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

Jenny Brown[1*], Leslie Bach[2], Allison Aldous[2], Abby Wyers[2], and Julia DeGagné[2]

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 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.

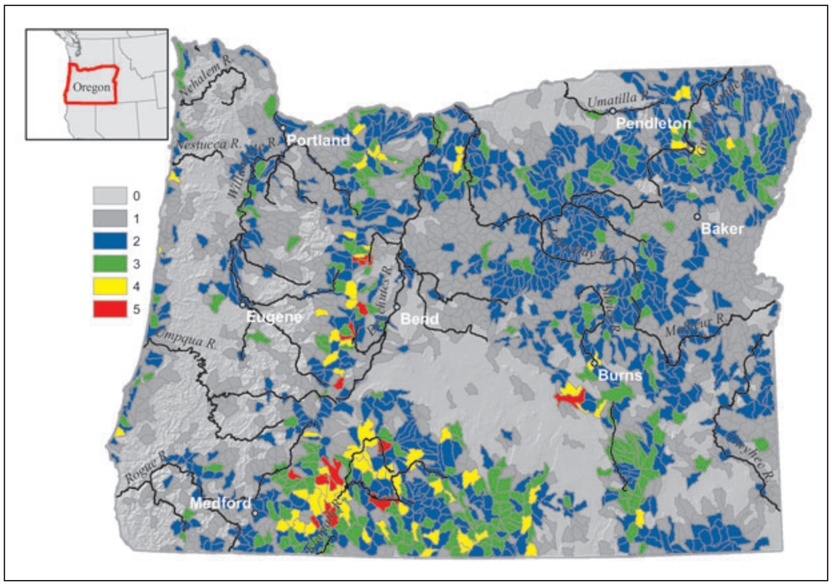


Figure 1. *Number of groundwater-dependent ecosystem (GDE) types per HUC6 in Oregon; springs and groundwater-dependent rivers, wetlands, and lakes. GDE clusters contain two or more GDEs (blue through red).*

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

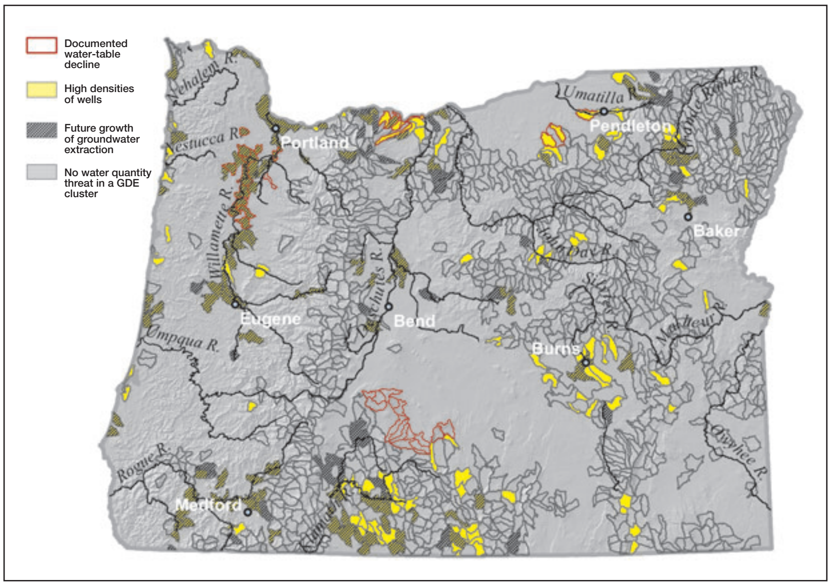


Figure 2. *Threats to groundwater quantity in GDE clusters. GDE clusters with documented declines in the water table (red outline); current high densities of either permitted or unregulated wells (yellow shading); future expected growth in either permitted or unregulated wells (hatching); and no identified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

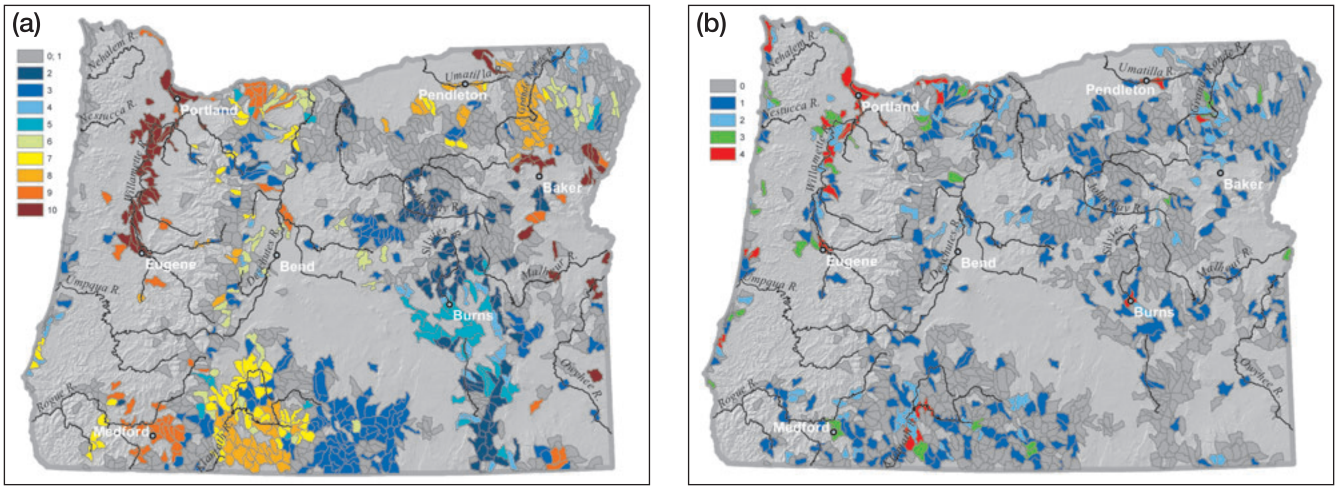
All four types of groundwater-dependent ecosystems studied here (springs, wetlands, rivers, and lakes) are widely, although unevenly, distributed across Oregon. Although different types of GDEs occur across different regions of the state, watersheds with multiple types of GDEs are found in both humid (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



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.

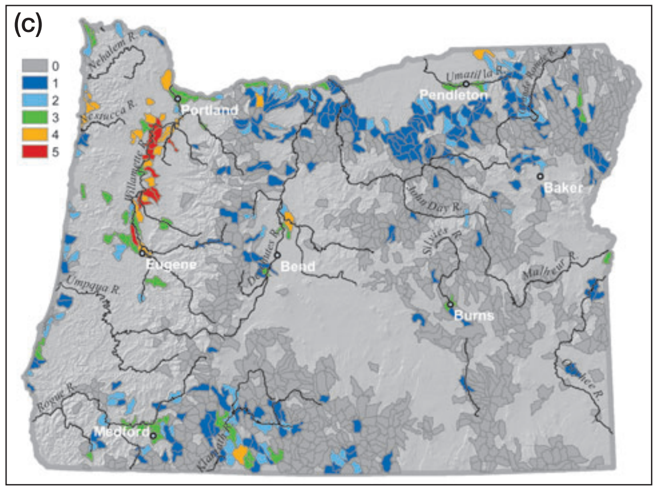


Figure 3. *Threats to groundwater quality in GDE clusters. (a) Agricultural pesticides: number of pesticides used; (b) other toxic chemicals: number of risk factors (eg land use, leaking underground storage tanks, hazardous waste spills, and underground injection control wells); and (c) nutrients: number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

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References

Boxall ABA, Sinclair CJ, and Kolpin DW. 2006. Potential risk of pesticide degradates to aquatic life. In: Gilliom RJ, Barbash JE, Crawford CG, *et al.* (Eds). Reston, VA: US Geological Survey. Circular 1291.

Brauman KA, Daily GC, Duarte TK, and Mooney HA. 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. *Annu Rev Env Resour* **32**: 67–98.

Brown J, Wyers A, Bach L, and Aldous A. 2009. Groundwater-dependent biodiversity and associated threats: a statewide screening methodology and spatial assessment of Oregon. Portland, OR: The Nature Conservancy. www.conserveonline.org/library/groundwater-dependent-biodiversity-associated/view.html. Viewed 1 Dec 2009.

Carpenter S, Caraco NF, Correll DL, *et al.* 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Iss Ecol* **3**: 1–12.

Clifton C, Cossens B, McAuley C, *et al.* 2007. Project REM-1: a framework for assessing the environmental water requirements of groundwater-dependent ecosystems. Report 1: Assessment toolbox. Prepared for Land and Water Australia, Braddon, Australia. Kent Town, Australia: Resource and Environmental Management Pty Ltd.

Colvin C, LeMaitre D, Saayman I, and Hughes S. 2007. An introduction to the aquifer-dependent ecosystems of South Africa: aquifer-dependent ecosystems in key hydrogeological typesettings in South Africa. Pretoria, South Africa: South Africa Water Research Commission. Report TT 301/07. www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=3687&FromURL=%2FPages%2FKH_DocumentsList.aspx%3Fdt%3D1%26su%3D4%26ct%3D1%26ms%3D4%253b5%253b. Viewed 10 Dec 2009.

Deacon JE, Williams AE, Williams CD, and Williams JE. 2007. Fueling population growth in Las Vegas: how large-scale groundwater withdrawal could burn regional biodiversity. *BioScience* **57**: 688–98.

DWAF (Department of Water Affairs and Forestry). 1997. White paper on a national water policy for South Africa. Pretoria, South Africa: Department of Water Affairs and Forestry. www.dwaf.gov.za/Documents/Policies/nwpwp.pdf. Viewed 1 Dec 2009.

Eamus D and Froend R. 2006. Groundwater-dependent ecosystems: the where, what and why of GDEs. *Aust J Bot* **54**: 91–96.

Environment Australia. 1994. The council of Australian governments' Water Reform Framework. Canberra, Australia: Department of the Environment, Water, Heritage and the Arts. www.environment.gov.au/water/publications/action/pubs/policyframework.pdf. Viewed 1 Dec 2009.

Gannett M. 1984. Groundwater assessment of the John Day basin. Salem, OR: Oregon Water Resources Department. www1.wrd.state.or.us/pdfs/GWStudies/OWRDMiscellaneousReports/GW_John_Day_Basin.pdf. Viewed 1 Dec 2009.

Gilliom RJ, Barbash JE, Crawford CG, *et al.* 2006. The quality of our nation's waters: pesticides in the nation's streams and ground water 1992–2001. Reston, VA: US Geological Survey. Circular 1291.

GWPC (Groundwater Protection Council). 2003. Oregon ground water conditions. State factsheet. Oklahoma City, OK: Groundwater Protection Council. www.gwpc.org/e-library/documents/state_fact_sheets/oregon.pdf. Viewed 1 Dec 2009.

Laetz CA, Baldwin DH, Collier TK, *et al.* 2009. The synergistic toxicity of pesticide mixtures: implications for risk assessment and the conservation of endangered Pacific salmon. *Environ Health Persp* **117**: 348–53.

MA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: biodiversity synthesis. Washington, DC: World Resources Institute.

Morris BL, Lawrence ARL, Chilton PJC, *et al.* 2003. Groundwater and its susceptibility to degradation: a global assessment of the problem and options for management. Early warning and assessment report series, RS 03–3. Nairobi, Kenya: United Nations Environment Programme. www.unep.org/DEWA/water/groundwater/pdfs/Groundwater_INC_cover.pdf. Viewed 1 Dec 2009.

Murray BR, Hose GC, Eamus D, and Licari D. 2006. Valuation of groundwater-dependent ecosystems: a functional methodology incorporating ecosystem services. *Aust J Bot* **54**: 221–29.

Richards JB, Hoffbuhr JA, Akins HC, *et al.* 1986. John Day River basin. Salem, OR: Water Resources Department.

TNC (The Nature Conservancy) and NatureServe. 2007. Rare species occurrences, compiled by The Nature Conservancy of Oregon with contributions from NatureServe, their member programs and partners. Portland, OR: The Nature Conservancy.

USEPA (US Environmental Protection Agency). 2002. CFR Title 40 Part 141 National Primary Drinking Water Regulations. Washington, DC: National Archives and Records Administration. Code of Federal Regulations. www.access.gpo.gov/nara/cfr/waisidx_02/40cfr141_02.html. Viewed 1 Dec 2009.

USFS (US Forest Service). 2007. Technical guide to managing ground water resources. Washington, DC: US Forest Service. Report # FS-881. www.fs.fed.us/r2/resources/mgr/geology/groundwater/index.shtml. Viewed 1 Dec 2009.

WISE (Water Information System for Europe). 2008. http://ec.europa.eu/environment/water/water-framework/groundwater/policy/current_framework/index_en.htm. Viewed 16 Sep 2008.

Winter TC. 2007. The role of groundwater in generating streamflow in headwater areas and in maintaining base flow. *J Am Water Resour As* **43**:15–25.

WebTable 1. Data sources and analyses for identification of GDEs

GDE	*Mapping data source*	*Groundwater-dependence analysis and data source*
Springs	(a) 1:24 000 Pacific Northwest Hydrography Framework water points (PNWHF 2005) (b) USGS Geographic Names Information System (GNIS) (USGS 1996) (c) Idaho EPSCoR Alvord Desert data (2006)	No data used; all springs are groundwater dependent
Wetlands	(a) Palustrine wetlands: National Wetland Inventory (USFWS 2007) (b) Hydric soils (>20% hydric in main component): SSURGO soil survey datasets (USDA NRCS 2006a) (c) Pacific Northwest Hydrography Framework water bodies data (PNWHF 2005) (d) Wetland ecosystems identified from remote sensing (TNC 2007) (e) Wetland communities identified in ecoregional assessments (Floberg *et al.* 2004; Vander Schaaf *et al.* 2004) (f) Communities of conservation concern tracked by NatureServe and Oregon Natural Heritage Information Center (TNC and NatureServe 2007) (g) Fen locations (TNC Preserve locations and expert input)	Assessed by wetland polygons: (1) All fens included as groundwater dependent (2) Wetlands within 100 m of a mapped spring (3) Wetland polygons containing organic soils (soils in the Order Histosol or subgroup histic): SSURGO soil survey datasets (USDA NRCS 2006a)
Rivers	(a) 1:100 000 NHDPlus streams (USGS 2006)	Assessed by HUC6: (1) More permeable geologic deposits occupy > 70% of HUC6 area OR 50–69% of area and are located in river valleys. Assignments of relative permeability made to 1:500 000 surficial geology deposits (Miller *et al.* 2002) (2) Mean monthly low flow > 15% of mean monthly flow per active and discontinued USGS gaging data (USGS 2007) with > 2 years of record from unregulated, perennial rivers without glaciers in headwaters
Lakes	1:24 000 Pacific Northwest Hydrography Framework water bodies (PNWHF 2005)	All lakes assumed to depend on groundwater
Species and communities of conservation concern	Species of conservation concern compiled by The Nature Conservancy of Oregon, with contributions from NatureServe and their member programs and partners, and tracked by Oregon Natural Heritage Information Center (TNC and NatureServe 2007)	Assessed for each species using: (1) Published literature and databases such as NatureServe Explorer (2008) and USDA Plants Database (USDA NRCS 2008) indicating dependence on habitat maintained by groundwater for some aspect of life cycle (2) Review by 11 taxonomic experts

Notes: Data sources used to map ecosystems and species, along with analysis and data sources used to assess groundwater dependence.

WebTable 2. Data sources to locate groundwater quantity threats

Threat	*Mapping data source*
Documented water-table decline	Groundwater Restricted Areas identified by Oregon Water Resources Department (OWRD 2007a)
Current groundwater pumping with exempt or permitted wells	Well log database (OWRD 2007b), a record of all wells constructed since the mid-1950s; permitted wells are those for irrigation, industrial or municipal use and exempt wells are those for domestic or livestock use
Future groundwater pumping – permitted wells	Pending groundwater rights applications (OWRD 2008)
Future groundwater pumping – exempt wells	Rural areas outside of urban growth boundaries (ODLCD 2007 and ODOT *et al.* 2005) Counties with expected population growth > 15% between 2005 and 2020 (OOEA 2004)

WebTable 3. Data sources to locate groundwater quality threats

Threat	*Source of threat*	*Mapping data source*
Documented groundwater contamination	Various	Draft Groundwater Management Areas (ODEQ 2003)
		Groundwater samples (ODEQ 2007a and USGS 2007) with detectable detectable amounts of pesticides or other chemicals
		Groundwater samples (ODEQ 2007a and USGS 2007) collected after 1 January 1996 in which the parameters, *"Nitrite plus nitrate, water, filtered, mg/L as nitrogen", Nitrate/nitrite as N (mg/L)* or *Nitrate/nitrite (mg/L as N)* exceeded 11 mg/L or the parameters *Total Phosphorus (mg/L)* or *Total Total Phosphorus (mg/L)* exceeded 0.01 mg/L. EPA Legacy STORET data (US EPA 2007) did not reveal exceedances of similar parameters
Groundwater contamination by nutrients	Agricultural N fertilizer use	Nationwide model of risk of nitrate contamination of shallow groundwater (Nolan *et al.* 2002)
		Nitrogen fertilizer use (Battaglin and Goolsby 1994); agricultural land use (USGS 2003); irrigated areas (place of use data; OWRD 2005); permeable geologic deposits (see WebTable 1 for rivers)
	Septic system density	Population density outside of urban growth boundaries (ODOT *et al.* 1995) determined from census blocks (US Census Bureau 2000). Divided by average Oregon household size, 2.46 people (US Census Bureau 2004), to estimate residence density, which was used as a surrogate for septic system density
	Concentrated animal feeding operations	ODA 2007
	Underground Injection Control wells (UICs)	Class V UICs (ODEQ 2007b) for septic waste disposal
	Agricultural P fertilizer use	Agricultural P fertilizer use (Battaglin and Goolsby 1994); agricultural land use (USGS 2003)
	Urban P fertilizer use	High and medium intensity developed areas (USGS 2003)
Groundwater contamination by pesticides	Agricultural pesticide use	Estimated locations of use for pesticides (Nakagaki and Wolock 2005) likely to contaminate groundwater (Vogue *et al.* 1994; USDA NRCS 2006b; Kegley *et al.* 2008) and toxic to aquatic life (Kegley *et al.* 2008; Pesticide Management Education Program, various dates). Soil leaching potentials calculated by the NRCS Windows Pesticide Screening Tool (USDA NRCS 2005) from SSURGO and STATSGO (USDA NRCS 2006a) soils data. Places with use of mobile, toxic pesticides in areas with high or intermediate soil leaching potential identified as threatened
	Urban pesticide use	High and medium intensity developed areas (USGS 2003)
Groundwater contamination by other toxic chemicals	Leaking underground storage tanks	Unregulated leaking underground storage tanks without completed cleanup (ODEQ 2007c)
	Underground Injection Control wells	Class V UICs for all waste except septic and gray water (ODEQ 2007b)
	Hazardous waste spills	Hazardous waste spill sites still needing cleanup (ODEQ 2007c)
	Gasoline stations	Underground storage tanks with certification numbers (ODEQ 2006)
	Dry cleaners	Dry cleaning operations that do not use an alternative to PERC (ODEQ 2007d)
	Mines	Active mines (ODGAMI 2007)
	Airports and military bases	USGS Geographic Names Information System (USGS 1996)

WebTable 4. Criteria used to identify HUC6s with GDEs

GDE	*Criteria*
Springs	Contains > 1 spring/2236 ha (5525 acres)
Wetlands	Contains a fen OR area of groundwater-dependent wetlands > 1% of HUC6 area
Rivers	Identified groundwater as important to river flow
Lakes	Contains a lake
Species and communities	Contains an obligately groundwater-dependent species or community of conservation concern

WebTable 5. Criteria used to identify GDE clusters with a threat of altered groundwater quantity

Threat	*Criteria*
Documented water-table decline	Presence of Groundwater Restricted Area
Current groundwater extraction	≥ 1 permitted well/ 2130 ha (5263 acres), primarily irrigation, municipal, and industrial water supply
	≥ 1 exempt well per 43.5 ha (108 acres), primarily domestic and livestock water supply
Future groundwater extraction	Presence of rural residential zoning in counties expected to grow by more than 15% ≥ 1 pending groundwater permit application

WebTable 6. Criteria and supporting citations for identifying GDE clusters with a threat of altered groundwater quality

Threat	*Source of threat*	*Criteria*
Documented groundwater contamination	Various	Presence of groundwater sample exceeding N or P threshold Presence of a Groundwater Management Area Presence of groundwater sample with detectable concentrations of pesticides, pesticide degradates, and other toxic chemicals
Groundwater contamination by nutrients	Agricultural N fertilizer use	Risk level $\geq$ 3 in USGS nationwide model of risk of nitrate contamination in shallow groundwater Presence of agricultural land use or irrigated land on permeable geologic deposits in counties with > 1401 kg/km^2 (4 $tons/mile^2$) of N fertilizer use
	Septic systems	Presence of > 2.5 systems/ha (1 septic system/acre)
	Concentrated animal feeding operations	$\geq$ 1 concentrated animal feeding operation
	Underground Injection Control wells	Presence of Class V UICs posing nutrient contamination risk
	Agricultural P fertilizer use	Contains agricultural land use and is in a county with a phosphorus fertilizer use rate > 420 kg/km^2 (1.2 $tons/mile^2$)
	Urban P fertilizer use	Presence of urban land use
Groundwater contamination by pesticides	Urban pesticide use	Presence of urban land use
	Agricultural pesticide use	Presence of $\geq$ 2 high risk pesticides in places where they are likely to contaminate groundwater
Groundwater contamination by other toxic chemicals	Leaking underground storage tanks	Presence of leaking underground storage tanks that have not undergone cleanup, located within 0.8 km (0.5 miles) of a GDE
	Underground Injection Control wells	Presence of Class V UICs associated with either all contaminants or industrial contaminants within 0.8 km (0.5 miles) of a GDE
	Hazardous waste spills	Presence of environmental cleanup sites needing current or future action within 0.8 km (0.5 miles) of a GDE
	Spills and leaching from specific land uses	Presence of activities that increase likelihood of spills within 0.8 km (0.5 miles) of a GDE: • gasoline stations • dry cleaners • active mines • military bases • airports

WebReferences

Battaglin WA and Goolsby DA. 1994. Estimates of nitrogen-fertilizer sales for the conterminous United States in 1991. Vector digital data. Lakewood, CO: US Geological Survey. Complete metadata available at: water.usgs.gov/GIS/metadata/usgswrd/XML/nit91.xml#stdorder

Floberg J, Goering M, Wilhere G, *et al*. 2004. Willamette Valley-Puget Trough-Georgia Basin ecoregional assessment, volume one: Report. Prepared by The Nature Conservancy with support from The Nature Conservancy of Canada, Washington Department of Fish and Wildlife. Oregon State Natural Heritage Information Center and the British Columbia Conservation Data Centre. www.ecotrust.org/placematters/assessment.html. Viewed 14 Dec 2009

Idaho EPSCoR (Experimental Project to Stimulate Competitive Research). 2006. Biocomplexity in extreme environments project. Spring coordinates database. Moscow, ID: University of Idaho. www.uidaho.edu/biogeochemistry/maps.html. Viewed 3 Nov 2006.

Kegley SE, Hill BR, Orme S, and Choi AH. 2008. PAN Pesticide Database, San Francisco (CA): Pesticide Action Network North America. www.pesticideinfo.org Viewed: 2007 and 2008.

Miller RJ, Raines GL, and Connors KA. 2002. Spatial digital database for the geologic map of Oregon. Reston, VA: US Geological Survey. Open-File Report 03-67. Digital database v. 2 of GW Walker and NS MacLeod geologic mapping. Available at: pubs.usgs.gov/of/2003/of03-067/of03-67.pdf

Nakagaki N and Wolock DM. 2005. Estimation of agricultural pesticide use in drainage basins using land cover maps and county pesticide data. Reston, VA: US Geological Survey. Open-File Report 2005-1188.

NatureServe. 2008. NatureServe Explorer Database. www.natureserve.org/explorer/. Viewed Nov 2006 to Jun 2007.

Nolan BT, Hitt KJ, and Ruddy BC. 2002. Probability of nitrate contamination of recently recharged ground waters in the conterminous United States. Raster digital data. Reston, VA: US Geological Survey. Complete metadata available at: water.usgs.gov/lookup/getspatial?gwrisk. Viewed 14 Dec 09.

ODA (Oregon Department of Agriculture). 2007. Confined animal feedlot operations (CAFO) database. Salem, OR: Oregon Department of Agriculture. Received 22 Feb 2007.

ODEQ (Oregon Department of Environmental Quality). 2003. 2003 Oregon groundwater conditions. Portland, OR: Oregon Department of Environmental Quality. Available at: www.deq.state.or.us/wq/groundwater/docs/orgwconds.pdf. Viewed 14 Dec 09.

ODEQ (Oregon Department of Environmental Quality). 2006. UST database. Portland, OR: Oregon Department of Environmental Quality. Available at: www.deq.state.or.us/lq/tanks/tankslists.htm. Viewed 3 Oct 2006.

ODEQ (Oregon Department of Environmental Quality). 2007a. Laboratory analytical storage and retrieval (LASAR) database. Portland, OR: Oregon Department of Environmental Quality. deq12.deq.state.or.us/lasar2/default.aspx. Viewed 4 Jan 2007 and 6 Aug 2007.

ODEQ (Oregon Department of Environmental Quality). 2007b. UIC database. Portland, OR: Oregon Department of Environmental Quality. Received 15 Feb 2007.

ODEQ (Oregon Department of Environmental Quality). 2007c. Facility profiler (version 2.0). Portland, OR: Oregon Department of Environmental Quality. deq12.deq.state.or.us/fp20/. Viewed 2 Jan 2007.

ODEQ (Oregon Department of Environmental Quality). 2007d. Dry cleaner database. Portland, OR: Oregon Department of Environmental Quality. Received 8 Jan 2007.

ODGAMI (Oregon Department of Geology and Mineral Industries). 2007. List of existing mining permits. Portland (OR): Oregon Department of Geology and Mineral Industries. www.oregongeology.com/sub/mlr/mlrhome.htm. Viewed 16 Aug 2007.

ODLCD (Oregon Department of Land Conservation and Development). 2007. Oregon zoning (1983–1986). Vector digital data. Available at: www.oregon.gov/DAS/EISPD/GEO/alphalist.shtml#Z. Viewed 14 Dec 2009

ODOT (Oregon Department of Transportation), State Service Center for GIS, and Metro Regional Council of Governments. 1995. Oregon urban growth boundaries. Vector digital data. Available at: www.oregon.gov/DAS/EISPD/GEO/alphalist.shtml#Z. Viewed 14 Dec 2009

OOEA (Oregon Office of Economic Analysis). 2004. Forecasts of Oregon's county populations and components of change, 2000–2040. Available at: www.oea.das.state.or.us/DAS/OEA/demographic.shtml. Viewed 14 Dec 2009

OWRD (Oregon Water Resources Department). 2005. Water Rights Information System (WRIS). Salem, OR: Oregon Water Resources Department. www.wrd.state.or.us/OWRD/MAPS/index.shtml. Viewed 15 Jan 2008.

OWRD (Oregon Water Resources Department). 2007a. Groundwater restricted areas. Salem, OR: Oregon Water Resources Department. Vector digital data. Received 22 Mar 2007.

OWRD (Oregon Water Resources Department). 2007b. Well log database. Salem, OR: Oregon Water Resources Department. www.wrd.state.or.us/OWRD/GW/well_data.shtml#Download_Water_Level_Data. Viewed Feb 2007.

OWRD (Oregon Water Resources Department). 2008. Pending groundwater applications. Salem, OR: Oregon Water Resources Department. Received 15 Jan 2008.

PNWHF (Pacific Northwest Hydrography Framework). 2005. Water bodies, water courses, water points. Vector digital data. Portland, OR: US Bureau of Land Management. Available at: www.oregon.gov/DAS/EISPD/GEO/alphalist.shtml#H.

PMEP (Pesticide Management Education Program). Various dates. Extension toxicology network pesticide information profiles. Ithaca, NY: Cornell University. pmep.cce.cornell.edu/profiles/extoxnet/index.html. Viewed 2007 to 2008.

TNC (The Nature Conservancy) and NatureServe. 2007. Rare species occurrences, compiled by The Nature Conservancy of Oregon with contributions from NatureServe, their member programs and partners. Portland, OR: The Nature Conservancy.

TNC (The Nature Conservancy) (Eds). 2007. Ecological systems for ecoregions intersecting OR. Compiled from data provided by LandFire, USGS, and NatureServe. Raster digital dataset. Portland, OR: The Nature Conservancy.

US Census Bureau. 2000. Oregon census data 2000. Vector digital data. Washington, DC: US Geography Division, US Census Bureau, Department of Commerce. Complete metadata available at: gis.oregon.gov/DAS/EISPD/GEO/docs/metadata/census.shtml. Viewed 14 Dec 2009

US Census Bureau. 2004. American factfinder Oregon factsheet. Washington, DC: US Geography Division, US Census Bureau, Department of Commerce. Available at: factfinder.census.gov/home/saff/main.html?_lang=en. Viewed 14 Dec 2009

USDA NRCS (US Department of Agriculture, Natural Resources Conservation Service). 2005. Windows pesticide screening tool (WIN-PST, version 3.0). www.wsi.nrcs.usda.gov/products/W2Q/pest/winpst.html#pst%20ppd. Viewed 14 Dec 2009

USDA NRCS (US Department of Agriculture, Natural

Resources Conservation Service). 2006a. Soil survey geographic database (SSURGO) and State soil geographic database (STATSGO). Washington, DC: US Department of Agriculture, Natural Resources Conservation Service. Available at: soildatamart.nrcs.usda.gov/. Viewed 14 Dec 2009

USDA NRCS (US Department of Agriculture, Natural Resources Conservation Service). 2006b. Pesticide properties database. www.wsi.nrcs.usda.gov/products/W2Q/pest/winpst.html#pst%20ppd. Viewed 14 Dec 2009.

USDA NRCS (US Department of Agriculture, Natural Resources Conservation Service). 2008. The PLANTS database. Baton Rouge, LA: National Plant Data Center. plants.usda.gov. Viewed 2007 to 2008.

US EPA (US Environmental Protection Agency). 2007. STORET database. www.epa.gov/storet/dbtop.html. Viewed 14 Aug 2007.

US FWS (US Fish and Wildlife Service). 2007. National wetlands inventory digital data and newly digitized data from Oregon Correctional Enterprises. Available at: www.fws.gov/nwi/. Viewed 14 Dec 2009

USGS (US Geological Survey). 1996. Geographic Names Information System (GNIS). Reston, VA: US Geological Survey. geonames.usgs.gov/pls/gnispublic/f?p=115:1:6542019009841479 Viewed 14 Dec 2009

USGS (US Geological Survey). 2003. National land cover database zone 60 land cover layer. National land-cover dataset. Raster digital data. Sioux Falls, SD: US Geological Survey. www.mrlc.gov/mrlc2k_nlcd.asp. Viewed 14 Dec 2009

USGS (US Geological Survey). 2006. NHDPoint, NHDLine, NHDFlowline, NHDArea, NHDWaterbody. 1:100 000 vector digital data. National Hydrography Dataset (NHD) Geodatabase. Reston, VA: US Geological Survey. Available at: nhd.usgs.gov/data.html. Viewed 14 Dec 2009

USGS (US Geological Survey). 2007. USGS water data for Oregon. National Water Information System (NWIS) database. Reston, VA: US Geological Survey. waterdata.usgs.gov/or/nwis/nwis. Viewed 5 Jan 2007 and 21 Feb 2007.

Vander Schaaf D, Schindel M, Borgias D, *et al*.. 2004. Klamath Mountains ecoregional conservation assessment. Portland, OR: The Nature Conservancy. Available at: conserveonline.org/workspaces/cbdgateway/era/reports/index_html Viewed 14 Dec 2009

Vogue PA, Kerle EA, and Jenkins JJ. 1994. OSU extension pesticide properties database. National Pesticide Information Center (NPIC). Corvallis, OR: Oregon State University. npic.orst.edu/ppdmove.htm. Viewed 2007 to 2008.

