JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 46, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2010

AN AQUIFER CLASSIFICATION SYSTEM AND GEOGRAPHICAL INFORMATION SYSTEM-BASED ANALYSIS TOOL FOR WATERSHED MANAGERS IN THE WESTERN U.S.[1]

Scott M. Payne and William W. Woessner[2]

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, an approach for classifying groundwater systems at the watershed scale is needed. A comprehensive classification system is proposed that combines recognized methods and new approaches. The purpose of classification is to provide groundwater professionals, policy makers, and watershed managers with a widely applicable and repeatable system that reduces sometimes cumbersome complex databases and analyzes to straightforward terminology and graphical representations. The proposed classification system uses basin geology, aquifer productivity, water quality, and the degree of groundwater/surface water connection as classification criteria. The approach is based on literature values, reference databases, and fundamental hydrologic and hydrogeologic principles. The proposed classification system treats dataset 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 mapping tools.

(KEY TERMS: hydrogeology; groundwater management; watersheds; watershed management; geographical information systems; rivers/streams; surface water/groundwater connection; land use.)

Payne, Scott M. and William W. Woessner, 2010. An Aquifer Classification System and Geographical Information System-Based Analysis Tool for Watershed Managers in the Western U.S. *Journal of the American Water Resources Association* (JAWRA) 46(5):1003-1023. DOI: 10.1111/j.1752-1688.2010.00472.x

INTRODUCTION

Ideally, every major land use decision should include consideration of the source(s) of water necessary to sustain the management decision, in addition to consideration of 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; Jury and Vaux, 2005). Clearly, the world faces growing water supply and availability challenges. In the arid and semiarid areas of the western United States (U.S.), demands for water will increase competition among agricultural, municipal, industrial, and ecological water users (Watson *et al.*, 1998; Loáiciga, 2000;

[1]Paper No. JAWRA-08-0201-P of the *Journal of the American Water Resources Association* (JAWRA). Received October 22, 2008; accepted June 22, 2010. **Discussions are open until six months from print publication**.

[2]Respectively, President, KirK Engineering & Natural Resources, Inc., P.O. Box 636, Sheridan, Montana; and Chairman, Department of Geosciences, The University of Montana, Missoula, Montana (E-Mail/Payne: scott_payne@kirkenr.com).

Loáiciga *et al.*, 2000; Field *et al.*, 2007; Kundzewicz *et al.*, 2007). Furthermore, groundwater is no longer regarded as a hydrologically independent natural resource. It is intimately connected to surface water often providing as little as 10% of perennial streamflow in watersheds dominated by low permeability materials to more than 90% in highly permeable settings (Winter *et al.*, 1998). The exchange between surface water and groundwater at multiple scales is considered a critical process underpinning the ecological systems associated with surface water systems (Naiman *et al.*, 1992; Stanford and Ward, 1992; Gibert *et al.*, 1997; Edwards, 1998; 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 inadvertently minimize the role of the groundwater system in resulting watershed plans. In an effort to assist managers with a mechanism by which they can incorporate watershed scale groundwater data in their planning process (Kendy, 2003; Carter *et al.*, 2007), a standardized framework is presented for basin conditions commonly found in the western U.S.

A methodology that summarizes hydrogeologic and hydrologic datasets and indices is proposed that is capable of describing both simple and complex groundwater systems in watershed settings. The methodology classifies and maps the watershed scale geological setting, aquifer productivity, groundwater quality, depth to groundwater, and the degree of groundwater/surface water exchange. The proposed methodology uses a tiered watershed groundwater classification approach that is based on an evaluation of the quantity and quality of available data. It organizes descriptions of groundwater conditions both graphically and descriptively (Figures 1-3; Appendix A). A nomenclatural scheme is developed for the primary purpose of facilitating communication among water scientists and professionals, managers, and citizens. The nomenclature is based on well supported classification ranges and hydrological principles that allow for users to organize, compare and contrast, and interpret groundwater datasets.

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 into units with similar hydrogeologic properties. Using grain size as an organizer Meinzer (1923, 1942) published some of the earliest tabulated hydraulic properties of

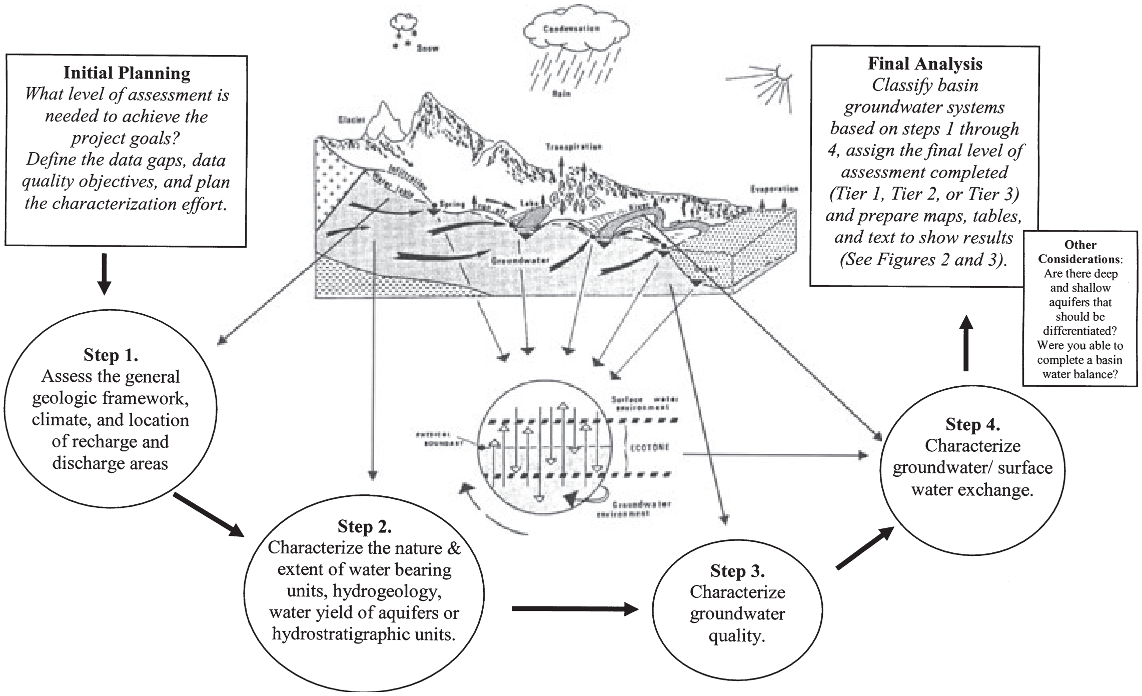

FIGURE 1. The Basic Components and Primary Steps Proposed to Classify Basin Groundwater Systems and a Diagrammatic Explanation of Groundwater/Surface Water Ecotones in the Mountain and Plains Landscapes (adapted from Gibert, 1991 and simplified from Payne, 2010).

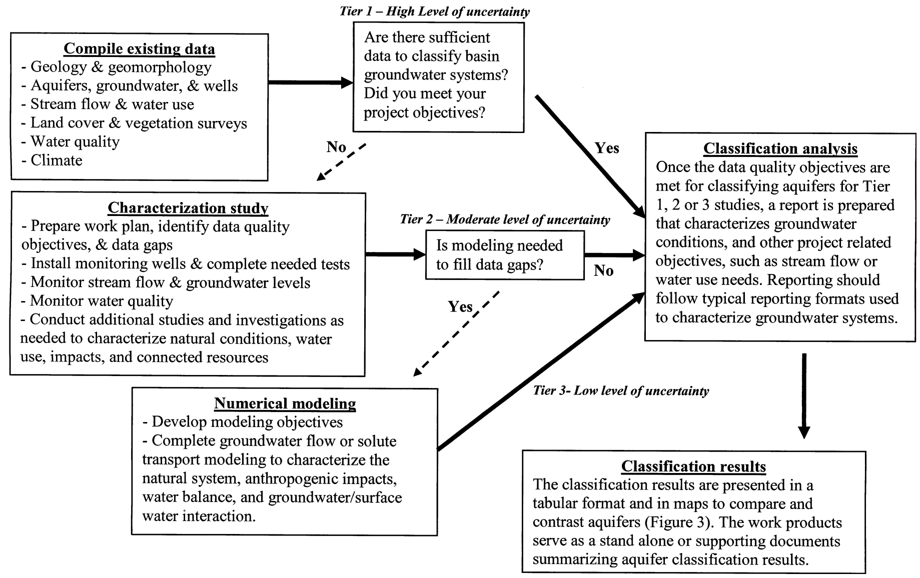

FIGURE 2. The Progression of Tier 1 Through Tier 3 Assessment Procedures and Types of Data Required to Classify Aquifers. Project budgets, schedules, and other factors may limit classification efforts to Tier 1 or 2 studies which have a lower level of reliability compared to Tier 3 studies.

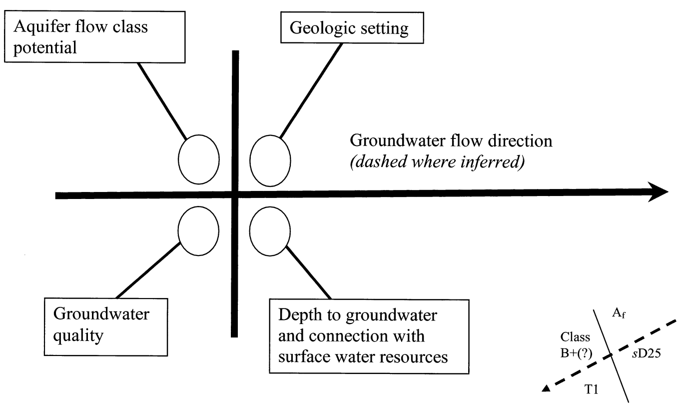

FIGURE 3. Aquifer Classification Mapping Framework. The arrow and aquifer classification information is positioned on maps at specific data points or within aquifers or areas within aquifers. The arrow indicates general groundwater flow direction and coded aquifer production, geologic setting, groundwater quality and depth to groundwater positioned in the four quadrants shown above. Aquifer class should be positioned in the upper right quadrant (or left quadrant, depending on the arrow direction). The groundwater flow direction arrow rotates similar to a compass arrow with each quadrant remaining stationary. An example is shown in the lower right portion of the figure. Question marks and dashed lines are used to show inferred groundwater flow direction or limited data support classification results.

sediments and rocks including 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). In 1937, Tolman described free water, confined water, fixed groundwater (or connate water), and perched groundwater. Tolman (1937), Thomas (1951), and Todd (1959) mapped and described groundwater occurrence in the U.S. within the general regions identified by Meinzer (1923). Characterization of groundwater resources of the U.S. was later expanded by Todd (1983) and Heath (1984) who both described the general characteristics of major groundwater production regions of the U.S. Heath (1984) classified transmissivity (relative aquifer transmission capacity) of major aquifers into four categories from very small (<25 m^2/day) to very large (>2,500 m^2/day). He based his ranking on reported literature values and common ranges of transmissivity. Heath also listed corresponding porosity, recharge, composition, and components of the primary aquifer systems.

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. Using mathematical models, Toth (1962, 1963) developed a groundwater flow system classification with local, intermediate, and regional flow systems. Conceptually, Toth's flow systems originate from a recharge area and end at a discharge area.

Bear (1972) classified aquifers on a qualitative scale ranging from good to poor aquifers, and relative permeability of groundwater systems on a scale ranging from pervious, semipervious, 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 regions in the U.S. with each region having unique mapping and reporting methods, hydrogeologic characteristics, and regional 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). Water-bearing units were grouped into aquifers and non-aquifers (aquitards, aquifuges, and aquicludes), and groundwater basins described as being comprised of one large aquifer or several connected and interrelated aquifers (Todd, 1959, 1980; Lohman, 1972; Poland *et al.*, 1972; Freeze and Cherry, 1979).

Broader basin scale classification was conceptually developed by Domenico (1972) who suggested groundwater systems are key components of watersheds, including their ecological systems. Research in ecohydrology has described groundwater dependent ecosystems and the river-groundwater exchange process (Hayashi and Rosenberry, 2002; Danielopol *et al.*, 2003, 2004, and 2006; Boulton and Hancock, 2005; Eamus and Froend, 2006). Winter (2001) classified landscapes into Fundamental Hydrologic Landscape Units where characteristic groundwater conditions are associated. Hibbs and Darling (2005), Anning and Konieczki (2005), and Maurer *et al.* (2004) used physiographic groundwater classifications and the flow characteristics of alluvial basins in western U.S. and Mexico in their classifications. Most were developed for specific geographic areas and are not necessarily applicable in other geographic areas. The 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. Similarly, the U.S. Geological Survey (USGS) (2000) published the Groundwater Atlas of the U.S.

In addition to the physical properties and flow characteristics approach to classifying groundwater systems, other classification methods use water supply potential, water quality, and the potential to contaminate groundwater systems as criteria. Groundwater development potential, aerial coverage, relative capacity of aquifers *vs.* demand, and vulnerability classifications are described using a scoring methodology by Kreye *et al.* (1998) and Berardinucci and Ronneseth (2002). EPAs DRASTIC model classifies aquifer vulnerability and was specifically developed to assess aquifer contamination potential (Aller *et al.*, 1987).

In general, groundwater quality has been classified from good to poor using several approaches (e.g., Walker, 2001; Lowe *et al.*, 2002; Texas Natural Resource Conservation Commission, 2003). The U.S. Clean Water Act of 1977 requires groundwater quality be classified and in most states these classifications are based 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.

In spite of these advances in classifying a wide range of local to regional scale groundwater conditions, there exists no comprehensive framework for describing groundwater conditions in watershed scale settings or an approach that is linked explicitly to land use planning. This paper proposes an approach and method for such a classification. The proposed classification scheme is designed to integrate methods described in the literature along with new approaches that are intended to enhance the exchange of information among hydrogeologists, watershed and land use planners and managers, and the public.

APPROACH

A hierarchical approach is proposed for organizing, presenting, and describing groundwater conditions for watershed management applications, and applying a standardized nomenclature, new mapping techniques, and a three-tiered assessment methodology. This approach is designed to improve communication between groundwater professionals and natural resource managers, similar to the classification system for natural rivers developed by Rosgen (1994, 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 the system. Rosgen's method has received criticism by some that suggested the classification system is limited in utility and is more appropriate as a communication tool (e.g., Juracek and Fitzpatrick, 2003; Simon *et al.*, 2007). This proposed groundwater classification is not a structural adaptation of Rosgen's method. It does not attempt to include an evolution and functional process approach as suggested by Rosgen.

This groundwater classification system does parallel Rosgen's approach as it is supported by a groundwater database including literature values that are used to define general characteristics of groundwater systems, and it emphasizes an approach to better communicate hydrological information to end users (Simon *et al.*, 2007). In addition, a tiered approach is adapted from Rosgen's methodology to define the level of assessment and the general quality or usefulness of data collected to complete the classification process. Criteria are also adapted from other published classification systems to describe basic groundwater quality and depth to groundwater, which are identified in the Methods section. The proposed classification scheme is based on fundamentally different scientific principles from Rosgen's approach (e.g., stream *vs.* aquifer function); however, the proposed method is similar in that end users benefit from a standardized classification system that is intended to improve communication at multiple levels.

Finally, a new mapping procedure that provides a graphical summation of watershed groundwater data is presented and applied using a Geographical Information System (GIS). The proposed mapping procedure is not intended to replace text, figures, maps, and tables in comprehensive groundwater reports, but to provide a practical graphical application that groundwater professionals and watershed specialists can use to illustrate and generalize groundwater conditions. The mapping is also designed to assist managers in determining the relative importance of groundwater as a component of a watershed and to allow for comparisons of watershed scale groundwater resources among sites.

METHODS

Four fundamental components are selected as the principal parameters needed to classify watershed scale groundwater conditions. These include the following:

- Geologic framework
- Aquifer productivity and corresponding hydrogeologic properties
- Groundwater quality
- Groundwater/surface water exchange and depth to groundwater

The selection of these four parameters is based on ensuring 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. Furthermore, by limiting the classification scheme to these factors, it was recognized that the availability of hydrogeological data compiled for individual watersheds will likely vary significantly. There are additional criteria that broaden the groundwater classification system, components that are described in Payne (2010); however, this paper is limited to the criteria listed above.

LEVEL OF ASSESSMENT

Groundwater system classification begins with characterizing the physical system, including the geology, groundwater hydraulics, surface water features, and in some cases wetland vegetation and aquatic biology (Figure 1). Specific field assessment procedures are not described within this work, and the reader is directed to standard texts and references. A three-tiered inventory approach for classifying basin groundwater systems is proposed (Table 1; Figure 2). Tier 1 assessments are completed using sparse datasets and are therefore less reliable. Tier 2 and Tier 3 assessments rely on more extensive information. In general, the higher the tier designation the more robust the dataset and likelihood that analyzes and interpretations appropriately represent (or lower uncertainty) the watershed groundwater conditions.

GEOLOGIC FRAMEWORK

The geologic framework of a watershed is ideally 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 sedimentary basin depositional models. Igneous and metamorphic settings can dominate some western U.S. watersheds, and basin systems can contain complex structural histories that need consideration. The goal of the geological framework analysis is to identify potential watershed scale hydrostratigraphic units and the likely physical conditions that affect the presence of groundwater, range of flow conditions, and aquifer properties (Maxey, 1964; Domenico, 1972).

Typically, for mountainous western basin 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 valley side groundwater systems dominated by

TABLE 1. A Three Tier Assessment Hierarchy for Aquifer Classification.

Class	Description	Data Collection Summary	Data Quality Objective
Tier 1	Semiquantitative	Tier 1 assessments generally rely on available local, state, and federal data sources for groundwater classification. New data are collected as budgets allow and are used to support 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, streamflow measurements, wetland surveys, and water quality monitoring, etc. to fill data gaps.	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.

alluvial fan deposits and lowland groundwater systems dominated by riverine deposits. In addition it is assumed that watersheds of the western U.S. have common geomorphic and geologic features that control groundwater movement, water production, and water quality (Table 2).

TABLE 2. Geological Framework for Aquifers Associated With Common Sedimentary/Bedrock Systems of the Western U.S.

Geologic Framework/ Depositional/Classification	Mapping Code
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[1]	B_x
Undifferentiated	U_x

Note: An “x” is included on the end of the mapping codes as an option to indicate local lithology changes.

[1]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 semiconsolidated materials should be included in the sedimentary codes in Table 2.

AQUIFER PRODUCTIVITY AND CORRESPONDING HYDROSTRATIGRAPHIC PROPERTIES

Once the geological framework has been classified 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 (Maxey, 1964) 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 levels should be compiled and mapped to interpret flow direction.

Aquifer productivity and hydraulic properties of groundwater systems can be compiled from available site-specific literature, concurrent studies, or from general hydrogeologic references. Aquifer properties include: porosity (n), specific yield (Sy), storage coefficient (S), hydraulic conductivity (K), transmissivity (T), thickness of the aquifer (b), and cross-sectional area perpendicular to flow (A) to allow the calculation of groundwater discharge (Q) as needed. A water balance computation and a surface water routing analysis (e.g., position of surface flow loss or gain in streams, rivers, and irrigation water conveyance) are also useful to help characterize aquifer function, groundwater/surface water exchange processes, and groundwater recharge and discharge relationships (Winter, 1981; National Research Council, 2004).

As part of this work, an aquifer productivity dataset was formulated from published groundwater studies and databases (Table 3) by compiling information of aquifer conditions, well production rates, and general aquifer properties (K, T, Sy, and specific capacity). The data were correlated to reported well production rates and grouped into four general categories: high flow, intermediate flow, low flow, and limited or no flow (Table 4). The parameter ranges selected to describe potential well production potential are based on over 20,000 individual well records and aquifer property descriptions. The data were organized into a spreadsheet database, and grouped by geographical location, and geological parent material. Data grouped into general aquifer flow potential categories were evaluated by constructing box and whisker plots to determine the 25th and 75th quartiles, maximum and minimum values, mean, median, standard deviation, and confidence intervals for data groups. The results reported in Table 5 were evaluated further by comparing them with the reported common ranges of hydraulic characteristics reported for low, intermediate, and highly productive aquifers by Heath (1984) and Bear (1972) (Appendix A; Figures S1-S3). The numerical classifications presented here were rounded to whole numbers using English units and then converted to metric units (Table 5).

The narrative classification in Table 4 (based on empirical criteria) and numerical productivity ranges in Table 5 are used together to support the aquifer productivity classification. It is suggested that during the classification process, most emphasis should be placed on using the narrative classification as the definitive factor for selecting the final productivity classification. In addition, while some aquifers may have less production potential than others, aquifers classified as having moderate or low production potential may serve as important water supplies or sources of discharge to wetland, river, and riparian ecosystems.

In addition to aquifer productivity classification, aquifer size, relative aquifer capacity *vs.* productivity (Kreye *et al.*, 1998; Berardinucci and Ronneseth, 2002), anthropogenic impacts associated with storage depletion and infiltration can be included in this classification system. These additional classification criteria are not included in this paper but their importance and application to groundwater classification are described by Payne (2010).

TABLE 3. Literature Cited and Geographic Location for Aquifer Productivity Data.

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 (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
Kontis *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

TABLE 4. Narrative Classification and Indicators for Classification of High, Moderate, and Low Production Aquifers.

Code	Flow Class Potential[1]	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% 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 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.

Note: L_f, aquitard.
[1]Aquifer flow potential is dependent on the geometry of the aquifer as well as the hydraulic properties in Table 5. Quantitative partitions are not proposed for this reason but described as narrative classification criteria.

TABLE 5. Hydraulic Indicators for Classification of High, Intermediate, and Low Production Aquifers.[1]

Class	Flow Potential	SpC	*K*	*T*	Sy[2]	*S*[3]	*i*[3]
A	High flow	>58	>76	>2,300	0.12-0.35	Variable	Variable
B	Intermediate flow	0.6-58	0.8-76	23-2,300	0.10-0.35	Variable	Variable
C	Low flow	<0.6-0.01	<0.8-0.01	<23-0.23	0.02-0.12	Variable	Variable
L_f	Limited or no flow	<0.01	<0.01	<0.23	<0.02	Variable	Variable

Notes: SpC, Specific capacity (l/min per meter of drawdown); *K*, hydraulic conductivity (m/day); *T*, transmissivity (m^2/day); Sy, specific yield in unconfined aquifers; *S*, storage coefficient for confined and semiconfined aquifers; *i*, gradient; L_f, aquitard.
[1]Numerical values in this table provide an indication of the potential aquifer productivity. The ranges in this table should be compared with the narrative aquifer flow criteria in Table 4 to classify aquifers as low, intermediate, or high flow systems. Additional productivity subclasses that separate the Class A, B, and C productivity ranges are described by Payne (2010).
[2]Adapted from Johnson (1967).
[3]Insufficient data to partition storage (*S*) into high, intermediate, and low flow aquifers.

GROUNDWATER QUALITY

A logical classification scheme for groundwater quality is to relate it to 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 and that criterion is used in this work (Table 6). Other criteria such as the dominant cation and anion chemistry, presence of common pollutants, and an aquifer's susceptibility to becoming contaminated, can also be used as additional water quality descriptors. These criteria are not included in this initial description of the classification, but an expanded version of the classification scheme is described in Payne (2010).

GROUNDWATER/SURFACE WATER EXCHANGE AND DEPTH TO GROUNDWATER

The primary purpose of this classification component is to characterize if streams are gaining or losing groundwater and if there is seasonal variability in the exchange. In addition, depth to groundwater is included in classification criteria since depth to groundwater is a critical component for assessing groundwater/surface water exchange, although depth to groundwater has other important relationships related to conserving and developing groundwater such as vulnerability assessments and installation of wells. The criteria used to classify how portions of the groundwater system are linked with surface water features include the depth of groundwater

TABLE 6. General Groundwater Quality Classification.

Criteria	Good Type 1 (T1)	Limited Type 2 (T2)	Poor Type 3 (T3)	Very Poor Type 4 (T4)
Specific conductance[1] (SC) (microsiemens per cm at 25°C)	<1,000[2]	1,000 and <2,500	2,500 and 15,000	>15,000
Domestic/municipal water supply	Yes[3]	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
Irrigation use	Yes[3]	Yes, typically	Yes, marginally useful	No
Commercial and industrial use	Yes[3]	Yes, marginally useful	Yes, marginally useful	Some uses
Wildlife/livestock/aquatic life/phreatophytes use	Yes	Yes, marginally useful	Yes, marginally useful	No

Note: CWA, Clean Water Act.
[1]Adapted from the State of Montana Administrative Rules 17.30.1011.
[2]An "e" modifier may be used with Type 1 water quality classification if the SC is below 250 suggesting a relatively good/excellent water quality is present: T1e.
[3]With cost-effective or no treatment.

below land surface, direction and magnitude of vertical groundwater gradients (with sufficient data from nested well sites), estimated proportion of surface water that is derived or lost to groundwater, and the presence or absence of ecological indicators associated with shallow groundwater (Winter *et al.*, 1998; Winter, 1999; Hayashi and Rosenberry, 2002; Hancock *et al.*, 2005; Eamus and Froend, 2006). Payne (2010) describes in more detail the groundwater recharge process and methods to determine rates, water level variability, and the need for completing a groundwater/surface water balance.

Developing a classification scheme describing the depth to groundwater below land surface is arbitrary. For example, shallow groundwater is defined as ranging from <0.33 m (1 foot) (U.S. Army Corps of Engineers, 1987) to 30 m (100 feet) (USGS, 1999) below ground surface. In this paper, descriptions from the literature and professional judgment were used to develop criteria describing depth to groundwater. This work establishes a classification using four depths: very shallow, shallow, proximal, and deep (Table 7). In addition, consideration must also be given to the length of time groundwater remains at or above the specified elevations (Table 7). Based on a literature review, a depth of 2 m is used to distinguish "very shallow" or near-surface groundwater from "shallow" groundwater (U.S. 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; U.S. Army Corps of Engineers, 1987; Hayashi and Rosenberry, 2002; Hancock *et al.*, 2005).

Groundwater levels 2 and <7 m below ground surface are classified as shallow groundwater. Some trees, shrubs, and herbaceous plants are able to tap groundwater at this depth (Candell *et al.*, 1996), but obligate wetland plant species commonly do not access the water table in this depth range (U.S. Army Corps of Engineers, 1987), and discharge to surface water is less likely.

Clearly, many portions of a watershed are likely to have depths to groundwater exceeding 7 m below ground surface. Depths of groundwater 7 and <30 m are classified as proximal depths. Table 7 also

TABLE 7. Depth to Groundwater Classes for Unconfined Aquifers.[1]

Criteria	*vs*	*s*	*p*	*d*
Depth to water (m)[2]	<2[3]	2 to <7[4]	7-30	>30
Strong GW/SW connection	Very common	Fairly common	Uncommon	Very uncommon
Water table gradient	Variable	Variable	Variable	Variable

Notes: *vs*, very shallow; *s*, shallow; *p*, proximal; *d*, deep.
[1]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., $d_{>200}$).
[2]Water tables <0.33 m below ground surface for more than 14 days/year are likely a wetland.
[3]High points must be maintained, on average, 14 days/year.
[4]Low point can be >7 m deep below the stream channel during the nongrowing season.

includes a class used to indicate that the water table is "deep" meaning it is 30 m or more below ground surface (USGS, 1999) and the ability to indicate if depth to groundwater is much deeper than 30 m. The depth to groundwater is designated for unconfined aquifer conditions as noted in Table 7; however, the depth to the top of confined and semiconfined aquifers can also be used if there is a direct groundwater connection between the confined system and surface water resource.

Table 8 partitions estimates of groundwater discharge contributions to wetlands, streams, rivers, and lakes (minor to significant). In some cases, surface water resources may recharge shallow aquifers. In these situations, the analysis is similar but reversed where losing lacustrine systems 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 streamflow lost to groundwater (Table 8) for a given stream reach or water body. If there are sufficient data to provide a more accurate range (e.g., R equals 5-10% or R5-10) or a specific percentage (e.g., D35), these percentages can be used instead of the quartiles in Table 8. Synoptic surface water flow data coupled with in or near channel groundwater/surface water elevation data provide information needed to characterize groundwater/surface water exchange (Winter *et al.*, 1998). In cases where an aquifer is distal from surface water or wetlands, the R and D subclasses should be left blank.

TABLE 8. Groundwater/Surface Water Exchange Classes for Unconfined Aquifers Near Surface Water Features.[1]

	Percent	Class
Gaining streams/stream reaches[2] – percent surface water flow gained from groundwater[3]		
Low contribution	<25%	D25
Moderate contribution	25-50%	D50
High contribution	>50-75%	D75
Very high contribution	>75%	D100
Losing streams/stream reaches[2] – percent surface water flow lost to groundwater[3]		
Low contribution	<25%	R25
Moderate contribution	25-50%	R50
High contribution	>50-75%	R75
Very high contribution	>75%	R100

[1]For 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). Seasonal classification of groundwater/surface water exchange may be required to classify variability using spatial and temporal presentations.

[2]In 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).

[3]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 streamflow lost along a reach to groundwater and *D* represents the percent streamflow gained along a reach from groundwater.

CLASSIFICATION OF MULTIPLE AQUIFER SYSTEMS

Classification of basin aquifers must include the ability to differentiate three-dimensional groundwater conditions including the presence of multiple aquifers. For example, an alluvial fan or fluvial plain setting may include deeper water-bearing units that exhibit very different groundwater production potential, 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 deep water-bearing units as commonly done when formulating a three-dimensional groundwater flow system of a complex watershed scale groundwater system (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 (e.g., Maxey, 1964; Wilkins, 1998; Woodward *et al.*, 1998; Magruder and Payne, 2008).

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. A case study completed by the authors classifies the deep and shallow aquifers in the Lower Ruby Watershed, Southwest Montana and demonstrates the classification of multiple aquifer systems (Payne, 2010).

RESULTS – APPLICATION OF AQUIFER CLASSIFICATION

This section outlines the proposed approach for organizing and tabulating groundwater classification results (Figure 1; Table 1; Appendix A). The assessment data and field observations may be averaged over the entire aquifer, to subareas 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 then 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 groundwater systems within and among watersheds. Below is the proposed order for classifying groundwater systems as well as a hypothetical example using the primary classification codes:

- Aquifer productivity class + geologic framework
- General water quality using specific conductance class
- Depth to groundwater + groundwater/surface water exchange class
- Level of analysis

An example set of classification codes for an aquifer:

Class A F_{pm} *Type 1 vsD25 Tier 2*

Mapping provides a visually appealing and concise way to represent spatial tabular data. Selecting the mapping method depends upon the desired level of analysis, scale, spatial and temporal data coverage, and budgetary limitations. Figure 3 illustrates the proposed mapping system for aquifer classification and Figure 4 shows hypothetical variability of depth to groundwater and groundwater and surface water exchange in riverine settings. Uncertainty is visually shown on the mapping symbol using dashed lines and question marks where flow direction is inferred or if specific classifications are inferred.

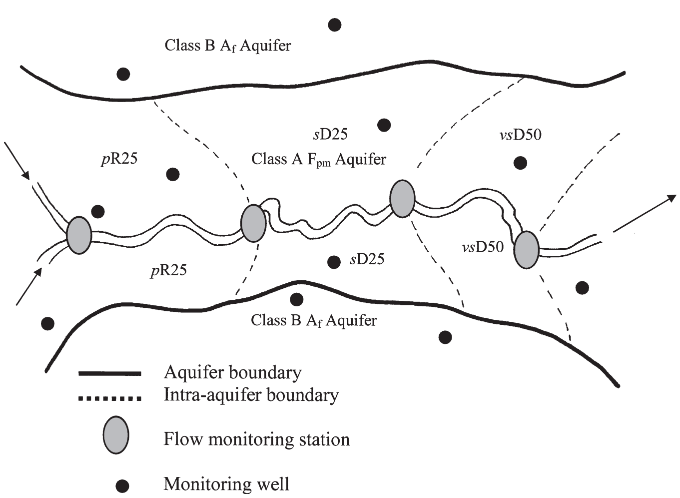

FIGURE 4. A Diagrammatic Example of Aquifer Classification Along a Fluvial Plain Aquifer and Meandering River Reach With Variable Groundwater/Surface Water Connection and Depths to the Water Table. See Tables 3, 4, 7, and 8 for classification criteria. Seasonal variability at some locations may change with time from gaining to loosing as a function of climate and use of water resources. Aquifer classification will also change seasonally and should be adjusted to reflect variability.

Application of the aquifer classification mapping is illustrated in Figures 5 and 6, and summarized in Table 9, showing simplified 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 sediments 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 at the watershed scale. Their work presented a water balance as well as synoptic streamflow monitoring data. The adjacent upland areas next to the basin fill sediments are classified but due to limited data in the upland and bedrock areas, the upland classification is considered a Tier 1 level analysis (Table 9). For applied studies, a large-scale map should be prepared for reporting purposes to graphically show classifications and tabulated results in a format similar to that used on geological maps. The tabulated results should be with the map to provide an explanation of the coded information on the map. Application of the classification mapping process is further developed by Payne (2010) illustrating how the mapping is applied to watershed settings in the western U.S. using large-scale maps and GIS in the Tahoe Basin, California; Paradise Valley Watershed, Nevada; Boulder – Longmont Watershed, Colorado; and Lower Ruby Valley Watershed, Montana.

Geographical Information System 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 and water wells. Groundwater systems should be assigned colors or geologic patterns to assist end users (Figure 6). 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.

DISCUSSION

The aquifer classification system described in this paper is intended to improve communication and provide government agencies, natural resource managers,

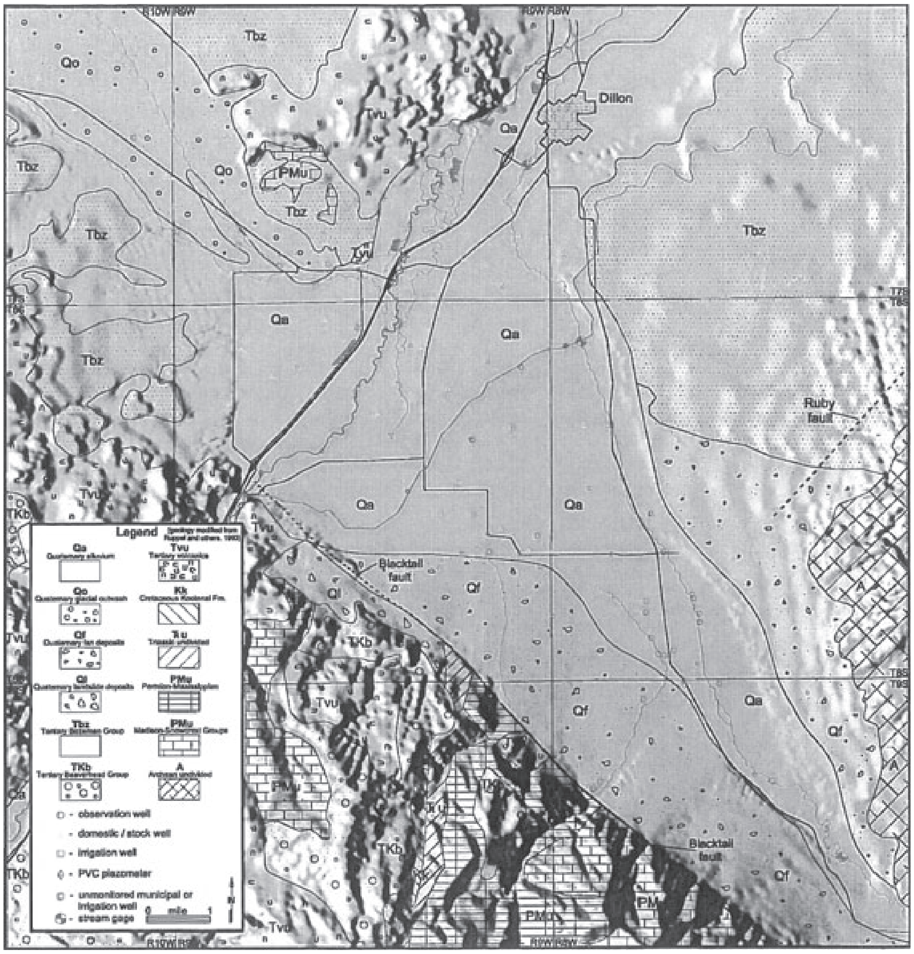

FIGURE 5. Generalized Geology of the Upper Beaverhead Basin
(adapted from Uthman and Beck, 1998 and modified from Ruppel *et al.*, 1993).

land use planners, and conservation organizations with a methodology that is repeatable, useful to manage watershed scale groundwater resources, and plan conservation activities. It is realized that the proposed classification system requires further application in order to test the proposed process and develop support for wider application and acceptance.

This classification includes four primary criteria: (1) geological framework, (2) aquifer properties/productivity, (3) groundwater quality, and (4) the degree of groundwater/surface water exchange. The proposed aquifer classification provides a format for mapping groundwater conditions across large regions and allows for comparison of conditions among watersheds as surface mapping units. Subsurface groundwater flow direction may not necessarily follow watershed boundaries topographic flow patterns and cross into adjacent watersheds. Once mapped and aquifers classified, the results 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 showing groundwater conditions provides the end user with a useful tool to integrate groundwater resource data with natural resource planning efforts. Most digital groundwater data are derived from accessing point files associated with wells, which is useful for some purposes, but for planning exercises on a landscape scale, aquifer characteristics generally have to be characterized across larger areas by groundwater professionals in order to be useful by others. This method provides an approach to consistently map and compile point data and develop groundwater condition maps at the watershed/basin scale. Further, classification can be depicted by applying GIS software that converts point file data into landscape interpretations of groundwater conditions.

The proposed mapping techniques are not meant to replace the text, figures, maps, and tables in ground-

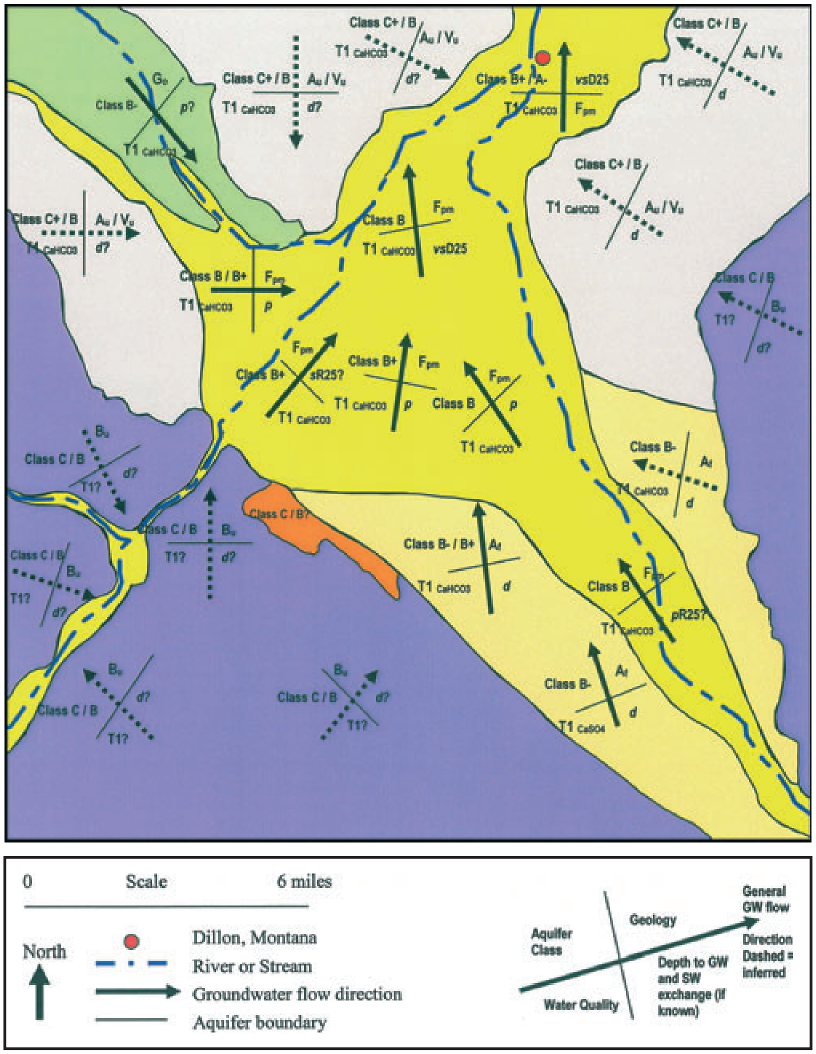

FIGURE 6. Simplified Upper Beaverhead Basin Aquifer Classification (see Tables 1 and 9 and Figure 3 for additional aquifer classification information). Adapted from Payne (2010).

TABLE 9. Upper Beaverhead Basin Aquifer Classification Summary (See also Figure 6).

Aquifer Name	Map Color	Flow Potential	Geologic Framework	Water Quality	Groundwater / Surface Water Connection	Level of Analysis and comments
Quaternary Fluvial Plain Beaverhead River		B+ / A-	F_{pm}	Type 1 $_{CaHCO3}$	*s* to *s*D25- near the Beaverhead River at Dillon	Tier 3: Beaverhead River gains groundwater on the lower reach.
Quaternary Fluvial Plain Blacktail Deer Creek		B	F_{pm}	Type 1 $_{CaHCO3}$	*d* to *vs*D25 near confluence with the Beaverhead River	Tier 3. Blacktail Deer Creek loses water along most of its length.
Quaternary Fluvial Plain Rattlesnake Creek		B	F_{pm}	Type 1 $_{CaHCO3}$	*d* to *s*	Tier 3: Rattlesnake Creek loses water along most of its length.
Quaternary Alluvial Fan		B-	A_f	Type 1 $_{CaHCO3 / CaSO4}$	*d*	Tier 3: fan aquifers interface with lower Tertiary units.
Quaternary Glacial Outwash		B-?	G_o	Type 1 $_{CaHCO3}$	*s*	Tier 1
Quaternary Landslide		C or B?	D_f	Type 1?	*d*?	Tier 1
Tertiary Bozeman & Volcanics (undifferentiated)		C+ to B	A_u / V_u	Type 1 $_{CaHCO3}$	*d*?	Tier 1. A thick sequence of gravel, fines, and volcanic deposits common.
Bedrock Undifferentiated		C / B	B_u	Type 1?	*d*?	Tier 1

Notes: *vs*, very shallow; *s*, shallow; *p*, proximal; *d*, deep; ?, professional judgment. Source: Uthman and Beck (1998).

water 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, or where conditions may not favor groundwater development because an area is highly developed or already impacted. Payne (2010) provides additional information on mapping impacts in groundwater settings and case studies showing examples. Mapping water supply wells and other wells as a GIS layer is also useful to support aquifer classification and consider the level of groundwater development in study areas. While aquifer classification provides a framework within which discussions and questions can be framed, the comprehensive studies used to develop the classification results are the primary source of information that ultimately quantitatively frames groundwater conditions. Further, mapping groundwater conditions, especially in relationship to surface water exchange, may need to include seasonal variability. Finally, groundwater flow direction may cross surface drainage patterns in watersheds and mapping groundwater interaction with adjacent watersheds is appropriate when classifying aquifers.

The mapping approach in Figure 3 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 can be applied that may improve the usability and comprehension of the classification results (Figure 7). As suggested by a reviewer of this work, 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 becomes more widely accepted.

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 repeatable and comprehensive classification framework that can be applied under conditions of when data are either sparse or rich. In cases where there are limited data, 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 groundwater systems in watershed settings.

Clearly, the spreadsheet aquifer productivity database developed to support this classification scheme can be improved upon with the addition of more data and rigorous statistical analysis. It would be desirable to have agencies such as the U.S. Geological Survey and state water and geological surveys develop a national database and improve the GIS mapping 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.

Within the professional community, most groundwater professionals exercise a fairly high level of freedom in technical reporting and interpretation of hydrologic data. From an applied perspective, all groundwater systems 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. Classifying watershed scale groundwater systems is not an either/or process, meaning that site-specific conditions may warrant not 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 giving weight to the representation of information that would most aid land use planning and watershed management decision making (e.g., the end user of hydrogeologic data). As supported above, 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 on how to coalesce the many reporting formats, mapping techniques, databases, and units into a single national database for groundwater systems.

CONCLUSIONS

Groundwater systems assessed on the scale of watersheds are often complex in that they are linked to surface water features, groundwater may cross watershed boundaries *vs.* following the surface drainage patterns, and they provide water for municipal, residential, agricultural, and industrial use. Traditionally, large-scale groundwater investi-

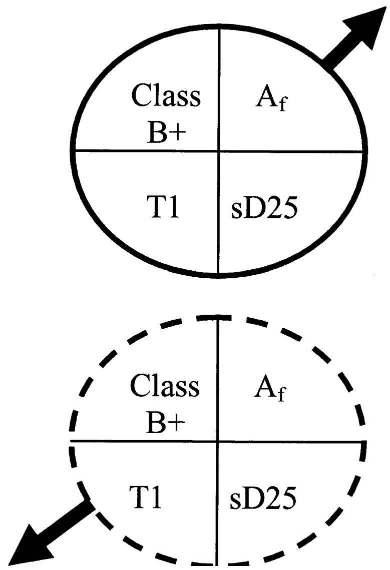

FIGURE 7. An Alternative Mapping Approach for Classification Results. A dashed circle is used to indicate uncertainty in the classification results. Each quadrant shows the same information as in Figure 3.

gations have not been reported in the context of a standardized groundwater classification system that can be applied in other groundwater settings. To address this need, the proposed method uses: (1) geological framework, (2) aquifer productivity, (3) groundwater quality, and (4) the proportion of surface water gained or lost to groundwater to classify watershed scale groundwater systems. The classification system results are displayed in both map and table form and the classification system provides a method to not only describe groundwater conditions in an individual watershed, but also compare groundwater conditions among watersheds using standardized classification criteria. It provides a communication tool for managers, planners, and conservation groups to consider groundwater conditions at the watershed scale and support natural resource decision making. To this end, the watershed scale groundwater classification system presented here is an important step in improving communication among scientists and engineers, planners and managers, and the public.

APPENDIX A

Recommended Contents, Description, and Examples for Tabulated Aquifer Classification.

Groundwater Classification Criteria	Description	Sample Code and/or Classification
Name of aquifers	Each classified aquifer should be named. Where areas within aquifers are classified separately because of changes in productivity, water quality, or connection with surface water resources those areas can be classed 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. Guidance for naming aquifers is provided in USGS (2000), Laney and Davidson (1986), and ASTM (2004).	- Blacktail fan aquifer - Ruby Range bedrock aquifer - Beaverhead River Floodplain 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 maximum, minimum, and median production values for specific capacity (SpC), hydraulic conductivity (*K*), transmissivity (*T*), and specific yield (Sy), as examples. The aquifer properties will range spatially depending on the number of wells and the quality of data. Professional judgment should be used to determine which measure, such as the median or 95th 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. Question marks can be used after classifications to indicate insufficient data.	Class B Intermediate flow aquifer SpC (min, max, median) 3, 42, 25 (l/min/m drawdown) *K* (min, max, median) 2, 80, 55 (m/day) *T* (min, max, median) 450, 9,400, 6,200 (m^2/day) Sy (estimated) 0.15
Aquifer thickness, annual head change, and related properties	These data are useful for aquifer analysis. Other hydraulic parameters can also be tabulated such as gradient or average groundwater velocity to help describe the aquifer. See Payne (2010) for classification of these data.	Aquifer thickness: 12-102 m Typical annual head change: 1.65 m
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_f (alluvial fan) B_{ls} (bedrock–limestone) F_p (fluvial plain) F_{pt} (fluvial plain older terrace) U_{bf} (undifferentiated basin fill)

APPENDIX A

Continued

Groundwater Classification Criteria	Description	Sample Code and/or Classification
Aquifer productivity, development, and aquifer size	See Payne (2010)	
Storage depletion and artificial recharge impacts	See Payne (2010)	
General groundwater quality	This 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 6. See Payne (2010) for common ion chemistry classification.	T3 or Type 3 water
Water quality impacts	See Payne (2010)	
Aquifer vulnerability	See Payne (2010)	
Depth to groundwater and groundwater/surface water exchange	This classification criterion identifies the 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 streamflow data and water level data are needed to make a clear distinction between classes of aquifer discharge to surface resources and surface water recharge to groundwater. In cases where there is insufficient data for selecting subclasses related to flow contribution, this part of the criteria can be blank 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 7 and 8).	*vs* Very shallow depth to groundwater – insufficient data to quantify connection with surface water (05/09-08/09) *s*D25 Shallow depth to groundwater with 0-25% of surface water flow coming from groundwater (09/09-04/10) *p*R25 to *p*D25 Proximal depth to groundwater with a variable connection to surface water (year long) *d* Annual deep depth to groundwater with no nearby contribution to surface water *vs*D90-95 Spring Creek 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 reliable the classification results and less uncertainty (see Table 1).	Tier 1, Tier 2, and Tier 3

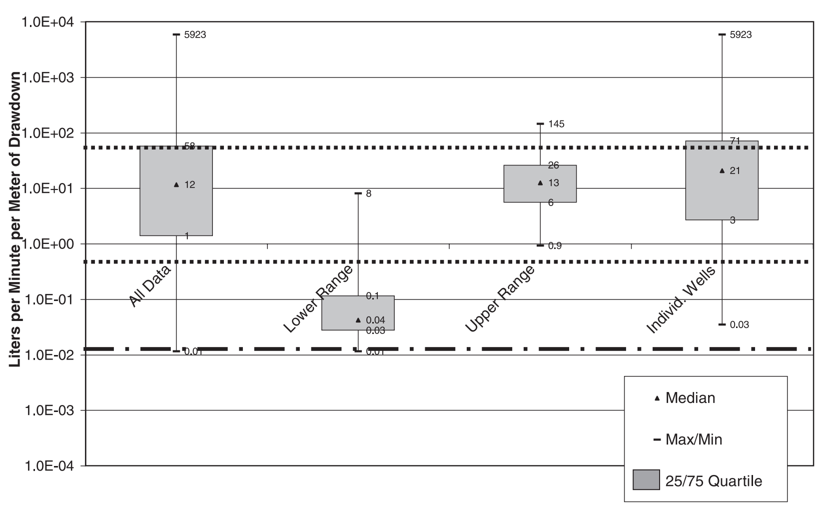

FIGURE A1. Box and Whisker Plot of Specific Capacity Datasets. Dashed lines identify high, medium, and low flow aquifers. The bottom line identifies aquitards.

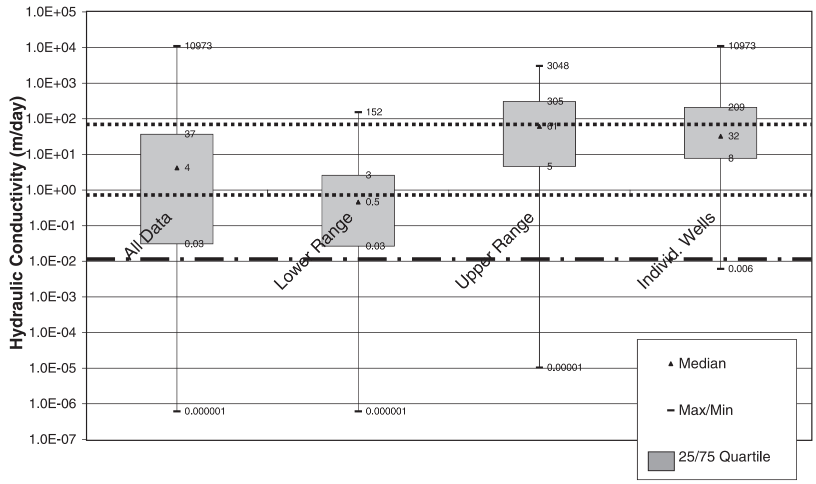

FIGURE A2. Box and Whisker Plot of Hydraulic Conductivity Datasets. Dashed lines identify high, medium, and low flow aquifers. The bottom line identifies aquitards.

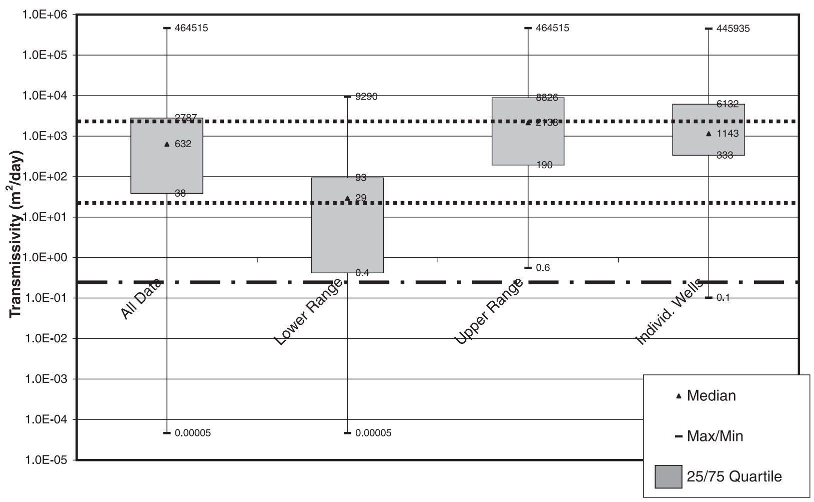

FIGURE A3. Box and Whisker Plot of Transmissivity Datasets. Dashed lines identify high, medium, and low flow aquifers. The bottom line identifies aquitards.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. The supporting information is a spreadsheet database summarizing aquifer properties using data compiled from literature cited in Table 3.

Please note: Neither AWRA nor Wiley-Blackwell is responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

LITERATURE CITED

Aller, L., T. Bennett, J. Lehr, R. Petty, and G. Hackett, 1987. DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Setting. EPA/600/2-87/035. Environmental Protection Agency, Ade, Oklahoma, 622 pp.

Alley, W.M., R.W. Healy, J.W. LaBaugh, and T.E. Reilly, 2002. Flow and Storage in Groundwater Systems. Science 296(5575): 1985-1990, doi: 10.1126/science.1067123.

Anderson, M.P. and W.W. Woessner, 1992. Applied Groundwater Modeling. Academic Press, Orlando, Florida, 381 pp.

Anderson, S.R., M.A. Krutz, and L.C. Davis, 1999. Geologic Controls of Hydraulic Conductivity in the Snake River Plain Aquifer at and Near the Idaho National Engineering and Environmental Laboratory, Idaho. USGS Water-Resources Investigations Report 99-4033. U.S. Geological Survey, Denver, Colorado, pp. 1-38.

Anderson, T.W., 1995. Summary of the Southwest Alluvial Basins, Regional Aquifer-System Analysis, South-Central Arizona and Parts of Adjacent States. USGS PP 1406-A. U.S. Geological Survey, Denver, Colorado, A33 pp.

Angeroth, C.E., 2002. Characterization of Hydraulic Conductivity of the Alluvium and Basin Fill, Pinal Creek Basin Near Globe, Arizona. Water-Resources Investigations Report 02-4205. U.S. Geological Survey, Denver, Colorado, 27 pp.

Anning, D.W. and A.D. Konieczki, 2005. Classification of Hydrogeologic Areas and Hydrogeologic Flow Systems in the Basin and Range Physiographic Province, Southwestern United States. USGS PP 1702. U.S. Geological Survey, Denver, Colorado, 48 pp.

ASTM, 2004. Standard Guide for Establishing the Nomenclature of Ground-Water Aquifers, D6706-97(2004). West Conshohocken, Pennsylvania, 17 pp.

Back, W., 1961. Techniques for Mapping of Hydrochemical Facies. USGS Geological Survey Research, Short Papers in the Geologic and Hydrologic Sciences, no. 423. U.S. Geological Survey, Denver, Colorado, pp D381-D382.

Bear, J., 1972. Dynamics of Fluids in Porous Media. Dover Publications, New York, 764 pp.

Berardinucci, J. and K. Ronneseth, 2002. Guide to Using the BC Aquifer Classification Maps, Ministry of Water, Land and Air Protection. Victoria, British Columbia, Canada, p. 54. http://env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf, *accessed* July 2010.

Bertoldi, G.L., R.H. Johnston, and K.D. Evenson, 1991. Ground Water in the Central Valley, California – A Summary Report, USGS PP 1401-A. U.S. Geological Survey, Denver, Colorado, A44 pp.

Boulton, A.J. and P.J. Hancock, 2005. Rivers as Ground-Water Dependant Ecosystems: A Review of the Degrees of Dependency, Riverine Process and Management Implications. Australian Journal of Botany 54(2):133-155, doi:10.1071/BT05074.

Bredehoeft, J.D. and R.N. Farvolden, 1963. Disposition of Aquifers in Intermontane Basins of Northern Nevada: International Association of Scientific Hydrology, Commission on Subterranean Waters Publication 64. New York, pp. 197-212.

California Department of Water Resources, 2003. California's Groundwater, Bulletin 118. http://www.groundwater.water.ca.gov/bulletin118/update2003/index.cfm, *accessed* July 2010.

Candell, J., R.B. Jackson, J.B. Ehleringer, H.A. Mooney, O.E. Sala, and E.D. Schulze, 1996. Maximum Rooting Depth of Vegetation Types at the Global Scale. Oecologia 108(4):583-595, doi: 10.1007/BF00329030.

Carter, T.R., R.N. Jones, X. Lu, S. Bhadwal, C. Conde, L.O. Mearns, B.C. O'Neill, M.D.A. Rounsevell, and M.B. Zurek, 2007. New Assessment Methods and the Characterisation of Future Conditions. *In*: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (Editors). Cambridge University Press, Cambridge, United Kingdom, pp. 133-171.

Commission on Geosciences, Environmental and Resources, 2000. Investigating Groundwater Systems on Regional and National Scales. National Academies Press, Washington, D.C., pp. 99-107.

Danielopol, D.L., J. Gibert, and C. Griebler, 2006. Efforts of the European Commission to Improve Communication Between Environmental Scientists and Policy Makers. Environmental Science and Pollution Restoration 13(2):138-139.

Danielopol, D.L., J. Gibert, C. Griebler, A. Gunatilaka, H.J. Hahn, G. Messana, J. Notenbloom, and B. Sket, 2004. Incorporating Ecological Perspectives in European Groundwater Management Policy. Environmental Conservation 3(3):185-189, doi: 10.1017/S0376892904001444.

Danielopol, D.L., C. Griebler, A. Gunatilaka, and J. Notenboom, 2003. Present State and Future Prospects for Groundwater Ecosystems. Environmental Conservation 30:104-130.

Daughton, C.G., 2004. Groundwater Recharge and Chemical Contaminants: Challenges in Communicating the Connections and Collisions of Two Disparate Worlds. Ground Water Monitoring & Remediation 24(2):127-138. http://www.epa.gov/nerlesd1/chemistry/ppcp/images/water-reuse.pdf, *accessed* August 2008.

Davis, R.A., 1983. Depositional Systems: A Genetic Approach to Sedimentary Geology. Prentice-Hall International, London, 669 pp.

Domenico, P.A., 1972. Concepts and Models in Groundwater Hydrology. McGraw-Hill, New York, 403 pp.

Eamus, D. and R. Froend, 2006. Groundwater-Dependent Ecosystems: The Where, What and Why of GDEs. Australian Journal of Botany 54:91-96.

Edwards, R.T., 1998. The Hyporheic Zone. *In*: River Ecology and Management, R.J. Naiman and R.E. Bilby (Editors). Springer, New York, pp. 399-429.

Field, C.B., L.D. Mortsch, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running, and M.J. Scott, 2007. North America. *In*: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (Editors). Cambridge University Press, Cambridge, United Kingdom, pp. 617-652.

Freeze, R.A. and J.A. Cherry, 1979. Groundwater. Prentice-Hall, Englewood Cliffs, New Jersey, 397 pp.

Frenzel, P.E. and C.A. Kaehler, 1992. Geohydrology and Simulation of Ground-Water Flow in the Mesilla Basin, Dona Ana County, New Mexico, and El Paso County Texas. USGS PP 1407-C. U.S. Geological Survey, Denver, Colorado, C105 pp.

Geldon, A.L., 2003. Hydrologic Properties and Ground-Water Flow Systems of the Paleozoic Rock in the Upper Colorado, New Mexico, Utah, and Wyoming, Excluding the San Juan Basin, USGS PP 1411-B. U.S. Geological Survey, Denver, Colorado, B153 pp.

Geldon, A.L., A.M.A. Umari, M.F. Fahy, J.D. Earle, J.M. Gemmell, and J. Darnell, 2002. Results of Hydraulic Tests in Miocene Tuffaceous Rocks at the C-Hole Complex, 1995-1997, Yucca Mountain, Nye County, Nevada, USGS Water-Resources Investigations Report 02-4141. U.S. Geological Survey, Denver, Colorado, 58 pp.

Gibert, J., 1991. Groundwater Systems and Their Boundaries; Conceptual Framework and Prospects in Groundwater Ecology. Verhandlungen International Verein Limnology 24:1605-1608.

Gibert, J., J. Mathieu, and F. Fournier, 1997. Groundwater/Surface Water Ecotones: Biological and Hydrological Interactions and Management Options. Cambridge University Press, United Kingdom, 246 pp.

Gutentag, E.D., F.J. Heimes, N.C. Krothe, R.R. Luckey, and J.B. Weeks, 1984. Geohydrology of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, USGS PP 1400-B. U.S. Geological Survey, Denver, Colorado, 63 pp.

Hancock, P.J., A.J. Boulton, and W.F. Humphreys, 2005. Aquifers and Hyporheic Zones: Towards an Ecological Understanding of Groundwater. Hydrogeology Journal 13(1):98-111, doi: 10.1007/s10040-004-0421-6.

Harlow, G.E. and G.D. Lecain, 1993. Hydraulic Characteristics of, and Groundwater-Water Flow in, Coal-Bearing Rock of Southwestern Virginia, USGS PP 2388. U.S. Geological Survey, Denver, Colorado, 36 pp.

Harrill, J.R. and A.M. Preissler, 1994. Ground-Water Flow and Simulated Effects of Development in Stagecoach Valley, a Small, Partly Drained Basin in Lyon and Storey Counties, Western Nevada, USGS PP 1409-H. U.S. Geological Survey, Denver, Colorado, H74 pp.

Hayashi, M. and D.O. Rosenberry, 2002. Effects of Ground Water Exchange on the Hydrology and Ecology of Surface Water. Ground Water 40(3):309-316.

Heath, R.C., 1984. Groundwater Regions of the United States. USGS WSP 2242. U.S. Geological Survey, Denver, Colorado, 78 pp.

Hibbs, B.J. and B.K. Darling, 2005. Revisiting a Classification Scheme for U.S.-Mexico Alluvial Basin-Fill Aquifers. Ground Water 43(5):750, doi: 10.1111/j.1745-6584.2005.00072.x.

Hollyday, E.F. and C.E. Hileman, 1996. Hydrologic Terranes and Potential Yield of Water to Wells in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States, USGS PP 1422-C. U.S. Geological Survey, Denver, Colorado, C30 pp.

Johnson, A.I., 1967. Specific Yield – Compilation of Specific Yield for Various Materials, USGS WS Paper 1662-D. U.S. Geological Survey, Denver, Colorado, pp. D1-D39.

Johnson, A.I., R.P. Moston, and D.A. Morris, 1968. Physical and Hydrologic Properties of Water-Bearing Deposits in Subsiding Areas in Central California, USGS PP 497-A. U.S. Geological Survey, Denver, Colorado, A71 pp.

Juracek, K.E. and F.A. Fitzpatrick, 2003. Limitations and Implications of Stream Classification. Journal of the American Water Resources Association 39(3):659-670.

Jury, W.A. and H. Vaux, 2005. The Role of Science in Solving the World's Emerging Water Problems. Proceedings of the National Academy of Sciences of the United States of America 102(44):15715-15720.

Kendy, E., 2003. The False Promise of Sustainable Pumping Rates – Technical Commentary for Groundwater. Groundwater 41(1): 2-4.

Kontis, A.L., A.D. Randall, and D.L. Mazzaferro, 2004. Regional Hydrology and Simulation of Flow of Stratified-Drift Aquifers in the Glaciated NW, USGS PP 1415-G. U.S. Geological Survey, Denver, Colorado, C156 pp.

Kreye, R., K. Ronneseth, and M. Wei, 1998. An Aquifer Classification System for Groundwater Management in British Columbia, Ministry of Environment, Lands and Parks Water Management Division, Hydrology Branch. http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/Aq_Classification/Aq_Class.html, *accessed* July 2010.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen, and I.A. Shiklomanov, 2007. Freshwater Resources and Their Management. *In*: Climate Change 2007. Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (Editors). Cambridge University Press, Cambridge, United Kingdom, pp. 173-210.

Laney, R.L. and C.R. Davidson, 1986. Aquifer-Nomenclature Guidelines, U.S. Geological Survey, Open-file Report 86-534. U.S. Geological Survey, Denver, Colorado, 46 pp.

Lindholm, G.F., 1996. Summary of the Snake River Plain Regional Aquifer-System Analysis in Idaho and Eastern Oregon, USGS PP 1408-A. U.S. Geological Survey, Denver, Colorado, pp. A1-A22.

Loáiciga, H.A., 2000. Climate Change Impacts in Regional-Scale Aquifers: Principles and Field Application. *In*: Groundwater Updates. K. Sato and Y. Iwasa (Editors). Springer, Tokyo, Japan, pp. 247-252.

Loáiciga, H.A., D.R. Maidment, and J.B. Valdes, 2000. Climate-Change Impacts in a Regional Karst Aquifer, Texas USA. Journal of Hydrology 227:173-194.

Lohman, S.W., and others, 1972. Definitions of Selected Ground-Water Terms – Revisions and Conceptual Refinements: U.S. Geological Survey. Water-Supply Paper 1988. U.S. Geological Survey, Denver, Colorado, 21 pp.

Lowe, M., J. Wallace, and J.L. Kneedy, 2002. Ground-Water Recharge-Area and Water Quality-Classification Mapping for Cedar Valley, Southwestern Utah – Tools for Land-Use Planning. GSA Rocky Mountain 54th Annual Meeting, May 7-9. http://gsn.contex.com/gsa/2002RM/Finalprogram/abstract_33532.htm, *accessed* July 2010.

Lyke, W.L. and A.R. Brockman, 1990. Ground-Water Pumpage and Water-Level Declines in the Peedee and Black Creek Aquifers in Onslow and Jones Counties, North Carolina, 1900-86. USGS Water-Resources Investigation Report 89-4197. U.S. Geological Survey, Denver, Colorado, 32 pp.

Magruder, I. and S.M. Payne, 2008. Ruby Groundwater/Surface Water Interaction Modeling Project Report, Unpublished Report Funded by the Ruby Valley Conservation District Through the Montana Department of Environmental Quality. KirK Engineering & Natural Resources, Inc., Sheridan, Montana, 80 pp.

Mason, J.L., 1998. Ground-Water Hydrology and Simulated Effects of Development in the Milford Area, an Arid Bain Southwestern Utah, USGS PP 1904-G. U.S. Geological Survey, Denver, Colorado, G69 pp.

Maurer, D.K., 2002. Ground-Water Flow and Numerical Simulation of Recharge From Streamflow Infiltration Near Pine Nut Creek, Douglas County, Nevada, USGS Water-Resources Investigations Report 02-4145. U.S. Geological Survey, Denver, Colorado, 37 pp.

Maurer, D.K. and D.L. Berger, 1997. Subsurface Flow and Water Yield From Watershed Tributary to Eagle Valley Hydrographic Area, West-Central Nevada, Water Resources Investigation Report 97-4191. U.S. Geological Survey, Denver, Colorado, p. 56.

Maurer, D.K., T.J. Lopes, R.L. Medina, and J.L. Smith, 2004, Hydrogeology and Hydrologic Landscape Regions of Nevada: U.S. Geological Survey Scientific Investigations Report 2004-5131. U.S. Geological Survey, Denver, Colorado, p. 35.

Maurer, D.K. and C.E. Thodal, 2000. Quantity and Chemical Quality of Recharge, and Updated Water Budgets, for the Basin-Fill Aquifer in Eagle Valley, Western Nevada, USGS Water Resources Investigations Report 99-4289. U.S. Geological Survey, Denver, Colorado, 46 pp.

Maxey, G.B., 1964. Hydrostratigraphic Units. Journal of Hydrology 2:124-129.

McFarland, W.D. and G.N. Ryals, 1991. Adequacy of Available Hydrogeologic Data for Evaluation of Declining Ground-Water Levels in the Fort Rock Basin, South-Central Oregon, USGS Water-Resources Investigation Report 89-4057. U.S. Geological Survey, Denver, Colorado, 47 pp.

Meinzer, O.E., 1923. The Occurrence of Ground Water in the United States. USGS WSP 489. U.S. Geological Survey, Denver, Colorado, 321 pp.

Meinzer, O.E., 1927. Large Springs in the United States. USGS WSP 557. U.S. Geological Survey, Denver, Colorado, p. 94.

Meinzer, O.E., 1942. The Occurrence, Origin, and Discharge of Ground Water, Chapter X. *In*: Physics of the Earth IX Hydrology, O.E. Meinzer (Editor). McGraw-Hill, New York, pp. 385-477.

Miall, A.D., 2000. Principles of Sedimentary Basin Analysis. Springer, New York, 616 pp.

Moore, A.W. and H.F. Rhoades, 1966. Soil Conditions and Root Distributions in Two Wet Meadows of the Nebraska Sandhills. Agronomy Journal 58:563-566.

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.E. MacDonald, M.D. O'Connor, P.L. Olson, and E.A. Steel, 1992. Fundamental Elements of Ecologically Healthy Watershed in the Pacific Northwest Coastal Ecoregion. *In*: Watershed Management – Balancing Sustainability and Environmental Change, R.J. Naiman (Editor). Springer-Verlag, New York, pp. 127-174.

National Research Council, 2004. Groundwater Fluxes Across Interfaces. Committee on Hydrologic Water Science and Technology Board, Board on Atmospheric Sciences and Climate Division on Earth Life Studies. The National Academies Press, Washington, D.C., 85 pp.

Payne, S.M., 2010. Classification of Aquifers. Doctorial Dissertation, University of Montana, Montana. http://www.kirkenr.com/ftp/phd/classification_of_aquifers_final_dissertation_012810w Appendices.pdf, *accessed* July 2010.

Payne, S.M. and I. Magruder, 2004. Lower Ruby Valley Groundwater Management Plan and Water Resource Data Report, Volume I and II, Unpublished Report Funded by the Ruby Valley Conservation District Through the Montana Department of Natural Resources and Conservation. KirK Environmental, LLC Sheridan, Montana, 45 pp.

Plume, R.W., 1996. Hydrogeologic Framework of the Great Basin Region of Nevada, Utah, and Adjacent States, USGS PP 1409-B. U.S. Geological Survey, Denver, Colorado, B64 pp.

Poland, J.F., B.E. Lofgren, and F.S. Riley, 1972. Glossary of Selected Terms Useful in Studies of the Mechanics of Aquifer Systems and Land Subsidence Due to Fluid Withdrawal. USGS WSP 2025. U.S. Geological Survey, Denver, Colorado, p. 9.

Pope, D.A., D.W. Clark, S.D. Shariro, and S.M. Lawlor, 1999. Hydrogeologic, Geophysical, Water Quality, Transient-Tracer, and Flow Model Analysis of the Ground-Water Flow System Near Dillon, Montana, USGS Water-Resources Investigations Report 98-4250. U.S. Geological Survey, Denver, Colorado, 75 pp.

Risser, D.W., 1988. Simulated Water-Level and Water-Quality Changes in the Bolson-Fill Aquifer, Post Headquarters Area, White Sands Missile Range, New Mexico, USGS Water-Resources Investigations Report 87-4152. U.S. Geological Survey, Denver, Colorado, 71 pp.

Rosgen, D., 1994. A Classification of Natural Rivers. Catena 22:169-199.

Rosgen, D., 1996. Applied Stream Morphology. Wildland Hydrology, Pagora Springs, Colorado, 324 pp.

Ruppel, E.T., J.M. O'Neill, and D.A. Lopez, 1993. Geologic Map of the Dillon 1 Degree x 2 Degree Quadrangle, Idaho and Montana, USGS Miscellaneous Investigation Series Map I-1803-H, Scale 1:250:000. Montana Bureau of Mines and Geology, Butte, Montana.

Ryder, P.D. and A.F. Ardis, 2002. Hydrology of the Texas Gulf Coast Aquifer Systems, USGS PP 1416-E. U.S. Geological Survey, Denver, Colorado, pp. E8-E67.

Simon, A., M. Doyle, M. Kondolf, F.D. Shields, B. Rhoads, Jr., and M. McPhillips, 2007. Critical Evaluation of How the Rosgen Classification and Associated "Natural Channel Design" Methods Fail to Integrate and Quantify Fluvial Processes and Channel Response. Journal of the American Water Resources Association 43(5):1-15.

Slagle, S.E., 1988. Geohydrology of Flathead Indian Reservation, Northwestern Montana, USGS Water-Resources Investigations Report 88-4142. U.S. Geological Survey, Denver, Colorado, pp. 18-27.

Stanford, J.A. and J.V. Ward, 1992. Management or Aquatic Resources in Large Catchments: Recognizing Interactions Between Ecosystem Connectivity and Environmental Disturbance. *In*: Watershed Management – Balancing Sustainability and Environmental Change, R.J. Naiman (Editor). Springer-Verlag, New York, pp. 91-127.

Steele, G.V., J.C. Cannia, and K.G. Scripter, 2002. Hydrologic Characteristics of Selected Alluvial Aquifers in the North Platte Natural Resource District, Western Nebraska, USGS Water-Resources Investigations Report 01-4241. U.S. Geological Survey, Denver, Colorado, 24 pp.

Swain, L.A., T.O. Mesko, and E.F. Hollyday, 2004. Summary of the Hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States, USGS PP 1422-A. U.S. Geological Survey, Denver, Colorado, 23 pp.

Texas Natural Resource Conservation Commission, 2003. Groundwater Quality Classification System. Texas Water Code Section 26.401. http://Tgpc.state.tx.us.GWinfo.htm, *accessed* July 2010.

Thomas, H.E., 1951. Conservation of Ground Water. McGraw-Hill Book Co, New York, 327 pp.

Thomas, J.M., S.M. Carlton, and L.B. Hines, 1989. Ground-Water Hydrolology and Simulated Effects of Development in Smith Creek Valley, A Hydrologically Closed Basin in Lander County, Nevada, USGS PP 1409-E. U.S. Geological Survey, Denver, Colorado, 87 pp.

Todd, D.K., 1959. Ground Water Hydrology. John Wiley & Sons, New York, New York, 336 pp.

Todd, D.K., 1980. Groundwater Hydrology (Second Edition). John Wiley & Sons, New York, New York, 535 pp.

Todd, D.K., 1983. Ground-Water Resources of the United States. Premier Press, Berkeley, California, 747 pp.

Tolman, D.F., 1937. Ground Water. McGraw-Hill, New York, New York, p. 593.

Topper, R., K.L. Spray, W.H. Bellis, J.L. Hamilton, and P.E. Barkmann, 2003. Ground Water Atlas of Colorado. Special Publication 53. Colorado Geological Survey, Denver, p. 210.

Toth, J., 1962. The Theory of Groundwater Motion in Small Drainage Basins in Central Alberta, Canada. Journal of Geophysical Research 67:4375-4387.

Toth, J., 1963. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. Journal of Geophysical Research 68:4785-4812.

U.S. Army Corps of Engineers, 1987. Corps of Engineers Wetlands Delineation Manual. Final Report, January, Wetlands Research Program Technical Report, Rpt. Y-98-1. U.S. Army Corps of Engineers, Washington, D.C., pp. 9-30.

USGS (U.S. Geological Survey), 1999. The Quality of Our Nation's Waters Nutrients and Pesticides. Circular 1225. http://pubs.usgs.gov/circ/circ1225/pdf/index.html, *accessed* July 2010.

USGS (U.S. Geological Survey), 2000. Groundwater Atlas of the United States, Series of 13 Chapters B Through N and Various Authors. http://pubs.usgs.gov/ha/ha730/, *accessed* July 2010.

Uthman, W. and J. Beck, 1998. Hydrogeology of the Upper Beaverhead Basin Near Dillon, MT, MBMG. Open File Report 384. Montana Bureau of Mines and Geology, Butte, Montana, pp. 63-71.

Vaccaro, J.J., 1992. Summary of the Columbia Plateau Regional Aquifer-System Analysis, Washington, Oregon, and Idaho, USGS PP 1413-A. U.S. Geological Survey, Denver, Colorado, pp. A3-A14.

Vaccaro, J.J., A.J. Hansen, and M.A. Jones, 1998. Hydrologic Framework of the Puget Sound Aquifer System, Washington and British Columbia, USGS PP 1424-D. U.S. Geological Survey, Denver, Colorado, D127 pp.

Van de Wetering, S.B., 2007. Bridging the Goverance Gap: Strategies to Integrate Water and Land Use Planning. Public Policy Research Institute, University of Montana, Montana, 15 pp.

Walker, G., 2001. Picking Horses for Courses: A Groundwater Systems Framework for Salinity Management. Restoring the Hydrologic Water Balance in Agricultural Lands – Plant Industry Crop Adaptation Seminar, May 1. http://www.ndsp.gov.au/catch class/research/gwflow.htm, *accessed* July 2010.

Watson, R.T., M.C. Zinyowera, and R.H. Moss, 1998. The Regional Impacts of Climate Change: An Assessment of Vulnerability. Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom, 517 pp.

Weed, D.L., 2005. Weight of Evidence: A Review of Concept and Methods. Risk Analysis 25(6):1545-1557.

Wilkins, D.W., 1998. Summary of the Southwest Alluvial Basins Regional Aquifer-Systems Analysis in Parts of Colorado, New Mexico, and Texas, USGS PP 1407-A. U.S. Geological Survey, Denver, Colorado, A49 pp.

Winter, T.C., 1981. Uncertainties in Estimating the Water Balance of Lakes. Water Resources Bulletin 17:82-115.

Winter, T.C., 1999. Relation of Streams, Lakes, and Wetlands to Groundwater Flow Systems. Hydrogology Journal 7(1):28-45, doi: 10.1007/s100400050178.

Winter, T.C., 2001. The Concept of Hydrologic Landscapes. Journal of the American Water Resources Association 37(2):335-349.

Winter, T.C., J.W. Harvey, O.L. Frankie, and W.M. Alley, 1998. Ground Water and Surface Water a Single Resource. USGS Circ. 1139:1-53. http://pubs.usgs.gov/circ1139/pdf/circ1139.pdf, accessed July 2010.

Woodward, D.G., M.W. Gannett, and J.J. Vaccaro, 1998. Hydrologic Framework of the Willamette Lowland Aquifer System, Oregon and Washington. USGS PP 1424-B. U.S. Geological Survey, Denver, Colorado, B82 pp.