SENSITIVITY AND VULNERABILITY OF THE AQUIFERS AND SPRINGS IN THE UINTA BASIN, UTAH, TO POTENTIAL CONTAMINATION ASSOCIATED WITH ENERGY RESOURCE DEVELOPMENT

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ABSTRACT

The vast Uinta Basin in eastern Utah is better known for productive oil and gas wells than for water resources. With the continued demand for domestic energy production, research and development activities for unconventional sources of oil and gas, such as oil shale and tar sand, have increased. The principal goal of this study is to investigate sensitivity and vulnerability of groundwater resources in the Uinta Basin to contamination from industrial and natural chemicals commonly associated with energy resource extraction (e.g., volatile organic compounds [VOCs]). The project scope is limited to the use and interpretation of existing data to produce VOC sensitivity and vulnerability maps through the application of Geographic Information System (GIS) analysis methods.

During summer of 2013, 22 water samples were collected from shallow water wells and springs in the Uinta Basin and analyzed for a suite of water-quality constituents including volatile organic compounds (VOCs). Data show overall good water quality, but some sites have VOC concentrations above detection levels including benzene, vinyl chloride, bromomethane, chlorobenzene, chloromethane, and toluene. We recognize the potential for these contaminants to reach groundwater in the Uinta Basin and use benzene as the representative VOC in our sensitivity/vulnerability analyses and assessment.

Using GIS analyses, we combined index-based, process-based, and overlay methods to determine aquifer sensitivity and vulnerability in the Uinta Basin. The resultant attribute and ranking assessment shows that the areas most sensitive to groundwater contamination by VOCs are located near streams and lakes, especially in areas having relatively high hydraulic conductivities, high VOC retardation factors, and low VOC attenuation factors. High vulnerability areas are located near water bodies, water wells, and in close proximity to oil/gas wells.

Our research is one component of a larger study to investigate the integrated management of water production and disposal for shale/tight-sand gas development in the Uinta Basin. Potential groundwater and surface water-quality degradation may result from an expected increase in mining and drilling activity if sound water-management practices are not enforced. Our regional water study will provide GIS-based information to help local planners and potential developers preserve the quality of shallow groundwater and springs by establishing best-management practices through careful land-use planning. The maps produced are intended to be used to advise water users on proper disposal of wastewater associated with non-conventional oil/gas development in the Uinta Basin and ultimately to provide local, state, and federal government agencies and industry operators with a base of information concerning sensitivity and vulnerability of groundwater to VOCs in the Utah part of the Uinta Basin.

INTRODUCTION

The Uinta Basin in eastern Utah has had extensive energy development, historically rich with oil and gas production, and has potential for further development of unconventional energy, especially tight gas, oil shale, and tar sands (figure 1). Water resource issues have also been a primary focus in the area. With continued energy development, it is important to address water resources by assessing the sensitivity and vulnerability of the aquifers in the basin.

This study provides information on groundwater sensitivity and vulnerability to volatile organic compounds (VOCs) in the shallow alluvial aquifers and springs of the Uinta Basin. Water-quality degradation from naturally occurring VOC sources is not considered in this study. Groundwater and surface water are important sources of water in many rural areas for human consumption and wildlife. Therefore, the potential for VOCs to contaminate water resources represents a threat to public health and the environment. Springs and drains flowing from contaminated aquifers may present a hazard to wildlife

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Wallace, J., Payne, N., and Emerson, R.L., 2015, Sensitivity and Vulnerability of the Aquifers and Springs in the Uinta Basin, Utah, to Potenital Contamination Associated with Energy Resource Development, *in* Vanden Berg, M.D., Ressetar, R., and Birgenheier, L.P., editors, Geology of Utah's Uinta Basin and Uinta Mountains: Utah Geological Association Publication 44, p. 189-206.

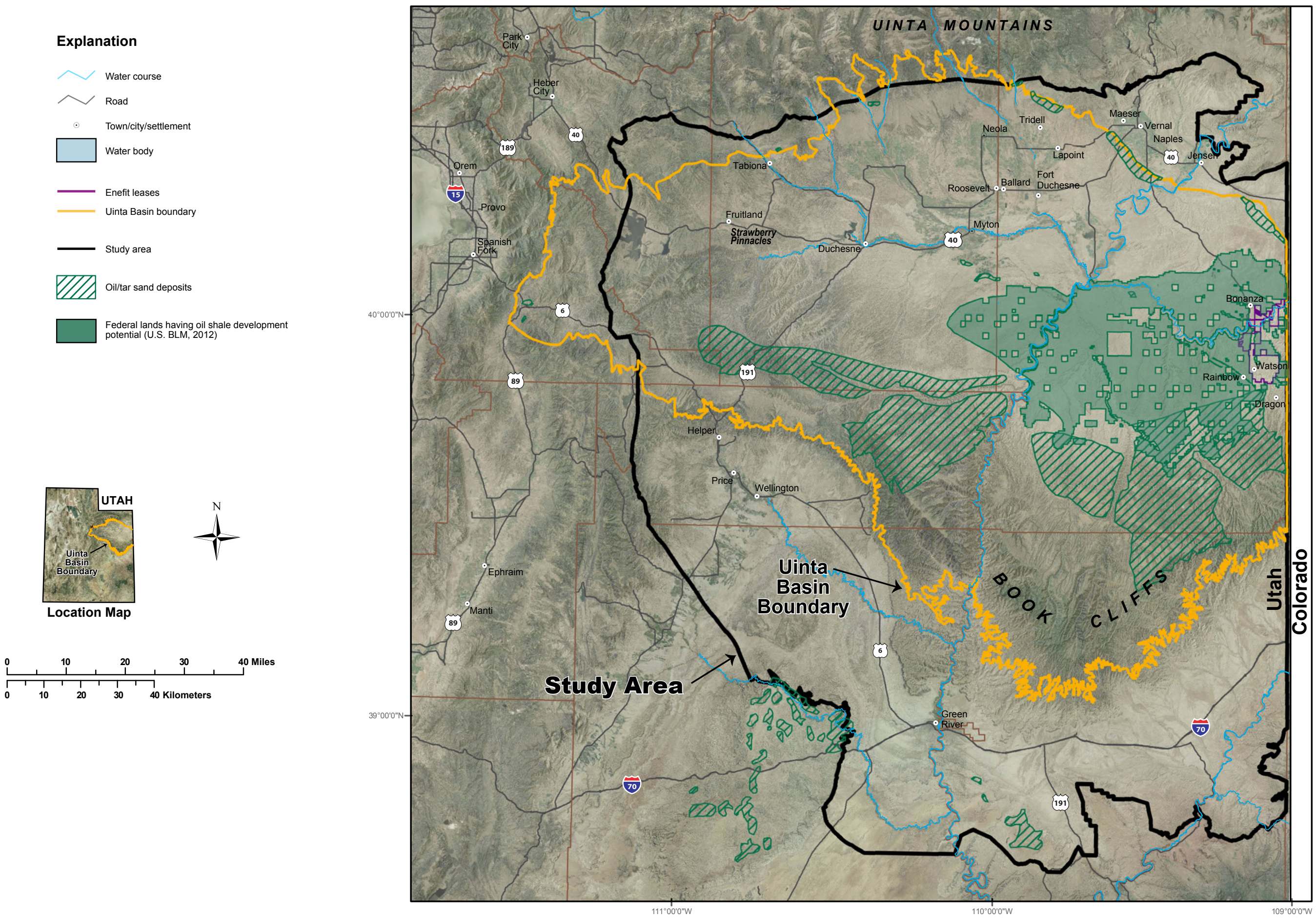

Figure 1. Location map of study area showing boundaries of shale oil/tar sands. Darker green areas highlight U.S. Bureau of Land Management land having oil shale development potential (BLM PEIS, 2012) (modified from Wallace, 2012a, 2012b; Vanden Berg and others, 2013).

that live in or consume the water. Once VOCs are in the environment, they can move between different media of atmosphere, soil, groundwater, and surface water.

Understanding the mechanisms by which VOCs migrate into groundwater allows us to determine which geographic areas are most vulnerable and require more concentrated efforts to protect. The ability to delineate areas of greater and lesser VOC vulnerability will allow for geographically focused mitigation measures and land-use practice restrictions.

The maps presented in this document are intended to provide federal, state, and local government agencies and energy-related development users with information concerning vulnerability of groundwater to VOCs, especially benzene, toluene, ethylbenzene, and xylene (collectively BTEX). Geographic variation of sensitivity and vulnerability and hydrologic and soil conditions that cause these variations are described herein. Plates 1 and 2 show the VOC sensitivity and vulnerability, respectively, of the alluvial aquifers and springs in the Uinta Basin.

APPROACH AND BACKGROUND

We used collected water quality data, existing land-use data, and an attribute ranking system specifically tailored to the western United States to produce sensitivity and vulnerability maps in Geographic Information System (GIS) analysis software. These maps show the sensitivity and vulnerability of the important alluvial aquifer(s) to potential contamination from VOCs associated with oil and gas development based on characteristics of the alluvial aquifer(s) and their geographic relation to unconventional gas development activities. The maps can show areas with high sensitivity and vulnerability and indicate where extra care should be taken for alluvial aquifer protection.

VOCs were analyzed because of their documented presence within the basin, mostly as atmospheric concentrations (U.S. EPA, 2012; Edwards and others, 2014). Once these contaminants are released into an environment, their chemical and physical characteristics allow for easy movement between the atmosphere, soil, groundwater, and surface water (Squillace and Moran,

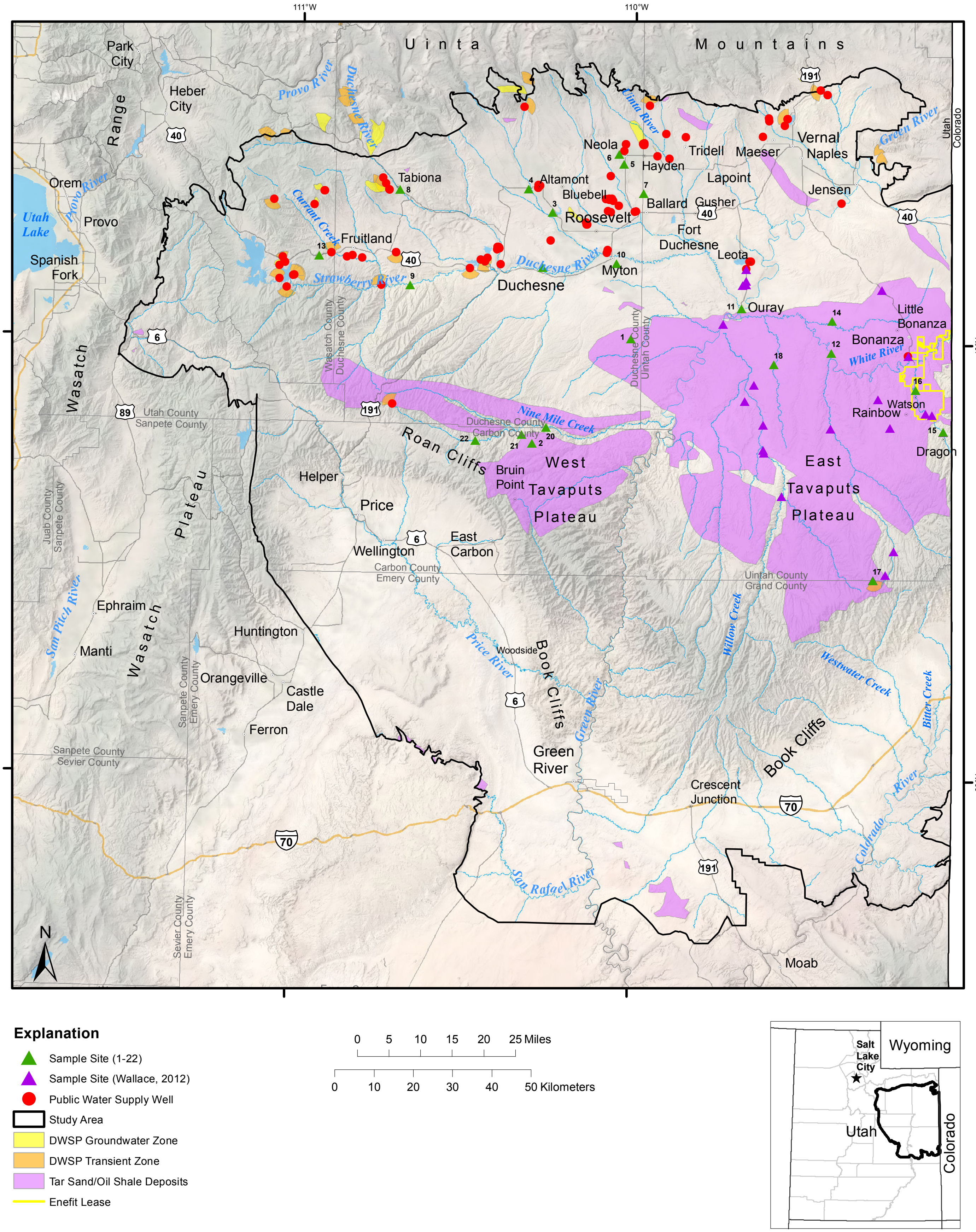

Figure 2. Location of sites sampled for water quality for this study, a previous water quality study (Wallace, 2012a, 2012b), public water supply wells, and drinking water source protection (DWSP) zones. DWSP transient zones refer to public supply sources that are used on a seasonal or intermittent basis. Leased areas for oil shale and tar sand are also shown.

2000; Squillace and others, 2002). VOCs readily dissolve in water or partition into soil vapor and, because of their relatively hydrophilic nature, may not be attenuated by the soil, resulting in long distance transport in groundwater systems (EUGRIS, 2014).

Groundwater chemical sensitivity is determined by assessing natural factors that may lead to the degradation of groundwater if VOCs are introduced into the environment. Some of these natural factors include permeability of geologic surficial units, soil hydraulic conductivity, natural retardation and attenuation of VOCs, and groundwater elevation. The location of active and potential oil/gas wells and their proximity to water bodies and/or water wells are used to determine groundwater vulnerability. Sensitivity to VOCs is determined by assessing natural factors favorable or unfavorable to the degradation of groundwater by VOCs, whereas vulnerability to VOCs is determined by assessing how groundwater sensitivity is modified by the activities of humans. For this study, groundwater sensitivity is assessed using depth to groundwater, permeability of surficial geologic units, and soil properties, including hydraulic conductivity, bulk density, organic content, and field capacity. Groundwater sensitivity also includes the influences of VOC physical properties, such as their capacity to adsorb to organic carbon in soil and the half-life of a VOC under typical soil conditions. Specific vulnerability accounts for the presence and type of potential contaminating activities. In the case of the Uinta Basin, active oil/gas wells as well as the areas leased with intent to mine and retort oil shale and tar sands are considered. The vulnerability analysis also incorporates well and spring water resources. Groundwater vulnerability includes human-controlled factors such as proximity to energy-related development (active and producing oil/gas wells and oil shale/tar sand deposits), proximity to water bodies, wells, or springs, and types of VOCs commonly associated with natural and synthetic products and by-products.

Groundwater Quality Standards

Maximum contaminant levels (MCLs) for VOCs in drinking water are established in Utah Administrative Code R309-100 through R309-605; organic chemicals are divided into three categories: pesticides/polychlorinated biphenyls (PCBs)/synthetic organic chemicals (SOCs), VOCs, and total trihalomethanes. Federal regulations are based on the U.S. Environmental Protection Agency's (EPA) protocols (EPA 816-F-09-0004, May 2009, Title 40, Chapter 1, Part 141, National Primary Drinking Water Regulations) (U.S. Environmental Protection Agency, 2006). MCLs are given in table 1 for the common BTEX VOCs. The vulnerability and sensitivity maps generated in this report rely on specific VOC-BTEX compounds; we do not address all VOCs that were analyzed as part of this study.

Volatile Organic Compounds in the Uinta Basin

VOCs are carbon-based chemicals that typically evaporate at the Earth's surface, but can reach groundwater under certain conditions. An estimated 98 to 99% of airborne Uinta Basin VOCs are from oil and gas operations (Utah State University, 2013), but can be introduced to groundwater from direct industrial or wastewater discharge, leaky underground storage tanks, infiltration from surface spills, and atmospheric deposition of vehicle and industrial emissions.

As part of this study, VOCs were analyzed for 22 sample sites—12 water wells and 10 springs (figure 2) (see Wallace, 2015, this volume). Chloromethane is the most commonly occurring VOC (14 sites), and toluene and bromomethane are the second most common (5 sites). Vinyl chloride was detected in 2 wells (sites 15 and 18). Other detected VOCs include benzene, bromoform, chloro dibromomethane, bromo dichloromethane, chlorobenzene, chloroethane, and total xylene. The range of concentrations for detected chloromethane is trace amounts to 18 µg/L. Toluene concentrations range from 0.24 to 10.2 µg/L. Vinyl chloride was above EPA MCL of 2 µg/L for sites 15 and 18 (6.6 and 3 µg/L, respectively), shallow alluvial monitor wells drilled by the U.S. Geological Survey (USGS) during the 1970s. We augmented the VOC data from this study with samples collected annually during 2009 to 2011 for 23 sample sites (figure 2; Wallace, 2012a, 2012b). Chlorobenzene, the most commonly occurring VOC, was detected in 18 samples over all sampling intervals, followed by chloroethane (detected in 6 samples), xylene (5 samples), and ethylbenzene (3 samples). Other VOCs include benzene, bromoform, bromoethane, toluene, naphthalene, chloro dibromomethane, bromo dichloromethane, and 1,2,4-trimethylbenzene (Wallace, 2012a, 2012b, 2013).

PREVIOUS WORK

Previous work on the hydrogeology and water quality within the Uinta Basin is summarized in another article in this publication (see Wallace, 2015, this volume). In general, groundwater in the Uinta Basin occurs in both unconsolidated alluvial material and consolidated rocks. Water quality is variable throughout the basin and even within specific formations (Wallace 2012a; 2012b; Vanden Berg and other, 2013).

The most recent studies evaluated water quality from 24 locations in the southeastern Uinta Basin as a means to assess the alluvial and bedrock aquifers on lands proposed by the BLM as having oil shale development potential (figure 2) (Wallace 2012a; 2012b; and 2013). Data from 85 water samples were analyzed from water wells and surface-water sites over 3 different sampling seasons from 2009 to 2011. Water-quality constituents analyzed included general chemistry (including TDS), nutrients, dissolved metals, and VOCs (listed above). Results indicate groundwater quality was variable, but generally had good TDS concentrations primarily below 3000 mg/L and ranged from 172 to 2832 mg/L. No VOC exceeded U.S. Environmental Protection Agency maximum contaminant level, but many samples had detectable levels of certain VOCs. The most frequently

Table 1. *Chemical and physical properties of BTEX compounds and the U.S. EPA maximum contaminant levels for select VOCs (BTEX) in drinking water (table modified from Koo [2012] and Weast and others [1990] using some data from Carey and Sundberg [1990], Fetter [1988], Lawrence [2006], and EUGRIS [2014]).*

Parameters	Benzene	Toluene	Ethylbenzene	Xylene
U.S. EPA MCL (mg/L)	0.005	1	0.7	10
Soil organic carbon-water partitioning coefficient (K_{OC})	97	242	622	570*
half life (days) not in () is uncontaminated**	238 (58 field contaminated matrix)	135-238 (5 in field with contaminated matrix)	238	238
Half life (years) converted	0.65	0.37-0.65	0.65	0.65

*Average values.
**From Lawrence (2006).

detected was chlorobenzene (in 17 samples over all sampling intervals) followed by chloromethane and xylene (5 samples).

Data were also collected to augment this study and are discussed in this UGA publication (Wallace, 2015, this volume) and summarized here. During summer 2013, water was sampled from 12 shallow wells and 10 springs. Total-dissolved-solids concentrations for all wells and springs sampled range from 214 to 5532 mg/L. Twelve different VOCs were detected (listed above).

METHODS

Methodologies for Groundwater Pollution Assessment

The potential for groundwater pollution can be assessed using index-based methods, process-based methods, overlay methods, or combinations of these. Focazio and others (2002) provide an overview of these methods, and Bernknopf and others (2001) discuss their underlying theory. Index-based methods, which commonly involve the use of map overlays, assign numerical scores to physical attributes to develop a range of subjective sensitivity/vulnerability categories (Aller and others, 1985). Process-based methods apply physical processes associated with the fate and transport of contaminants in the environment (Rao and others, 1985). Using Drinking Water Source Assessment and Protection (DWSAP) methods, Harter (2001) discussed the uses of index-and-overlay methods by highlighting possible contaminating activities (PCAs) at the land surface.

Rao and others (1985) developed process-based indices for ranking the potential for contamination of groundwater. The method of Rao and others (1985) uses a calculated retardation factor to characterize movement and an attenuation factor to characterize persistence of a chemical constituent(s) in the vadose zone. These factors vary with different soil properties and different characteristics of specific chemical species. Equations for these indices enable calibration of hydrogeologic and other data to more realistically represent actual conditions. However, the results are only a qualitative assessment of a contaminant's potential to pollute groundwater. Quantitative assessment of a contaminant's potential to pollute groundwater, including loss via runoff and leaching, requires complex computer modeling (Rao and others, 2006) that utilizes chemical-suite specific information, soil type, and the amount, frequency, and duration of precipitation events.

Harter (2001) used index-based and overlay methods to evaluate DWSAP vulnerability analyses. His study focused on the type of possible contaminating activities at the land surface to assess vulnerability of groundwater and surface water sourced drinking water in California. This method considers the contaminant type and proximity to the water supply and drinking water source protection (DWSP) zones of possible contaminated activities (PCAs) that could release contaminants. In the case of the Uinta Basin, PCAs include pre-existing oil/gas wells in addition to unconventional energy resources, particularly tar sands and oil shale deposits.

While efforts to predict the potential for groundwater pollution from VOCs combine index-based and process-based methods (Siegel, 2000; Harter, 2001) (including the one we devised for this study), they remain qualitative rather than quantitative tools because of their inability to incorporate site- and temporal-specific data. The summarized methods above vary in design based on their geographic scale, the subsurface zone of interest, the inclusion of VOC-specific properties (or any other

Table 2. *Summary of methods used, data sources used to calculate and derive parameters, and determination of ranges of values used to rank attributes from our GIS analysis of aquifer sensitivity and vulnerability in the Uinta Basin.*

Sensitivity Input Parameters	Method	Derived or Calculated	Source
BTEX Retardation Factor (RF)	Process	Calculated	Rao and others (1985)
BTEX Attenuation Factor (AF)	Process	Calculated	Rao and others (1985)
Permeability (See Table 3)	Index and Overlay	Derived	SSURGO* and Geologic Maps
Soil Hydraulic Conductivity	Index	Derived	SSURGO*
Depth to Groundwater	Index and Overlay		SSURGO* and Geologic Maps
Sensitivity Output	**Method**	**Derived or Calculated**	**Source**
Sensitivity Map	GIS Analysis (Combined Process, Index, and Overlay)	Both	This study
Vulnerability Input Parameters	**Method**	**Derived or Calculated**	**Source**
Sensitivity	GIS Analysis (Combined Process, Index, and Overlay)	Both	This Study
Active/Producing Well Density	Index and Overlay	Derived	DOGM** See Figure 3
Located Within Oil Shale/Tar Sand Lease	Index and Overlay	Derived	See Figure 1
Proximity to Public Supply Well	Index and Overlay	Derived	See Figure 2
Proximity to River/Stream	Index and Overlay	Derived	See Figure 2
Vulnerability Output	**Method**	**Derived or Calculated**	**Source**
Vulnerability Map	GIS Analysis (Combined Process, Index, and Overlay)	Both	This study

* SSURGO: National Soil Survey Center's Soil Survey Geographic Database
** Division of Oil, Gas, and Mining

potential contaminant of interest, such as pesticides), and the types of information available to incorporate into the methods. Field-scale evaluations (such as Rao and others, 1985; Meeks and Dean, 1990) require more detailed soils and geological data than evaluations at county or groundwater-basin scales (such as Shukla and others, 2000; Lowe and Sanderson, 2000, 2003; Schlosser and others, 2002; Lowe and others, 2004; Sinkevich and others, 2005), which, in turn, require more detailed soils and geologic data than regional or statewide evaluations (such as Lowe and others, 2003; Mehnert and others, 2005). The index-based component of the evaluations requires subjective decisions be made regarding the numerical scoring that results in the sensitivity/vulnerability map output.

Combined Methodologies applied to the Uinta Basin

The project scope is limited to the use and interpretation of existing data to produce VOC sensitivity and vulnerability maps through the application of GIS analysis methods. Using GIS, we devised a combined index-based, process-based, and overlay method to determine aquifer sensitivity and vulnerability in the Uinta Basin (table 2). The interplay between hydrogeology, groundwater recharge, soil conditions, and BTEX behavior in the vadose zone determines whether groundwater in a particular area is likely to become contaminated with a VOC (the type of BTEX is a critical factor since each component has unique physical and chemical properties) (table 1).

This is a first attempt to develop VOC sensitivity and vulnerability maps and a lack of some data limits our analysis; better data and tools may become available in the future so that better maps can be produced. For example, recharge is typically a component used in the production of sensitivity/vulnerability maps, but the data we used from The National Soil Survey Center's Soil Survey Geographic (SSURGO) database (National Soil Survey Center, 2006) does not provide recharge amount specific to the Uinta Basin in Utah. We analyzed precipitation and evapotranspiration data in an attempt to determine average annual recharge. By subtracting average annual evapotranspiration from annual precipitation an estimate of annual elevation-based recharge could be determined. The results of this calculation showed zero recharge in low elevation areas where evaporation potential exceeded precipitation. However, recharge can occur in low elevations where streams flow from mountainous areas during spring runoff and prolonged storm events. But since no comprehensive datasets pertain to recharge/discharge zones in the study area, this method of estimating recharge at low elevations was not possible. Therefore, recharge/discharge data were not used in our sensitivity/vulnerability analysis. Soil data for this study were collected at a scale of 1:63,360 or smaller and are too general to accurately depict areas of soil versus areas of bedrock outcrop. Organic carbon in soils is one major factor that determines the potential for VOCs to reach groundwater, but due to the small scale of 1:63,360, the higher sensitivity and vulnerability of these areas are not reflected in our maps. To produce the maps, we made some subjective decisions regarding the quality and the types of data available based on our knowledge of the hydrogeology of the area. For example, we calculated a weighted average from all soil horizons for organic carbon, field capacity, and bulk density values, and selected 5 feet (1.5 m) as the reference depth for applying VOC retardation and attenuation equations. Table 2 summarizes the methods we employ, the source(s) of information we use to calculate or derive parameters, and how we determine ranges of values used to rank attributes from our GIS analysis of aquifer sensitivity and vulnerability.

SENSITIVITY ANALYSIS

Groundwater sensitivity to VOCs can be determined by assessing natural factors favorable or unfavorable to the degradation of groundwater by VOCs present and/or leaked onto the land surface. Aquifer permeability, soil hydraulic conductivity, retardation of VOCs, attenuation of VOCs, and estimated depth to groundwater (or permeable layer) are the factors primarily determining groundwater sensitivity to VOCs in the aquifers within the Uinta Basin. Sensitivity represents the sum of natural influences that facilitate the entry of VOCs into groundwater.

Aquifer Permeability

Permeability was delineated for each geologic unit present in the Uinta Basin (table 3), based on the work of Schlotthaeur and others (1981). For GIS analyses, each unit was assigned a qualitative permeability rank of (1) low, (2) heterogeneous, or (3) medium to high. A geologic map for the study area was compiled from pre-existing 1:100,000 scale geologic maps (Witkind and Weiss, 2002; Weiss and others, 2003; Witkind, 2004; Gualtieri, 2004; Sprinkel, 2006, 2007, 2009, 2013) and simplified to show surficial exposures that have similar permeability properties.

For our GIS analysis, we characterized terrain directly underlain by hydrostratigraphic units having medium to high permeability as potentially having groundwater and surface water that is more vulnerable to potential contaminants, terrain directly underlain by those units having low permeability as potentially having groundwater and surface water that is less vulnerable to potential contaminants, and terrain directly underlain by geologic units the heterogeneous permeability rank category to be intermediate between the medium-to-high and low-permeability rank categories. For example, geologic units considered to have medium to high permeability (a rank of 3) included alluvium and unconsolidated deposits. Geologic units considered to be heterogeneous (rank of 2) include the Mesaverde Group and some undivided mapped units (such as the Curtis/Stump, Entrada, and Carmel Formations). The Mancos Shale is an example of a low permeability layer with a ranking of 1. Localized high, moderate, and/or low permeable units within the study area could not be identified at a map scale of 1:100,000, so were not included in the analysis.

Hydraulic Conductivity of Soils

Hydraulic conductivity is a measure of the rate at which soils can transmit water. Values for soil hydraulic conductivity and depth to groundwater for the Uinta Basin were obtained from SSURGO database (National Soil Survey Center [NRCS}, 2006). For GIS analysis, areas were divided into two hydraulic conductivity ranges (based on SSURGO data natural divisions): low (<0.57 inch/hour) and high (≤0.57 inch/hour) (table 4).

VOC Retardation

Retardation is a measure of the differential between movement of water and the movement of a potential contaminant (e.g., VOCs) in the vadose zone (Rao and others, 1985). Certain VOCs can be adsorbed to organic carbon in soil and thus move through soil more slowly than water. Slower moving BTEX compounds (e.g., toluene and xylene) may be more readily degraded by bacteria in the vadose zone than compounds that move more quickly to the saturated zone (e.g., benzene). The relative rate of movement of a VOC is dependent on many factors and may be calculated using the retardation factor (RF). The retardation factor is a function of dry bulk density, organic carbon fraction and field capacity of the soil, and the organic carbon sorption distribution coefficient of the specific VOC. A relatively low RF indicates a contaminant will not be adsorbed to organic carbon and can move more quickly into groundwater, increasing potential for groundwater pollution. Rao and others (1985) presented the following equation:

$$R_F = 1 + (\rho_b F_{oc} K_{oc})/\theta_{fc} \tag{1}$$

where:

R_F = retardation factor (dimensionless);

ρ_b = bulk density (kg/L);

F_{oc} = fraction, organic carbon;

K_{oc} = organic carbon sorption distribution coefficient (L/kg); and

θ_{fc} = field capacity (volume fraction).

Table 3. *Permeability ranking of geologic units in the Uinta Basin (modified from Schlotthauer and others [1981]). The units from the compiled 1:100,000 scale geologic map have been grouped and simplified from 328 units to 32 units. Permeability is ranked based on Schlotthauer's permeability ranking (as feet per day), transmissivity data for each unit (in feet squared per day, if available), and well or spring yield (in gallons per minute, if available). A low ranking for permeability ranges from 0.5 to 5 feet/day, and moderate ranking ranges from 51 to 50 feet/day, and a high ranking ranges from 51 to 500 feet/ day.*

Geologic Unit Description	Permeability Ranking
Water	3
Human disturbance	3
Mass wasting	2
Eolian deposits	3
Spring tufa deposits	2
Alluvium	3
Talus	3
Colluvium	3
Pediment mantle deposits	3
Young and Old alluvium - undifferentiated	3
Older pediment mantle	3
Volcanic rocks - undifferentiated	2
Uinta and Duchesne Formations - undivided	2
Green River Formation	1
Colton/Wasatch Formation	1
Flagstaff, North Horn, and Currant Creek Formations - undivided	2
Tertiary - undifferentiated	2
Mesaverde Groupe - undivided	2
Mancos Shale - undivided	1
Mancos Shale and Dakota Sandstone - undivided	2
Morrison, Summerville, Dakota, Burro Canyon, and Cedar Mountain Formations - undivided	2
Cretaceous rocks - undifferentiated	2
Summerville, Curtis/Stump, and Preuss Formations - undivided	1
Entrada Sandstone Formation	2
Curtis/Stump, Entrada and Carmel Formations - undivided	2
Twin Creek Limestone Formation	2
Carmel Formation	2
Navajo/Nugget Sandstone Formation	2
Glen Canyon Group - undifferentiated	2
Jurassic rocks - undifferentiated	2
Triassic - undifferentiated	2
Permian and Pennsylvanian undifferentiated	2
Pennsylvanian and Mississippian rocks - undifferentiated	2
Proterozoic and Archean rocks - undifferentiated	2

Table 4. *VOC sensitivity and the attribute rankings used to assign sensitivity for the Uinta Basin, Utah.*

Aquifer Sensitivity Input Parameters	Attribute	Ranking
BTEX Retardation Factor (RF)	High if RF>5	0
	Low if RF ≤5	1
BTEX Attenuation Factor (AF)	Low if AF is 0	0
	High if AF>0	1
Permeability (see table 3)	Low	1
	Heterogeneous	2
	Medium to High	3
Soil Hydraulic Conductivity	Less than 0.57 inch/hour (low transmissivity)	1
	Greater than or equal to 0.57 inch/hour (high transmissivity)	2
Depth to Groundwater	Greater than 5 feet to permeable layer	1
	Less than 5 feet to permeable layer	2
Aquifer Sensitivity Output	**Attribute**	**Ranking**
Sensitivity	Low	3 to 4
	Moderate	5 to 6
	High	7 to 9

Retardation factors typically range from (1 + 4 Kd) to (1 + 10 Kd) (Freeze and Cherry, 1979) (where Kd is the distribution coefficient) for unconsolidated sediments (ρ_b = 0.06 — 0.08 lb/in^3[1.7–2.2 kg/L]) with porosity range of 0.2 to 0.4. Dissolved constituents in groundwater with low RF values (~1), such as nitrate (a relatively mobile cation), move through the subsurface at the same rate as groundwater. Constituents with RF values that are orders of magnitude larger than 1 are essentially immobile (Freeze and Cherry, 1979). The relative velocity is the reciprocal of the retardation factor and describes the rate at which a contaminant moves relative to solvent-free groundwater.

For this study, data from the SSURGO database were used to help map aquifer sensitivity. The database provided information for bulk density, organic carbon fraction, and field capacity of soil in the Uinta Basin at a scale of 1:24,000 (table 5).

In order to establish a rationale for dividing high and low VOC retardation for GIS analysis, variables in equation 1 are set to values that represent conditions likely to be encountered in the natural environment (table 5). Digital soil information unique to particular soil groups from SSURGO data was applied for organic carbon. We used the organic carbon sorption distribution coefficient (table 1) for benzene (97), the BTEX compound among the four having the least tendency to adsorb to organic carbon in the soil (Carey and Sundberg, 1990; Weast and others, 1990; Weber, 1994; and Fetter, 1988). Bulk density and field capacity were derived from a soil texture triangle hydraulic properties calculator (Saxton, undated). To compute R_F values, bulk density end members of 0.04 and 0.07 pounds per cubic inch (1.2 and 2.0 kg/L) and field capacity end members of 14 and 42 percent, were applied to represent naturally occurring conditions in the Uinta Basin, a variable soil organic carbon content, and a water depth of 3 feet (1 m). Average organic carbon content in soils in aquifers within the Uinta Basin ranges from 0.029 to 8.7 percent (table 5); the mass fraction of organic carbon was computed by dividing the organic matter parameter in the SSURGO data by a conversion factor of 1.72 (Siegel, 2000). The organic carbon content end members were used to compute the extreme RF values; equation 1 results in retardation factors ranging from 1.1 to 25, with a median of 5. This means the highest relative velocity from the data is 0.9 and the lowest is 0.04; the former indicates benzene in groundwater moves at a rate about 90 percent that of groundwater free of benzene, whereas the latter indicates that VOCs in groundwater are essentially immobile. For the GIS analysis, VOC retardation is divided into two ranges: greater than or equal to, and less than 5.

VOC Attenuation

VOC attenuation is the rate at which a potential contaminate can degrade under certain soil conditions (Rao and others, 1985). The rate of attenuation indirectly controls the depth to which a BTEX compound may reasonably be expected to migrate under specific conditions. The attenuation factor (A_F) is a function of vertical depth or horizontal length of the soil column, net annual groundwater recharge, half-life of the specific VOC considered, and field capacity of the soil. Attenuation factors range between 0 and 1 (Rao and others, 1985); high attenuation factors represent conditions of low attenuation. Rao and others (1985) presented the following equation:

$$A_F = \exp(-0.693 z R_F \theta_{fc} / q t_{1/2}) \quad (2)$$

where:

A_F = attenuation factor (dimensionless);

z = reference depth (m);

R_F = retardation factor (dimensionless);

θ_{fc} = field capacity (volume fraction);

q = net annual groundwater recharge (precipitation minus evapotranspiration) (m); and

$t_{1/2}$ = VOC half-life (years).

Using equation 2, we calculated attenuation factors for ranges of values common to soils within the Uinta Basin, similar to the approach for retardation, to delineate high and low VOC attenuation factors for GIS analysis. To represent naturally occurring conditions in this area that would result in the greatest sensitivity to groundwater contamination, we used the median retardation factor of 5; the half-life for benzene (table 1), the BTEX with a half-life the same as other BTEX compounds (and longer than toluene) (Koo, 2012); a field capacity of 14 percent; and a bulk density value of 0.04 pounds per cubic inch (1.2 kg/L). For the negligible net annual groundwater recharge typical of the most areas across the Uinta Basin, equation 2 results in an attenuation factor approaching 0.

Although quantities of VOCs spilled and/or leaked to the ground surface would intuitively seem to have a direct bearing on the amount of VOC impacting groundwater, Rao and others' (1985) equations do not support this. Note that the quantity of VOC does not enter into either equation as a variable; the half-life, however, is essential and remains fairly constant.

Depth to Groundwater (Permeable Layer)

The closer groundwater is to the land surface the more sensitive it is to being degraded by VOCs. Depth to groundwater maps are not available for the study area, so we used the depth to the permeable layer attribute (table 4) to estimate depth to groundwater using Soil Hydraulic Conductivity and Depth to Groundwater data from NRCS SSURGO Soils database. We used 5 feet (1.5 m) as the depth-to-groundwater attribute to evaluate sensitivity of geographic areas to VOCs. Permeability was determined for each geologic formation based on work from Schlotthauer and others (1981). A qualitative permeability rank was assigned to formations based on work by Lowe and others (2003).

GIS Analysis Methods

Aquifer sensitivity (intrinsic susceptibility) to VOC compounds is characterized as "low," "moderate," or "high" based on the sum of numerical values (rankings) assigned to soil retardation of benzene, soil attenuation of benzene, permeability, soil hydraulic conductivity, and depth to shallowest groundwater (permeable layer) attributes as shown in table 4. Rasters (400 meter-resolution) based on the ranking in table 4 were created for each input parameter. Numerical ranking for each attribute category is subjective but reflects the relative level of importance we believe the attribute plays in determining sensitivity of areas to VOCs. A sensitivity attribute of low is assigned when the summed ranking ranges from 3 to 4. A sensitivity attribute of moderate is assigned when the summed ranking ranges from 5 to 6, and a sensitivity attribute of high is assigned when the summed ranking ranges from 7 to 9.

VULNERABILITY ANALYSIS

As discussed above, sensitivity to oil and gas development is determined by assessing natural factors favorable or

Table 5. *Hydrologic soil groups, field capacity, bulk density, and fraction of organic carbon content generalized for Utah soils. Soil description and organic content from National Soil Survey Center (2006). Field capacity based on sediment grain size calculated from a soil texture triangle hydraulic properties calculator (Saxton, undated).*

Soil Group	Soil Description	Grain size (mm) (Field Capacity %)	Bulk Density Range (kg/L) (average)	Organic Carbon Content, Fraction (F_{OC})*
A	Sand, loamy sand, or sandy loam; low runoff potential and high infiltration rates even when thoroughly wetted; consists of deep, well to excessively drained sands or gravels with high rate of water transmission.	0.1 – 1.0 (14-21)	1.5 – 2.0 (1.75)	Variable and ranges from 0.029 to 8.7 %
B	Silt loam or loam; moderate infiltration rate when thoroughly wetted; consists of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures.	0.015 - 0.15 (25-28)	1.3 - 1.61 (1.4)	Variable and ranges from 0.029 to 8.7 %
C	Sandy clay loam; low infiltration rates when thoroughly wetted; consists of soils with layer that impedes downward movement of water; soils with moderately fine to fine structure.	0.01 - 0.15 (26)	1.3 - 1.9 (1.6)	Variable and ranges from 0.029 to 8.7 %
D	Clay loam, silty clay loam, sandy clay, silty clay, and/or clay; highest runoff potential of all soil groups; low infiltration rates when thoroughly wetted; consists of clay soils with a high swelling potential, soils with a permanent high water table, soils with a hardpan or clay layer at or near the surface, and shallow soils over nearly impervious material.	0.0001 - 0.1 (32-42)	1.2-1.3 (1.25)	Variable and ranges from 0.029 to 8.7 %
G	Gravel	2.0 and greater (less than 12)	2.0 (2)	0.029 %**

* F_{OC} is calculated from SSURGO organic matter data divided by 1.72 and is unique for soil polygons.

**No value for F_{OC} exists in the SSURGO database for gravel; we assigned the lowest value in the SSURGO database.

unfavorable to the degradation of groundwater by anthropogenic chemicals, whereas groundwater vulnerability is determined by assessing how groundwater sensitivity is modified by the activities of humans. Vulnerability includes human-controlled factors such as proximity to a water well, boundaries of DWSPs, proximity to active oil/gas well(s) and/or tar sands/tight gas land leases, and types of chemicals produced. Our vulnerability analysis includes input of 5 parameters: groundwater sensitivity, oil/gas well density and proximity to nearby oil shale/tar sand leases, and proximity to streams, water bodies, water wells, and public supply wells (table 6). All of the input parameters, except sensitivity, are derived from a combined index- and overlay-based method (table 2). Absolute numerical ranking for each attribute category is arbitrary and subjective, but reflects the relative level of importance the attribute plays in determining vulnerability to the area's aquifers.

Groundwater Sensitivity

We mapped aquifer sensitivity based on hydrostratigraphy (using primary and secondary permeability of geologic units), soil properties (including hydraulic conductivity, bulk density, organic content, and field capacity), BTEX (specifically benzene) chemical properties (such as the capacity of molecules to adsorb to organic carbon in soil), and depth to groundwater (permeable layer).

We consider groundwater sensitivity (intrinsic susceptibility) to be the principal factor that determines the vulnerability of aquifers in the Uinta Basin to degradation from VOCs (table 6). For example, we believe sensitivity is the most important attribute with respect to groundwater vulnerability (e.g., based on the inherent properties of the surficial/geologic material) and weighted this attribute heavier than the other parameters, which we rank equally (table 6). Consequently, low, moderate, and high sensitivity input rankings were assigned numerical values for the vulnerability analysis that are more heavily weighted than the other parameters, which we rank equally.

Proximity to Wells, Rivers, and Streams

Streams and water bodies used to create a proximity-to-water-bodies GIS layer were sourced from the National Hydrology Dataset. We selected major streams and water bodies larger than 3 acres for the analysis. Water well and spring locations were compiled from data collected from this study, Wallace's 2012 study, and public supply wells (Mark Jensen, Utah Division of Drinking Water, written communication, December 2014) (figure 2). DWSP zones were provided by the Utah Division of Drinking Water (Mark Jenson, written communication, December, 29, 2014). A low ranking is for water bodies and wells located greater than 3 miles, a moderate ranking is for 1-3 miles, and a high ranking is for those located less than one mile away. We use a buffer of 1-mile proximity to be protective of groundwater quality (see table 6).

Active/Producing Well Density and Location near Oil Shale /Tar Sand Leases

A list of active oil and gas wells was obtained from the Utah Division of Oil, Gas, and Mining database (Utah Automated Geographic Reference Center portal [gis.utah.gov]). The final oil/gas well density GIS layer was calculated with the Kernel Density tool in ArcGIS 10.2.2 at a resolution of 400 meters (610 ft) and a search radius of 1 kilometer (1.6 mi). Oil shale and tar sand BLM lease areas were obtained from the BLM's Oil Shale and Tar Sands Programmatic EIS (http://ostseis.anl.gov/eis/index.cfm).

The Enefit oil shale (figure 1) lease was also incorporated into the final oil shale and tar sand lease area calculation. Polygons with greater than 5 producing wells per square kilometer (1.6 mi) were selected as having a greater influence since active wells are more likely to contribute potential VOCs in the Uinta Basin (figures 1 and 3; table 6).

GIS Analysis Methods

VOC vulnerability is "low," "moderate," and "high" based on all 5 input parameters discussed above (table 6). Rasters (400-meter resolution) based on these rankings (table 6) were created for each input parameter. Low vulnerability is assigned when the summed ranking ranges from -2 to 1, moderate vulnerability is assigned when the summed ranking ranges from 2 to 5, and high vulnerability is assigned when summed ranking ranges from 6 to 10. Once again, numerical ranking for each attribute category is subjective, but reflects the relative level of importance the attribute plays in determining vulnerability of areas potentially contributing VOCs. As stated above, we believe aquifer sensitivity is the most important attribute with respect to groundwater vulnerability to VOCs, and therefore, weighted it more heavily than other parameters.

RESULTS OF MAPPING

Groundwater Sensitivity

Plate 1 shows the aerial extent of aquifer sensitivity. Most of the study area is moderately sensitive to VOC contamination. The breakdown in sensitivity is: 43 percent low sensitivity, 48 percent moderate, and 10 percent high.

Much of the Uinta Basin having low sensitivity (43%) to VOC contamination is due to protective clay layers or unmapped permeable layers. VOCs in these areas are unlikely to degrade groundwater quality but could, however, affect surface water. Areas with high hydraulic conductivities (≥0.57 inches/hour), high VOC retardation factors, and low VOC attenuation factors coincide with high sensitivity (10%). Most high sensitive areas are near streams and lakes where shallow alluvium covers

Table 6. *VOC vulnerability and the attribute rankings used to assign vulnerability for Uinta Basin, Uinta County, Utah.*

Aquifer Vulnerability Input Parameters	Attribute	Ranking
Sensitivity	Low	-2
	Moderate	0
	High	2
Active/Producing Well Density *	<1 well per sq. km.	0
	1-5 wells per sq. km.	1
	>5 wells per sq. km.	2
Located Within Oil Shale/Tar Sand Lease	Y	0
	N	2
Proximity to Well/Spring*	>3 miles	0
	1-3 miles	1
	<1 mile	2
Proximity to Water Body*	>3 miles	0
	1-3 miles	1
	<1 mile	2
Aquifer Vulnerability Output	**Attribute**	**Ranking**
Vulnerability	Low	-2 to 1
	Moderate	2 to 5
	High	6 to 1 0

*The attributes and ranking are subjective as part of the index-based method we employed (see table 2). We selected a range of values for each parameter that more realistically modeled land-use patterns based on the output of values generated from GIS analysis. The ranges represent a natural break in the distribution of GIS generated values that we modified and lumped together to minimize the number of classifications that were generated by GIS analysis. For example, we use a range category for proximity to water bodies as <1, 1-3, and >3 miles with "1" mile as a buffer zone surrounding a water body to be protective of water quality.

the land surface and shallow groundwater likely exists.

Groundwater Vulnerability

Plate 2 shows groundwater vulnerability to VOCs of aquifers for the Uinta Basin. Areas of high vulnerability are near water bodies, water wells, and oil/gas wells. Less than 2 percent of the surface area of the aquifers within the Uinta Basin has high vulnerability. Of particular concern are areas where groundwater is shallow or where oil/gas wells are near open water bodies. Areas of moderate vulnerability coincide, in general, with areas of moderate or high sensitivity. About 37 percent of the aquifer surface area has moderate vulnerability. Low-vulnerability areas generally coincide with areas farther away from public supply wells and with low density of active oil/gas wells. About 62 percent of the aquifer surface area

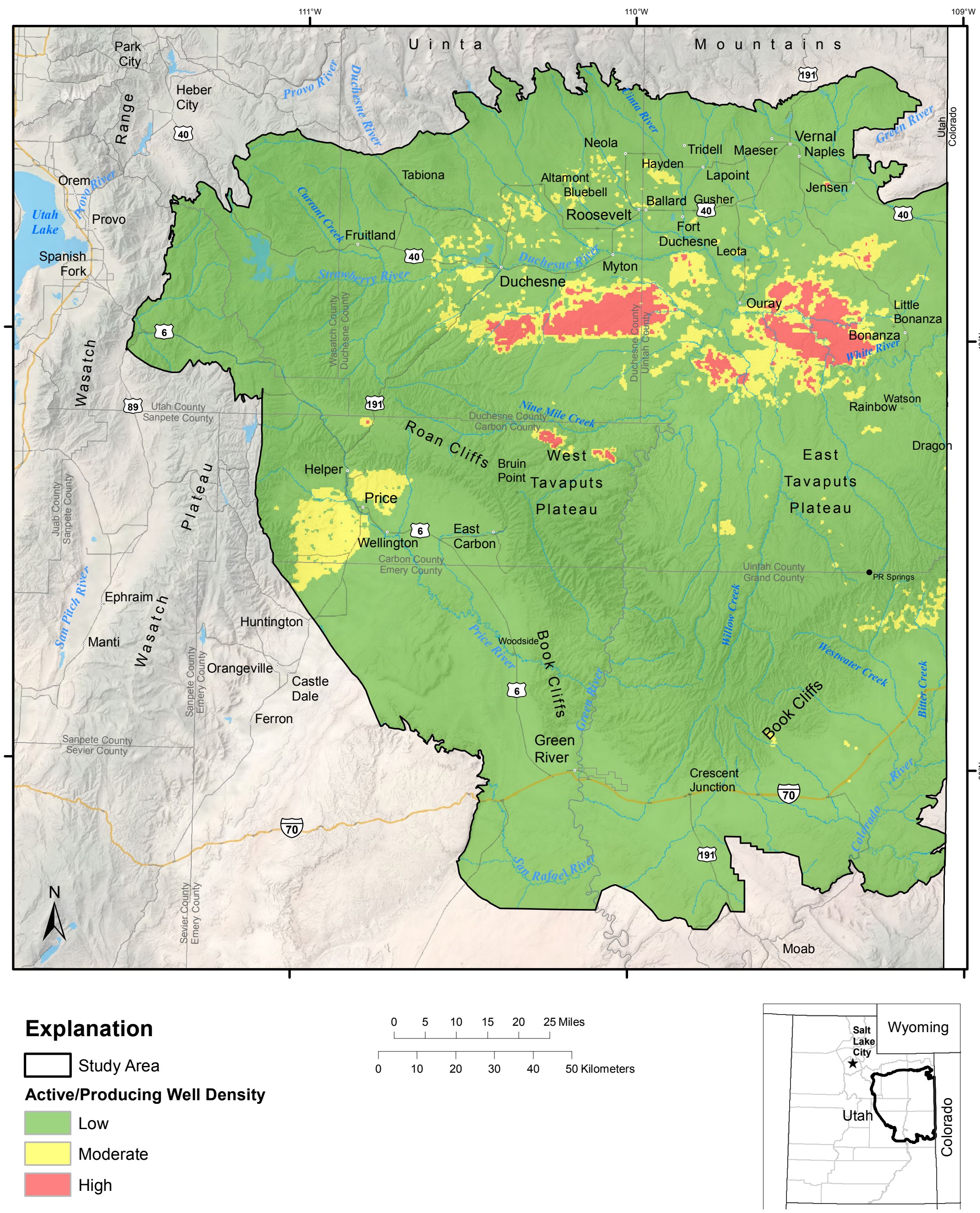

Figure 3. Density of active oil/gas wells obtained from Utah Division of Oil, Gas, and Mining.

within the Uinta Basin has low vulnerability. Most DWSP zones are located within moderately vulnerable areas. We recommend these areas be monitored for VOCs on a regular basis to ensure groundwater protection from potential pollution associated with any nearby development.

DISCUSSION

In areas of the Uinta Basin where groundwater is unconfined or in aquifers categorized as having high permeability, degradation of the aquifers by VOCs could occur whenever chemicals infiltrate through the vadose zone to the aquifer. In confined or lower permeability aquifer settings, VOCs would need to find pathways through confining layers to cause water-quality degradation. Thus, the ability of soils at the surface to retard or attenuate the downward movement of VOCs, and the hydrogeologic setting where VOCs may be present, have a fundamental effect on the likelihood that they can travel downward to the aquifer. Withdrawal of water from the aquifers via water wells could cause changes in vertical head gradient that may increase the potential for water-quality degradation. Wells themselves, if not properly constructed, or poorly developed in fractured/faulted areas near springs, could provide pathways for water with VOCs to reach the aquifers.

Areas of moderate and high vulnerability are primarily where greatest density of oil-gas development occurs within main or tributary drainages where groundwater sensitivity to VOCs is high. Of particular concern are streams that flow across the basin. Streams may be important sources of recharge to some, if not all of the aquifers. Efforts to preserve water quality at these locations would help to preserve groundwater quality in the Uinta Basin.

CONCLUSIONS

This project was conducted to establish water quality at representative wells and springs for lands in the Uinta Basin where conventional and unconventional energy extraction processes exist. We also examined the aquifer sensitivity and vulnerability of areas currently producing oil and gas and those with oil shale/tight-sand gas production potential. The Uinta Basin in eastern Utah generally lacks sufficient shallow, groundwater quality data to determine the effects that current and future oil and gas development may have on the area's aquifers. We used existing data and made assumptions for areas lacking data, to produce sensitivity and vulnerability maps by applying an attribute-ranking system specifically tailored to the arid conditions of the western United States using Geographic Information System analysis methods. As part of a two-year project to understand water-related issues of potential oil shale/tight-sand gas development in the Uinta Basin, this study establishes a snapshot of recent water quality and examines the vulnerability of the area's shallow alluvial wells and springs.

Thousands of wells within the Uinta Basin tap groundwater, but at depths tens of hundreds of feet below the surface where water is classified as too salty for human consumption. Most of the wells exist as part of the vast energy extraction industry of the Uinta Basin, namely oil and natural gas that could contain VOCs, among other chemical constituents of concern. VOCs, once released into the environment, can readily move among the atmosphere, soil, groundwater, and surface water. Potential VOC contamination from chemical spills, defective oil and gas wells, or other industrial use threatens drinking water sources, recreation areas, and wildlife habitats.

The areas with the highest potential for water-quality degradation associated with VOCs in the Uinta Basin occur where near-surface permeable layers are near water bodies, water wells/springs, and high-density oil/gas development, some within DWSP zones. VOC groundwater monitoring may be necessary in areas of high sensitivity or high vulnerability areas in and near DWSP zones. Water sampling and testing in areas of the basins characterized by low and moderate sensitivity and vulnerability may also be warranted, but at a lower frequency than for areas with higher sensitivity and vulnerability. The maps and accompanying report are based on analyses of 1:100,000 or smaller scale data, and are not applicable for site-specific evaluations. This study is based on GIS analysis of available land-use data and some data collected from groundwater wells and springs, and therefore has many limitations for vulnerability assessments.

ACKNOWLEDGMENTS

This project was funded by the Small Producer Program of the Research Partnership to Secure Energy for America (RPSEA) and the Utah Geological Survey. Rebekah Stimpson (Utah Geological Survey) provided field assistance and research on some sources of water wells. Critical review comments were provided by Richard Allis, Brittany Dame, Stephanie Carney, Kimm Harty, Mike Lowe, and David Tabet (Utah Geological Survey [UGS]). Kim Nay (UGS) prepared some figures and tables for this publication.

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