Groundwater-dependent ecosystems in Oregon: an assessment of their distribution and associated threats

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Effective protection and management of groundwater-dependent ecosystems (GDEs) are hindered by inadequate information on their locations and the condition of associated groundwater supplies. We addressed this knowledge gap by developing a methodology that uses existing datasets to locate GDEs (including groundwater-dependent springs, lakes, rivers, wetlands, and species) and assess threats to groundwater quantity and quality. Here we report on the application of this method across the US state of Oregon. Nearly 40% of watersheds in Oregon contain two or more types of GDEs – termed "GDE clusters" – indicating the widespread importance of groundwater to ecosystems. Documented problems may underestimate the threat to ecosystems from altered groundwater supply or quality. Although documented occurrences of water-table declines are limited, high densities of permitted wells (for irrigation or other commercial purposes) pose a threat to groundwater availability in 18% of GDE clusters. Furthermore, although only 5% of GDE clusters have known groundwater contamination, our assessment indicates that 30% of GDE clusters are threatened with groundwater contamination by nitrates, 30% by industrial chemicals, and 70% by pesticides. This initial assessment of GDEs and threats to their groundwater supply highlights the ecological importance of groundwater and the need to incorporate protection of GDEs in water management policy.

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Groundwater is a vital source of water, globally sustaining both ecosystems and human communities (Morris *et al*. 2003). Wetlands, rivers, and lakes often receive inflow from groundwater, which maintains water levels and the water temperature and chemistry required by the plants and animals they support. Groundwater provides late-summer flow for many rivers and can create cool-water upwellings critical for aquatic species during the summer heat. Fens are wetlands fed largely by groundwater, often creating unusual water chemistry that supports habitat for rare species. Groundwater is the only water source for springs and subterranean ecosystems, which harbor a distinctive and poorly understood fauna. These and other ecosystems that rely on access to groundwater to maintain ecological structure and function are termed groundwater-dependent ecosystems, or GDEs (Murray *et al*. 2006). Such ecosystems also contribute to human well-being, through the provisioning of ecosystem services such as water storage and purification.

In the US and other developed countries, the value of groundwater for drinking water, irrigation, and industry is reflected in government policies that control groundwater availability and quality (eg USEPA 2002). However, in most countries, including the US, few or no policies currently exist to protect groundwater for ecosystems. Although groundwater monitoring is incomplete in many parts of the world, available data suggest that groundwater supply and quality are widely threatened by over-extraction and contamination (MA 2005). This loss and degradation are likely to increase in the future, as a result of climate-change-induced drought and human population growth, with serious consequences for both people and ecosystems.

At the local scale, resource managers working to protect or restore GDEs are often fully aware of the ecological role that groundwater plays. In the US state of Missouri, local organizations united to address land-use changes threatening the quality of groundwater that maintains the largest spring system in the central US (B Heumann pers comm). Water demands by the city of Las Vegas, Nevada, are now being balanced against groundwater needs of springs and wetlands in the Great Basin (Deacon *et al*. 2007). Despite these individual examples, water management policies in most places often ignore the importance of groundwater in supporting ecosystems and species. Exceptions to this are recent water management policies in South Africa, Australia, and European Union nations that have included groundwater protection for ecosystems, although they are still early in implementation (Environment Australia 1994; DWAF 1997; WISE 2008).

Effective policies to protect GDEs depend on understanding (1) where they occur; (2) their groundwater requirements for flow volume and timing, as well as water quality; and (3) whether and how their groundwater supplies are threatened. Unfortunately, in the US and many

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other countries, little of the relevant information is readily available at the scale of a region or entire country. To address this knowledge gap, we developed a Geographic Information System (GIS)-based screening methodology that uses existing datasets to identify where groundwater sustains ecological processes and where groundwater flowing to ecosystems is threatened by human activities. Here, we report on the application of this method to the US state of Oregon. A detailed description of the analysis methods and the complete results are available online (Brown *et al.* 2009).

Methods

To locate where groundwater flow sustains ecosystems and where it is at risk from human activities, we identified and mapped (1) GDEs and (2) threats to GDEs – due to changes in groundwater quantity and quality – using a GIS (ArcGIS version 9.2). To conduct this assessment across the entire state, we had to rely on incomplete datasets and to make assumptions in data interpretation (see WebTables 1–3 for data sources). We managed this issue in two steps. First, we summarized our findings at the scale of a small watershed, a HUC6 (Hydrologic Unit Code-6; mean size = 8055 ha or 19 905 acres; $n = 3111$), rather than at specific mapped locations of either GDEs or threats. Second, we identified indicators and established threshold criteria for determining whether a HUC6 contained either a GDE or a threat (see WebTables 4–6 for threshold criteria). HUC6s containing GDEs or threats to GDEs were identified by the presence of indicators above the threshold criteria. HUC6s that contained two or more types of GDEs (eg wetlands *and* rivers) were termed "GDE clusters", and these were the focus of the threat assessment. The criteria for evaluating threats to GDE clusters depended on our confidence in the data used. For example, if the data were from actual water samples demonstrating groundwater contamination, then only one data point was needed to identify a threat in any given HUC6. However, if the data indicated the presence of a land use that is associated with groundwater contamination, then multiple indicators were required to identify a threat in a HUC6. The presence of a threat within a HUC6 signifies that a potential risk exists, not necessarily that degradation has actually occurred.

Groundwater-dependent ecosystems

Six types of ecosystems may be groundwater dependent: springs, wetlands, rivers, lakes, phreatophytic (deep-rooted plants), and subterranean ecosystems (Eamus and Froend 2006). This assessment focused on the first four types. We did not include phreatophytic or subterranean ecosystems because there was limited information on these types of ecosystems in Oregon. Although springs are groundwater dependent regardless of location, the groundwater dependence of wetlands, rivers, and lakes is a function of their hydrological, geological, and climatic setting. We first mapped these latter three types of ecosystems and then assessed the likelihood that each occurrence is groundwater dependent. Wetlands were identified as groundwater dependent if they were known fens, contained organic soils, or were adjacent to springs. Groundwater-dependent rivers were identified as: (1) perennial rivers in watersheds dominated by geologic deposits classified as moderately to highly permeable or (2) unregulated rivers with measured flow data that indicated substantial baseflow. All natural, perennial lakes were assumed to be groundwater dependent, as experts indicated few such lakes in Oregon are likely to be isolated from groundwater. As an additional locator of GDEs, we also used species and ecological communities of conservation concern, designated as such by TNC and NatureServe (2007), that rely on habitat maintained by groundwater for some aspect of their life cycle (termed "obligately groundwater dependent"). We then mapped HUC6s that met our criteria for each type of GDE and identified GDE clusters.

Water quantity threats

Although many land-use activities can alter the volume and timing of groundwater discharging to GDEs, the primary source of such change in Oregon is groundwater extraction, which lowers the elevation of the water table or changes the direction of groundwater movement (USFS 2007). We used documented water-table declines to identify HUC6s where GDEs are threatened by changes in groundwater quantity, and we enhanced this analysis by including areas where GDEs may be at risk from groundwater over-extraction. In Oregon, groundwater extraction occurs in two types of wells: permitted wells, which are primarily for irrigation, industrial, and municipal uses, and unregulated (ie exempt) wells, which are for livestock and domestic uses. High densities of each type of well (see WebTable 5) were used as indicators of current threats from groundwater pumping. Pending groundwater permits and projected growth in rural residential development were used as indicators of future threats from increased well installations.

After applying our criteria to identify HUC6s with water quantity threats, we intersected threatened HUC6s with GDE clusters to locate where GDEs may be at risk from reduced groundwater availability.

Water quality threats

We assessed the threat to GDEs from groundwater contamination by nutrients (nitrogen and phosphorus), pesticides, and other toxic chemicals. When possible, we used documented groundwater contamination to identify threatened HUC6s. We supplemented this analysis by locating land uses associated with an increased risk of

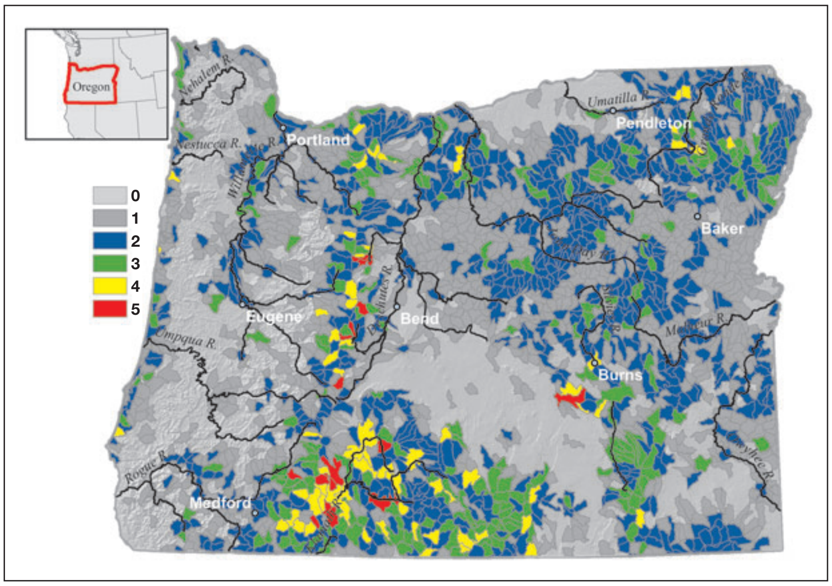


Figure 1. *Number of groundwater-dependent ecosystem (GDE) types per HUC6 in Oregon: springs and groundwater-dependent rivers, wetlands, and lakes. GDE clusters contain two or more GDEs (blue through red).*

groundwater contamination to identify threatened HUC6s. The threat of groundwater contamination by nutrients was indicated by agricultural areas with high levels of fertilizer use, concentrated animal feeding operations, high densities of septic systems, underground injection control wells for septic waste, and urban land use. The threat of groundwater contamination by pesticides was assessed by identifying agricultural areas where mobile pesticides (characterized by low volatility, high solubility, and long half-life) are used on soils that are unlikely to bind or otherwise remove the chemicals. Pesticide and phosphorus fertilizer use per acre is often higher in urban areas than in agricultural fields (Gilliom *et al.* 2006). However, data on urban chemical use are not available in Oregon, so we used urban land use as a surrogate. The threat of groundwater contamination by other toxic chemicals was indicated by the presence of a suite of land uses, such as dry cleaners, gasoline stations, or underground injection control wells, adjacent to a GDE.

After applying our criteria to identify HUC6s with water quality threats, we intersected threatened HUC6s with GDE clusters to locate where GDEs may be at risk from contaminated groundwater.

■ Results

Groundwater-dependent ecosystems

Groundwater sustains ecosystems in more than a third of Oregon watersheds (Figure 1). The most common GDEs in Oregon are springs (47% of HUC6s) and groundwater-dependent rivers (40%). Groundwater-dependent wetlands (15% of HUC6s) and lakes (7%) were identified less frequently, partly because maps of these ecosystems are incomplete. One hundred and forty-one species of conservation concern are obligately groundwater dependent and occur in 10% of HUC6s. This includes over a third of the invertebrate species of conservation concern.

Water quantity threats

Only 3% of GDE clusters are located in areas with documented water-table declines, and yet threats from existing wells and projected well installations are found in nearly a quarter of Oregon watersheds (Figure 2). Currently, in Oregon, there are approximately 21 000 permitted wells, high densities of which threaten over 18% of GDE clusters. More than 200 000 exempt wells are recorded in Oregon well logs, and high densities coincide with 7% of GDE clusters. In just under 10% of GDE clusters, at least one groundwater-right application is pending and increases in the installation of domestic wells are predicted.

Water quality threats

Although groundwater contamination has been measured in only 5% of GDE clusters in Oregon, human activities threaten almost three-quarters of these watersheds with groundwater contamination (70% of GDE clusters). The most widespread groundwater contamination threat is from agricultural pesticide use. Two or more mobile pesticides are used in 53% of GDE clusters (Figure 3a). The most common pesticides used in GDE clusters are metribuzin and carbofuran, each used in 500 or more GDE clusters.

Land uses associated with other threats of groundwater contamination – either by toxic chemicals other than pesticides (33% of GDE clusters) or by nitrates (28%) – are equally prevalent (Figure 3b, c). Industries associated with chemical spills that can contaminate groundwater (eg dry cleaners, gasoline stations, airports, and mines) are found near GDEs in 28% of GDE clusters. In many parts of the state, four or more indicators of potential groundwater contamination by nitrates occur (Figure 3c). Furthermore, the threat of groundwater contamination by phosphorus from agricultural fertilizer use occurs in 8% of the GDE clusters, and urban areas pose a threat to groundwater contamination by pesticides and phosphorus in 27% of clusters.

Limitations and caveats

As a result of subsurface geological complexity, groundwater movement is difficult to predict without detailed hydrogeological studies. This complexity, in conjunction

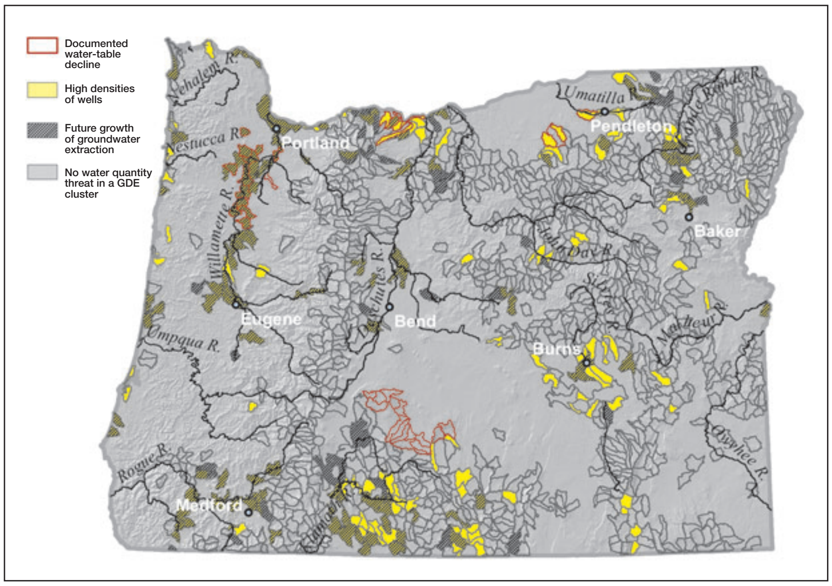


Figure 2. *Threats to groundwater quantity in GDE clusters. GDE clusters with documented declines in the water table (red outline); current high densities of either permitted or unregulated wells (yellow shading); future expected growth in either permitted or unregulated wells (hatching); and no identified threat to groundwater quantity (gray outline).*

with incomplete mapping of some ecosystems in Oregon, means that our maps of GDEs may fail to include all places where groundwater is important. For example, even though few HUC6s in the Coast Range were identified as having groundwater-dependent rivers, rivers in these low permeability watersheds probably receive locally important inputs of groundwater (see Winter 2007). Subsurface complexity also means it was not possible to link a particular threat to the impairment of a specific GDE with a high degree of confidence. To guard against drawing erroneous conclusions, we tested the validity of our assumptions when possible and otherwise used precautionary criteria for identifying the presence of GDEs and their associated threats. Despite these efforts, false positives may occur in identifying threats. For example, a high density of wells may not tap into the same groundwater source as a nearby GDE and therefore may not pose a threat. Although we included potential sources of contamination only if they were spatially close to a GDE, these activities only pose an ecological risk to that GDE if they are in the recharge area for its groundwater supply.

Discussion

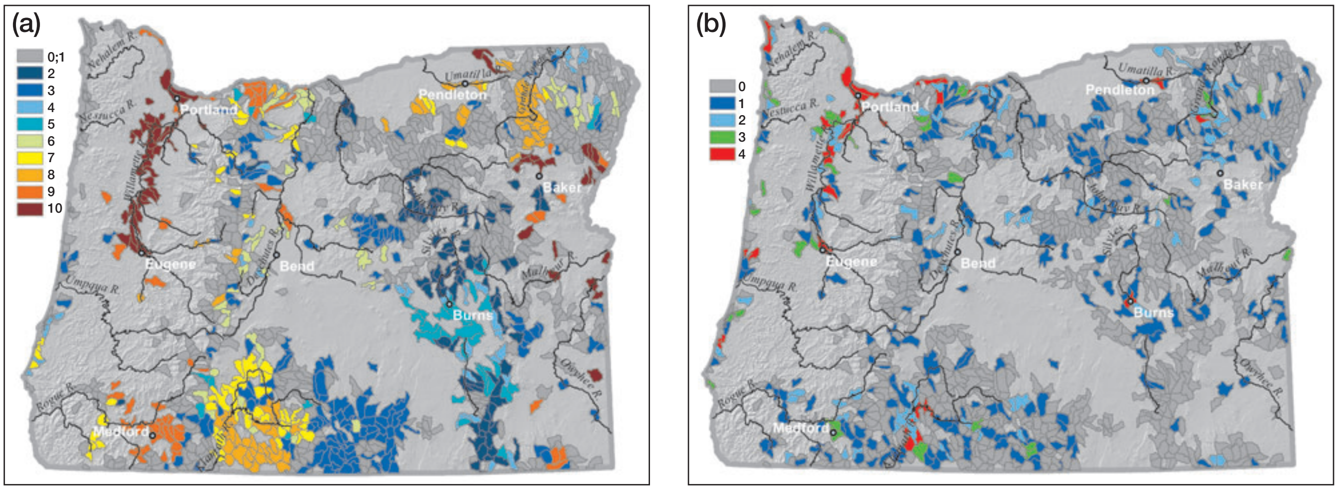
All four types of groundwater-dependent ecosystems studied here (springs, wetlands, rivers, and lakes) are widely, although unevenly, distributed across Oregon. Although different types of GDEs occur across different regions of the state, watersheds with multiple types of GDEs are found in both humid (eg coastal) and more arid regions. Concentrations of these GDE clusters are found along the crest of the Cascade Mountains, and in the Klamath and John Day river basins.

Threats to the quality and quantity of groundwater supporting GDEs are far more pervasive than is indicated by documented impacts to groundwater in Oregon. Only 7% of the state has been evaluated for groundwater contamination and only 15% for reduced supply (GWPC 2003). Assessing human activities associated with impaired groundwater is therefore an essential step for prioritizing threats to GDEs. These activities differ across the state, and depend on climate and geology, population size and growth rate, and predominant land use. Despite this variation, every part of Oregon in which GDEs are found faces threats to groundwater quantity or quality.

This assessment provides a picture of the distribution of GDEs and potential threats to their groundwater supply across a large area. In countries where the ecological requirements for groundwater are integrated into water management decisions, the process of locating GDEs and their threats has had great utility. Even at relatively coarse scales, this type of analysis has provided guidance for developing policies and making decisions about groundwater allocation (Colvin *et al.* 2007), and it has spurred research to develop the scientific underpinnings that can support GDE management and protection (Clifton *et al.* 2007). Most importantly, however, this type of analysis elevates awareness of the abundance, distribution, and types of ecosystems that depend on groundwater and the extent to which their supply of clean groundwater is threatened.

One important result of this analysis is our ability to compare where groundwater is ecologically important with where it is important for human uses. An initial assessment suggests that these two areas do not always overlap. For example, groundwater in the John Day river basin is not considered to be an important source of water for irrigation (Richards *et al.* 1986). However, our work revealed the highest average spring density in Oregon (23 per HUC6) and confirmed other findings that groundwater supports baseflow in more than half the watersheds in this basin (eg Gannett 1984).

The disconnect between ecological and human uses of groundwater is important, because it suggests that policies that protect groundwater for human uses may not necessarily protect GDEs. For example, state and federal groundwater programs are mandated to protect the quality of drinking water, so water quality standards address nitrate but not phosphorus. While not directly toxic to humans, phosphorus loading leading to eutrophication is a major problem for aquatic ecosystems (Carpenter *et al.* 1998), and was found to be a potential threat in several parts of the state. The ecological implications of the



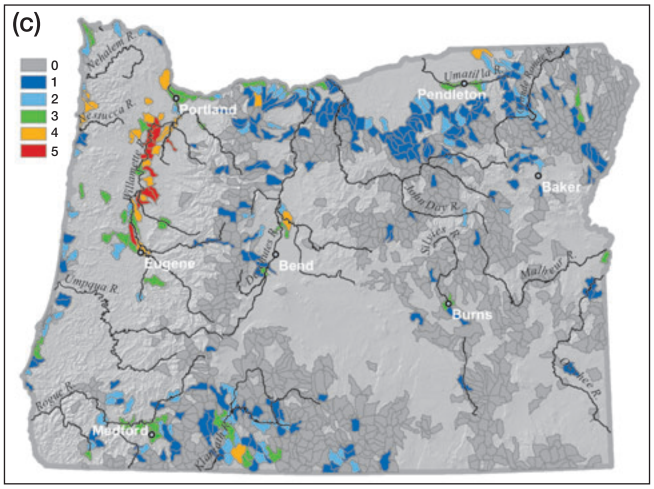


Figure 3. *Threats to groundwater quality in GDE clusters. (a) Agricultural pesticides: number of pesticides used; (b) other toxic chemicals: number of risk factors (eg land use, leaking underground storage tanks, hazardous waste spills, and underground injection control wells); and (c) nutrients: number of risk factors (eg agricultural fertilizer use, septic system density, underground injection control wells for septic waste, and concentrated animal feeding operations).*

widespread threat of pesticide contamination may be substantial because few standards currently exist for pesticide byproducts, some of which are more toxic than the parent chemical (Boxall *et al.* 2006). Furthermore, the synergistic effects of multiple pesticides have only recently become clear (Laetz *et al.* 2009) and are, for the most part, not addressed by regulations. Our analysis raises this as a priority issue for more detailed assessment.

With a growing global population and the impacts of land use and global climate change, water is increasingly being over-allocated and contaminated. GDEs are important not just for their rich flora and fauna, but also for the suite of ecosystem services they provide (Brauman *et al.* 2007). To protect these resources, it is critical that we begin to manage water in a way that is more inclusive of all users, including ecosystems and species.

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