Overcoming data shortfalls to locate groundwater-dependent ecosystems and assess threats to groundwater quantity and quality

[1]Jenny F. BROWN, [2]Leslie BACH, [2]Allison ALDOUS, and [2]Abby WYERS

[1] The Nature Conservancy, 34307 SE 39th Pl., Fall City, WA 98024, jfbrown@tnc.org
[2] The Nature Conservancy, 821 SE 14th St., Portland, OR 97214, lbach@tnc.org, aaldous@tnc.org, awyers@tnc.org

Abstract: Effective conservation strategies to abate threats to groundwater quantity and quality must be based on a solid scientific framework. Currently, there is little information describing where and how ecosystems and species depend upon groundwater and how this supply is threatened. We developed analysis methods using GIS and a suite of indicators to 1) map groundwater-dependent biodiversity and 2) identify and map current and future threats to groundwater quantity and quality in the Pacific Northwestern United States. These methods were developed in a pilot program in Oregon, U.S.A. and will be applied elsewhere in this region. Application of these methods fills the current information gap and allows us to make informed decisions about where to focus our conservation efforts and the types of conservation actions that are most likely to be effective.

Keywords: conservation, groundwater contamination, groundwater quantity, groundwater-dependent ecosystems

Introduction:

Groundwater supply and quality is critical to the conservation of aquatic biodiversity, and yet groundwater is increasingly threatened around the globe. The Northwestern United States is no exception to this trend. Over 60% of the population already uses groundwater for drinking water and this demand likely will intensify as population growth of over 25% is expected in some largely rural areas over the next fifteen years (Oregon Office of Economic Assessment, 2007). Surface water supplies in the region have been fully allocated for use, thus water management agencies and water users are increasingly turning to groundwater to meet future water needs (Gannett et al., 2007; Oregon Water Resources Department (OWRD) Strategic Outlook, 2007). Furthermore, groundwater in several parts of this region fails to meet drinking water standards (Oregon Department of Environmental Quality (ODEQ), 2003). Recent studies indicate that groundwater contamination by nutrients or chemicals from agriculture, waste disposal, and industrial operations (Jones and Wagner, 1995; Wentz, et al., 1998) is prevalent and many additional areas likely are susceptible to future contamination. Consequently, groundwater depletion and contamination pose a looming and potentially widespread threat to aquatic ecosystems in this region.

In response to this threat, The Nature Conservancy is working to identify conservation actions that will protect groundwater-dependent biodiversity in the Northwestern United States. To accomplish this goal, we needed to identify the locations of groundwater-dependent ecosystems and species, evaluate their requirements for groundwater, and determine whether and how that groundwater is impaired. Upon initiating this project, we faced two critical information gaps. First, there were no assessments with detailed information about groundwater-dependent biota or the condition of groundwater across the region. Second, in many cases the actual datasets required to conduct such an assessment did not exist. To address these information gaps, we developed new analytical methods, using a suite of surrogate indicators and GIS mapping.

Our overall project objective was to build a framework for developing effective conservation strategies for groundwater-dependent ecosystems by (1) producing spatially explicit information on ecosystems and species that depend upon groundwater; (2) describing the groundwater requirements of those species both in terms of supply and quality; and (3) evaluating the condition of those groundwater supplies. This paper describes the methods we developed as well as some of the lessons we learned during their development.

Study location:

This assessment is being conducted in two Pacific Northwestern states - Oregon and Washington – encompassing 421 000 km^2 (Figure 1).

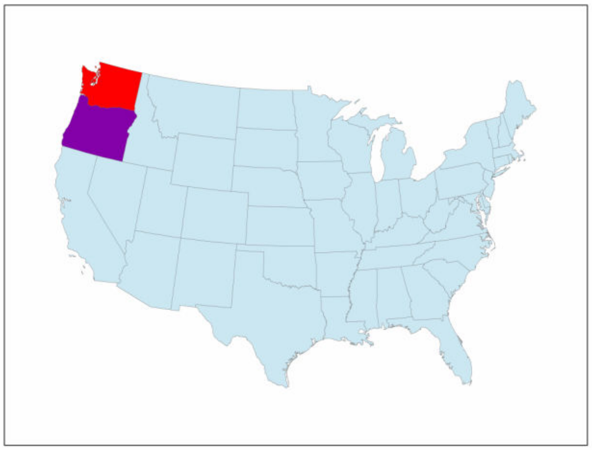

Figure 1: Location of Oregon and Washington State

The diversity of ecosystems and hydrogeologic settings across this region provides an excellent testing ground for tools to understand the ecological importance of groundwater. This area encompasses a spectrum of habitat and climatic conditions ranging from temperate rain forests (> 4.6 m of annual precipitation) and coastal conifer forests along the Pacific coast, to mesic prairies and grasslands in the Puget Trough and Willamette Valley, to montane forest and grasslands in the Cascade Mountains, to xeric grassland and shrublands and desert playas (<0.2 m of annual precipitation) in the eastern side of the states. These ecosystems occur in a variety of hydrogeologic settings underlain by geologic deposits that vary from Jurassic marine-derived sedimentary rocks on the coast to relatively recent volcanic and glacial deposits in the High Cascades and to the east.

The methods and analysis tools are being developed and tested in Oregon. Subsequently, the methods will be applied to Washington, and a methods guide will be developed for use in other regions. The following discussion focuses on how the methods were developed for Oregon.

Groundwater-dependence: A definition

Ecosystems, communities and species are *obligately* groundwater-dependent if every occurrence relies 1) on groundwater to provide all or part of the water supply, pressure, chemistry, or temperature seasonally, intermittently (e.g. during drought) or persistently or 2) on a shallow water table during any time of the year. Species or ecosystems are obligately groundwater-dependent if they are restricted to locations of groundwater discharge. In contrast, biota are *facultatively* groundwater-dependent if groundwater maintains their habitat conditions – such as late season flow - in some locations but not others As a result, some ecosystems are groundwater-dependent by virtue of their type but most are groundwater-dependent by virtue of their location on the landscape.

Identifying and mapping groundwater-dependent ecosystems and species:

To manage the data and information, we divided the state into regional analysis units. We identified eleven regions, based on similarities in biota and groundwater processes due to the relative homogeneity of hydrogeologic, ecological, and climatic conditions within each region.

Five ecosystem types have the potential to be dependent upon groundwater (Eamus and Froend, 2006): rivers, lakes, springs, wetlands, and caves. We developed digital datalayers locating these ecosystems and then conducted analyses to identify those that are likely to depend upon groundwater due to their hydrogeologic setting. We also identified species of conservation concern that rely on habitat conditions maintained by groundwater.

<u>Rivers:</u> In certain hydrogeologic settings, groundwater can maintain the hydrologic regime of rivers and streams and their associated riparian ecosystems; in particular, the base flow component of the hydrograph is often a result of groundwater inputs to rivers. However, even in streams with inputs of groundwater that are small relative to those of surface water or snowmelt, groundwater can create thermal refugia that are essential to aquatic organisms. We identified rivers that depend on groundwater to maintain either a hydrologic or thermal regime.

Hydrologic regime: The vertical and horizontal permeability of geologic deposits in the watershed plays a major role in determining the importance of groundwater to the hydrologic regime of a river (Wolock et al., 2004; Higgins et al., 2005). Generally, in a watershed dominated by more permeable surficial geologic deposits, precipitation and snowmelt will infiltrate downwards, recharging the groundwater that supplies streams and rivers. Using a 1:500 000 surficial geology datalayer of Oregon (Walker and MacLeod, 1991), we assigned relative permeability ratings to each geologic deposit. Rivers within watersheds (mean area = 44 174 ha) dominated by permeable geologic deposits were classified as groundwater-dependent for their hydrologic regime.

The initial classification based on geologic permeability was refined by examining the hydrographs of gaged rivers in Oregon, in places where these data exist (USGS NWIS). We used the shape of the annual hydrograph of a river and the ratio of mean monthly low flow to annual mean monthly flow to determine the importance of groundwater to the hydrologic regime of a river. Rivers for which groundwater controlled the hydrologic regime were characterized by high baseflow throughout the year, muted peak flows, and mean low flows that were more than 30% of the annual mean monthly flow. In addition, rivers with significant baseflows (15-30% of annual mean monthly flow) also were classified as groundwater-dependent. Hydrologic experts evaluated active and discontinued gages with at least two years of record from rivers unaffected by dams or by glacial snowmelt, and identified 97 groundwater-dependent river reaches.

After further refinement using information from the literature and expert input we produced a final map of groundwater-dependent rivers (Figure 2). Eighty-one percent of the rivers identified by gage data as groundwater-dependent were correctly predicted by the geologic permeability analysis. The gage sites were well distributed across the state, so this gives us confidence in the remaining predictions based solely on geologic characteristics.

Thermal regime: We used the presence of springs (Pacific Northwest Hydrography Framework, USGS GNIS, and University of Idaho EPSCoR data) adjacent to a stream segment as an indicator that groundwater played an important role in providing thermal refugia. Using GIS, all streams were buffered by 50 m; stream reaches for which this buffer intersected a mapped spring were classified as depending upon groundwater for the thermal regime (Figure 2).

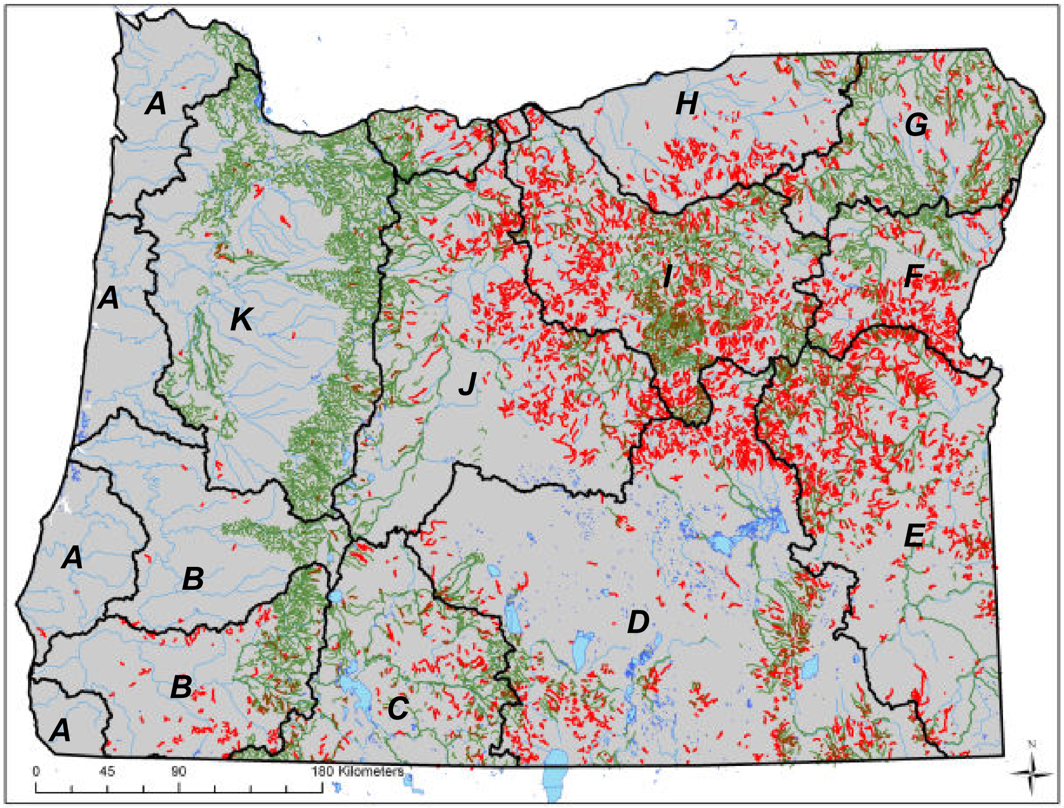

Figure 2: Predictions of groundwater-dependent rivers for hydrologic regime (green) and thermal regime (red). Blue are mainstem rivers unlikely to depend on groundwater. Regions of analysis are A) coast; B) Umpqua/ Rogue; C) Klamath; D) Oregon Basin & Range; E) Owyhee; F) Powder & Burnt; G) Lower Snake drainages; H) Middle Columbia drainages; I) John Day; J) Deschutes; and K) Willamette Valley.

<u>Springs:</u> All springs were assumed to be groundwater-dependent; however, the source of groundwater is likely to vary as a function of the geologic terrain upon which the springs occur (Sada et al., 2001). We divided springs into two different categories – springs that occur on either low permeability or high permeability deposits. Springs on low permeability deposits are more likely to be maintained by shallow groundwater that is vulnerable to different threats than are springs maintained by deeper and more distant groundwater sources. Springs that occur on high permeability deposits could be maintained by either regional or local groundwater sources, depending on site specific conditions.

<u>Lakes:</u> Most lakes in the Pacific Northwest probably receive groundwater inputs. Even small inputs of groundwater can be ecologically important (Sebeysten and Schneider, 2004; Rosenberry et al., 2000), so we assumed that all lakes in Oregon are groundwater-dependent unless they are immediately adjacent to snowfields. In these cases, the snowmelt hydrology was believed to be the dominant supply of water.

<u>Wetlands:</u> To date, there is no comprehensive map of wetlands in Oregon; therefore we used four datasets to identify and map wetland locations:

- National Wetland Inventory: This is a national program, lead by the US Fish and Wildlife Service (http://www.fws.gov/nwi/), to map existing wetlands across the United States based on aerial photos. Digital information was available for approximately half of Oregon.
- County soil surveys: This is also a national program to map soils in areas potentially suitable for agricultural activities (http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/). Areas with more than 20% hydric soils were assumed to be existing or historic wetland. These data are available digitally for about 2/3 of Oregon.
- Remote sensing data: A datalayer was recently produced of ecosystems across Oregon that is based on analysis of Landsat imagery (TNC, 2006). We mapped 21 of these ecosystems that are wetlands.
- Rare species and ecosystems data: The Oregon Natural Heritage Information Center tracks the location of rare species and ecosystems in Oregon. In addition, The Nature Conservancy identified species and communities of conservation concern in ecoregional assessments conducted of the state. We used these data points known to be associated with wetlands as an additional indicator of wetland locations.

To determine the groundwater dependence of the mapped wetlands, we began by assuming that both riparian and lacustrine wetlands were groundwater-dependent if their associated river and lake ecosystems relied on groundwater. We then identified wetlands classified as fens, which are by definition obligately groundwater-dependent. The groundwater dependence of the remainder of the wetlands was identified using the following analyses:

- Presence of organic soils: In much of Oregon, organic soils tend to form in locations of groundwater discharge. Wetlands with soils classified as Order Histosol or the subgroup histic on the county soil survey database were classified as groundwater-dependent.
- Presence of springs: Wetlands associated with spring locations were assumed to be groundwater-dependent.
- Slope: Wetlands on slopes generally receive groundwater discharge, so we used a 10 m DEM to identify all wetlands with more than a 5% slope as groundwater-dependent.

<u>Caves:</u> Caves were located using the USGS GNIS database. All caves, except for ice caves, were assumed to be groundwater-dependent.

<u>Species:</u> Species of conservation concern were selected as those identified by The Nature Conservancy in ecoregional assessments, tracked by the Oregon Natural Heritage Information Center, or suggested by taxonomic experts. We classified the groundwater dependence of over 1780 species and nearly 70 communities of conservation concern based on habitat requirements indicated in on-line databases (e.g. NatureServe Explorer and Flora of North America) or the published and gray literature. Vascular plants were the largest and most difficult group of species evaluated. In this analysis, we first determined the wetland indicator status of each species (US Department of Agriculture Plants database); all species rated as FACW or OBL (defined as usually or always occurring in wetlands) were included as facultatively groundwater-dependent. Those plant species associated with fens were classified as obligately groundwater-dependent. Eleven experts reviewed the assessments for all taxonomic groups except for bugs, mammals, and bats.

Seven percent (131 of the 1782 species) were found to be obligately dependent upon groundwater while 30% (532) were facultatively dependent. Some taxonomic groups were more likely to obligately depend upon groundwater than others. For example, over 45% of the freshwater mollusks of conservation concern were obligately dependent on groundwater. As a group, nearly 30% of other invertebrates of conservation concern were groundwater-dependent, and this is dominated by dragonflies, mayflies, and stoneflies (84% of these species were obligately groundwater-dependent) and caddisflies (42%). Facultatively groundwater-dependent species occurred in all aquatic habitats including lakes, rivers and wetlands.

Identifying and mapping current and future threats: We evaluated the threats posed to groundwater-dependent ecosystems and species by identifying areas on the landscape where there was a risk of alteration to groundwater quantity or quality. Although there is some direct information on groundwater use and contamination, data are limited, so we used a variety of surrogates to capture potential impacts.

Threats to quantity:

Groundwater supply can be altered by either groundwater extraction or reduction in groundwater recharge. To determine groundwater extraction, irrigation and municipal groundwater wells were located using the OWRD database of legal groundwater rights (Figure 3). Household wells producing less than 18,925 liters/day are not regulated and therefore are not included in these data. To locate these lower volume wells we used reports filed by well-drillers, which have been required by OWRD (well logs) since the 1950's. To capture future growth in groundwater demand, we used projected county population growth rates (OEA). In addition, we used land use plans to identify areas in the state that are projected to be developed as 'rural residential' because these areas are most likely to require individual household wells. To identify areas with a high potential risk of reduced groundwater recharge, we mapped areas with urban land use (National Land Cover Database, 2001) on permeable geologic deposits.

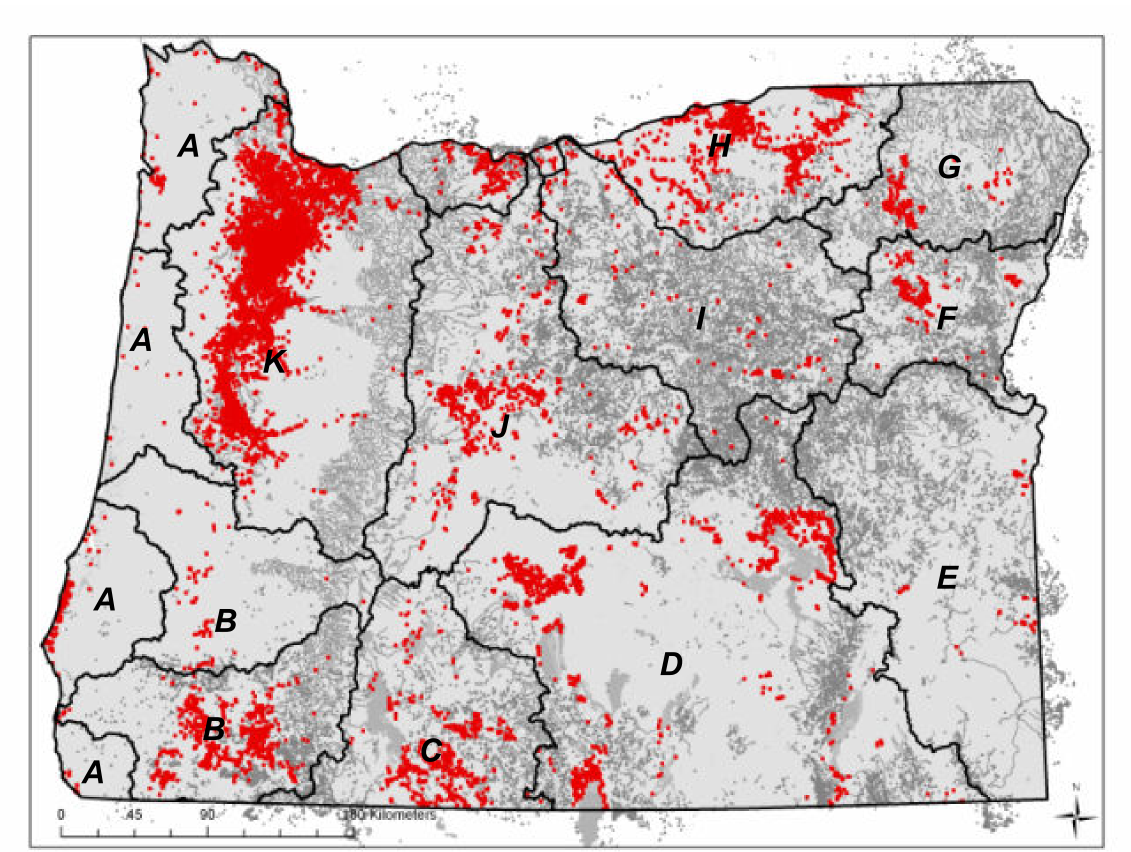

Figure 3: Groundwater rights (red) and groundwater-dependent ecosystems (gray). Well locations are from OWRD Water Rights database.

Threats to quality:

We found little direct information on groundwater contamination, so our analysis was primarily based on identifying the risk of contamination across the state. Risk is a combination of the *susceptibility* of a site to groundwater contamination, should the contaminants be present at the surface, and the *vulnerability* of a site to contaminants given the existing land uses.

Susceptibility to groundwater contamination is a function of seven factors that increase the likelihood that contaminants can reach the groundwater (Huddleston, 1996): highly permeable soils, low soil water holding capacity, low soil binding capacity (organic and clay content), shallow water table, highly permeable geologic deposits, high precipitation, and low slope. We obtained data to account for all of these factors, except for depth to water table, across most of the state. To identify high permeability soils with lower water holding capacity, we used the county soil survey database where it existed, to locate soils with an A or B hydrologic group (US Department of Agriculture Natural Resources Conservation Service, 2002). These two hydrologic groups are characterized as having a lower propensity for creating surface runoff and a greater likelihood that surface water will infiltrate. We used this same database to identify soils with lower organic (see Wetlands section) and clay contents to address the binding capacity. Permeability of the geologic deposits was assigned through our earlier analysis of groundwater-dependent rivers. We obtained mean annual precipitation between 1971 and 1990 from the Oregon Climate Service. Finally we used the 10 m DEMs (see Wetlands section) to identify areas with slopes less than 5%. Areas susceptible to groundwater contamination were identified as those where all of these factors co-occur.

We then evaluated the vulnerability of susceptible areas to potential contamination from nutrients, pesticides, and industrial contaminants:

Nutrients: Nutrient contamination is likely to result from commercial agricultural operations (US EPA, 2000), use of fertilizers both in irrigated agricultural and urban settings (Jones and Wagner, 1995; Wentz et al., 1998; Hamilton et al., 2004), and high densities of septic systems. Livestock operations with high densities of animals, termed ‘confined animal feedlot operations’, are regulated by the state and can be mapped using the Oregon Department of Agriculture database. Irrigated agricultural land use was mapped from the OWRD water rights database which identifies surface or groundwater irrigation rights. Urban land use served as an indicator of higher potential phosphorus inputs (NLCD, 2001). We used population density outside of urban areas, from the Oregon Census (2000), as an indicator of the density of septic systems in Oregon.

Pesticides: Pesticide contamination of groundwater is a significant issue in the United States; studies by the US Geological Survey have found more than 50% of all wells in shallow groundwater (less than 6 m) in both urban and agricultural areas had detectable levels of pesticides (Gilliom et al., 2006). Additionally, approximately 30% of shallow wells in either mixed land uses or undeveloped land use and more than a third of deep wells in major aquifers were contaminated by pesticides. Although the levels of pesticides found in groundwater very rarely violated human health standards, we included pesticides in our analysis for several reasons: 1) Groundwater contamination by pesticides was prevalent. Studies suggest that when groundwater is contaminated by one pesticide is also contaminated by others (Gilliom et al., 2006) and our understanding of the cumulative effects of these occurrences is poor; 2) No health standards exist for the breakdown products of pesticides and these by products are often present in higher concentrations than the original pesticides (Boxall et al., 2006); 3) Toxicity benchmarks for aquatic life can be lower than human health standards (Boxall et al., 2006) suggesting that even low levels of contamination may pose a risk to biodiversity.

Pesticides that pose the greatest risk to groundwater are those that have the highest usage, highest solubility, lowest volatility, and longest half life (Hamilton et al., 2004). We identified the most commonly used pesticides from estimates of the volume of 220 pesticides used in each county in Oregon (Thelin and Gianessi, 2000). The Oregon State University Pesticide Properties Database and the Cornell University Pest Management Education Program's pesticide profile database were consulted to identify 66 of these pesticides with a high likelihood of contaminating groundwater due to their chemical characteristics. Each was evaluated for known toxic or lethal affects to aquatic biota using the Pesticide Action Network's Pesticide Database; 21 pesticides were retained as potential threats to groundwater-dependent biodiversity. The patterns of use of nine of these in Oregon (Nakagaki and Wolock, 2005) recently were made available and included in our final analysis.

Industrial chemicals: The risk of contamination by industrial chemicals, including petroleum products, was indicated by the location of gas stations, reported spills, underground injection sites (also known as dry wells), and dry cleaners. All of these data were obtained from Oregon Department of Environmental Quality databases maintained as part of the water quality regulatory process.

Finally, we used the data that do exist of current groundwater conditions. The state of Oregon has identified three Groundwater Management Areas where drinking water standards for groundwater are not met due to contamination (ODEQ, 2003). Additionally, we located contaminated areas through groundwater quality data in the USGS NWIS and National Water Quality Assessment (NAWQA) databases and the ODEQ Laboratory Analytical Storage and Retrieval (LASAR) database.

Lessons Learned:

In the development of these methods, some approaches did not work as expected, and required modifications to the analysis methodology. These challenges provided an opportunity to identify lessons learned and to suggest additional analyses that could be tried in future efforts.

1) To identify rivers dependent on groundwater for their hydrologic regime we first used an analysis of drainage density, defined as stream miles per area of watershed. Several studies suggest that in watersheds dominated by subsurface water movement the drainage density is lower than in watersheds dominated by surface runoff (Tague and Grant, 2004; O'Connor et al, 2003). When we conducted this analysis using two hydrography datalayers for Oregon, our results varied with the amount of detail in the digital stream network rather than actual differences in stream density across the state. In the future, stream density could be calculated using a synthetic stream network developed from topographic data.
2) Springs, lakes and wetlands are poorly mapped in Oregon. We found that there was significant value in exploring the internet and asking experts for additional sources of data. We received and used much more detailed datalayers for springs in eastern Oregon as well as a draft coverage of wetlands for central and eastern Oregon, both of which improved our assessment.
3) One of the sources of information we used to identify wetlands was a datalayer developed from remote sensing analysis. These data were excellent for identifying larger wetland complexes and lengths of riparian vegetation that were otherwise unmapped. However, many of the obligately groundwater dependent wetlands, such as fens, are small and thus not detected by a remote sensing analysis. It is clear that the identification of some groundwater-dependent ecosystems requires fairly detailed information that can be supplemented, but not replaced, by coarser analyses.

Choosing where and how to take action:

The objective of developing these methods was to provide a foundation for identifying where conservation action is needed to protect groundwater-dependent ecosystems and species. Our first set of products identified where biota of conservation concern depend on groundwater and our second set of products indicated whether and how the supply and quality of that groundwater is threatened. Overlaying these two sets of information will allow us to identify the areas in Oregon where more detailed investigation is warranted of the ecological importance of groundwater and its condition.

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