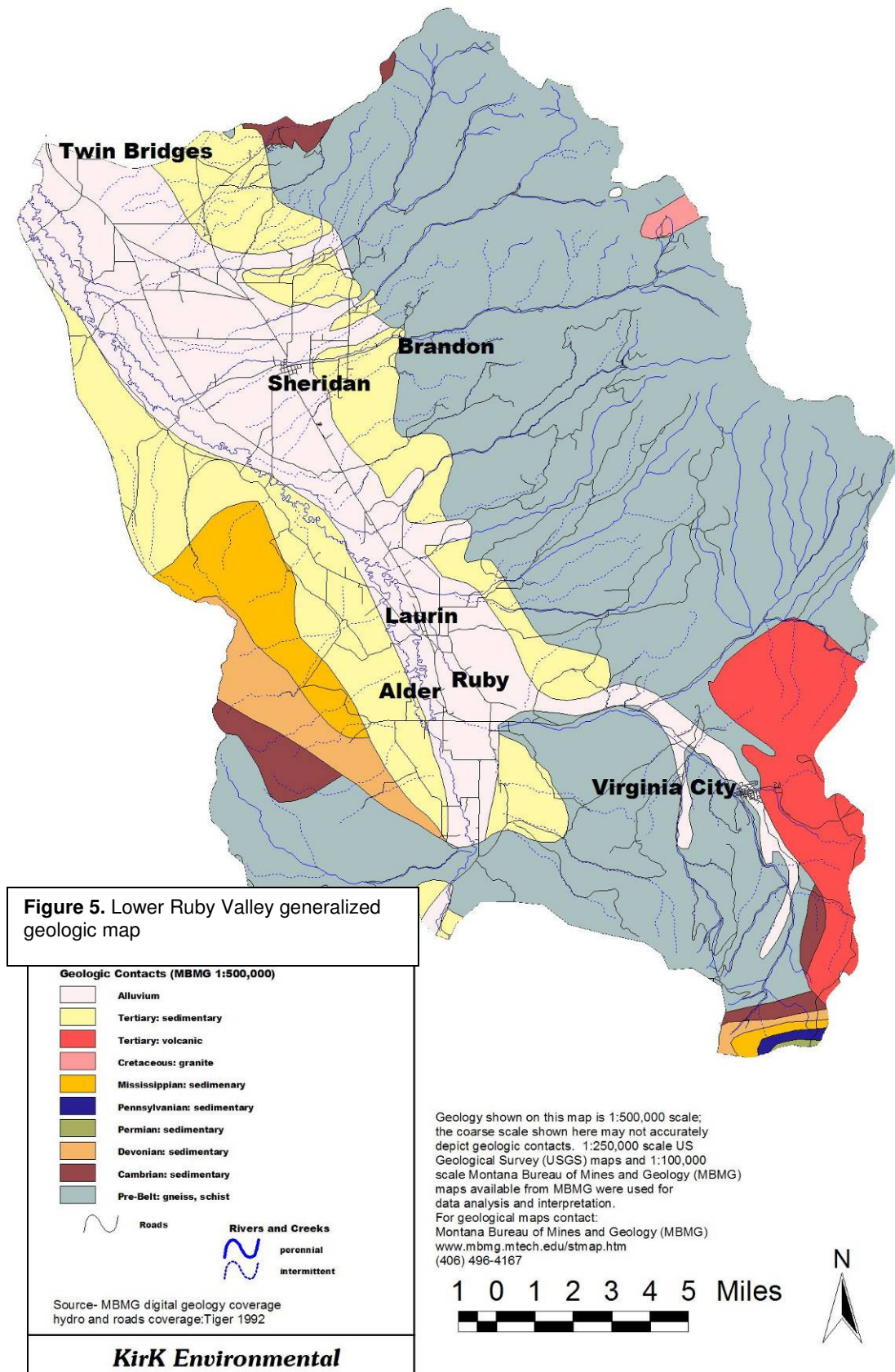


Figure 4. Aquifer classification mapping framework. The arrow and aquifer classification information is positioned on maps within aquifers or areas within aquifers. The arrow is rotated to indicate general groundwater flow direction in 360 degrees with aquifer production, geologic setting, groundwater quality and depth to groundwater positioned in the same general position as shown below, similar to how a north arrow rotates around a compass. Aquifer class should be positioned in the upper right quadrant (or left quadrant, depending on the arrow direction). An example for applying the aquifer classification arrow is shown in the lower right portion of the figure. All numbers are in meters.



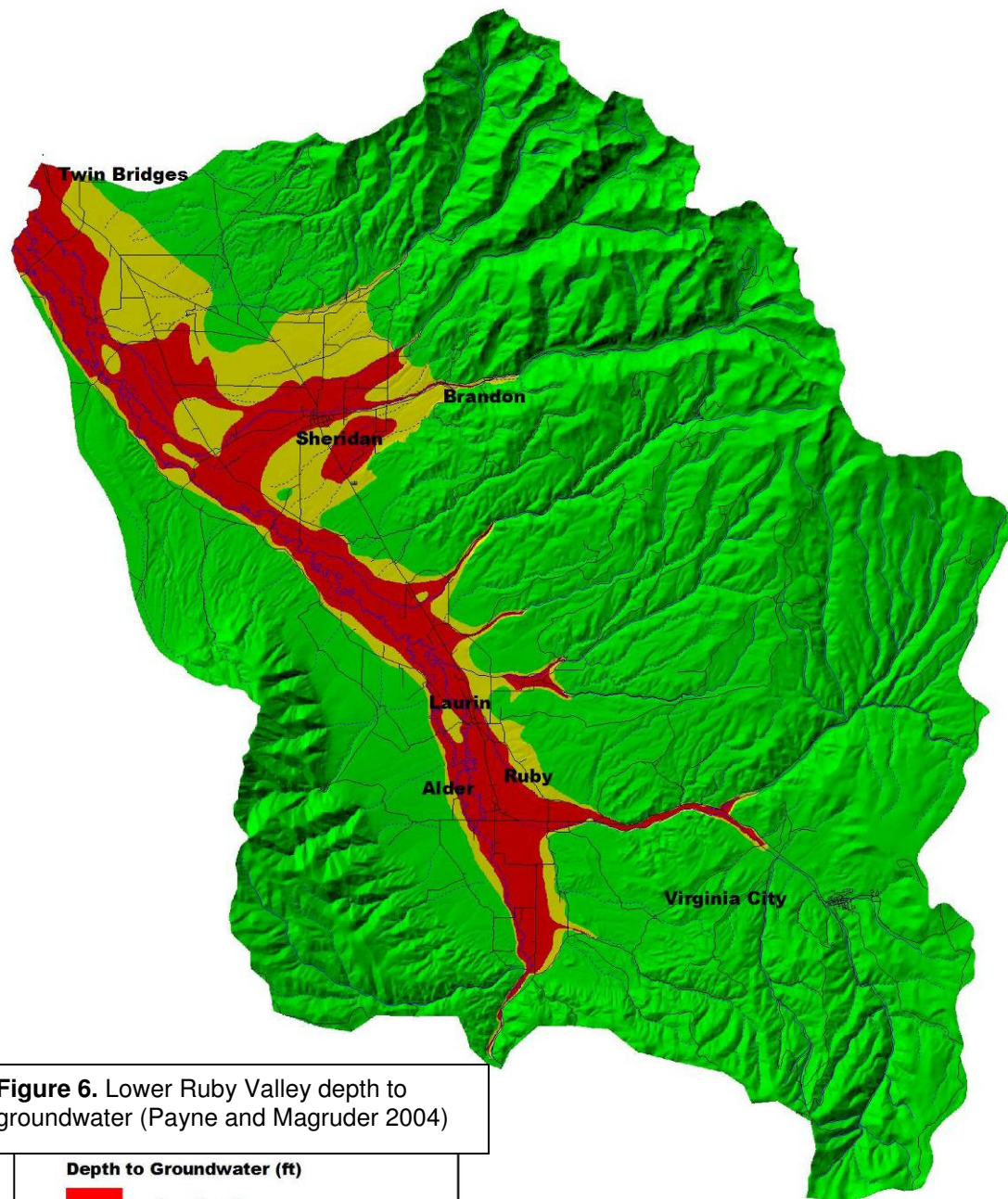
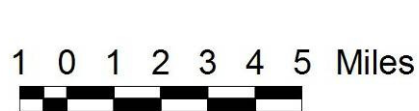
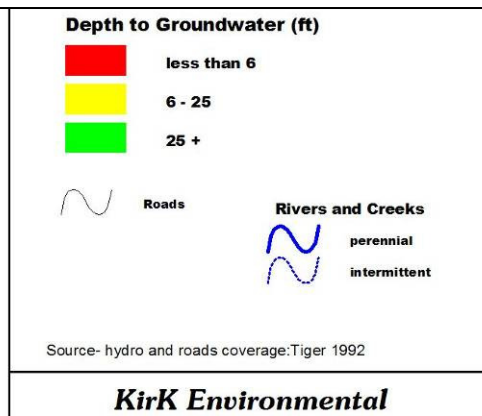
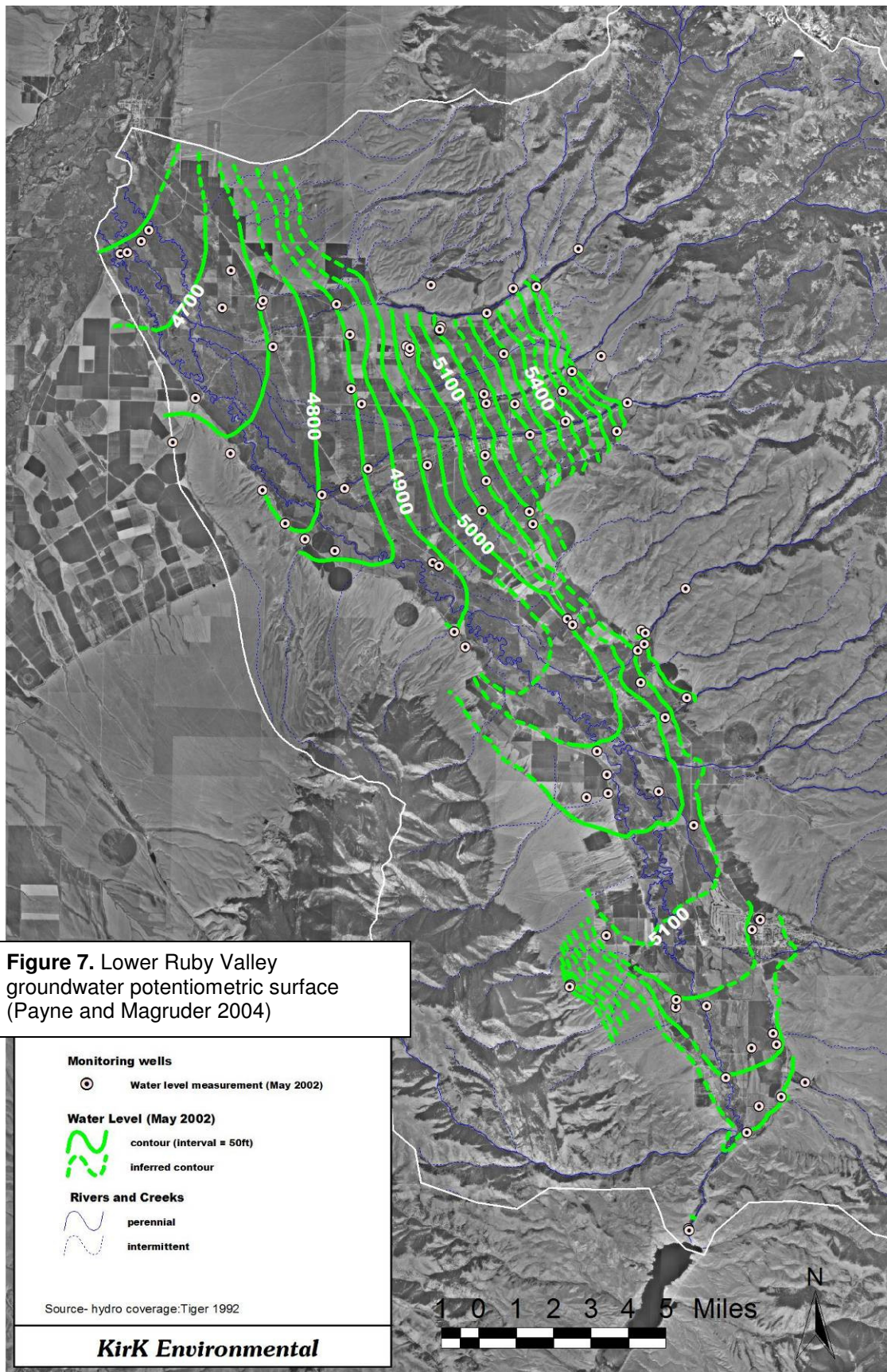
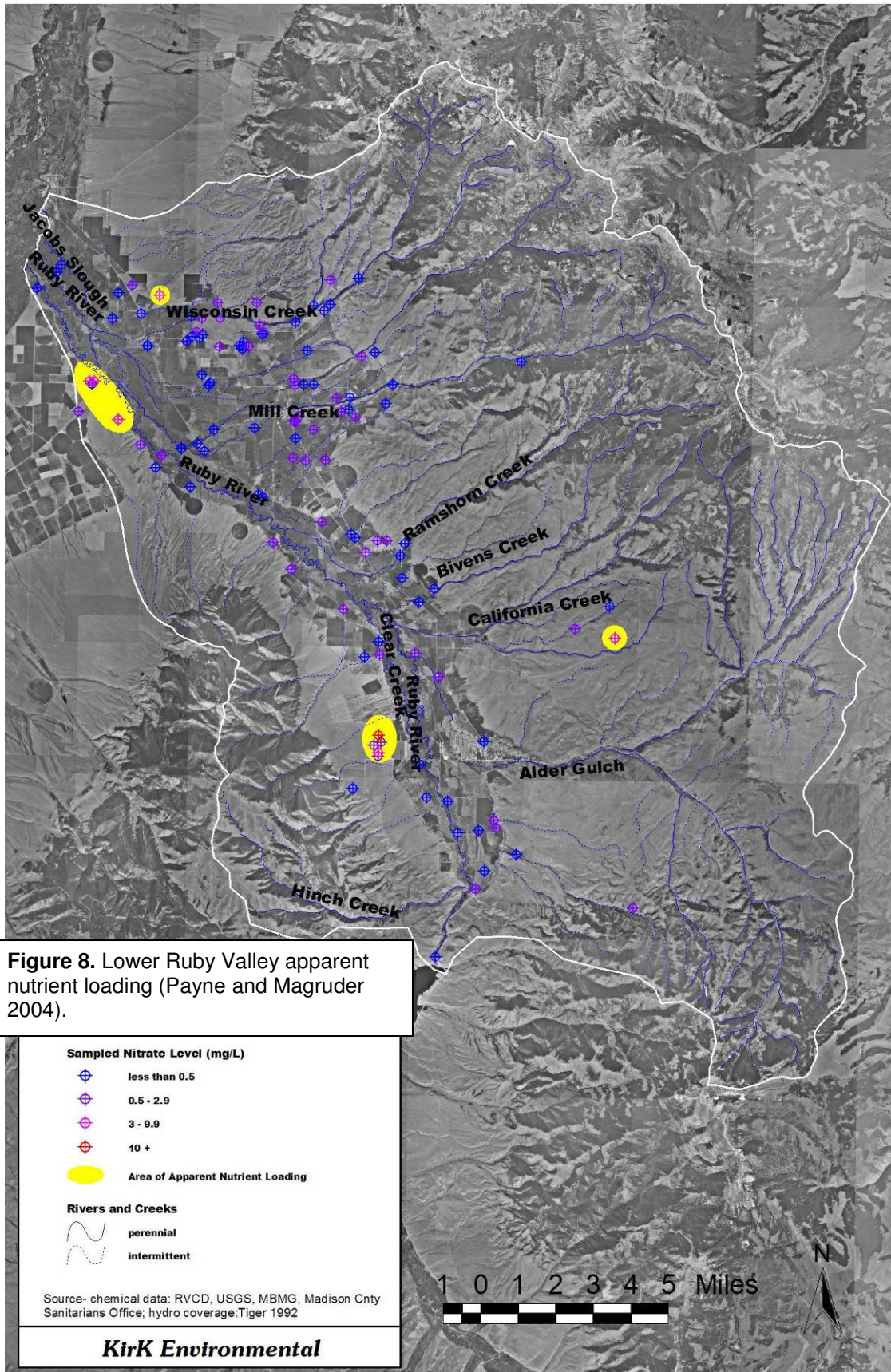
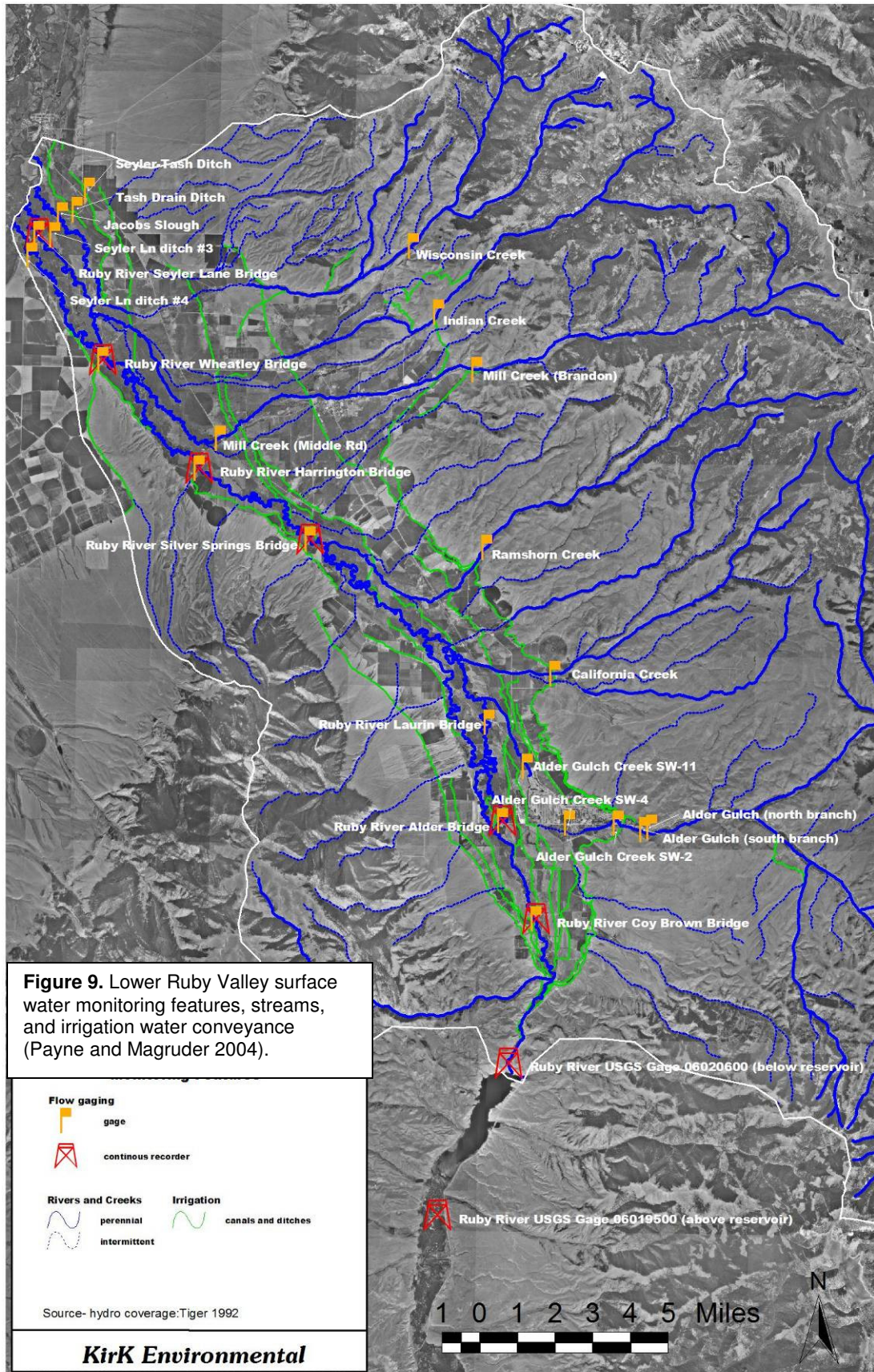


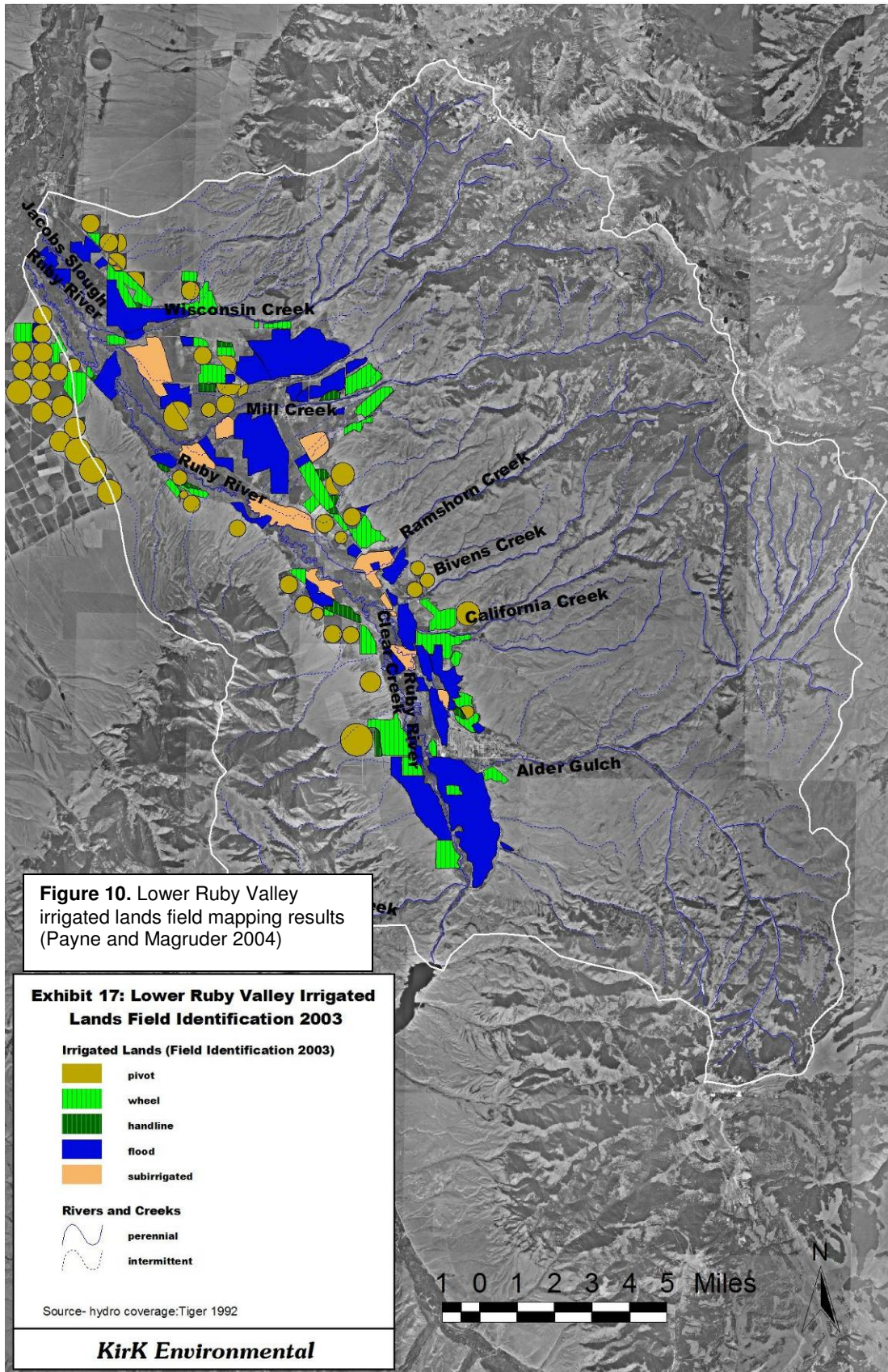
Figure 6. Lower Ruby Valley depth to groundwater (Payne and Magruder 2004)











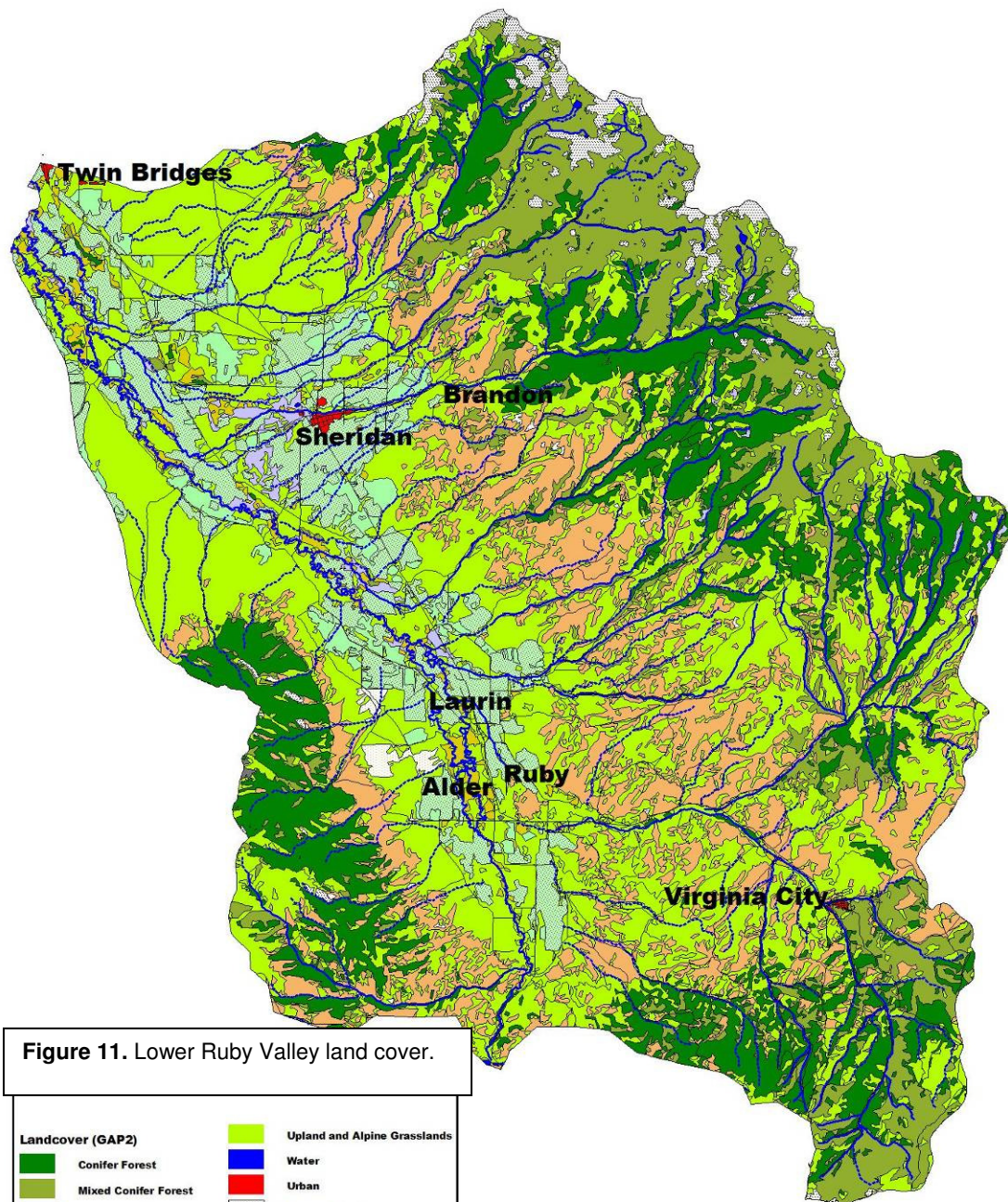
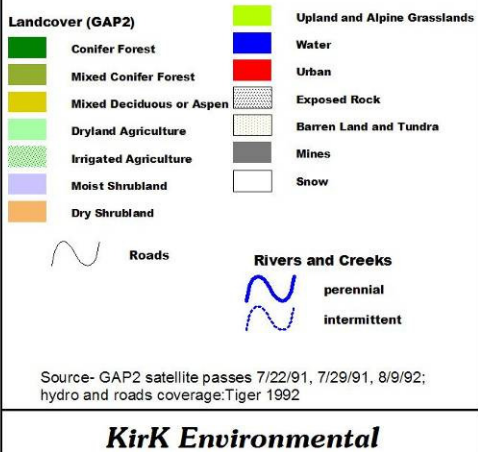


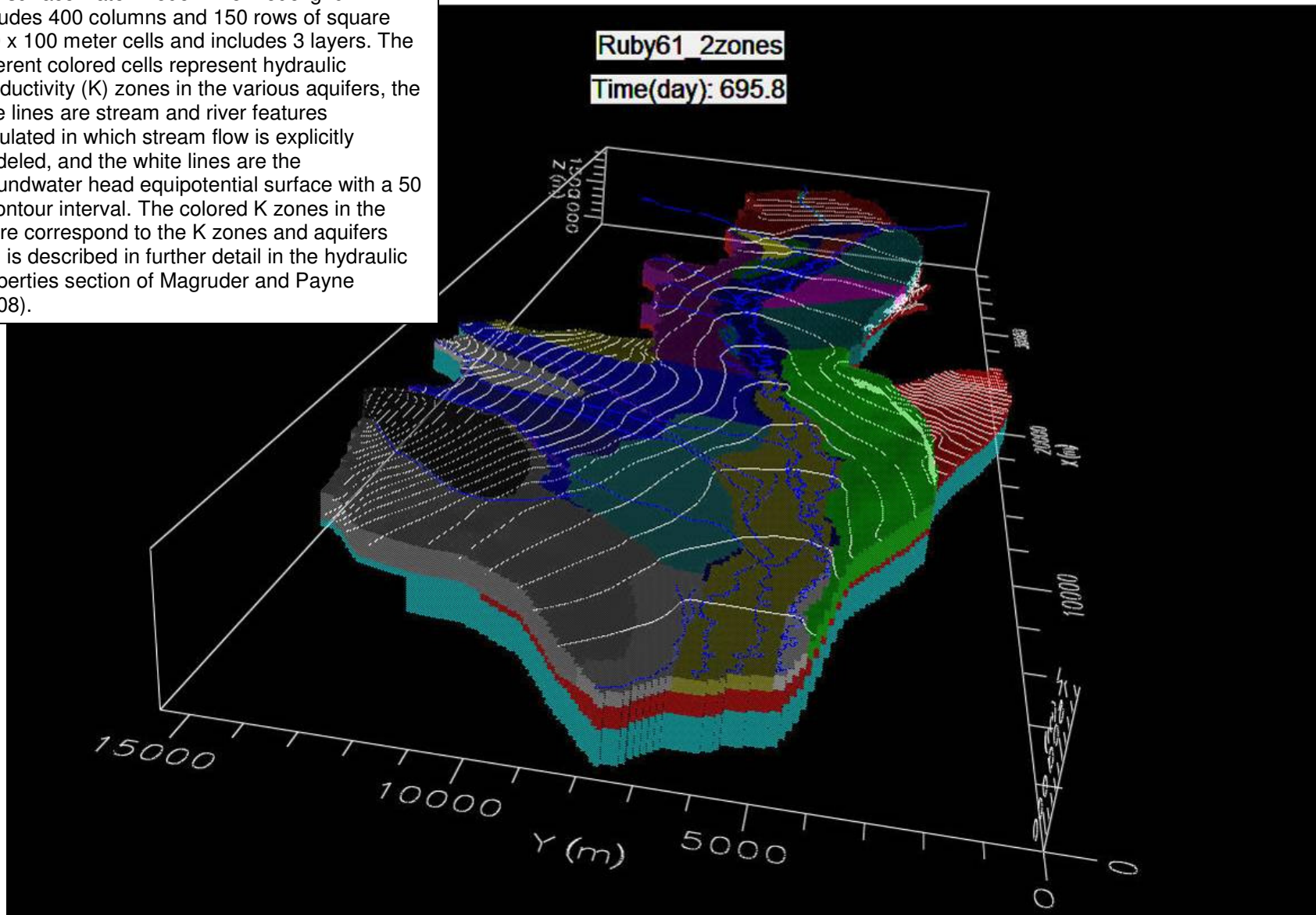
Figure 11. Lower Ruby Valley land cover.



1 0 1 2 3 4 5 Miles



Figure 12. The Lower Ruby Valley groundwater and surface water model. The model grid includes 400 columns and 150 rows of square 100 x 100 meter cells and includes 3 layers. The different colored cells represent hydraulic conductivity (K) zones in the various aquifers, the blue lines are stream and river features simulated in which stream flow is explicitly modeled, and the white lines are the groundwater head equipotential surface with a 50 ft contour interval. The colored K zones in the figure correspond to the K zones and aquifers and is described in further detail in the hydraulic properties section of Magruder and Payne (2008).



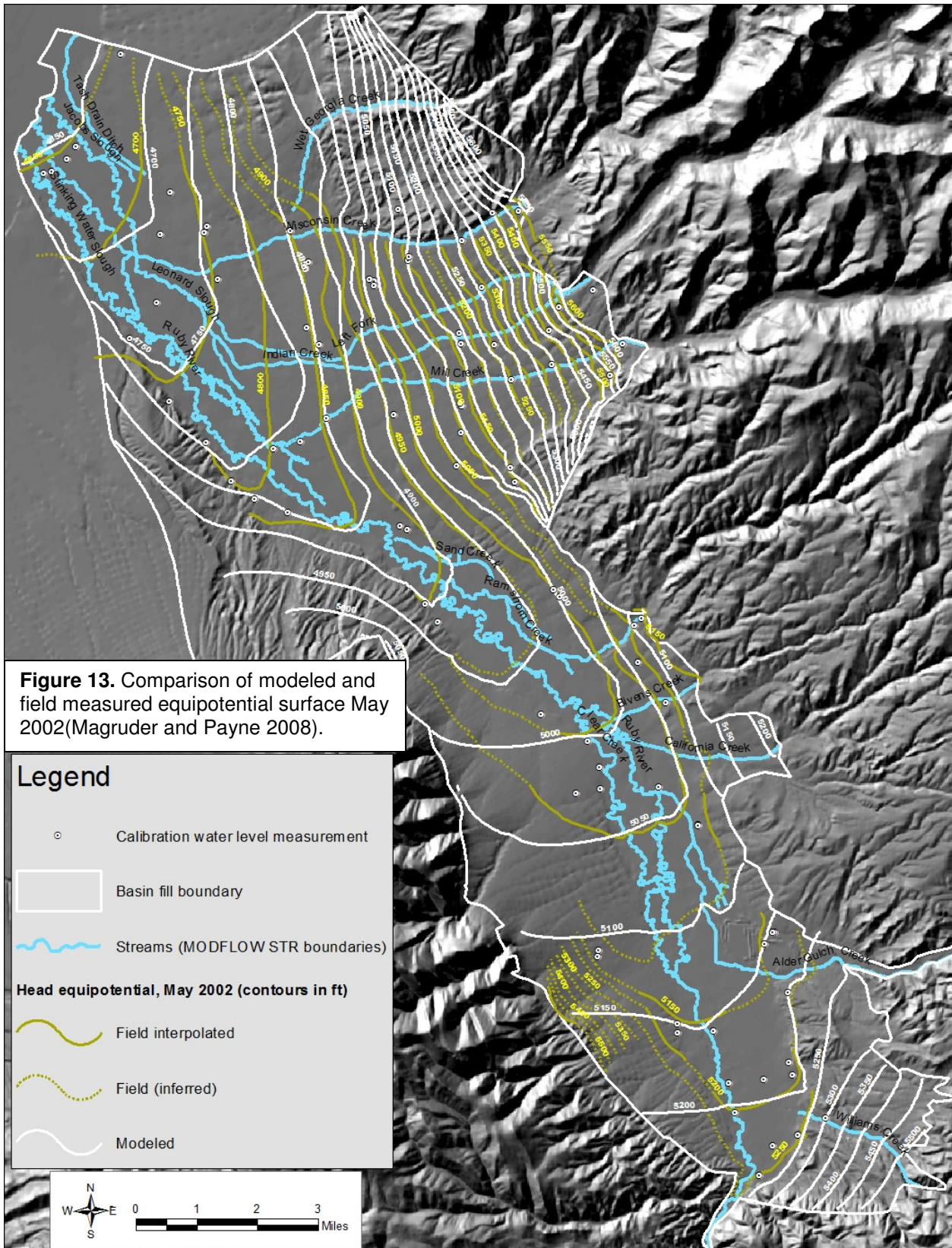




Figure 14. Flow in Leonard Slough is from groundwater discharge which recharges the Ruby River and provides important brown trout spawning water in the late summer and fall when the Ruby River and tributaries are flow limited (see Plate B1 for location).



Figure 15. Silver Springs flows about 15,000 gallons per minute or 20 cubic feet per second (see Plate B1 for location).

Appendix B

Supporting Information for Paper 2

(See plates B1 and B2)

**Application of an Aquifer Classification Methodology to Three Western
Watersheds: Case Studies of the Truckee Watershed, California; Paradise Valley,
Nevada; and the lower Boulder – Longmont Watershed, Colorado**

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Abstract

Three case studies are presented in this work to demonstrate a standardized method for classifying watershed-scale groundwater systems. The classification system uses geologic setting, groundwater flow direction, aquifer productivity, water quality, anthropogenic water level impacts, depth to groundwater, and exchange between groundwater and surface water as an organizational scheme. The case studies represent watersheds in the Basin and Range geologic province and the Rocky Mountain Foreland Basin of central Colorado. GIS is used to map groundwater conditions using a set of symbols. A new mapping approach is developed and the maps are accompanied by tabulated summaries of aquifer descriptions. The application of the classification system to the selected watersheds used data gathered from published reports and maps. The methodology organizes hydrogeologic data into formats that can be evaluated by hydrogeologists, watershed managers, and planners, and promotes the wider use of a standardized method for classifying aquifers.

Key Terms: Case study, hydrogeology, groundwater classification system, groundwater management, watersheds, watershed management, geographical information systems, rivers/streams, surface water/groundwater connection, and land use.

1.0 Introduction

The world faces water supply challenges and conserving diminishing water resources is amongst one of the most challenging water resource issues facing our society in terms of competition amongst agricultural, municipal, industrial, and ecological water users (Watson et al. 1998, Loáiciga 2000, Loáiciga et al. 2000, Field et al. 2007, and Kundzewicz et al. 2007). The organization of hydrogeologic data, accessibility, and ensuring it is understandable to scientists, resource managers and the public is challenging (Jury and Vaux 2005). Much of water management at the watershed scale has focused on surface water, with only passing attention given to groundwater systems (Yaffee et al. 1996). To this end, a standardized method to organize watershed scale groundwater data and support watershed and land use planning is needed (Carter et al. 2007 and Kendy 2003).

Payne and Woessner (2010) proposed an aquifer classification system for watersheds of the mountainous west that can be used to organize basin scale groundwater data, compare groundwater settings, and broadly characterize groundwater resources on a scale of 1:100,000 to 1:250,000. The methodology classifies and maps aquifer systems using the following main criteria: geologic setting, aquifer productivity, groundwater flow

direction, anthropogenic water level impacts, groundwater quality, depth to groundwater, and the degree of groundwater/surface water exchange (Figure 1).

Payne et al. (2010) provided an example application of the aquifer classification scheme for a case study in the lower Ruby Valley Watershed, Southwest Montana. In this paper, the proposed classification methodology is further tested by its application to three additional watersheds. Datasets were obtained from published reports, maps, electronic databases, and field observations obtained during field visits. Geographical Information System (GIS) software was used to digitally map aquifer classification results by overlaying existing studies and hydrogeologic data available as GIS shapefiles.

Classification maps and tabular summaries are presented to illustrate how hydrogeologic data derived from the literature (previous studies) and/or newly completed studies can be analyzed and presented. It is hoped that this paper will encourage a wider application of the proposed classification method and a recognition of its utility in providing end users with a standardized approach to aquifer classification.

1.1 Study Sites

The Truckee watershed of California Lake Tahoe Basin, Paradise Valley watershed of northwestern Nevada, and the lower Boulder – Longmont watershed of central Colorado are used to illustrate how the proposed classification system is applied to varied geologic and hydrogeologic settings in the western United States (Figure 2). The three watersheds were selected because groundwater and surface water resources are well characterized in published reports, datasets are accessible, and multiple GIS layers are available allowing

the digital mapping of aquifer characteristics. In addition, watershed scale natural resource management issues related to aquatic resources, preservation of groundwater supplies, and water quality are considered important in these regions.

2.0 Methodology

The aquifer classification methodology described by Payne and Woessner (2010) was initially applied in the lower Ruby Valley Watershed of southwest Montana (Payne et al. 2010). The lower Ruby Valley Watershed case study relied on literature values/data, collection of new data, and the development of a numerical groundwater flow model. The five steps in Figure 1 were completed and the shallow and deep aquifer systems in the project area were classified. The information available for this analyses ranked the classification a Tier 3 study (Table 1).

After conducting a literature review of several dozen basin scale (1:100,000 to 1:250,000) aquifer studies for locations throughout the western United States, three watersheds were chosen to illustrate and evaluate the application of the proposed aquifer classification system. The watersheds selected had to have sufficient data sets available so that a Tier 2 or 3 level classification could be completed (Table 1 and Payne and Woessner, 2010). Further, each watershed was chosen to represent different physiographic and geologic settings, and have a well defined project boundary and a common conservation or planning issue (rapid urban or rural development, groundwater supply or dewatering issues, or mandates to protect and conserve aquatic resources).

Based on these criteria, the Truckee watershed of California Lake Tahoe Basin, Paradise Valley watershed of northwestern Nevada, and the lower Boulder – Longmont watershed of central Colorado were selected for the application of the classification system. After selecting the study areas, a field visit of each project area was completed to assess the landscape and watershed conditions, map important surface features, observe possible surface indications of shallow groundwater and its potential to interact with surface water, conduct interviews with local groundwater experts, and develop a basic understanding of the project boundary for the preparation aquifer classification maps.

In each of these three study areas, only the upper basin fill groundwater system was targeted for classification both to simplify the analyses for publication and because the shallow systems typically have a higher level of hydrogeological characterization as compared to deeper aquifer systems. In addition, the shallow systems generally have higher potential for groundwater/surface exchange, are often used for water supply, and natural resource planning issues are commonly linked to shallow groundwater in these watersheds. The surrounding bedrock aquifers were also included in the aquifer classification analysis; however, in all cases the available groundwater data were sparse in the upland and bedrock settings (Figure 3). In valley upland and bedrock portions of the selected watersheds only a Tier 1 level aquifer classification approach was possible (Table 1).

GIS software (ESRI ArcGIS 9.3) was used to prepare aquifer delineation maps. Based maps were composed of multiple digital layers that supplied information on the geology,

topography, hydrography, hillshading/digital elevation distributions, soils, cities/towns, roads, and other layers as needed. Aerial photography was assessed and additional data sets incorporated into the GIS base map. The primary sources of the digital information used to map aquifers in the three watersheds are Saucedo (2005), Colton (2003), and Hess and Johnson (1996) with other less important sources of digital information available from USGS, state, or private digital data clearinghouses. The GIS layers, coupled with data gathered from recent literature and field inspections from the basis for the digitally mapping of the aquifer classification system.

The data sets for each basin were analyzed, organized then interpreted to classify the aquifer system using the identified geologic setting and origin, occurrence and flow directions of groundwater, aquifer productivity, groundwater quality, anthropogenic threats to water quality and water levels, depth to groundwater, and the degree of groundwater/surface water exchange in major surface water features (Payne and Woessner 2010). Table 2 summarizes the classification codes and descriptions developed by Payne and Woessner (2010) and Figure 1 shows the five steps completed to classify aquifers in the project areas.

Step one of the classification process focused on the geological framework analysis. It is used to identify potential hydrostratigraphic units and geologic conditions that affect groundwater occurrence, flow, and aquifer properties (Maxey 1964 and Domenico 1972). This process included gathering geologic reports and maps for the project areas (Crosby 1978, Hall et al. 1979, Hillier and Schneider 1979a and b, Prudic and Herman 1996,

Bruce and O'Riley 1997, Thodal 1997, and Rowe and Allender 2000). Once the geological framework was assessed, the second step identified aquifers and groundwater systems, aquifer boundaries, aquifer productivity, and groundwater flow direction. This involved developing a conceptual basin scale model of the individual basin hydrogeological systems including identifying aquifers, aquitards and groundwater system boundaries (Anderson and Woessner 1992).

As part of step two, aquifer productivity, flow direction, and characteristic hydraulic properties of the principal groundwater systems were characterized. This included gathering porosity (n), specific yield (S_y), storage coefficient (S), hydraulic conductivity (K), transmissivity (T), thickness of the aquifer (b), and aquifer cross-sectional areas (A) perpendicular to flow necessary to calculate groundwater flow (Q) for sites. In addition, aquifer size and relative aquifer capacity vs. productivity was assessed by mapping the aerial extent of aquifers and qualitatively comparing groundwater availability with groundwater use as described by Kreye et al (1998) and Berardinucci and Ronneseth (2002).

Step three assessed the degree of dewatering and artificial recharge occurring at each site to identify if aquifer system water levels are impacted by current water management practices. Basin groundwater quality was classified next based on specific conductance, the dominate cation-anion water chemistry, presence of pollutants, and aquifer vulnerability as part of step four. The final step focused on interpreting groundwater/surface water exchange related to major surface water features using depth

to groundwater, the slope of the ground surface compared to the water table, the direction and magnitude of local hydraulic vertical gradients (as known or interpreted), the relative amount of groundwater exchange with surface water based on synoptic stream flow data, and the presence or absence of field indicators of shallow groundwater system using techniques described by Payne and Woessner (2010) and the work of others (Vereiskii and Vostokova 1966, Winter et al. 1998, Winter 1999, Hayashi and Rosenberry 2002, Hancock et al. 2005, and Eamus and Froend 2006). Classification results for each watershed were tabulated, the level of assessment ranked, and then information was mapped. The mapping was used to summarize the project assessment data, and provide a visually appealing and concise way to represent spatial tabular data (Figure 4).

Large scale maps showing classification results and tabular summaries of mapped information, similar to how geological maps are prepared and supported, were formulated. Payne and Woessner (2010) describe the mapping approach and the importance of summarizing mapping results in tables as well as in cross sections. Generally, each aquifer is assigned a color or geologic pattern and dashed lines are used to divide aquifers into smaller groundwater units, if appropriate, with solid lines separating aquifer boundaries. The aquifer delineation maps (Appendix C) were created using ESRI ArcGIS 9.3 and multiple GIS layers are used to map aquifer boundaries by overlaying informational layers such as geology and well data, and then digitizing the aquifer boundaries based on GIS layers and field mapping.

3.0 Results

Results of aquifer classification in the Truckee, Paradise Valley, and the lower Boulder – Longmont watersheds are shown on Plates C1 through C3 in Appendix C. The maps delineate the upper aquifers in basin fill, upland, and bedrock aquifers. Also shown are the primary aquifer boundaries, general groundwater flow direction, general aquifer productivity, geologic setting, groundwater chemistry, depth to groundwater, and groundwater/surface water connection (where sufficient data are available). Tabulated results on page two of the maps provide a summary of aquifer classification results including descriptions of primary aquifers, complete classification results, unique groundwater conditions, and the level of aquifer assessment.

The three watersheds represent common settings in the western United States and each watershed has local anthropogenic stresses. The Truckee watershed is located on the western flank of the basin and range geologic province (USGS 2004a) in a valley within the Sierra Nevada Mountains. The uplands of the watershed are mostly granitic bedrock that was heavily glaciated and much of the basin fill sediments are deposits of glacial till and outwash. The project area has an urban corridor associated with the community of South Lake Tahoe as well as rural and roadless lands in the mountainous headwaters. There are significant natural resource management issues concerning surface water and groundwater because the watershed is a headwaters for Lake Tahoe, an exceptionally important natural lake and a premier location for skiing, vacationing, and second home ownership. Water resource issues include the protection of streams, rivers, and Lake Tahoe water quality, groundwater supplies for municipal use, mitigating impacts from

rapid development, and conservation of sensitive lands and ecological resources (Thodal 1997 and US Army Corps of Engineers 2003). Hydrogeologic and hydrology assessments by Rowe and Allender (2000) and Thodal (1997) provide excellent data sources of hydrological data. Additional data were provided by Bonham and Burnett (1976), Trexler and Bell (1979), U.S. Army Corps of Engineers Hydraulic Engineering Center (2003), and Saucedo (2005).

To illustrate the utility of classification results for this watershed, consider the South Lake Tahoe portion of the map where commercial use and residential development is moderate to high within the municipality and all groundwater is classified as flowing towards and discharging into Lake Tahoe (Plate C1). A Tier 3 level assessment was completed and the aquifers in this area include the artificial fill, lacustrine deposits, and fluvial plain. Up gradient groundwater, which also includes land with significant commercial and residential development, is funneled to this area as shown by the groundwater mapping symbols. The water table is mapped as shallow to very shallow with intermediate aquifer productivity near the lake. The classification results are useful to illustrate the vulnerability of the shallow aquifer, which in turn could impact Lake Tahoe if contaminated. From a watershed conservation planning perspective, natural resource managers could use the classification maps to evaluate proposed land use, assess development proposals, and improve planning targeted at mitigating future impacts to groundwater and surface water quality.

Paradise Valley is located in the basin and range geologic province (USGS 2004a) of northern Nevada which is bounded by lithologically complex bedrock mountains and has thick deposit of alluvial basin sediments filling the basin. The climate in the valley is semi-arid and dry conditions require crop irrigation, which is supplied by surface water and groundwater resources. One small town, Paradise, is located in the north end of the rural setting with a population of about 300 people. There are unique natural characteristics including a playa lake and sand dunes at the south end of the valley.

Alluvial deposits up to 8,000 feet thick are found in the center of the valley (Prudic and Herman 1996). These sediments are attributed to fluvial deposits of the Little Humboldt River and alluvial fan deposits emanating from the Osgood and surrounding mountain ranges. The basin fill sediments form a productive aquifer system capable of yielding moderate to large quantities of water that supply agricultural irrigation wells. Generally speaking, groundwater can be routinely pumped from irrigation wells in the valley at rates that exceed aquifer recharge. To this end, groundwater pumping over several decades has resulted in significant dewatering issues in the valley. Groundwater flow modeling by Prudic and Herman (1996), and reports by Loeltz et al. (1963), and Willden (1963) and Harrill and Moore (1970) provided excellent sources of data and analyses used to classify the watershed aquifers.

To illustrate the utility of classification results in this watershed, consider the southwest portion of the Paradise Valley, west of the playa lake, where the mapping symbols show groundwater flow. The classification captures the presence of a cone of depression that is present (Plate C2). In this area, the Tier 3 classification results identify a major

groundwater dewatering issue. This is an example of a major dewatering impact associated with long-term irrigation water pumping from groundwater. The classification system shows groundwater in this area is routinely pumped at rates exceeding aquifer recharge. The classification results help to spatially identify where hydraulic impacts in the Paradise Valley are located and provide a visual representation of the water management issues landowners face if they currently use groundwater or plan to develop new groundwater supplies in the Paradise Valley.

The lower Boulder – Longmont Watershed, Colorado project area is located on the west flank of the Rocky Mountain Foreland Basin and extends west into the Rocky Mountains (USGS 2004b). The upper watershed is mostly mountainous crystalline bedrock with sparse groundwater data except in developed stream valleys. The lower watershed is composed of thin layers of alluvial sediments, tens of feet thick, deposited in the fluvial valley bottoms and on broad pediment uplands composed of relatively impervious sedimentary rocks. The lower watershed has excellent groundwater data coverage primarily because it is a well studied urban corridor with multiple municipalities, industry, rural development, and significant agricultural land use. Crosby (1978), Hall et al. (1979), Hillier and Schneider (1979a and b), and Bruce and O’Riley (1997) prepared comprehensive reports and maps useful to classify aquifers and characterize groundwater conditions in the project area. Demand for water in this area (e.g., surface water from Boulder Creek, St. Vrain Creek, and groundwater from the fluvial system aquifers) is a longstanding issue as well as rapid land development (Murphy 2006). The fluvial aquifer system is hydraulically connected to the two major creeks in the project area and water is

diverted in numerous places for competing water uses. There are also multiple surface water discharges from municipal waste water treatment plants into the area creeks. Groundwater and surface water quality are a major concern in this project area and there are localized groundwater quality impacts associated with elevated common ion chemistry (sulfate, iron, etc), trace metals, bacteria, and radiochemical constituents (Hall et al. 1980). The scale of contamination is broad yet impacts are detected sporadically across the entire mapped area. To this end, these water quality impacts are not shown on the aquifer classification map (Plate C3) because the spatial variability reported by Hall et al. (1980) would require a much smaller scale map and multiple maps to map pollutants using this classification system.

To illustrate the utility of the classification system mapping in this watershed, consider the central portion of the map in the upland pediment complex, where the aquifer system is mapped as limited flow (L_f) in the area next to the mountain front. In this area, the shallow sediments are very thin and while they are saturated with groundwater, they are so thin they do not provide a reliable source of groundwater for domestic use and therefore are classified as a non-aquifer in terms of productivity. Further east, the upland pediment complex sediments are thicker and groundwater can be developed for water supplies. In addition, the fluvial plain and terrace aquifer systems in the area north and south area are classified as moderate to high productivity. These aquifer systems are identified as more likely to yield greater quantities of groundwater compared to the upland pediment complex. The classification results are useful to quickly compare aquifer productivity ranges, and while the overall range of productivity varies because of

the scale and generalization of data, the results (for example) are useful for developers and land use planners to evaluate potential groundwater supply issues in areas mapped as limited flow. The classification results are not intended to support all decision making concerning aquifer productivity without review of supporting information, however, the classification results provide a visual representation of common conditions useful to identify potential aquifer yield and reference more detailed or site specific data if needed.

4.0 Discussion

The maps in Appendix C provide a general overview of the watershed-scale groundwater and aquifer conditions of the three project areas. Each map was prepared relatively quickly, requiring about six to eight days of time to prepare, not including travel for site visits and interviews. The aquifer classification maps and tabular data were developed as stand-alone summaries that are supported by detailed studies and useful to broadly characterize groundwater conditions in the three watersheds. Deep groundwater conditions were not assessed because classification of deep groundwater conditions would have proved challenging for two of the three project areas due to a lack of data. The exception is Paradise Valley where three dimensional groundwater flow modeling (Prudic and Herman 1996) provides a conceptual model and framework for classifying deep groundwater conditions.

The classification results have advantages and limitation when used to describe conditions for each watershed. As an example, consider Paradise Valley where the available reports describing groundwater conditions are technical documents and for the

lay person would prove challenging, in most cases, to understand from an applied perspective or without expert help. In this case, the classification results provide a more general summary of the groundwater conditions including groundwater flow direction, locating water level declines, general water quality, groundwater/surface water exchange sites and magnitudes, and basic information describing the geologic setting.

In the Tahoe basin, many of the available reports and publications provide a fairly easy to read format for describing groundwater flow direction and surface water/groundwater exchange, thus, the classification results do not provide a significant advantage over the supporting literature for some aspects of watershed planning. However, productivity data for the aquifer systems is not clearly described for the lay person in available literature. The classification results are viewed as providing a useful summary of productivity, depth to groundwater, and groundwater quality.

In the Boulder-Longmont area, the available detailed maps and reports used to complete the classification maps describe the shallow groundwater system and to some degree the surface water system. While the classification results provide a useful summary for interpretation of groundwater/surface water exchange locations and magnitudes, the existing maps and reports outline data for the groundwater system quite well. However, individual maps must be reviewed at various scales, which is time consuming and the results are not consolidated. The classification mapping provides a single work product for assessment and interpretation.

The classification methodology enhances the availability and interpretation of watershed scale groundwater information for the three project areas. The classification results bring together the various reports and findings for the three watersheds under a common mapping and table format allowing for the comparison of basin systems. As stand-alone work products, the classification maps are similar to geologic maps where the mapped aquifers and classification results are used to show existing conditions and help scientists and managers assess the impact or benefit of existing and proposed natural resource management decisions. The classification results do not replace site-specific groundwater studies and comprehensive assessments, but the method does bring forth a common language for which aquifer production, basic groundwater resource conditions, and the degree of exchange between groundwater and surface can be discussed using consistent terms. Groundwater and natural resource studies for each of the project areas should be consulted to understand focused objectives and review data that cannot be included on the aquifer classification maps.

The mapping results can be reviewed in hard copy, such as the plates in Appendix C, or as downloadable GIS layers. As GIS layers, aquifers can be mapped across large regions and routinely compared using the same basic classification criteria. The use of GIS software was instrumental in delineating aquifer boundaries and layers. Once mapped, the aquifer layers can be overlain with other natural resource layers (e.g., soil, hydrography, geology, groundwater contamination plumes, etc), existing infrastructure (e.g., roads, cities, sewer lines, fuel pipelines, water supply lines, irrigation land use, water supply wells, etc.), and proposed developments or new land uses (e.g.,

subdivisions, irrigation projects, gravel operations, dams, etc.). The ability to overlay GIS layers including aquifer classifications provides the end user with a powerful tool to integrate groundwater resource data into natural resource planning efforts. Currently, this is a challenging task because available GIS layers may not provide standard groundwater resource mapping information. In addition, most digital groundwater data are derived from accessing point files associated with wells, which is useful information for some purposes, but for planning exercises on a landscape scale, aquifer characteristics generally have to be summarized and mapped aerially by groundwater professionals in order to be used by others for planning. The methodology demonstrated here provides an approach to consistently map and compile point data (which should be included as a GIS layer for mapping) and develop aquifer delineation maps by applying GIS software that expands point file data into landscape interpretations of groundwater conditions.

It is recommended that the amount of detail on the aquifer classification maps should be purposely limited to ensure the maps are simple and informative. Summary tables should be kept brief to ensure they do not attempt to replace a detailed hydrological report.

Additional groundwater information could be included in the classification system to more fully represent localized conditions as appropriate. Examples include adding groundwater pollution data for the Boulder-Longmont area or more detailed groundwater/surface water exchange information for all three watersheds. This information was not included on the maps because more detail would have made the maps difficult to read, but it could be included if a larger scale map is developed. The groundwater professional preparing the aquifer delineation map must consider the map

scale and end user when deciding what information is included on the final product. The approach utilized needs to balance the needs for clarity, scale, and utility, which is similar to how different scale geologic maps are prepared.

5.0 Conclusions

This case study describes a methodology to classify aquifers and an approach to consistently compare groundwater databases and studies at the watershed scale. For many watersheds groundwater data are described in a variety of published reports, maps, and databases, each of which has unique information, interpretations, level of assessments, and reporting styles. The application of the proposed groundwater classification methodology is designed to visually present and summarize groundwater data at the watershed scale for evaluation efficiently. The methodology is designed to be completed with a relatively small investment of time using available hydrogeologic data. An experienced hydrogeologist should be able to develop draft classification results within one to two weeks of reviewing existing data. Further, the classification results serve as a planning tool and mapping system for watershed managers and land use planners to broadly and consistently compare groundwater systems in watershed settings. The case studies utilize a GIS shapefile approach that easily merges with other GIS natural resource and infrastructure layer datasets. Further, the classification results synthesize various reports and findings for the three case study watersheds and provides a method to compare groundwater conditions. Through ongoing research and application of the method to other watershed settings, the system can be expanded and hopefully further benefit those responsible watershed scale groundwater and resource management.

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Table 1. A three tier assessment hierarchy for aquifer classification.

Class	Description	Data Collection Summary	Data Quality Objective
Tier 1	Semi-Quantitative	Tier 1 assessments generally rely on available local, state, and federal data sources for groundwater classification. These assessments rely on limited new data as budgets allow and are aimed at generating large-scale aquifer classification mapping units.	Broad groundwater system analysis and aquifer classification. Results are useful for baseline analysis, limited planning, and data gap identification.
Tier 2	Quantitative	Tier 2 assessments are quantitative hydrogeologic assessments that require characterization of groundwater and surface water resources. Tier 2 assessments use existing data and new data from monitoring wells, aquifer tests, groundwater age dating, geophysical surveys, stream flow measurements, wetland surveys, and water quality monitoring, etc.	A detailed groundwater system analysis and aquifer classification that expands baseline data. Results are useful for planning needs and characterizing suspected groundwater issues or needs.
Tier 3	Quantitative Coupled with Predictive Modeling	Tier 3 assessments are quantitative assessments coupled with predictive modeling. Results can be used to address specific aquifer or watershed issues. These assessments use the data sets generated from Tier 1 and Tier 2 assessments and groundwater modeling approaches. Tier 3 level analysis is typically aimed at understanding complex watershed/groundwater relationships including groundwater quality, quantity, or interaction with surface water, and end products typically support groundwater management and protection.	Tier 2 objectives and development of a predictive tool useful for comprehensive planning.

Table 2. Summary of aquifer classification codes and descriptions (adapted from Payne and Woessner 2010). Numeric classes, special conditions, and narrative descriptions and framework are described in Payne and Woessner (2010) in Tables 1 through 12. The appropriate table is indicated in the left column in parentheses.

Geologic Framework (2)	Alluvium (A _x) Colluvium (C _x) Alluvial fan (A _{fx}) Fluvial plain meandering (F _{pm}) Fluvial plain braided (F _{pb}) Fluvial plain older terrace (F _{pt}) Volcanic unconsolidated (V _u) Glacial till (G _t) Glacial outwash (G _o) Glacial moraine (G _m) Lacustrine/Playa (L) Eolian (E _x) Debris flow / Landslide (D _{fx}) Bedrock (B _x) Undifferentiated (U _x)			
Flow Class Potential (3, 4)	(Class A) high flow potential (A-, A+, A++)	(Class B) intermediate flow potential (B-, B+)	(Class C) low flow potential (C-, C+)	(Class L _f) limited or no flow potential
Aquifer Capacity vs. Productivity (6)	(i) heavy <i>aquifer is at or near capacity</i>	(ii) moderate <i>significant increases in water use could impact capacity</i>	(iii) light <i>aquifer is far from capacity</i>	
Aquifer Size (6)	(a) small < 5km ²	(b) intermediate 5-25 km ²	(c) large >25 km ²	
Hydraulic Impact (7)	(I _{Am}) extreme artificial recharge	(I _A) moderate artificial recharge	(I _D) moderate dewatering	(I _{Dm}) extreme dewatering
General Water Quality (8)	(T1) Type 1	(T2) Type 2	(T3) Type 3	(T4) Type 4
Ion Chemistry (8)	(Ca, Na, Si, Mg, etc.) dominant cations		(HCO ₃ , SO ₄ , Cl, etc.) dominant anions	
Pollutants (9)	Fuel related contaminants (f) Metals (m) Nutrients (n) Pathogen / biological (p) PCB (pcb) Radiological (r) Semi-volatile organic compounds (sv) Volatile organic compounds (v) Other organic (xo) Other inorganic (xi) Other biological (xb)			
Vulnerability (10)	(H) high vulnerability	(M) moderate vulnerability	(L) low vulnerability	
Depth to groundwater (11)	(vs) very shallow <2m	(s) shallow 2 to <7m	(p) proximal 7 to <30m	(d) deep > 30m
Groundwater / Surface Water Exchange (12)	D (Groundwater discharges to surface water, % flow) (D1-100 or D25, D50, D75, D100)		R (Surface recharges to aquifer, % loss) (R1-100 or R25, R50, R75, R100)	
Level of Assessment (1)	Tier 1	Tier 2	Tier 3	

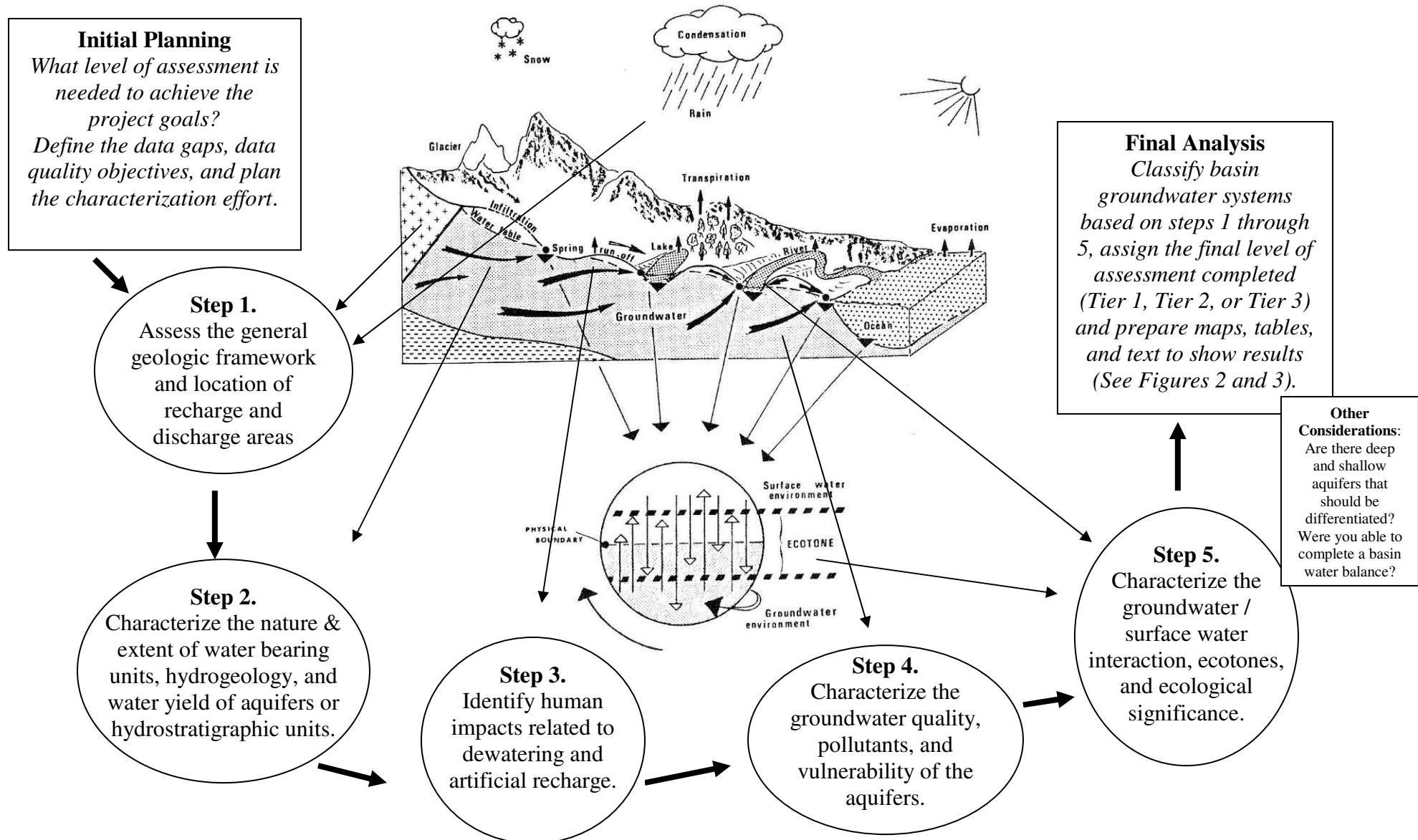
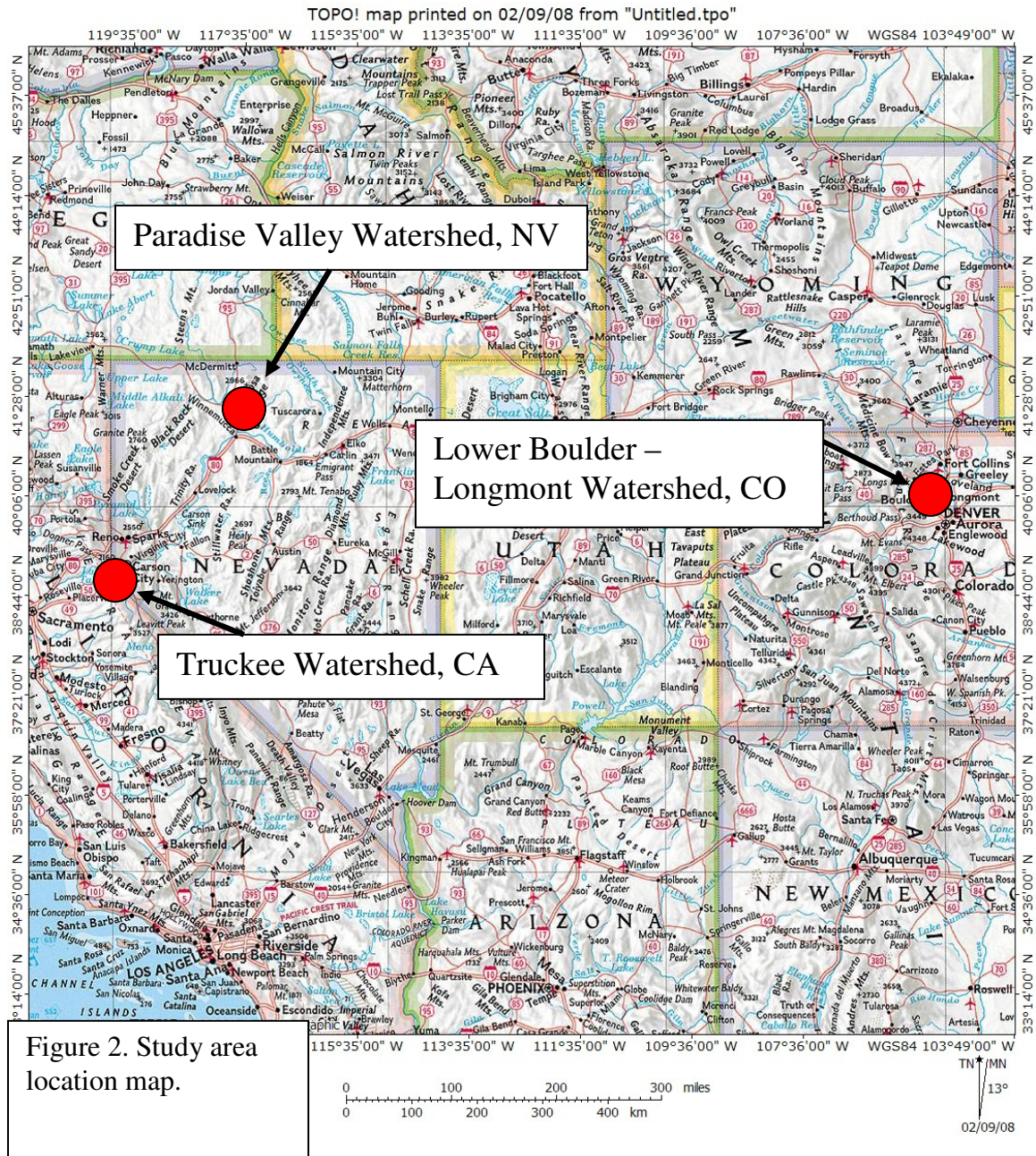
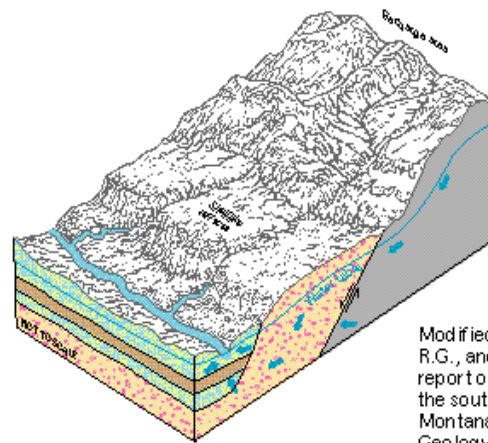


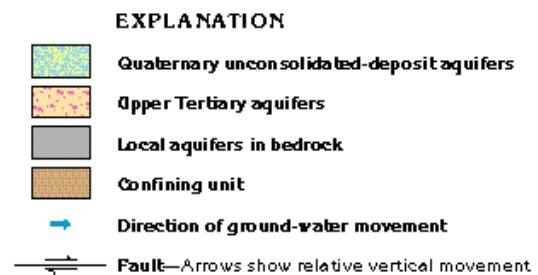
Figure 1. The basic components and steps proposed to classify basin groundwater systems and a diagrammatic explanation of groundwater/surface water ecotones in the mountain and plains landscapes (adapted from Gibert 1991). 154





Modified from Konizeski, R.L., McMurtrey, R.G., and Brietkrietz, Alex, 1962, Preliminary report on the geology and water resources of the southern part of the Deer Lodge Valley, Montana: Montana Bureau of Mines and Geology Bulletin 31, 24 p.

Figure 3. Geologic conceptualization of a western valley watershed with basin fill sediments in the valley, deep and shallow aquifers, and bedrock uplands.



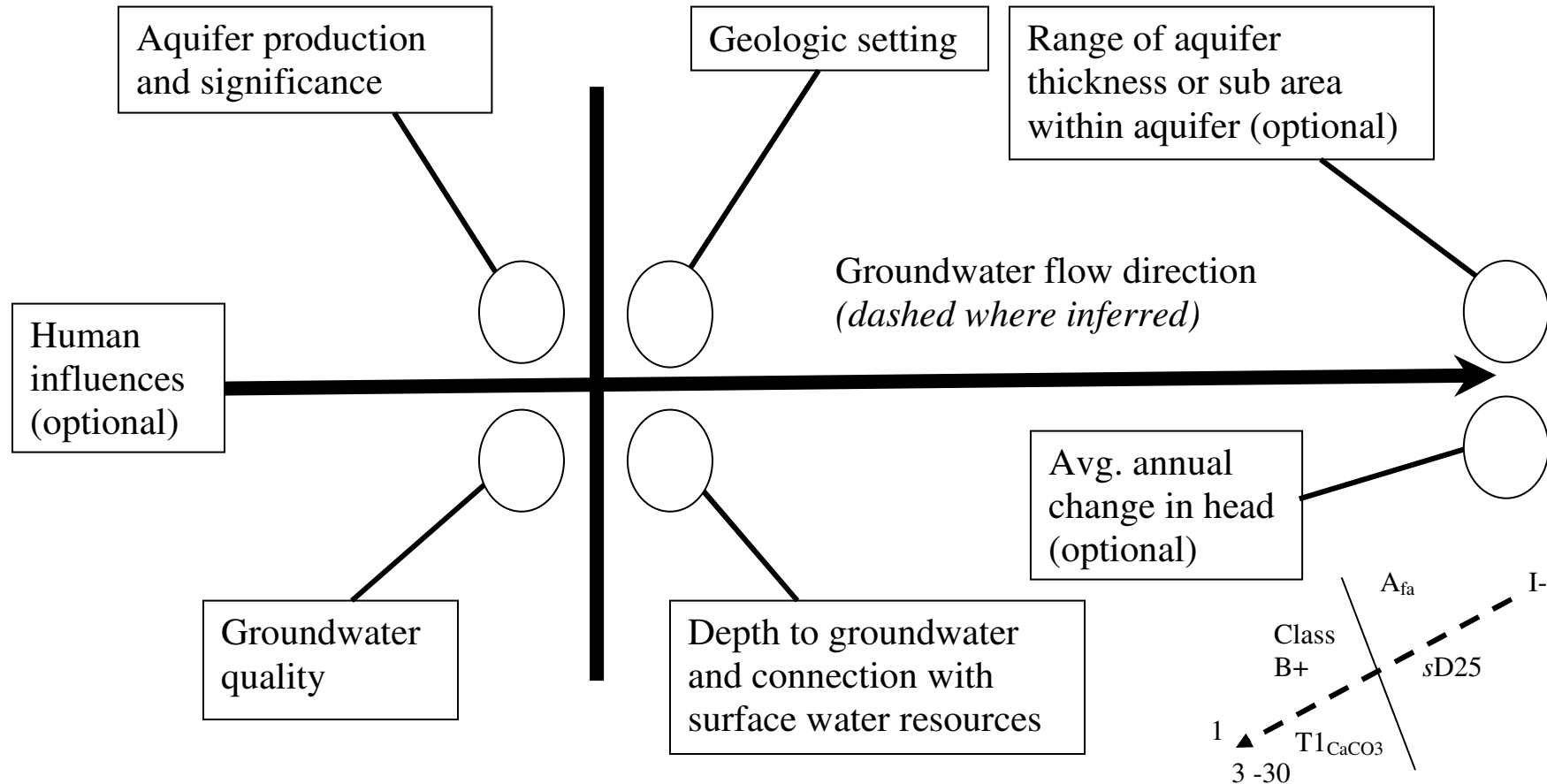
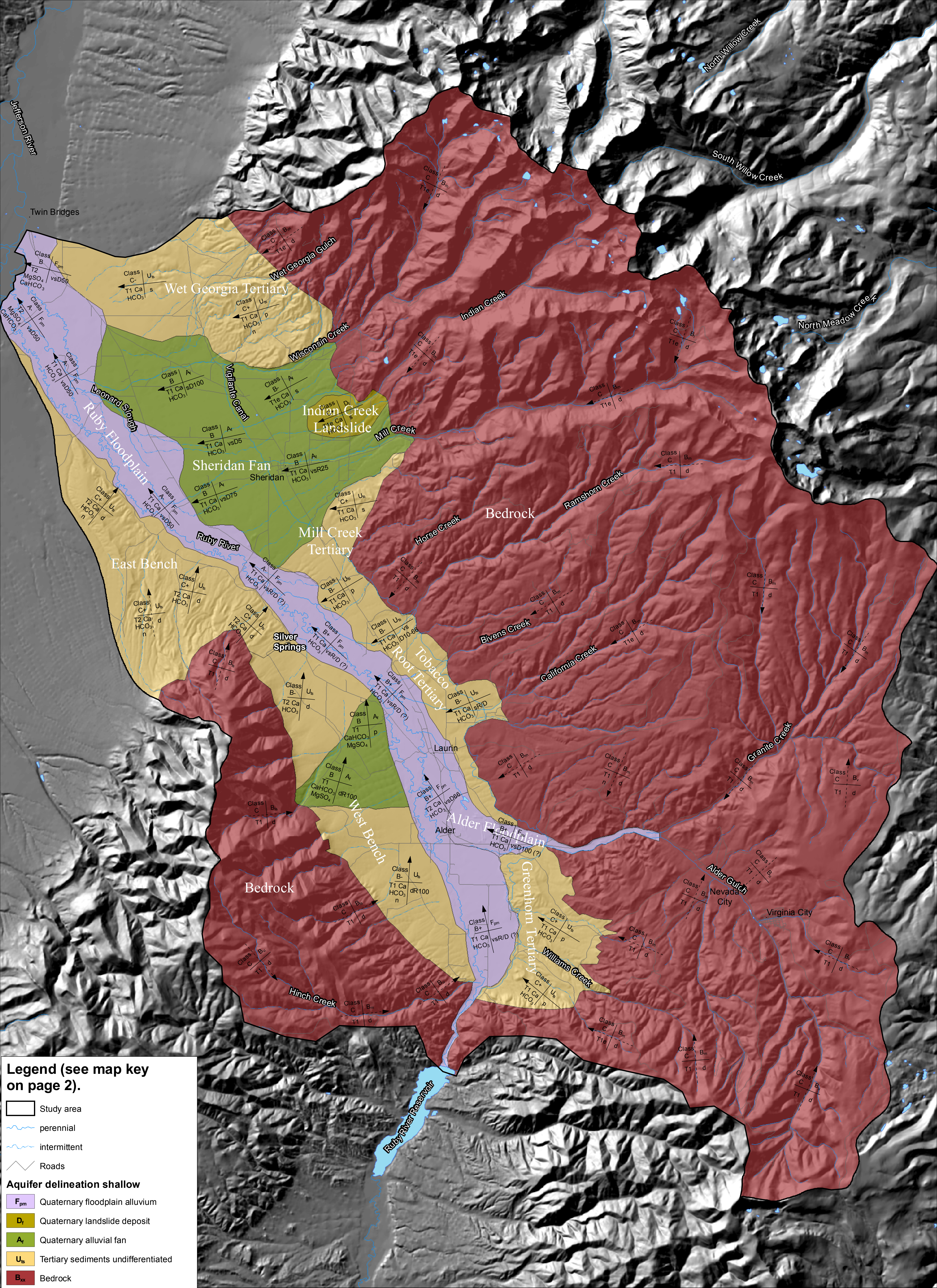


Figure 4. Aquifer classification mapping framework. The arrow and aquifer classification information is positioned on maps within aquifers or areas within aquifers. The arrow is rotated to indicate general groundwater flow direction in 360 degrees with aquifer production, geologic setting, groundwater quality and depth to groundwater positioned in the same general position as shown below, similar to how a north arrow rotates around a compass. Aquifer class should be positioned in the upper right quadrant (or left quadrant, depending on the arrow direction). An example for applying the aquifer classification arrow is shown in the lower right portion of the figure. All numbers are in meters.

Appendix C

Supporting Information for Paper 3

(See Plates C1 through C3)



Legend (see map key on page 2).

Study area

perennial

intermittent

Roads

Aquifer delineation shallow

F_{pm} Quaternary floodplain alluvium

D_r Quaternary landslide deposit

A_r Quaternary alluvial fan

U_s Tertiary sediments undifferentiated

B_{sx} Bedrock

Aquifer production

Optional: Hydraulic impact

Geologic setting

Groundwater flow direction (dashed where inferred)

Groundwater quality

Depth to groundwater and connection with surface water resources

Plate B1. Shallow Aquifer Delineation of the Lower Ruby Valley, Montana

Sources:
1) Payne and Magruder (2004)
2) Magruder and Payne (2008)
3) Ruppel et al. (1993)

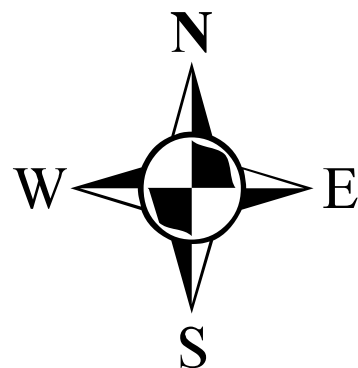
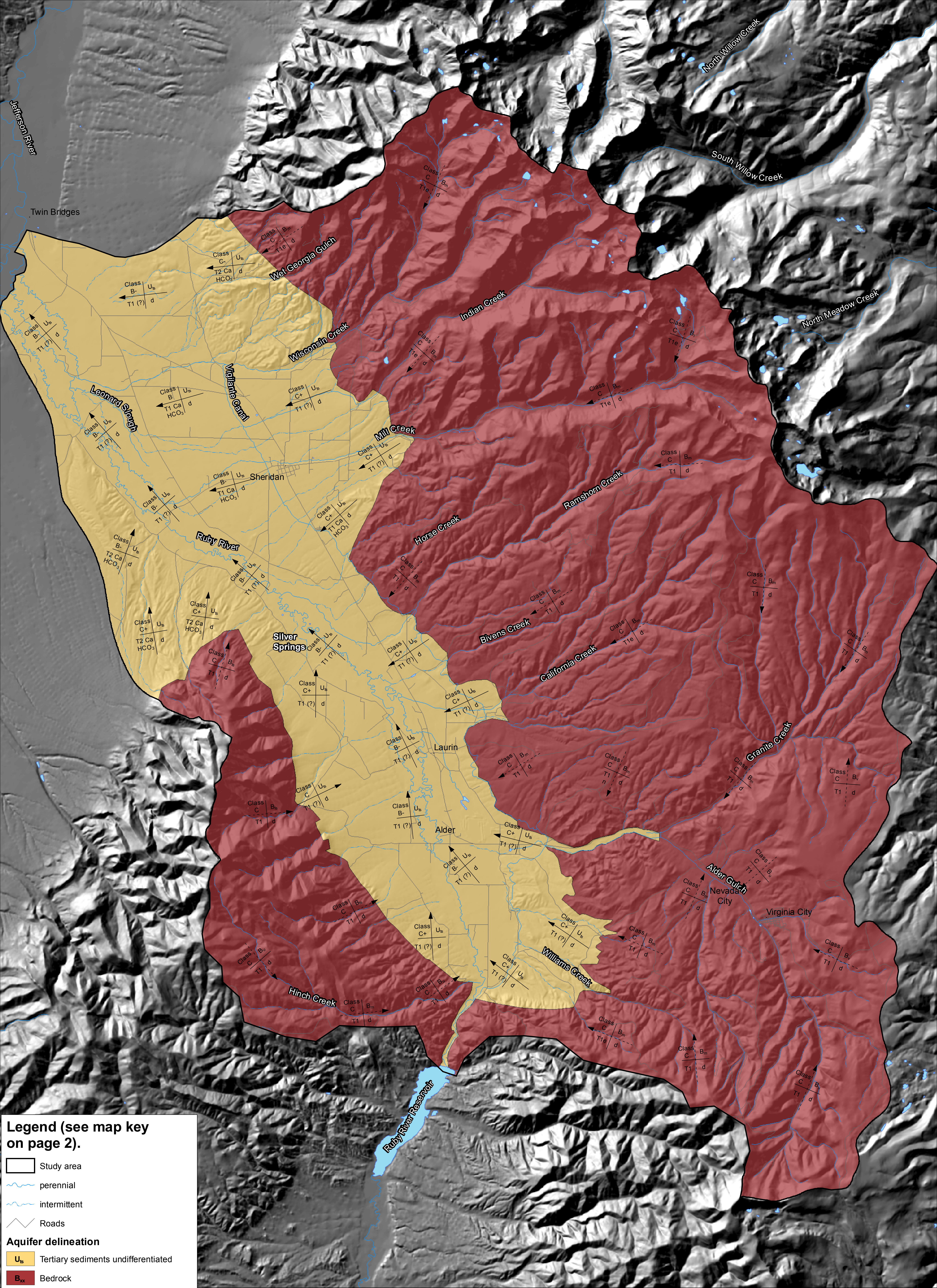


Plate B1 Shallow Aquifer Classification Key, Lower Ruby Valley Shallow Aquifer, Montana (Page 2 of 2)

Aquifer Name	Map Color	Aquifer Productivity Classification	Geologic Framework Code	Geologic Age	Capacity vs. Productivity Classification	Aquifer Size Classification	Hydraulic Anthropogenic Impact Classification	General Water Quality Classification	Major Common Ions & Pollutants (if any)	Qualitative Aquifer Vulnerability Classification	Depth to Groundwater Classification	Groundwater / surface water Connection	Level of Analysis (Tier Level)	Aquifer Classification	Aquifer Description
Quaternary Floodplain Alluvium (Ruby Floodplain and Alder Floodplain)	F _{pm}	Class B to B+ in the upper valley and B to A in the lower valley (intermediate to high productivity)	Fluvial Plain Meandering (F _{pm}) with Fluvial Plain Undifferentiated (F _{pu}) in the Alder Creek area (disturbed by placer mining)	Quaternary	Light (iii) water use	Large Size Aquifer (c)	None	Type 1 (T1) with some Type 2 (T2) in the upper Valley	CaHCO ₃ and some MgSO ₄ in the upper valley	High Vulnerability (H) due to shallow water table and high productivity	Very Shallow (vs)	D66 on the Ruby River near Alder (groundwater discharges to surface water and typically provides about 66% of the stream flow during nonrunoff conditions). D100 on Alder Creek where placer works block stream flow in the upper watershed and groundwater provides 100 percent of surface water flow on Alder Creek near its confluence with the Ruby River under nonrunoff conditions. D66 on the Ruby River near Alder (groundwater discharges to surface water and typically provides about 50% of the stream flow during nonrunoff conditions). The Ruby River is mostly steady in the central valley (R/D) although more accurate flow data may show minor to moderate groundwater / surface water exchange. Ruby Reservoir regulates flow in the lower Ruby River.	Tier 3	Class B- to A- F _{pm} iiic Type 1 CaHCO ₃ H vs D50 to D66 or R/D Tier 3 (isolated D100 on Alder Gulch Creek)	The Floodplain Alluvium is an intermediate to high flow aquifer system, yielding moderate to large amounts of groundwater from wells. The aquifer is associated with fluvial deposits of the Ruby River and Alder Gulch Creek, which are meandering fluvial systems, although Alder Gulch is placer mined and highly impacted. The aquifer is lightly used compared to the amount of recharge and is greater than 25 km ² in area. There are no dewatering issues and groundwater is a good source of drinking water. The chemistry is a calcium bicarbonate type water with some magnisium sulfide type water in the lower valley. The aquifer has a high vulnerability from surface contamination and depth to groundwater is very shallow. Surface water of the Ruby River and Alder Gulch Creek recieves groundwater discharge. For the Ruby, discharge ranges from 50 to 66 percent of stream flow during nonrunoff conditions in the upper and lower valley. 100 percent of stream flow is from groundwater on Alder Gulch Creek below placer workings blocking the stream channel. Important fisheries are sustained in the lower Ruby River by groundwater return flows in the late summer and fall.
Quaternary Landslide Deposit (Indian Creek Landslide)	D _f	Class C+ (upper low productivity)	Debris Flow (D)	Quaternary	Light (iii) water use	Small Size Aquifer (a)	None (Low aquifer productivity could result in local dewatering issues if overdeveloped and groundwater is used as the primary water supply)	Type 1e (T1)	CaHCO ₃	Moderate Vulnerability (M)	Shallow (s) (The water table is Deep (d) near the contact with berock)	Distal relationship. Not quantified.	Tier 3	Class C+ D _f iia Type 1e CaHCO ₃ M s to d Tier 3	The Quaternary Landslide Deposit Aquifer is a low flow production system, capable of yielding small amounts of groundwater from wells. The aquifer is associated with debris flow deposits of the Tobacco Root Mountains. The aquifer is lightly used compared to the amount of recharge and is a small size aquifer. There are no dewatering issues, but excessive development and use of groundwater could result in dewatering the groundwater supply. Groundwater is a good source of drinking water and it is a calcium bicarbonate type water. The aquifer has a moderate vulnerability from surface contamination based on the depth to groundwater, with groundwater depths ranging from shallow on the south edge of the aquifer to deep on the west portion of the aquifer near the mountain uplands.
Quaternary Alluvial Fan (West Bench and Sheridan Fans)	A _f	Class B in most areas with Class B- near Wisconsin Creek and Indian Creek (Intermediate). Some groundwater producing zones in the Sheridan Fan may be isolated high production hydrostratigraphic units.	Alluvial Fan (A) Arid	Quaternary	Moderate (ii): near the Town of Sheridan otherwise: light (iii).	Intermediate Size Aquifer (b) on the West Bench and Large Size Aquifer (c) on the Sheridan Fan	None	Type 1 (T1)	CaHCO ₃ and some MgSO ₄ on the West Bench	High Vulnerability (H) on the Sheridan Fan due to a shallow or very shallow water table and Low Vulnerability (L) on the West Bench where the water table is deep.	Shallow (s) to Very Shallow (vs) on the Sheridan Fan and Proximal (p) to Deep (d) on the West Bench Fan	D100 on Leonard Slough which flows into the Ruby River below Wisconsin Creek (groundwater discharges to surface water and typically provides 100% of the stream flow during nonrunoff conditions). D5 on Indian Creek (groundwater discharges to surface water and typically provides atleast 5% or more of the stream flow during nonrunoff conditions). R25 on upper Mill Creek (about 25 percent of surface water flow in Mill Creek is lost and recharges the shallow aquifer). D75 on lower Mill Creek (groundwater typically provides about 75% of the stream flow during nonrunoff conditions near the Ruby River).	Tier 3	Class B to B- A _f iiic Type 1 CaHCO ₃ + MgSO ₄ H vs to d D5-100 (near Ruby River) R25 (upper Mill Creek) Tier 3	The Quaternary Alluvial Fan Aquifer system is a intermediate flow production system capable of yielding moderate amounts of groundwater from wells. The aquifer is associated with alluvial fan deposits of the Tobacco Root and Ruby Mountains. The aquifer is lightly used compared to the amount of recharge except around Sheridan where it is heavily used for the town's water supply. The aquifer is large in the Sheridan area, >25 km ² , and is intermediate in size aquifer, 5 km ² and 25 km ² , on the West Bench. There are no significant dewatering issues and groundwater is a good source of drinking water. The chemistry is a calcium bicarbonate to magnisium sulfate type water. Depth to groundwater is very shallow to shallow on the Sheridan Fan and proximal to deep on the West bench. The aquifer is highly vulnerable from contamination on the Sheridan Fan and has a low vulnerability ranking on the West Bench due to depth of groundwater and productivity. Groundwater discharges into Leonard Slough, Indian Creek, and Lower Mill Creek, providing 5 to100 percent of nonrunoff stream flow. Upper Mill Creek loses 25 percent of its flow, recharging the shallow aquifer system.
Tertiary Sediments Undifferentiated (West Bench, East Bench, Greenhorn Tertiary, Tobacco Root Fans, and Wet Georgia Tertiary	U _{ts}	Class C+ to B- (limited data, low to intermediate productivity)	Undifferentiated sediments (U _{ts}) (alluvium, fluvial, volcanic, and debris flow sedimentary deposits)	Tertiary	Light (iii) in most areas. Some heavy groundwater use (i) for irrigation wells is present on the East Bench adjacent to the western edge of the project area.	Large Size Aquifer (c)	None in most areas. There is Extreme Artificial Recharge (I _{am}) on the East Bench or western portion of the project area where seepage from the East Bench Canal has raised the watertable over 100 feet in some areas. Not mapped because it borders the project area.	Type 1 (T1) with some Type 2 (T2) in the East Bench and West Bench areas. There is isolated nitrate contamination in wells on the East Bench, West Bench Tertiary sediment aquifers (as mapped).	CaHCO ₃	Moderate (M) to Low (L) Vulnerability in most areas with some High Vulnerability (H) in portions of the Wet Georgia, Tobacco Root, and Mill Creek Tertiary aquifers where groundwater is shallow to very shallow.	Proximal (p) to Deep (d) most areas with some shallow (s) to very shallow (vs) in portions of Wet Georgia, Tobacco Root, and Mill Creek Tertiary aquifers.	D10-66 on Rams Horn Creek (groundwater discharges to surface water and typically provides between 10% to 66% of the stream flow during nonrunoff conditions). The rest of the Tertiary aquifers have a distal relationship and is not quantified.	Tier 3	Class C+ to B- U _{ts} iiic Type 1 to 2 CaHCO ₃ M (some H) p to d D10-66 (Ramshorn Creek Only) Tier 3	The Tertiary Sediments Aquifer system is a low to intermediate flow system associated with undifferentiated alluvial, fluvial, volcanic, and debris flow Tertiary deposits. The aquifer system is a large size aquifer greater than 25 km ² in area. Overall, groundwater use is light, but there is significant groundwater water use adjacent to the project area on the East Bench as well as extreme artificial recharge associated with seepage from the East Bench Canal, which has raised the water table over 100 feet. Depth to groundwater is proximal to deep in most areas, but is shallow to very shallow in the Tobacco Root Fans and Mill Creek Tertiary. Groundwater is a good source of drinking water and is a calcium bicarbonate type water, although isolated nitrate contamination is noted on the East Bench and West Bench systems. The aquifer has moderate to low vulnerability from surface contamination but is high in areas with shallow or very shallow groundwater. Groundwater discharges into Ranshorn Creek, providing 10 to 66 percent of nonrunoff stream flow.
Bedrock Undifferentiated (Limestone, Volcanic, Granitic, and Metamorphic formations)	B _{xx}	Class C (limited data, low productivity)	Limstone (B _{ls}), Volcanic (B _v) Granitic (B _g) and Metamorphic (B _m) Bedrock formations as mapped	Archian (Precambrian) to Cretaceous	Light (iii) water use	Large Size Aquifer (c)	None	Type 1e (T1e) (?) Isolated nitrate contamination is noted east of Alder in the bedrock aquifer system.	CaHCO ₃ (?)	Low Vulnerability (L)	Deep (d) - May be Shallow (s) / Very Shallow (vs) in mountain stream valley bottoms	Distal relationship. Not quantified. Groundwater likely discharges into mountain stream valley bottoms and recharges basin fill aquifers. The source of Silver Springs groundwater, which flows about 20 cubic feet per second, is suspected to be groundwater discharge from limestone formations in the Ruby Mountains.	Tier 1	Class C B _{ls} / B _m / B _v / B _i iiic Type1e(?) L d Tier 1	The Bedrock Aquifer is generatlly a low flow production system, although some fractures may be capable of yielding large amounts of groundwater, such as Silver Springs which flows about 20 cubic feet per second and is suspected to be groundwater discharge from Ruby Mountain limestone formations. The aquifer has very light use compared to the amount of recharge and is a large size aquifer greater than 25 km ² . There are no known dewatering issues, groundwater is a good source of drinking water, and is a calcium bicarbonate dominate type water. Isolated nitrate contamination is noted in groundwater east of Alder. The aquifer has a low potential to be impacted from surface contamination and the water table is deep, although shallow groundwater may be associated with mountain stream bottom and springs that feed tributary streams.

Gray highlighted columns provide additional information not mapped on page 1 of 2



Legend (see map key on page 2).

Study area

perennial

intermittent

Roads

Aquifer delineation

U_s Tertiary sediments undifferentiated

B_x Bedrock

Aquifer production

Optional: Hydraulic impact

Geologic setting

Groundwater flow direction (dashed where inferred)

Groundwater quality

Depth to groundwater and connection with surface water resources

Plate B2. Deep Aquifer Delineation of the Lower Ruby Valley, Montana

Sources:
1) Payne and Magruder (2004)
2) Magruder and Payne (2008)
3) Ruppel et al. (1993)

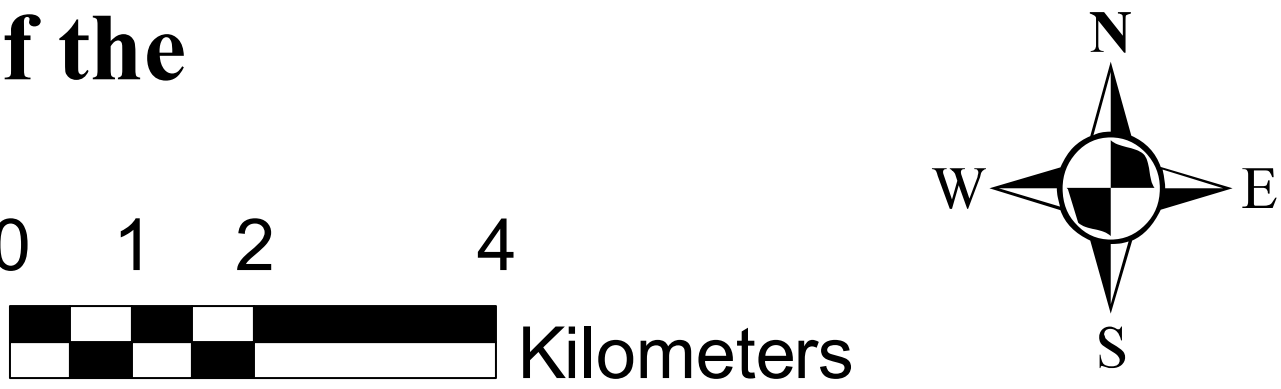


Plate B2 Deep Aquifer Classification Key, Lower Ruby Valley Shallow Aquifer, Montana (Page 2 of 2)

Aquifer Name	Map Color	Aquifer Productivity Classification	Geologic Framework Code	Geologic Age	Capacity vs. Productivity Classification	Aquifer Size Classification	Hydraulic Anthropogenic Impact Classification	General Water Quality Classification	Major Common Ions & Pollutants (if any)	Qualitative Aquifer Vulnerability Classification	Depth to Groundwater Classification	Groundwater / surface water Connection	Level of Analysis (Tier Level)	Aquifer Classification	Aquifer Description
Tertiary Sediments Undifferentiated (West Bench, East Bench, Greenhorn Tertiary, Tabacco Root Fans, and Wet Georgia Tertiary)	U _{ts}	Class C+ to B (limited data, low to intermediate productivity)	Undifferentiated sediments (U _{ts}) (alluvium, fluvial, volcanic, and debris flow sedimentary deposits)	Tertiary	Light (iii) in most areas. Some heavy groundwater use (i) for irrigation wells is present on the East Bench adjacent to the western edge of the project area.	Large Size Aquifer (c)	None in most areas. There is Extreme Artificial Recharge (I _{art}) on the East Bench or western portion of the project area where seepage from the East Bench Canal has raised the water table in the shallow aquifer over 100 feet in some areas. A similar rise is present in the confined deeper aquifer system. Not mapped because it borders the project area.	Type 1 (T1) with some Type 2 (T2) in the East Bench and West Bench areas. There is isolated nitrate contamination in wells on the East Bench, West Bench Tertiary sediment aquifers (as mapped).	CaHCO ₃	Low (L) Vulnerability	Deep (d)	Distal relationship. Not quantified.	Tier 3	Class C+ to B U _{ts} iiic Type 1 to 2 CaHCO ₃ L d Tier 3	The deep Tertiary Sediments Aquifer system is a low to intermediate flow system associated with undifferentiated alluvial, fluvial, volcanic, and debris flow Tertiary deposits. While hydraulic conductivity is relatively low and fines are commonly layered in the sedimentary sequence, the aquifer is relatively thick at over 800 feet thick in the valley center. Because of the relatively thick sedimentary sequence, transmissivity is high enough to yield moderate to large amount of groundwater from wells, which likely diminishes closer to the valley sides where the unit is thinner and bedrock is shallow. Tertiary sediments below the deep aquifer may yield limited amounts of groundwater based on modeling. The aquifer system is a large size aquifer greater than 25 km ² in area. Overall, groundwater use is light, but there is significant groundwater water use adjacent to the project area on the East Bench as well as extreme artificial recharge associated with seepage from the East Bench Canal, which has raised the potentiometric surface 100 feet. Depth to groundwater is deep, the groundwater is a good source of drinking water and is a calcium bicarbonate type water. The aquifer has low vulnerability.
Bedrock Undifferentiated (Limestone, Volcanic, Granitic, and Metamorphic formations)	B _{xx}	Class C (limited data, low productivity)	Limstone (B _{ls}), Volcanic (B _v) Granitic (B _g) and Metamorphic (B _m) Bedrock formations as mapped	Archian (Precambrian) to Cretaceous	Light (iii) water use	Large Size Aquifer (c)	None	Type 1e (T1e) (?) Isolated nitrate contamination is noted east of Alder in the bedrock aquifer system.	CaHCO ₃ (?)	Low Vulnerability (L)	Deep (d) - May be Shallow (s) / Very Shallow (vs) in mountain stream valley bottoms	Distal relationship. Not quantified. Groundwater likely discharges into mountain stream valley bottoms and recharges basin fill aquifers. The source of Silver Springs groundwater, which flows about 20 cubic feet per second, is suspected to be groundwater discharge from limestone formations in the Ruby Mountains.	Tier 1	Class C B _{ls} / B _m / B _v / B _l iiic Type 1e(?) L d Tier 1	The Bedrock Aquifer is generally a low flow production system, although some fractures may be capable of yielding large amounts of groundwater, such as Silver Springs which flows about 20 cubic feet per second and is suspected to be groundwater discharge from Ruby Mountain limestone formations. The aquifer has very light use compared to the amount of recharge and is a large size aquifer greater than 25 km ² . There are no known dewatering issues, groundwater is a good source of drinking water, and is a calcium bicarbonate dominate type water. Isolated nitrate contamination is noted in groundwater east of Alder. The aquifer has a low potential to be impacted from surface contamination and the water table is deep, although shallow groundwater may be associated with mountain stream bottom and springs that feed tributary streams.

Gray highlighted columns provide additional information not mapped on page 1 of 2

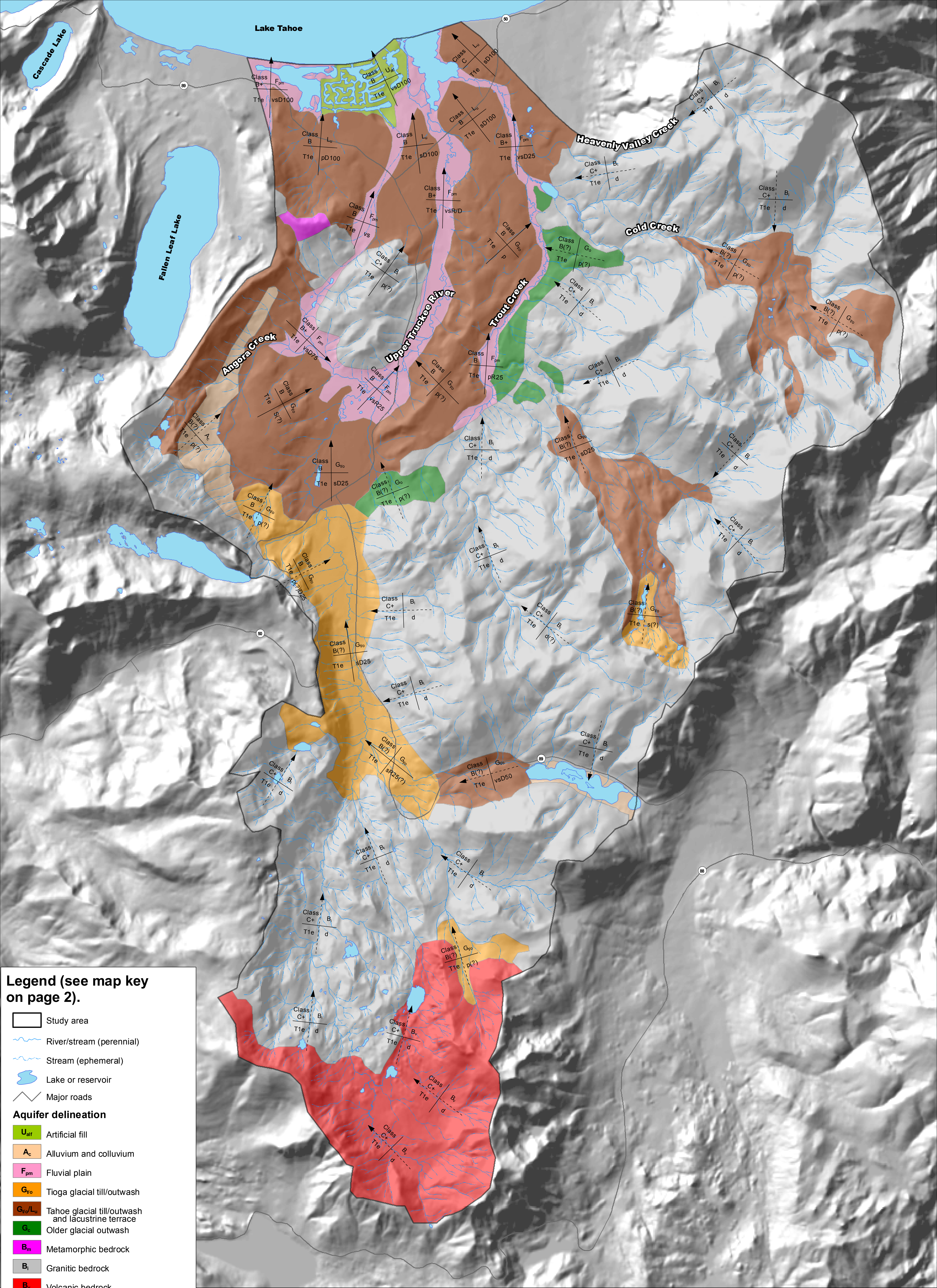


Plate C1. Shallow aquifer Delineation of the Upper Truckee River and Trout Creek Watersheds South Lake Tahoe, California

Sources:
1) Bonham and Burnett (1976)
2) Rowe and Allender (2000)
3) Thodal (1997)
4) US Army Corp Engineers (2003)
5) Saucedo (2005)
6) Trexler and Bell (1979)

0 0.5 1 2

Kilometers

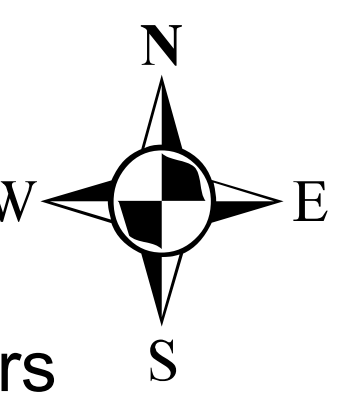
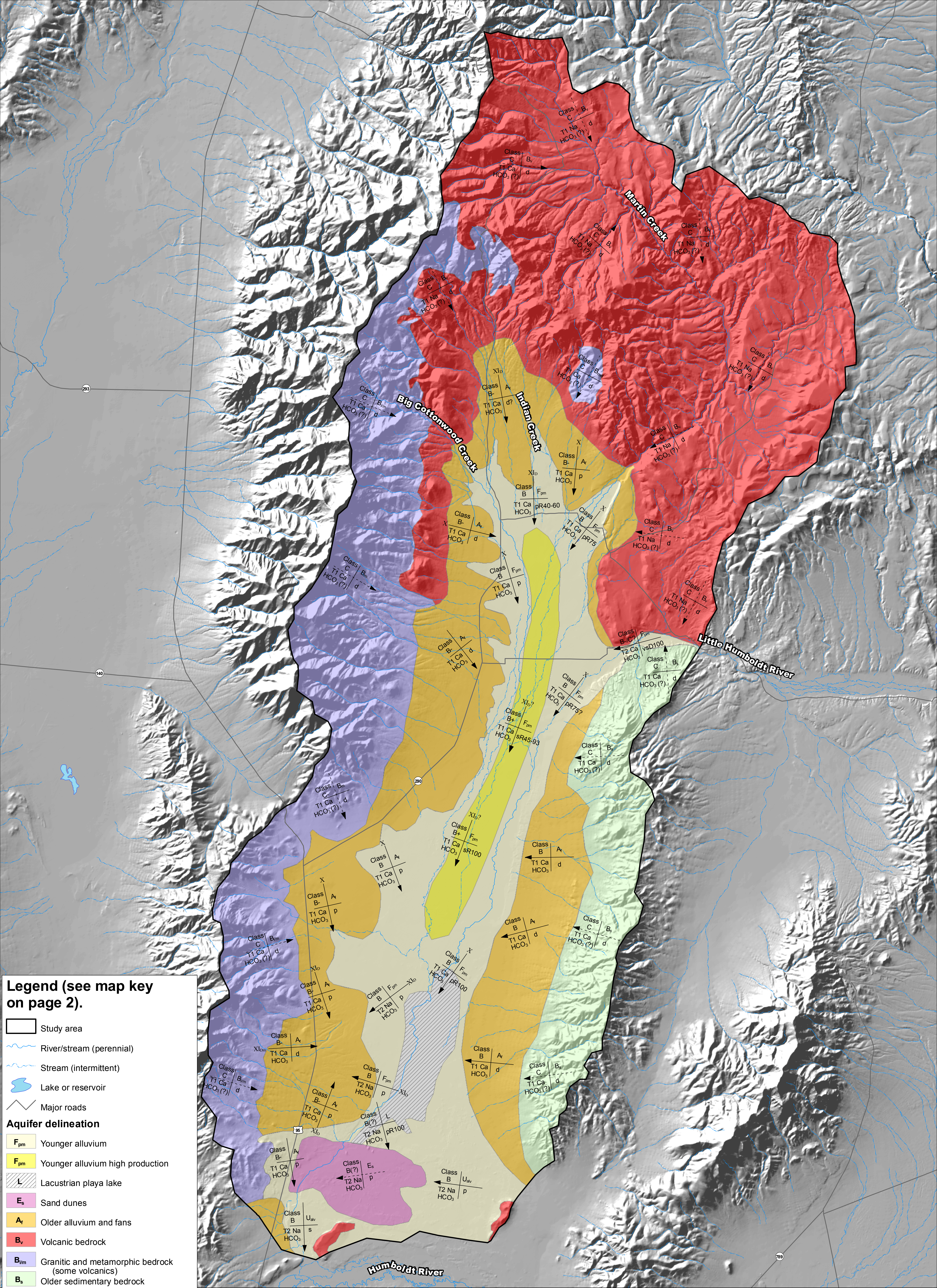


Plate C1 Shallow Aquifer Classification Key, Upper Truckee River and Trout Creek Watersheds, South Lake Tahoe, California (Page 2 of 2)

Aquifer Name	Map Color	Aquifer Productivity Classification	Geologic Framework Code	Geologic Age	Capacity vs. Productivity Classification	Aquifer Size Classification	Hydraulic Anthropogenic Impact Classification	General Water Quality Classification	Major Common Ions & Pollutants (if any)	Qualitative Aquifer Vulnerability Classification	Depth to Groundwater Classification	Groundwater / surface water Connection	Level of Analysis (Tier Level)	Aquifer Classification	Aquifer Description
Artificial Fill	U _{atf}	Class B (intermediate productivity)	Undifferentiated (U _{und}) artificial fill, mixed composition	Holocene	Light (iii): limited or no groundwater use in artificial fill.	Small Size Aquifer (a)	None	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	High Vulnerability (H) due to shallow water table and intermediate productivity.	Very Shallow (vs)	D100 (groundwater discharges into Lake Tahoe)	Tier 3	Class B U _{atf} iia Type 1e mixed-HCO ₃ H vs D100 Tier 3	The Artificial Fill Aquifer is a thin manmade system with intermediate aquifer productivity. The aquifer is not heavily used compared to the amount of recharge and is smaller than 5 km ² in area. There are no major groundwater dewatering issues. The water quality is excellent for drinking water, mostly a mixed cation and bicarbonate type water. The aquifer has a high vulnerability from surface contamination and the water table depth is very shallow. Groundwater discharges into Lake Tahoe. Urbanization and upgradient / deep aquifer municipal/domestic water use results in a complex relationship between water resources in the mapped area.
Alluvium / Colluvium	A _c	Class B (?) (intermediate productivity)	Alluvium / Colluvium (A _c)	Quaternary	Light (iii): groundwater use is minor and the land is currently undeveloped.	Small Size Aquifer (a)	None	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	Moderate Vulnerability (M)	Proximal (p)? Very limited data for depth to groundwater: depth inferred from area data.	Distal relationship. Not quantified. Groundwater may discharge into local tributary streams and nearby water bodies.	Tier 1	Class B(?) A _c iia Type 1e mixed-HCO ₃ M p Tier 3	The Alluvium / Colluvium Aquifer is an intermediate productivity aquifer, capable of yielding moderate amounts of groundwater from shallow wells. Only limited well data are available for this unit. The aquifer is lightly used compared to the amount of recharge and is smaller than 5 km ² in area. There are no major groundwater dewatering issues, but large quantities of groundwater pumped from this aquifer could reduce discharge to adjacent aquifers and eventually surface water. The water quality is excellent for drinking water, mostly a mixed cation and bicarbonate type water. The aquifer has a moderate vulnerability from surface contamination and the water table depth is inferred as proximal based on area data. Groundwater likely discharges to adjacent aquifers and potentially local tributaries, but there are insufficient data to quantify groundwater / surface water connection.
Fluvial Plain	F _{pm}	Class B to B+ (intermediate and upper-intermediate productivity)	Fluvial Plain Meandering (F _{pm})	Quaternary	Heavy (i): significant groundwater use associated with urban development.	Intermediate Size Aquifer (b) (limited lateral extent)	None, although large or sustained groundwater use in this aquifer has the potential to affect stream flow in rivers / creeks due to a connection with surface water.	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	High Vulnerability (H) due to shallow water table and intermediate productivity	Very Shallow (vs) (most areas) to proximal (p) in upper Trout Creek fluvial plain.	Variable. Truckee River section is D75 (50 to 75% of stream flow is from groundwater), steady (R/D), to R25 (River loses 0 to 25% of flow to shallow aquifer). Trout Creek ranges from R25 to D25 (0 to 25% of stream flow recharges shallow aquifer to 0 to 25% of stream flow is from groundwater). The fluvial plain aquifer system is D100 near Lake Tahoe (100 percent of shallow groundwater discharges into lake).	Tier 3	Class B/B+ F _{pm} ib Type 1e mixed-HCO ₃ H vs D/R(variable) Tier 3	The Fluvial Plain Aquifer is an intermediate to upper-intermediate flow aquifer, yielding moderate to large amounts of groundwater from shallow wells. The aquifer is generally associated with floodplain deposits of the major drainages. The aquifer is heavily used compared to the amount of recharge and is an intermediate size aquifer between 5 km ² and 25 km ² in area. There are no major groundwater dewatering issues, but groundwater consumed from this aquifer will likely reduce discharge into local surface water and eventually Lake Tahoe. The water quality is excellent for drinking water, mostly a mixed cation and bicarbonate type water. The aquifer has a high vulnerability from surface contamination and the depth to groundwater is very shallow. Groundwater discharges to surface water in the Truckee River and Trout Creek drainages, although locally conditions are reversed along short reaches. This aquifer discharges to Lake Tahoe. Urbanization and nearby / deep aquifer municipal/domestic water use results in a complex relationship between water resources in the mapped area.
Tioga Glacial Till / Outwash	G _{t/o}	Class B (intermediate productivity) with till units having potentially lower productivity. Inferred aquifer production in higher elevation Tioga Glacial units.	Glacial till / outwash (G _{t/o})	Quaternary	Heavy (i): significant groundwater use in urban development to Light (ii) in undeveloped areas.	Intermediate Size Aquifer (b) (limited lateral extent)	None, although large or sustained groundwater use in this aquifer has the potential to affect stream flow in rivers / creeks due to a connection with surface water.	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	High Vulnerability (H) due to shallow water table and intermediate productivity	Shallow (s) near surface water features to proximal (p) on valley edges. Depth to groundwater is inferred in higher elevation Tioga Glacial units.	Variable. Truckee River section is D25 (0 to 25% of stream flow is from groundwater) to R25 (River loses 0 to 25% of flow to shallow aquifer). Higher elevation Tioga Glacial units have insufficient data to determine groundwater / surface water interaction.	Tier 3 (lower elevation) to Tier 1 (higher elevation)	Class B G _{t/o} ib Type 1e mixed-HCO ₃ H s to p D/R(variable) Tier 1 to 3	The Tioga Glacial Till / Outwash Aquifer is an intermediate flow aquifer, yielding moderate amounts of groundwater from shallow wells completed in outwash sediments and reduced production from till / fine grained sediments. The aquifer is associated with Quaternary Glacial geology. The aquifer is heavily used compared to the amount of recharge and is an intermediate size aquifer between 5 km ² and 25 km ² in area. There are no major groundwater dewatering issues, but groundwater pumped from this aquifer could reduce discharge into local surface water and eventually Lake Tahoe. The water quality is excellent for drinking water, mostly a mixed cation and bicarbonate type water. The aquifer has a high vulnerability from surface contamination and the depth to groundwater is shallow near surface water and proximal in uplands. Groundwater discharges to surface water in the Truckee River drainage, although locally conditions are reversed along short reaches. Urbanization and nearby / deep aquifer municipal/domestic water use results in a complex relationship between water resources in the mapped area.
Tahoe Glacial Till / Outwash and Lacustrine Terrace	G _{t/o} / L _u	Class B (intermediate productivity) with till units having potentially lower productivity. Inferred aquifer production in higher elevation Tahoe Glacial units.	Glacial till / outwash (G _{t/o}) and Lacustrine undifferentiated (L _u) sands and fine grained sediments	Quaternary	Heavy (i): significant groundwater use in urban development to Light (ii) in undeveloped areas.	Large Size Aquifer (c) near South Lake Tahoe to Small Size Aquifer (a) / Intermediate Size Aquifer (b) in higher elevation areas.	None, although large or sustained groundwater use in this aquifer has the potential to affect stream flow in rivers / creeks due to a connection with surface water.	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	High Vulnerability (H) due to shallow water table and intermediate productivity	Shallow (s) near surface water features to proximal (p) on valley edges and hills. Depth to groundwater is inferred in higher elevation Tahoe Glacial units.	Variable. Truckee River section is D25 (0 to 25% of stream flow is from groundwater) to distal relationship in uplands. The aquifer system is D100 near Lake Tahoe (100 percent of shallow groundwater discharges into lake). Higher elevation Tahoe Glacial units have insufficient data to determine groundwater / surface water interaction.	Tier 3 (lower elevation) to Tier 1 (higher elevation)	Class B G _{t/o} ic Type 1e mixed-HCO ₃ H s to p D/R(variable) Tier 1 to 3	The Tahoe Glacial Till / Outwash Aquifer is an intermediate flow aquifer, yielding moderate amounts of groundwater from shallow wells completed in outwash sediments and reduced production from till / fine grained sediments. The aquifer is associated with Quaternary Glacial geology. The aquifer is heavily used compared to the amount of recharge and is a large size aquifer over 25 km ² in area. There are no major groundwater dewatering issues, but groundwater pumped from this aquifer could reduce discharge into local surface water and eventually Lake Tahoe. The water quality is excellent for drinking water, mostly a mixed cation and bicarbonate type water. The aquifer has a high vulnerability from surface contamination and the depth to groundwater is shallow near surface water and proximal in uplands. Groundwater discharges to surface water in the Truckee River and Trout Creek drainages, although conditions are reversed along short reaches. This aquifer also discharges to Lake Tahoe. Urbanization and nearby / deep aquifer municipal / domestic water use results in a complex relationship between water resources in the mapped area.
Older Glacial Outwash	G _o	Class B (?) (intermediate productivity)	Glacial Outwash (G _o)	Quaternary	Moderate (ii)? : some groundwater use in developed areas	Intermediate Size Aquifer (b) (limited lateral extent)	None	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	Moderate Vulnerability (M)	Proximal (p)? Very limited data for depth to groundwater: depth inferred from area data.	Distal relationship. Not quantified. Groundwater discharges to adjacent aquifer which discharges into Trout Creek.	Tier 1	Class B(?) G _o ii?b Type 1e mixed-HCO ₃ M p Tier 1	The Older Glacial Outwash Aquifer is an intermediate productivity aquifer, capable of yielding moderate amounts of groundwater from shallow wells. Only limited well data are available for this unit. The aquifer is moderately used compared to the amount of recharge and is an intermediate size aquifer between 5 km ² and 25 km ² in area (with all areas combined). There are no major groundwater dewatering issues, but large quantities of groundwater pumped from this aquifer could reduce discharge to adjacent aquifers and eventually surface water. The water quality is excellent for drinking water, mostly a mixed cation and bicarbonate type water. The aquifer has a moderate vulnerability from surface contamination and the water table depth is inferred to be proximal based on area data. Groundwater likely discharges to adjacent aquifers and potentially local tributaries, but there are insufficient data to quantify the groundwater / surface water connection.
Metamorphic Bedrock	B _m	Class C+ (upper-low productivity)	Metamorphic Bedrock (B _m)	Jurassic	Light (iii): very limited groundwater use in undeveloped area	Small Size Aquifer (a)	None	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	Low Vulnerability (L)	Proximal (p)? Very limited data for depth to groundwater: depth inferred from area data.	Distal relationship. Not quantified. Groundwater discharges to adjacent aquifer which discharges into Lake Tahoe.	Tier 1	Class C+ B _m iia Type 1e mixed-HCO ₃ L p Tier 1	The Metamorphic Bedrock Aquifer is an upper-low flow production aquifer, although some fractures may be capable of yielding large amounts of groundwater. The aquifer has very light use compared to the amount of recharge and is a small size aquifer <5km ² . There are no known dewatering issues and the water quality is excellent for drinking water and is a mixed cation and bicarbonate type water. The aquifer has a low potential to be impacted from surface contamination, although locally in stream bottoms vulnerability is higher. The depth to groundwater is proximal, although shallow groundwater may be associated with stream bottoms and springs that feed tributary streams. There is a distal connection with surface water in the study area, but there are insufficient data to characterize discharge/recharge relationship between groundwater and surface water and this aquifer.
Granitic Bedrock	B _i	Class C+ (upper-low productivity)	Granitic Bedrock (B _i)	Cretaceous	Light (iii): limited groundwater use near South Lake Tahoe to no water use in undeveloped areas.	Large Size Aquifer (c)	None	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	Low Vulnerability (L)	Deep (d) - May be Shallow (s) / Very Shallow (vs) in stream valley bottoms or near springs	Distal relationship. Not quantified. Groundwater may discharge into mountain stream valley bottoms and recharge basin fill aquifers.	Tier 1	Class C+ B _i iic Type 1e mixed-HCO ₃ L d Tier 1	The Granitic Bedrock Aquifer is an upper-low flow production aquifer, although some fractures may be capable of yielding large amounts of groundwater. The aquifer has very light use compared to the amount of recharge and is large in size greater than <25km ² . There are no known dewatering issues and the water quality is excellent for drinking water and is a mixed cation and bicarbonate type water. The aquifer has a low potential to be impacted from surface contamination, although locally in stream bottoms vulnerability is higher in areas where development or human access is present. The depth to groundwater is deep, although shallow groundwater may be associated with stream bottoms and springs that feed tributary streams. There is a distal connection with surface water in the study area, including Lake Tahoe, but there are insufficient data to characterize discharge/recharge relationship between groundwater and surface water and this aquifer.
Volcanic Bedrock	B _v	Class C+ (low productivity)	Volcanic Bedrock (B _v)	Miocene	Light (iii): no groundwater use.	Large Size Aquifer (c)	None	Type 1e (specific conductance is <250 microsiemens per centimeter)	Mixed cation (Ca, Mg, Na, Si) and bicarbonate (HCO ₃)	Low Vulnerability (L)	Deep (d) - may be Shallow (s) / Very Shallow (vs) in stream valley bottoms or near springs	Distal relationship. Not quantified. Groundwater may discharge into mountain stream valley bottoms and recharge basin fill aquifers.	Tier 1	Class C+ B _v iic Type 1e mixed-HCO ₃ L d Tier 1	The Volcanic Bedrock Aquifer is an upper-low flow production aquifer, although some fractures may be capable of yielding large amounts of groundwater. The aquifer has very light use compared to the amount of recharge and is large in size greater than <25km ² . There are no known dewatering issues and the water quality is excellent for drinking water and is a mixed cation and bicarbonate type water. The aquifer has a low potential to be impacted from surface contamination, although locally in stream bottoms vulnerability is higher in areas where human access or development is present. The depth to groundwater is deep, although shallow groundwater may be associated with stream bottoms and springs that feed tributary streams. There is a distal connection with surface water in the study area but there are insufficient data to characterize discharge/recharge relationship between groundwater and surface water and this aquifer.



Legend (see map key on page 2).

Study area

River/stream (perennial)

Stream (intermittent)

Lake or reservoir

Major roads

Aquifer delineation

F_{pm} Younger alluvium

F_{pm} Younger alluvium high production

L Lacustrine playa lake

E_s Sand dunes

A_r Older alluvium and fans

B_v Volcanic bedrock

B_{vm} Granitic and metamorphic bedrock (some volcanics)

B_s Older sedimentary bedrock

Aquifer production

Optional: Hydraulic impact

Geologic setting

Groundwater flow direction (dashed where inferred)

Groundwater quality

Depth to groundwater and connection with surface water resources

Plate C2. Shallow Aquifer Delineation of Paradise Valley, Nevada

Sources:
1) Prudic and Herman (1996)
2) Harrill and Mooney (1970)
3) Loeltz et al. (1949)
4) Willden (1963)

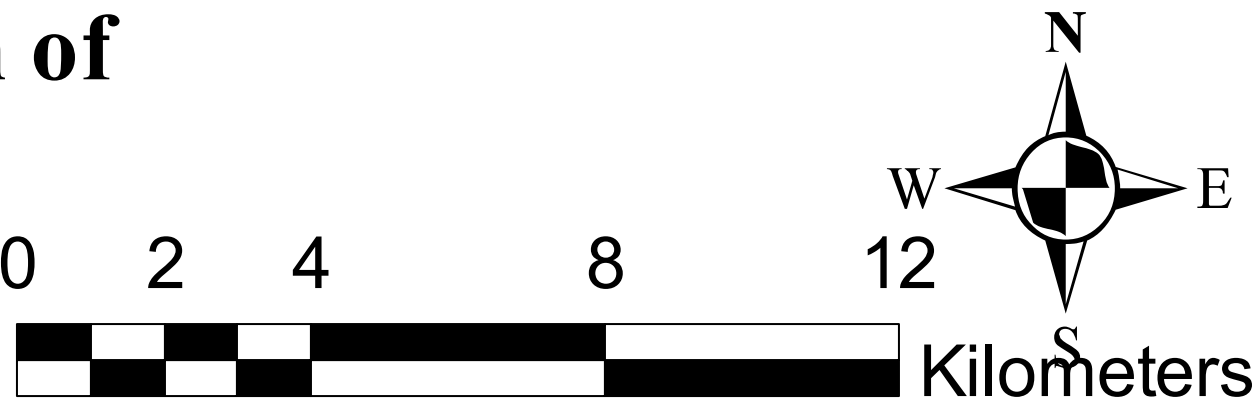
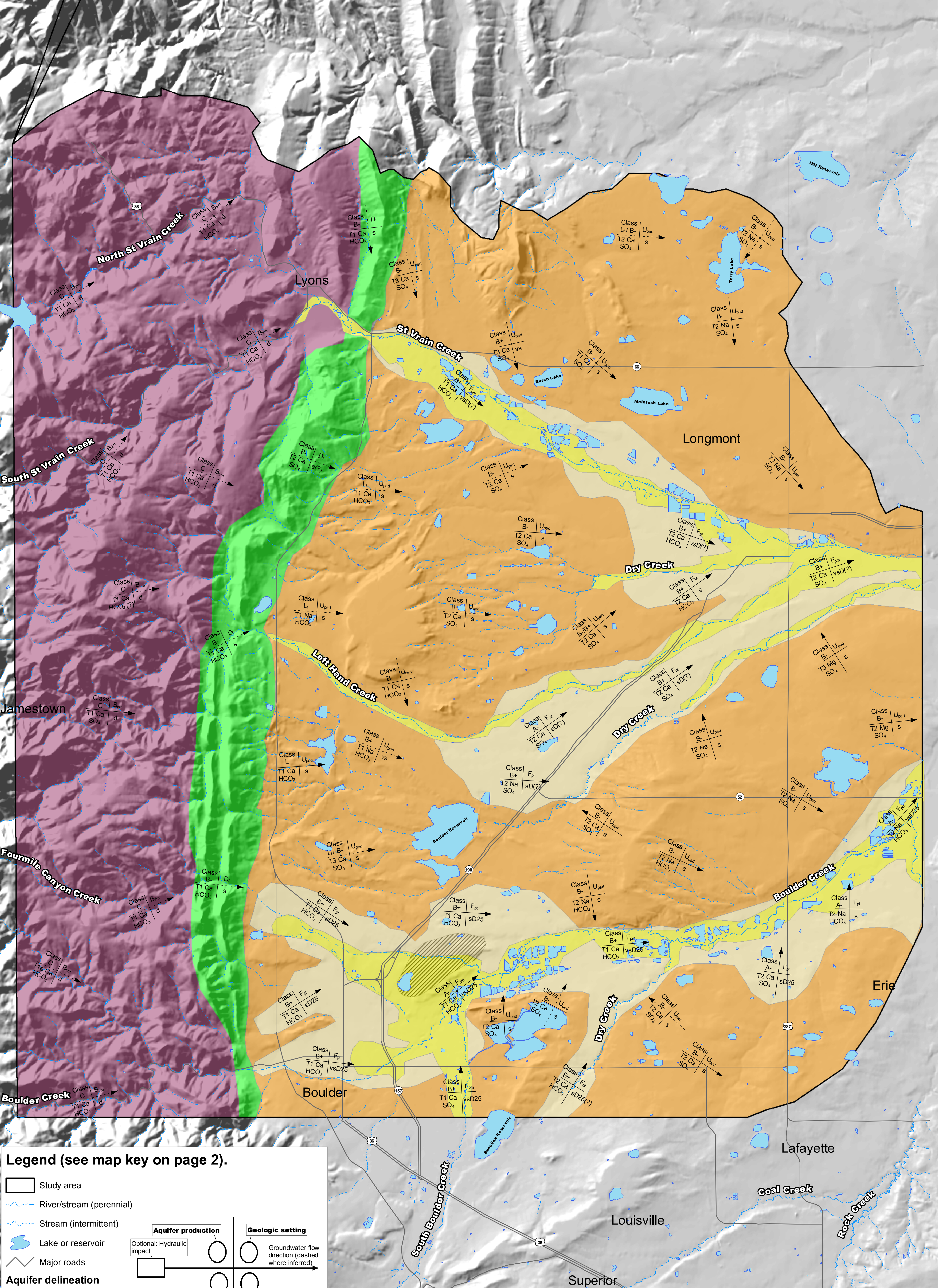


Plate C2 Shallow Aquifer Classification Key, Paradise Valley, Nevada (Page 2 of 2)

Aquifer Name	Map Color	Aquifer Productivity Classification	Geologic Framework Code	Geologic Age	Capacity vs. Productivity Classification	Aquifer Size Classification	Hydraulic Anthropogenic Impact Classification	General Water Quality Classification	Major Common Ions & Pollutants (if any)	Qualitative Aquifer Vulnerability Classification	Depth to Groundwater Classification	Groundwater / surface water Connection	Level of Analysis (Tier Level)	Aquifer Classification	Aquifer Description
Younger Alluvium	F _p / A _f	Class B (Intermediate productivity)	Fluvial Plain (F _p) transitions to arid Alluvial Fan (A _f) on valley edge. Undifferentiated alluvium in south valley.	Quaternary	Heavy (I): significant groundwater use for irrigation.	Large Size Aquifer (c)	Moderate Dewatering, north valley? (I _b). Limited Data	Type 1 (T1) with some Type 2 (T2) in the South Valley	CaHCO ₃ and some NaHCO ₃ in the South Valley	Moderate Vulnerability (M)	Proximal (p) most areas, Shallow (s) in far south and Very Shallow (vs) on Little Humboldt River confluence eastern valley edge, Paradise Valley.	R40-60 (Surface water recharges groundwater: 40% to 60% of stream flow recharges shallow aquifer in the North Valley area. Isolated D100 (Groundwater discharges into Little Humboldt River near confluence with Paradise Valley. 100% of non-storm stream flow is groundwater discharge to river).	Tier 3	Class B F _p / A _f ic I _D Type 1 CaHCO ₃ M p R40-60 Tier 3 (isolated D100 on Little Humboldt River at eastern valley edge)	The Younger Alluvium Aquifer is a intermediate flow aquifer, yielding moderate to large amounts of groundwater from wells. The aquifer is associated with basin fill sediments of Little Humboldt River, transitioning to arid alluvial fan deposits on the valley edge. The aquifer is heavily used compared to the amount of recharge and is greater than 25 km ² in area. There are moderate dewatering issues in the north valley, which could be severe with sustained long-term / new groundwater use. Groundwater is a good source of drinking water and is a calcium bicarbonate type water with sodium bicarbonate type water in the south valley. The aquifer has moderate vulnerability from surface contamination and depth to groundwater is shallow near the valley center to proximal on the valley edge. Very shallow groundwater is present on the eastern edge of the valley. Surface water of the Little Humboldt River recharges shallow groundwater, loosing 40 to 60 percent of stream flow to groundwater. However, on the eastern edge of the valley, groundwater discharges into the Little Humboldt River and sustains the aquatic ecosystem during base flow.
Younger Alluvium High Production	F _p	Class B+ (upper-intermediate productivity)	Fluvial Plain (F _p)	Quaternary	Heavy (I): significant groundwater use for irrigation.	Intermediate Size Aquifer (b)	Moderate Dewatering (I _b) some areas in north and south valley.	Type 1 (T1)	CaHCO ₃	High Vulnerability (H) due to shallow water table and high productivity	Shallow (s)	R45-100 (Surface water recharges groundwater: 45% to 100% of stream flow is lost to shallow aquifer). South Central Valley.	Tier 3	Class B+ F _p ib I _D Type 1 s R45-100 Tier 3	The Younger Alluvium High Production Aquifer is a intermediate to high flow production system, capable of yielding large amounts of groundwater from wells. The aquifer is associated with basin fill sediments of the Little Humboldt River fluvial plain. The aquifer is heavily used compared to the amount of recharge and is an intermediate size aquifer. There are moderate dewatering issues, which could be severe with sustained long-term or new groundwater withdrawal. Groundwater is a good source of drinking water and it is a calcium bicarbonate type water. The aquifer has a high vulnerability from surface contamination based on the shallow depth to groundwater and high productivity. Surface water of the Little Humboldt River recharges the shallow groundwater of the fluvial plain, loosing 45 to 100 percent of stream flow to the aquifer.
Lacustrine Playa Lake (Alluvium at depth)	L	Class B (limited data, intermediate productivity, shallow saturated zone may be less permeable)	Lacustrine (L) with Alluvium at depth in water producing zones.	Quaternary	Heavy (I): significant groundwater use for irrigation.	Intermediate Size Aquifer (b)	Moderate Dewatering on west side of lake? (I _b). Limited Data	Type 1 and 2 (T1 and T2)	CaHCO ₃ and NaHCO ₃	Moderate Vulnerability (M)	Proximal (p)	R100 (Surface water recharges groundwater: 100% of stream flow is lost to shallow aquifer in the South Central Valley.	Tier 3	Class B L ib I _D Type 1 Type 2 NaHCO ₃ M p R100 Tier 3	The Lacustrine Aquifer is a intermediate flow production system at depth, although shallow saturated sediments may be low permeability. The aquifer is associated with the basin fill sediments of Little Humboldt River fluvial plan and sand dunes in the south valley that block historically have stream flow from leaving the valley. The aquifer is heavily used compared to the amount of recharge and is an intermediate size aquifer between 5 km ² and 25 km ² in area. There are moderate dewatering issues on the west side of the aquifer, which could be very severe with sustained long-term or new groundwater use. The groundwater is a good to fair source of drinking water and ranges from a calcium bicarbonate to sodium bicarbonate type water. Depth to groundwater is proximal. The aquifer has a moderate vulnerability from surface contamination based on the proximal groundwater depth. Surface water of the Little Humboldt River recharges the shallow groundwater system, loosing 100 percent of stream flow to groundwater.
Sand Dunes	E _s	Class B (?) (limited data, intermediate productivity)	Eolian (E _s)	Quaternary	Moderate (II): adjacent groundwater use includes irrigation groundwater use.	Intermediate Size Aquifer (b)	None	Type 2 (T2)	NaHCO ₃	Moderate Vulnerability (M)	Proximal (p)	Distal relationship. Not quantified.	Tier 3	Class B W iib Type 2 p R100 Tier 3	The Sand Dunes Aquifer is a intermediate flow production system, with sand deposits on the surface transitioning to fluvial plain or alluvial fan deposits at depth. The adjacent aquifer is heavily used compared to the amount of recharge and this an intermediate size aquifer between 5 km ² and 25 km ² in area. While there are no dewatering issues noted for this aquifer, there is limited data for the sand dunes area and groundwater pumping northwest of the sand dunes could result in severe dewatering impacts with sustained long-term or new groundwater use, affecting groundwater levels in the sand dunes area. The depth to groundwater is proximal and the groundwater is a fair source of drinking water and is a sodium bicarbonate type water. The aquifer has moderate vulnerability from surface contamination based on the proximal water table depth. The sand dunes block the Little Humboldt River, which forms the upgradient playa lake that fills when stream flow exceeds infiltration capacity.
Older Alluvium and Fans	A _f	Class B to B- (intermediate to low-intermediate productivity)	Alluvial Fan (A _f) Arid	Quaternary	Heavy (I): significant groundwater use. Major dewatering issues in the southwest valley.	Large Size Aquifer (c)	Major to Moderate Dewatering issues in the south and north valley areas (I _{DM} to I _b), respectively.	Type 1 (T1) with some Type 2 (T2) in the South Valley	CaHCO ₃ and some NaHCO ₃ in the South Valley	Moderate Vulnerability (M)	Proximal (p) to Deep (d)	Distal relationship. Not quantified. Groundwater may discharge into tributary streams on upper slopes of fans.	Tier 3	Class B / B- A _f ic I _D / I _{DM} Type 1 CaHCO ₃ & Type 2 NaHCO ₃ M p to d Tier 3	The Older Alluvium and Fans Aquifer is a low-intermediate flow aquifer, yielding moderate to large amounts of groundwater from wells. It is associated with basin fill alluvium and alluvial fan deposits on the valley edge. The aquifer is very heavily used in the southwest valley compared to the amount of recharge and is greater than 25 km ² in size. There are major dewatering issues in the south and north valley area, which could become more severe with sustained long-term or new groundwater use. The groundwater is a good source of drinking water and is a calcium bicarbonate type water with sodium bicarbonate type water in the south valley. The aquifer has moderate vulnerability from surface contamination and depth to groundwater is proximal near the river and deep on the valley edge. While no direct groundwater - surface water connection is noted for this aquifer, groundwater withdrawal from this aquifer in the north and south likely influences the local groundwater flow system and reduces the natural flow out of downgradient aquifers by capturing groundwater via numerous irrigation water supply wells.
Volcanic Bedrock	B _v	Class C (?) (low productivity)	Volcanic Bedrock (B _v)	Quaternary and Tertiary	Light (III) water use	Large Size Aquifer (c)	None	Type 1(?)	CaHCO ₃ (?)	Low Vulnerability (L)	Deep (Dp) - May be Shallow (s) / Very Shallow (vs) in mountain stream valley bottoms	Distal relationship. Not quantified. Groundwater likely discharges into mountain stream valley bottoms and recharges basin fill aquifers.	Tier 1	Class C B _v iic Type 1(?) L d Tier 1	The Volcanic Bedrock Aquifer is generally a low flow production system, although some fractures may be capable of yielding large amounts of groundwater. The aquifer has very light use compared to the amount of recharge and is a large size aquifer greater than 25 km ² . There are no known dewatering issues, groundwater is a good source of drinking water, and is a calcium bicarbonate dominate type water. The aquifer has a low potential to be impacted from surface contamination and the water table is deep, although shallow groundwater may be associated with mountain stream bottoms and springs that feed tributary streams.
Granitic and Metamorphic Bedrock	B _m	Class C (?) (low productivity)	Granitic (B _v) and Metamorphic (B _m) Bedrock	Triassic, Cretaceous, and Tertiary	Light (III) water use	Large Size Aquifer (c)	None	Type 1(?)	CaHCO ₃ (?)	Low Vulnerability (L)	Deep (d) - May be Shallow (s) / Very Shallow (vs) in mountain stream valley bottoms	Distal relationship. Not quantified. Groundwater likely discharges into mountain stream valley bottoms and recharges basin fill aquifers.	Tier 1	Class C B _{int} / B _{met} iic Type1(?) L d Tier 1	The Granitic and Metamorphic Bedrock Aquifer is generally a low flow production system, although some fractures may be capable of yielding large amounts of groundwater. The aquifer has very light use compared to the amount of recharge and is a large size aquifer greater than 25 km ² . There are no known dewatering issues, groundwater is a good source of drinking water, and is a calcium bicarbonate dominate type water. The aquifer has a low potential to be impacted from surface contamination and the water table is deep, although shallow groundwater may be associated with mountain stream bottom and springs that feed tributary streams.
Older Sedimentary Bedrock	B _s	Class C (?) (low productivity)	Sedimentary (B _s) Bedrock	Cambrian to Permian	Light (III) water use	Large Size Aquifer (c)	None	Type 1(?)	CaHCO ₃ (?)	Low Vulnerability (L)	Deep (d) - May be Shallow (s) / Very Shallow (vs) in mountain stream valley bottoms	Distal relationship. Not quantified. Groundwater likely discharges into mountain stream valley bottoms and recharges basin fill aquifers.	Tier 1	Class C B _{sed} iic Type 1(?) L d Tier 1	The Older Sedimentary Bedrock Aquifer is generally a low flow production system, although some fractures may be capable of yielding large amounts of groundwater. The aquifer has very light use compared to the amount of recharge and is a large size aquifer greater than 25 km ² . There are no known dewatering issues, groundwater is a good source of drinking water, and is a calcium bicarbonate dominate type water. The aquifer has a low potential to be impacted from surface contamination and the water table is deep, although shallow groundwater may be associated with mountain stream bottom and springs that feed tributary streams.

Gray highlighted columns provide additional information not mapped on page 1 of 2



Legend (see map key on page 2).

	Study area
	River/stream (perennial)
	Stream (intermittent)
	Lake or reservoir
	Major roads
Aquifer delineation	
	Young fluvial plain
	Fluvial plain terrace
	Upland pediment complex
	Ridge landslide bedrock
	Mountain complex bedrock
	Shallow bedrock outcrops
Aquifer production	Geologic setting
Groundwater quality	Depth to groundwater and connection with surface water resources

Sources:
1) Robson et al. (2000)
2) Hillier et al. (1979)
3) Hall et al. (1979)
4) Hall et al. (1980)
5) Bruce (1997)
6) Crosby (1978)

Plate C3. Shallow Aquifer Delineation of the Boulder-Longmont Area, Colorado



Plate C3 Shallow Aquifer Classification Key, Boulder-Longmont Area, Colorado (Page 2 of 2)

Aquifer Name	Map Color	Aquifer Productivity Classification	Geologic Framework Code	Geologic Age	Capacity vs. Productivity Classification	Aquifer Size Classification	Hydraulic Anthropogenic Impact Classification	General Water Quality Classification	Major Common Ions & Pollutants (if any)	Qualitative Aquifer Vulnerability Classification	Depth to Groundwater Classification	Groundwater / surface water Connection	Level of Analysis (Tier Level)	Aquifer Classification	Aquifer Description
Young Fluvial Plain	F _{pm}	Class B+ (upper-intermediate productivity) with isolated Class A- (lower-high productivity) areas on Boulder Creek.	Fluvial Plain Meandering (F _{pm})	Quaternary	Heavy (i): significant groundwater use urban development.	Large Size Aquifer (c) (limited lateral extent)	None	Type 1 (T1) with some Type 2 (T2) in the eastern portion of the aquifer.	CaHCO ₃ and isolated NaHCO ₃ and CaSO ₄ . Pollutants may include Fe, SO ₄ , some metals, bacteria, and radionuclides. Localized low-level water quality exceedances.	High Vulnerability (H) due to shallow water table and high productivity.	Very Shallow (vs) to Shallow (s)	D25 (shallow groundwater discharges into surface water: 0% to 25% of stream flow in Boulder Creek). Insufficient data are available for Dry Creek, Left Hand Creek, and St. Vrain Creek drainages, but conditions similar to the Boulder drainage may be present in areas with very shallow to shallow groundwater.	Tier 2	Class B+ F _{pm} ic Type 1 CaHCO ₃ /mixed H vs to s D25 (Boulder Cr) Tier 2	The Young Fluvial Plain Aquifer is a thin (i.e., <60 feet) intermediate to high flow aquifer, yielding moderate to large amounts of groundwater from shallow wells and is associated with floodplain deposits of the major drainages. The aquifer is heavily used compared to the amount of recharge and is greater than 25 km ² in area. There are no major groundwater dewatering issues, but groundwater use may reduce discharge to surface water. Groundwater is a good source of drinking water, but local pollution issues are common. The chemistry is mostly a calcium bicarbonate type water with some areas of sodium sulfate and sodium bicarbonate water. The aquifer has a high vulnerability from surface contamination and depth to groundwater is very shallow. Groundwater discharges to surface water in the Boulder Creek, although locally conditions may be reversed. Similar conditions are likely on the other drainages but there are insufficient data to characterize recharge/discharge relationships. Urbanization, municipal/domestic water use, waste water, and agricultural water use results in a complex relationship between water resources.
Fluvial Plain Terrace	F _{pt}	Class B+ (upper-intermediate productivity) with some isolated Class A- (lower-high productivity) areas on Boulder Creek and Left Hand Creek fluvial systems.	Fluvial Plain Terrace (F _{pt})	Quaternary	Heavy (i): significant groundwater use in urban development areas.	Large Size Aquifer (c) (limited lateral extent)	None	Type 1 (T1) with some Type 2 (T2)	CaHCO ₃ and isolated NaHCO ₃ and CaSO ₄ . Pollutants may include Fe, SO ₄ , some metals, bacteria, and radionuclides. Localized low-level water quality exceedances.	High Vulnerability (H) due to shallow water table and high productivity	Shallow (s) with some areas with Very Shallow (vs) areas.	D25 (shallow groundwater discharges into surface water: 0% to 25% of stream flow in Boulder Creek). Insufficient data are available for Dry Creek, Left Hand Creek, and St. Vrain Creek drainages, but conditions similar to the Boulder drainage may be present in areas with very shallow to shallow groundwater.	Tier 2	Class B+ F _{pt} ic Type 1 CaHCO ₃ /mixed H s D25 (Boulder Cr)Tier 2	The Fluvial Plain Terrace Aquifer is a thin (i.e., <60 feet) intermediate to high flow aquifer, yielding moderate to large amounts of groundwater from shallow wells and is associated with older fluvial terraces / sediments of the major drainages. The aquifer is heavily used compared to the amount of recharge and is greater than 25 km ² in area. There are no major groundwater dewatering issues, but groundwater use may reduce discharge to surface water. Groundwater is a good to fair source for drinking water, but local pollution issues are common. The chemistry is mostly a calcium bicarbonate type water with some sodium sulfate and sodium bicarbonate water. The aquifer has a high vulnerability from surface contamination and depth to groundwater is shallow. Groundwater discharges to surface water in the Boulder Creek drainage, although locally conditions may be reversed. Similar conditions are likely on the other major drainages but insufficient data are available to characterize the recharge/discharge relationships. Urbanization, groundwater use, waste water discharge, and agricultural water use results in a complex relationship between water resources.
Upland Pediment Complex	U _{ped}	Class B- (lower-intermediate productivity) with some areas of upper-intermediate productivity and limited-flow (L) aquifer conditions.	Undifferentiated Pediment (U _{ped}) of valley fill (sheet wash and eolian deposits) and sedimentary shale and sand stone formations	Quaternary valley fill and Cretaceous sedimentary formations	Heavy (i): significant groundwater use in developed areas with Moderate (ii) use is rural areas.	Large Size Aquifer (c)	None, although groundwater developed in the limited-flow area of the western flank are easily dewatered for all groundwater uses.	Type 1 (T1) on the west with increasing specific conductivity towards the east and Type 2 (T2) water quality	Mixed ion / cation chemistry with CaHCO ₃ , NaHCO ₃ , CaSO ₄ , MgSO ₄ , and NaSO ₄ type waters common. Dissolved solids content tends to increase from west to east. Pollutants may include Fe, SO ₄ , some metals, bacteria, and radionuclides. Localized low-level water quality exceedances.	High Vulnerability (H) due to shallow water table and moderate productivity	Shallow (s)	Distal relationship. Not quantified. Groundwater may discharge into local tributary streams and water bodies on upper slopes of pediment complex.	Tier 2	Class B-/L _i U _{ped} i/iic Type 2 mixed H s Tier 2	The Upland Pediment Complex Aquifer is a low to intermediate production system with some limited-flow conditions. The aquifer is composed of thin quaternary valley fill deposits (poorly sorted sheet wash and eolian deposits) overlaying Cretaceous sedimentary shale and sandstone formations. The aquifer system yields moderate amounts of groundwater from shallow wells but is flow-limited on the western flank near the Ridge Landslide Bedrock aquifer. The aquifer is heavily used compared to recharge (where production is sufficient) and is much greater than 25 km ² in area. There are no significant dewatering issues. Groundwater is a fair to poor source of drinking water and local pollution issues are common. The groundwater is a mixed ion/cation chemistry with increasing dissolved solid content west to east. The aquifer has a high vulnerability from surface contamination and depth to groundwater is shallow. There is no or limited direct groundwater connection to major creeks, but groundwater discharges to the fluvial plain aquifers which recharge the major creeks. Shallow groundwater may discharge locally to tributary streams.
Ridge Landslide Bedrock	D _f	Class B- (low-intermediate productivity) with lower flow potential in competent bedrock formations.	Resistant sandstone hogback with landslide / debris flow deposits on lower slopes composed of colluvium (D _f), and stream gravels / alluvium with some outcrops of sandstone / limestone in the valley unit	Quaternary valley unit and Cretaceous, through Pennsylvanian sedimentary units	Moderate (ii): some water use in developed areas.	Small (a) to Intermediate (b) Size Aquifer (Valley unit only and limited lateral extent)	None	Type 1	CaHCO ₃	Moderate Vulnerability (M)	Shallow (s) in valley unit and Deep (d) within the upper hogback unit.	Distal relationship. Not quantified. Groundwater may discharge into mountain stream valley bottoms and recharge basin fill aquifers.	Tier 2	Class B- D _f iia/b Type 1 M s Tier 2	The Ridge Landslide Bedrock Aquifer is a hogback setting with resistant sandstone uplands, debris flow slopes, and colluvium and stream gravels in the valley unit. Unconsolidated sediments are thin and sedimentary bedrock formations outcrop locally in the valley unit. Groundwater production is moderate, although in fracture controlled formations production likely decreases, yielding less groundwater. The aquifer has light use compared to the amount of recharge and is an intermediate size aquifer of 5 km ² to 25 km ² in area, although it is laterally limited within the valley units. There are no reported dewatering issues, groundwater is a good source of drinking water, and the chemistry is a calcium bicarbonate type water. The aquifer has moderate vulnerability from surface contamination and groundwater is shallow in the valley unit, but is likely deep in the upland bedrock formations. Shallow groundwater is generally associated with the mountain stream bottoms and springs that feed tributary streams. There is no direct groundwater connection to major creeks in the study area, but may connect downgradient with streams.
Mountain Complex Bedrock	B _{i/m}	Class C (?) (low productivity)	Intrusive and metamorphic crystalline bedrock (B _{i/m})	Precambrian	Light (iii) water use in undeveloped areas. Heavy use possible in developed mountain stream valleys.	Large Size Aquifer (c)	None	Type 1	CaHCO ₃	Low Vulnerability (L)	Deep (d) - May be Shallow (s) / Very Shallow (vs) in stream valley bottoms or near springs.	Distal relationship. Not quantified. Groundwater may discharge into mountain stream valley bottoms and recharge basin fill aquifers.	Tier 1	Class C(?) B _{i/m} iiic Type 1 L d Tier 1	The intrusive and metamorphic Bedrock Aquifer is a low flow production system, although some fractures may be capable of yielding large amounts of groundwater. The aquifer has very light use compared to the amount of recharge and is a large size aquifer. Locally, groundwater use may be greater in developed areas. There are no reported dewatering issues, groundwater is excellent source for drinking water, and the chemistry is a calcium bicarbonate type water. The aquifer has a low potential to be impacted from surface contamination, although locally in developed areas or stream bottoms vulnerability is higher. The water table is deep, although shallow groundwater may be associated with stream bottoms and springs that feed tributary streams. There is likely a groundwater connection with major creeks in the study area, but there are insufficient flow data to characterize discharge/recharge relationship between groundwater and major creeks / tributaries.

Gray highlighted columns provide additional information not mapped on page 1 of 2