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ORIGINAL RESEARCH

Geologic and Geomorphic Controls on the Occurrence of Fens in the Oregon Cascades and Implications for Vulnerability and Conservation

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Abstract Montane fens are biologically diverse peat-forming wetlands that develop at points of groundwater discharge. To protect these ecosystems, it is critical to understand their locations on the landscape and the hydrogeologic systems that support them. The upper Deschutes Basin has a groundwater flow system that supports baseflow in many rivers, but little is known about the wetland types and groundwater dependence of the thousands of wetlands within the watershed. In 292 randomly selected wetlands, we quantified landscape metrics thought useful for discriminating montane fens from non-peat-forming wetlands. We inspected these wetlands and classified 67 of them as fens. Of the landscape metrics, only geology reliably differentiated fens from other types of wetlands. Nearly all fens develop in low-permeability glacial till found at approximately 1400–1800 m in elevation, and are concentrated in areas mantled by pumice deposits that originated primarily from the eruption of Mt. Mazama approximately 7700 years BP. Stratigraphic and hydrologic factors indicate the fens are supplied by perched aquifers in glacial till, instead of the deeper regional aquifer system. Their hydrogeologic setting makes the fens highly vulnerable to expected changes to recharge associated with climate change, but not to groundwater pumping from the regional aquifer.

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Introduction

Fens develop where groundwater discharges into the biologically active zone of the soil at a rate that is sufficient and constant enough to promote peat accretion. These wetlands harbor high species richness and endemism due to their unique hydrogeologic, edaphic, and geochemical conditions (Amon et al. 2002; Bedford and Godwin 2003). Montane fens may be distant from more extensive riparian and floodplain wetland complexes and river networks, yet they are integrally linked to the freshwater landscape as headwater areas or through subsurface flows. Biologically diverse wetlands such as these face unprecedented threats world-wide from habitat loss and hydrologic alteration due to human activities (Brinson and Malvarez 2002; van Diggelen et al. 2006; Dahl 2011).

The landscape-scale distribution, within-site ecosystem processes, and species composition of fens are determined largely by the amount and chemistry of groundwater discharge. Thus conservation and management plans must protect both the fens themselves as well as their supporting groundwater sources. A key component of fen conservation and management is knowledge of their distribution and extent, but they are typically poorly characterized by datasets such as the National Wetlands Inventory (U.S. Fish and Wildlife Service 2014) and the National Hydrography Dataset (U.S. Geological Survey 2014). Better topographic, hydrogeological, or ecological criteria for distinguishing montane fens from other types of wetlands at the scale of whole watersheds, using readily available landscape information, is a first step in achieving protection of these biologically diverse ecosystems.

The hydrogeologic setting is a useful framework for understanding the development of fens, their connections to the surrounding landscapes, and their vulnerability to anthropogenic stresses (Winter 1988; Thompson et al. 1992; Bedford 1996, 1999; Godwin et al. 2002). The hydrogeologic setting influences the flow of groundwater to wetlands, and is defined by (1) lithology and stratigraphy of subsurface geological materials in the watershed and underlying the wetland; (2) flow paths, chemistry, and discharge rates of the supporting groundwater flow systems; (3) topography and slope; and (4) forms and amounts of precipitation and evapotranspiration within the watershed and wetland (Komor 1994; Winter 1988, 1992).

Numerous studies describing the hydrogeologic settings of fens were published over the last three decades from the eastern and midwestern U.S. and Europe (e.g., Foster and Fritz 1987; Siegel and Glaser 1987; Thompson et al. 1992; Glaser et al. 1997; Almendinger and Leete 1998; Winter 1988; Amon et al. 2002; Bedford and Godwin 2003). These studies were conducted largely in watersheds with relatively flat topography and uniform geology, sometimes including fens as one component of large peatland complexes, and emphasized the importance of topographic features such as breaks in slope and climatic characteristics such as annual precipitation exceeding evapotranspiration. At that time there were few fens documented from more topographically and geologically heterogeneous landscapes such as mountainous regions of North America and where annual precipitation is less than evapotranspiration (Bedford and Godwin 2003). More recent papers, including work done in these montane areas, discuss diverse aspects of fen ecology but do not emphasize details of their hydrogeologic setting (Chimner et al. 2010; Lemly and Cooper 2011; Drexler et al. 2013). With this increase in the documentation of fens in varying topographic, geologic, and climatic landscapes, we can gain knowledge of the full range of hydrogeologic conditions in which fens occur in order to ensure their protection and persistence in diverse settings.

The upper Deschutes Basin, which drains about one-third the length of the Cascade Range in Oregon, provides an ideal opportunity to study the hydrogeology of fens in a western mountain range. This basin contains nearly 7900 wetlands mapped by the National Wetlands Inventory that are classified as types that could be fens (U.S. Fish and Wildlife Service 2014), but no systematic wetland surveys have been conducted in the basin. Also, the hydrology of the upper Deschutes Basin is well characterized (James et al. 2000; Gannett et al. 2001, 2003), and there are hydrologic data sets and models with which to assess fen occurrence and vulnerability (Gannett and Lite 2004; Waibel et al. 2013).

Fens and other groundwater-dependent ecosystems in the upper Deschutes Basin could be vulnerable to anthropogenic and climatic stresses. Groundwater is extracted for municipal and agricultural supply (Gannett and Lite 2013) and future climate warming will affect the amount, timing, and distribution of runoff, and groundwater recharge and discharge (Elsner et al. 2010; Waibel et al. 2013). Widespread changes in groundwater levels already have resulted from climate and pumping stresses (Gannett and Lite 2013). By understanding the distribution and hydrogeologic setting of fens, we can better evaluate their vulnerability to such external stresses.

The objectives of this study were to develop a series of landscape metrics to differentiate the hydrogeologic settings of fens from non-fen wetlands in the upper Deschutes Basin and to use this information to evaluate fen vulnerability to groundwater pumping and climate change. We addressed these objectives by sampling 292 wetlands across the study area to make a determination of whether they are fens, classifying them using a series of geomorphic and geologic metrics, and evaluating their vulnerability to pumping and climate change using published data and models.

We anticipate that our results will be useful for resource management. Much of the upper Deschutes Basin is public land, including 67 % managed by the U.S. Forest Service, and our results should be useful to this agency as they develop groundwater, timber, road, and recreation management plans. For example, there are many campgrounds that generally use groundwater wells for water supply. Shallow groundwater also is used to fight wildfires in this area. The Forest Service is interested in balancing societal water needs with those of ecosystems (Aldous and Bach 2014), and these data can be used in that balancing process.

Methods

Study Area Description

The Cascade Range, which extends from northern California to northern Washington, separates the humid western part of the state from the semiarid east. The upper Deschutes Basin study area covers about 8100 km^2 and encompasses roughly a third of the length of the Cascades in Oregon (Fig. 1). Much of the range in the study area is above 1500 m, but it is punctuated with large stratovolcanos exceeding 3000 m. Precipitation ranges from 4200 to about 250 mm in the central part of the basin due to the rain shadow effect. Most precipitation falls in the winter, predominantly as snow at higher elevations. Monthly average minimum and maximum temperatures in the Cascade Range (1961–1990) are −6.1 and 1.2 °C respectively in January and 5.8 and 22.4 °C respectively in July (Western Regional Climate Center 2012).

The geology of the Cascade Range is dominated by Quaternary lava flows, vent complexes, pyroclastic deposits, and volcanic-derived fluvial and lacustrine sediments (Macleod and Sherrod 1992; Sherrod et al. 2004). Because much of this material is highly permeable, precipitation infiltrates readily, reducing surface runoff, and resulting in a sparse and locally

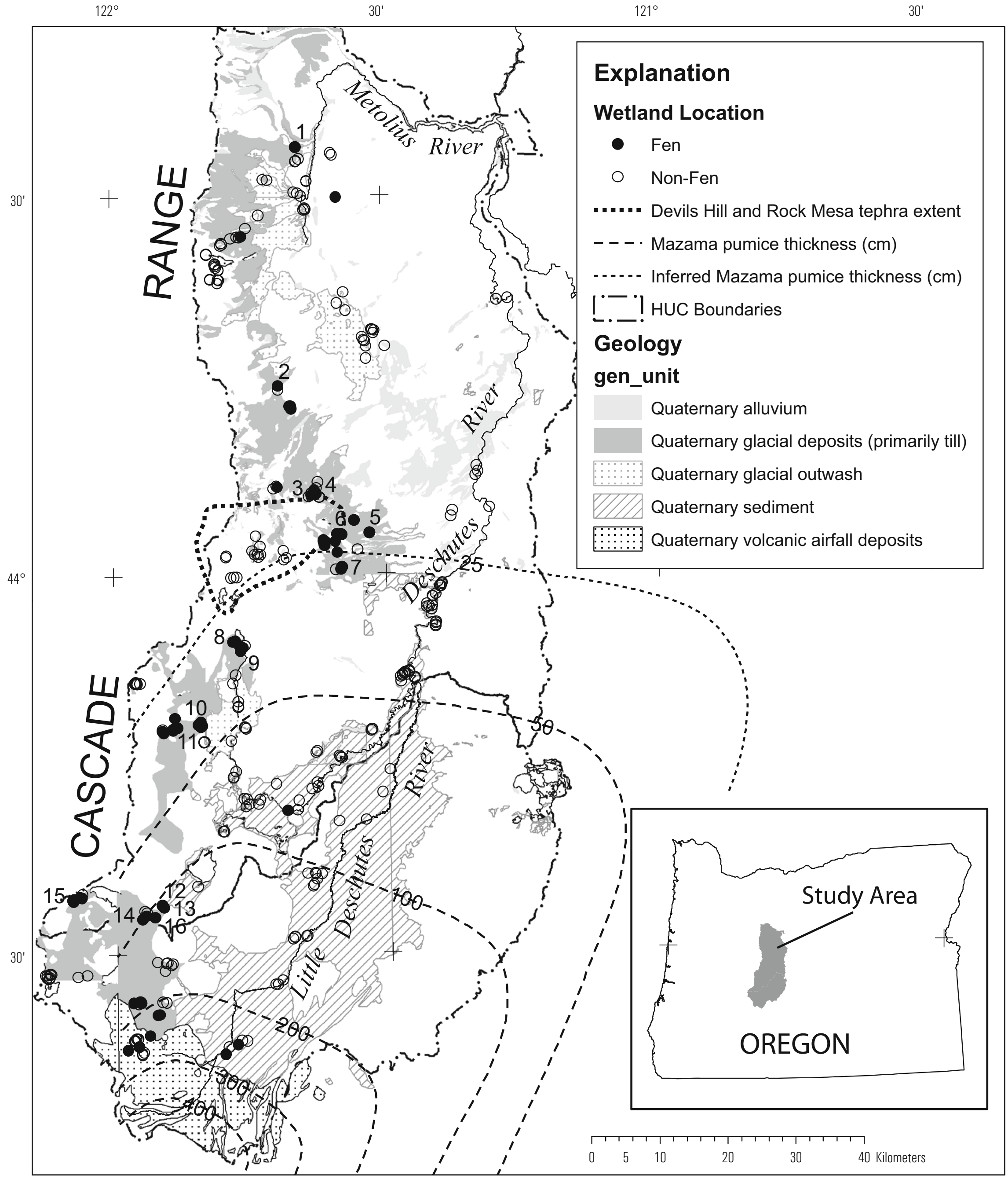

Fig. 1 Field inventoried wetlands, Quaternary surficial sedimentary deposits, and distribution of major tephras in the western half of the the upper Deschutes Basin, central Oregon. *Line* showing the extent of the Devils Hill and Rock Mesa tephras corresponds to the 10 cm thickness line of Sherrod et al. (2004). Mazama pumice thickness contours (with the exception of the inferred 25 cm contour) are from Macleod and Sherrod (1992). *Numbers* coincide with fens shown on Fig. 2

disconnected stream network (O'Connor et al. 2003). The volcanic deposits are locally mantled by glacial till and outwash left by late Pleistocene alpine glaciers and small ice caps that extend away from the tall stratovolcanoes (Scott 1977; Sherrod et al. 2004).

The study area hosts a substantial regional groundwater system, with as much as 70 % of the precipitation becoming groundwater recharge (Manga 1997; Gannett et al. 2001). Groundwater flows from the high Cascades through a system of interconnected aquifers eastward toward the basin interior. The depth to the regional water table (top of the saturated zone) is up to 100–200 m below land surface (Caldwell and Truini 1997). Groundwater discharge supports streamflow and a variety of groundwater-dependent ecosystems and human uses throughout the study area (Gannett et al. 2001, 2003; Brown et al. 2011).

Several Holocene tephras (ejected fragmental volcanic deposits) have been mapped in the upper Deschutes Basin, including the dominant pumice from the eruption of Mount Mazama 7700 years ago which resulted in the formation of Crater Lake (Macleod and Sherrod 1992; Bacon 2008). The thickness of the Mazama tephra exceeds 3 m in the southern part of the study area and thins northward. Two other mapped tephra deposits, the Devils Hill chain of vents and Rock Mesa tephras, occur in the central part of the study area and have a ^{14}C age of about 2000 to 2300 years (Sherrod et al. 2004).

The groundwater system of the upper Deschutes Basin responds to both climatic and anthropogenic stresses including drought cycles, long-term climate trends, and groundwater pumping (Gannett et al. 2001; Gannett and Lite 2013). Analysis of historic data (Jefferson 2011; Mayer and Naman 2011) and modeling studies (Tague and Grant 2009; Waibel et al. 2013) show that warming will result in a shift in the form of winter precipitation from snow to rain. The smaller and earlier-melting winter snowpack will cause a shift in the timing of runoff and groundwater recharge to earlier in the year.

Field Methods

Spatial data for 7836 wetlands in the study area classified as palustrine were obtained from the National Wetlands Inventory (U.S. Fish and Wildlife Service 2014). Of these, 3023 polygons were wetland types that could be fens, including emergent, forested, moss-lichen, or scrub-shrub. Here we use the definition of montane fens as peat-accumulating wetlands where groundwater discharge maintains soil saturation during the dry summers (Chimner et al. 2010; Drexler et al. 2013). In these wetlands, water level fluctuations associated with snowmelt-dominated surface flow are minimized. Wetlands were selected randomly from across the study area for field verification, and a total of 292 wetland polygons were surveyed from 2011 to 2013.

Wetland surveys were based on protocols for identifying whether freshwater ecosystems are dependent on groundwater (in contrast to surface water, such as streams) based on hydrology, geology, soils, and vegetation (Brown et al. 2007; U.S. Forest Service 2012). The 292 wetland polygons field visited were classified as fens if they met all three of the following criteria: (i) *Hydrology: groundwater is the primary source of water to the wetland during the summer.* Fens had little or no stream inputs other than short spring runs at their upper ends (determined by walking the perimeter) and the water table was at or near the surface throughout the growing season or there was evidence of springs discharging into or near the wetland at a rate that was too low to cause soil erosion. (ii) *Soils: at least 40 cm of peat is present within the wetland.* The presence and approximate thickness of peat was determined by probing with a fiberglass rod. Peat was readily distinguished from mineral soils by feel and sound. Soil cores were taken using an 8 cm-diameter AMS™ mud auger at 17 of the sites to confirm interpretations from the fiberglass rod probes. Identification of peat soils was done using field indicators (Natural Resource Conservation Service 2010). (iii) *Vegetation: the wetland had one or more plant indicator species,* listed in Appendix 1. We measured the pH and conductivity of water in springs and streams found within the fens (Oakton™ pH/CON 10 Series) to assist in classification.

Geomorphology

Seventeen geomorphic metrics divided into groups quantifying wetland dimensions, elevation, and topography were calculated to discriminate fens from non-fens. Metrics were selected to (1) represent landscape characteristics that we judged to be relevant to the hydrology and landscape development of wetland locations, and (2) to represent geomorphic settings identified in the literature as important to fen development (e.g., Winter 1992; Amon et al. 2002; Godwin et al. 2002) (Table 1). Analyses were conducted using ArcGIS 10.0 supplemented with Geospatial Modeling Environment (GME) version 0.7.2.0. Geomorphic analyses were conducted with a 1 m LiDAR digital elevation model (DEM) where available, and a 10 m DEM otherwise.

Table 1 List of geomorphic metrics calculated using GIS

Group	Metric (# of metrics per sub-group)	Description	Units
Dimensions	Area (1)	Area of wetland	m^2
	Perimeter (1)	Perimeter of wetland	m
	Shape index (1)	Area / perimeter	m
Elevation	Elevation (3)	Average, minimum, and maximum elevations of all DEM cells across the polygon	m
Topography	Relief (1)	maximum – minimum elevation within the polygon	m
	Topographic roughness (1)	Standard deviation of elevation	m
	Slope (5)	Average, minimum, maximum, range, and standard deviation in slope of all DEM cells across the polygon	%
	Break in slope (3)	Distance to nearest slope break (at 10, 15, and 20° of degrees)	m
	Distance to springs (1)	Distance to springs	m

Geomorphic metrics of fens and non-fens were compared using stepwise logistic regression with forward selection (SAS Inst. 2012). Significance levels were set at 0.3 (to allow a variable into the model) and 0.35 (for a variable to stay in the model). Because several of the geomorphic metrics are correlated and multicollinearity of independent variables may add redundancy to the model and make it unstable (Sokal and Rohlf 1995), we tested the sensitivity of the regression to correlated metrics. This had little effect on the results, so all metrics were included in the regression.

Geology

To understand the geologic controls on fens, the geologic settings of all field-visited wetlands were determined using a digital compilation of geologic maps (Oregon Department of Geology and Mineral Industries 2013) and ArcMap. The 400 different geologic map units were grouped into a set of 22 generalized units based on age, gross lithology, hydrologic characteristics, and depositional history (Appendix 2). In addition to mapped surficial deposits, wetland locations were compared to the distribution of mapped tephras (Fig. 1).

Hydrogeology

We mapped the distribution of fens and evaluated their relation to geology, the distribution of recharge, horizontal and vertical hydraulic head gradients, and regional and local flow paths (Caldwell and Truini 1997; James et al. 2000; Gannett et al. 2001, 2003).

We tested our conceptual understanding of fen hydrogeology by comparing stable isotope signatures (^{18}O and Deuterium) with the prevailing model for isotope hydrology of the Cascades. It has been shown that the δ^{18}O and δD of precipitation in the upper Deschutes Basin can be used to infer mean recharge elevations (Ingebritsen et al. 1994; James et al. 2000). James et al. (2000) developed a regression relation based on snow core data to infer recharge elevation of groundwater from the ^{18}O content. They demonstrated that springs with isotopically-inferred recharge elevations similar to the spring elevations are fed by relatively local groundwater. Where isotopically-inferred recharge elevations are much higher than the spring elevations, regional sources are indicated. This technique works in part because isotopic signatures of springs in the Cascade Range are stable with time. James et al. (2000) note that the δ^{18}O at springs varies less than 0.1 ‰ over their 5-year period of study.

Water samples from 28 fens and 13 non-fen wetlands were analyzed by the USGS isotope laboratory in Reston, Virginia. Samples were taken from ponds or springs associated with fens using a syringe and tube to ensure minimal exposure to the atmosphere. Where no such features were present, samples were obtained from piezometers. Where possible, samples were obtained from permeable pumice strata directly underlying peat deposits. Samples were stored in 20 ml polyethylene bottles with as little air in the head space as possible. Where water was turbid or contained organic debris, samples were filtered through 32 mm Pall Acrodisc 0.45 μm disposable in-line filters.

Results

Field Surveys

Of the 292 wetland polygons visited and classified, there were 67 fens, 16 springs, and 209 other wetland types. Fen waters had a mean pH of 6.2 (SD=0.4 μS/cm) and mean conductivity of 103.9μS/cm (SD=80.5 μS/cm), thus they can be classified as moderate-rich fens (Zoltai and Vitt 1999). Our conductivity measurements from fens are comparable with spring water elsewhere in the Cascade Range (Ingebritsen et al. 1994; Caldwell 1998).

Soil cores taken from 16 sites throughout the study area showed high spatial variation in stratigraphy (Fig. 2). All fens, by definition, had at least 40 cm of peat in the surface layer. At some sites, some individual cores did not meet this criterion indicating either low peat accretion rates or they have not been accreting peat for very long. Thickness of the upper peat layer ranged from 18 to 250 cm (mean=77 cm). The peat was generally underlain by pumice or volcanic ash, which is most commonly a distinctive light yellowish-brown well-sorted very-coarse-grained sand. These materials contrasted strongly with the peat which was dark brown to black. Several sites included a thin layer of pumice or ash within the peat, indicating deposition from eruptions that occurred during peat accretion. This was particularly noticeable at Jack Pine Fen and Farewell Spring Fen, which are within the mapped zone of tephra deposits from the Devils Hill and Rock Mesa events (2000–2300 YBP) (Sherrod et al. 2004). At some sites, we were not able to core below the pumice layer due to auger hole collapse.

Geomorphology

We found no geomorphic characteristics that reliably differentiated fens from non-fen wetlands. In the logistic regression analysis, the only significant metrics retained in the model were distance to springs (fens were closer to springs, χ^2=35.3, p<0.0001), average elevation (fens were at higher elevation, χ^2=22.7, p<0.0001), and area (fens are slightly larger, χ^2=17.4, p<0.001) but all of these relationships are relatively weak (Fig. 3).

Geology

Most fens in the upper Deschutes Basin occupy a relatively specific geologic setting. Of the 67 field-inventoried fens, all

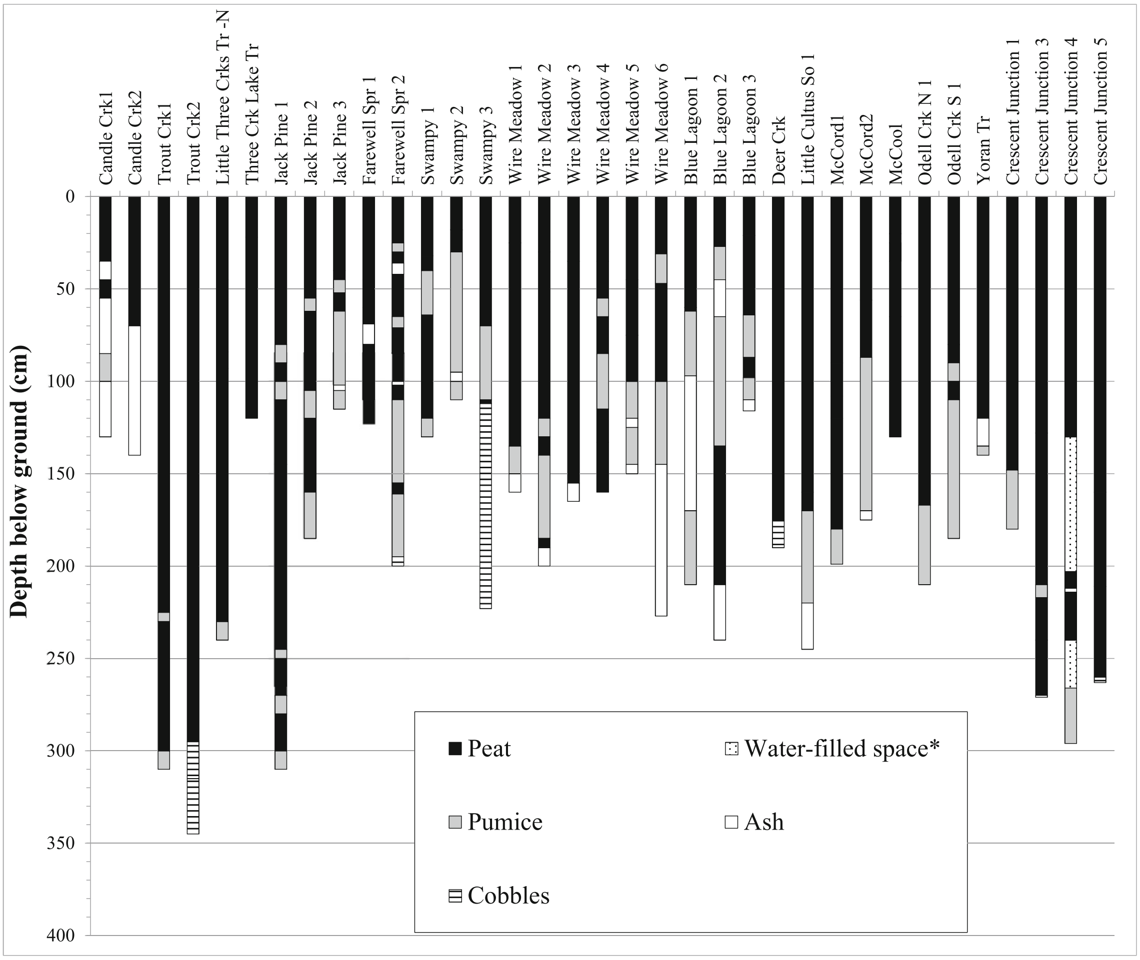

Fig. 2 Soil cores collected from 17 fens throughout the study areas. Where multiple cores were taken at an individual site, all replicates are shown. Locations are shown on Fig. 1 and numbered as follows: 1, Candle Crk; 2, Trout Crk; 3, Little Three Crks Tr; 4, Three Crk Lake Tr; 5, Jack Pine; 6, Farewell Spr; 7, Swampy Lk; 8, Wire Meadow; 9, Blue Lagoon; 10, Deer Crk; 11, Little Cultus; 12, McCord; 13 McCool; 14, Odell Crk; 15, Yoran Tr; 16, Crescent Jct. *water-filled space indicates a pocket within the peat profile that is filled with water rather than soil

but six are associated with glacial deposits of generalized unit Qg (Fig. 1). This unit consists almost exclusively of glacial till but may contain a minor component of outwash in the southern part of the study area where till and outwash are not differentiated on maps (MacLeod and Sherrod 1992). The glacial tills in the basin are largely correlative with the Suttle Lake advance of the Cabot Creek Glaciation of Scott (1977) which culminated about 20,000 years ago (Sherrod et al. 2004).

Cored peats were generally underlain by 10 cm to more than a metre of well sorted medium- to very-coarse-grained pumice sand that was identified as the 7700 year old Mazama Pumice (MacLeod and Sherrod 1992; Bacon 2008) (Fig. 2). The identification is based on the spatial distribution, thickness, stratigraphic position, and color of the pumice. Most of the fens occur in the southern part of the study area, closer to Crater Lake, where Mazama pumice is thickest. In cases where cores penetrated to the base of the pumice, it was directly underlain by sand- to cobble-sized volcanic clasts interpreted to be glacial till.

Pumice layers thought to be correlative with the tephras of Rock Mesa and the Devils Hill chain of vents, based on their geographic location and stratigraphic position, were encountered in some cores in the central part of the study area. Where encountered, the 2000–2300 year old deposits occurred at about the middle of the peat section, indicating that the lower half of peat section developed between about 7700 and 2000–2300 years ago, and that the upper part of the section is younger than 2000–2300 years.

Hydrogeology

The glacial tills with which fens are associated have very low permeability and are generally restricted to a relatively narrow elevation band ranging from about 1400 to 1800 m. The associated groundwater systems are spatially restricted and have very low flow rates. In sharp contrast, the surrounding and underlying Quaternary volcanic deposits are highly permeable. All large spring complexes discharging regional groundwater emerge

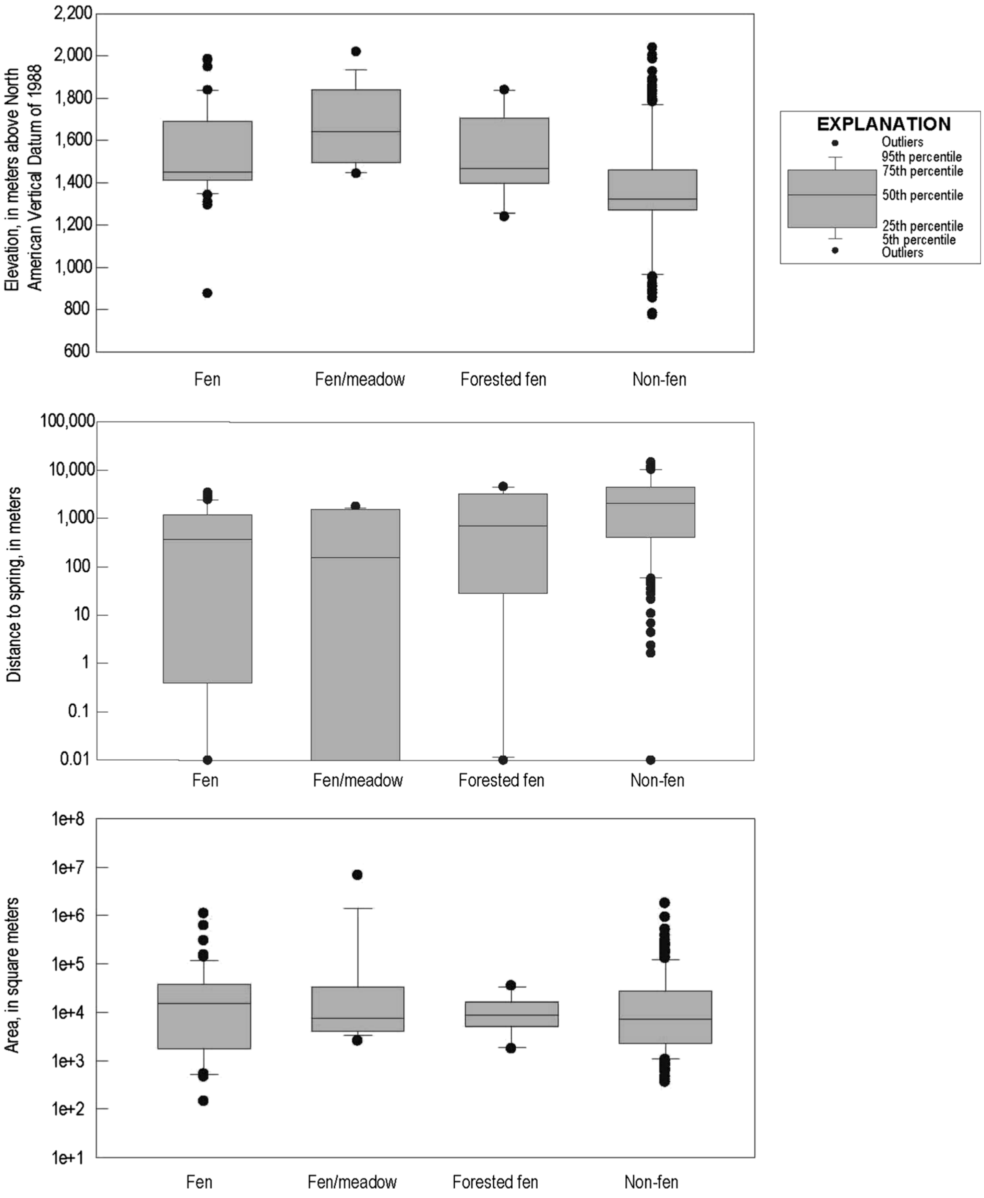

Fig. 3 Box plots comparing elevation, distance to springs, and area for the three fen types and the non-fen wetlands

from these Quaternary lava flows, generally at elevations below the glacial deposits. Water emerging from most regional spring complexes is sourced near the crest of the Cascade Range, requiring that it flows at depth through volcanic strata beneath the glacial deposits (James et al. 2000; Gannett et al. 2003).

These observations and data lead us to the conclusion that the fens are being supplied by local aquifer systems in glacial deposits above (or otherwise isolated from) the regional groundwater flow system. This model is consistent with the lack of large-volume springs associated with fens, the 100–200 m depth to regional groundwater and large downward vertical head gradients observed throughout the Cascade Range (Robison et al. 1981; Caldwell and Truini 1997; Gannett et al. 2001). The presence of local flow systems in or on glacial tills isolated from the regional flow system with lower head does not necessarily require or preclude the presence of an underlying unsaturated zone.

Although not conclusive, our model is consistent with isotope data and the prevailing thinking in the literature on isotopic systematics and hydrology in the Cascades. Ingebritsen et al. (1994) and James et al. (2000) demonstrate the relation between isotopic content of groundwater and recharge elevation, and use stable isotopes in conjunction with discharge elevation to differentiate relatively locally recharged groundwater from that which has followed long, regional flow paths. Our data, although scattered, generally follow the δ^{18}O /elevation line developed from snow cores by James et al. (2000) (Fig. 4). The recharge elevations for our sites inferred from δ^{18}O signatures are within about 300 m of the sampled elevations (median difference is 308 m). Some difference is to be expected given the uncertainty of the James et al. (2000) line and the fact that

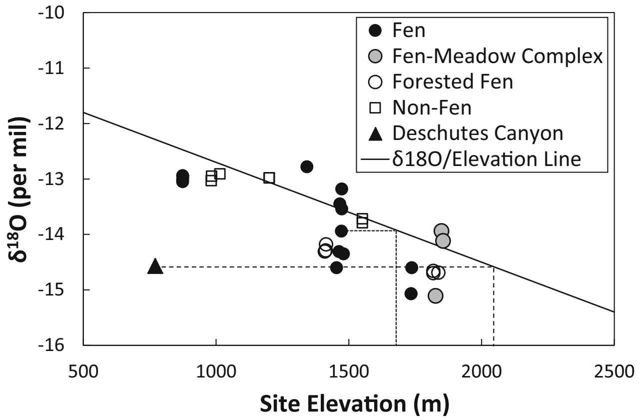

Fig. 4 δ^{18}O versus elevation for sampled sites in the upper Deschutes Basin. The δ^{18}O versus elevation *regression line* is from James et al. (2000). Isotopically-inferred mean recharge elevations can be determined by projecting lines from plotted points horizontally to the *regression line* and then downward to the X-axis (see *dashed* examples)

continuous areas of glacial deposits commonly extend 100 to 400 m upslope of sampled fen locations. In contrast to fen sites, the isotopically-inferred recharge elevation for the Deschutes Canyon spring complex is 1268 m above the discharge elevation, indicating a long regional flow path (Fig. 4).

Discussion

This work aimed to increase knowledge of the factors controlling the occurrence, distribution, and hydrology of fens in the Oregon Cascade Range, and to evaluate the vulnerability of these ecosystems to anthropogenic stressors. Of the 17 hydrogeologic setting metrics we calculated, only geology was successful in separating 61 of the 67 fen polygons from the 225 non-fen polygons. Analysis of the geology of mapped wetlands showed that fens in the central Oregon Cascade Range occur where two conditions are present. First, they occur almost exclusively in glacial till, with only six occurring on other types of mapped surficial deposits. Second, they occur where the glacial till is mantled by coarse pumice sand from the eruption of Mount Mazama. In the southern part of the study area closer to former Mt. Mazama, approximately 50 % of wetlands on glacial till are fens compared to 13 % in the northern third of the study area (Fig. 1). Although there are ash and pumice deposits to the north, they are generally thinner and sparsely distributed. Furthermore, peat was never observed beneath the Mazama pumice deposits, supporting the conclusion that pumice was necessary for fens to develop.

The following conceptual model places the hydrology and evolution of fens in the central Oregon Cascades within the context of geology and groundwater flow. Models of regional groundwater flow and hydraulic head show that recharge occurs primarily at high elevations in the Cascade Range, and groundwater moves through permeable volcanic deposits toward lower elevations where it discharges to springs and streams (James et al. 2000; Gannett et al. 2001, 2003). In our conceptual model (Fig. 5), fens in the Upper Deschutes basin occur on the glacial tills because of the low vertical permeability of the till and modest recharge. Movement and

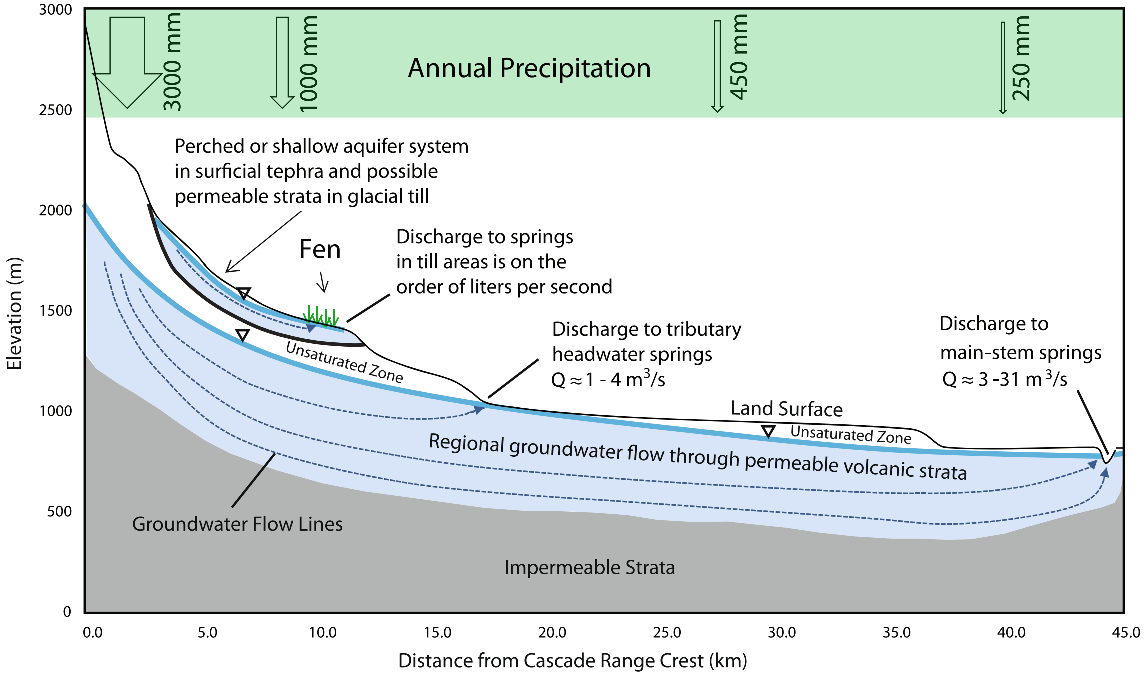

Fig. 5 *Diagram* showing conceptual cross section from the Cascade Range crest east to the main stem of the Deschutes River. The water table is marked by inverted *triangles*. An unsaturated zone is shown beneath the glacial deposits for illustrative purposes, but is not necessary to the basic model. Headwater and main-stem spring discharge values from James et al. 2000 and Gannett et al. 2003

storage of groundwater supporting the fens is limited to rare permeable strata or small outwash and channel deposits within the till and in the overlying tephra. These factors combine to create shallow, low-volume, low-discharge groundwater systems perched above the underlying regional flow system.

The difference between the regional flow system and the local perched systems is reflected in spring discharge. All of the large-discharge springs in the Cascade Range emerge from Quaternary lava flows and discharge rates commonly range from about 1–4 m^3/s (Caldwell 1998; Manga 1999), and there are no known fens associated with them. This is likely because the velocity and erosive power of the discharge precludes peat accretion. We observed that spring discharge associated with fens in this study, when present at all, was orders of magnitude less than that reported rates from Quaternary lavas. Groundwater discharge to three fens to the south of the study area but also underlain by Mazama pumice deposits was estimated to range from $2*10^{-4}$ to $5*10^{-4}$ m^3/s (Aldous et al. 2014).

The presence of a layer of coarse pumice sand on top of the glacial till appears to be important to fen development. In all cases where our cores penetrated to glacial deposits, there was a layer of pumice sand between those deposits and the overlying peat. In no cases was peat found directly overlying and in contact with glacial till. The same result was found for the three fens referenced above (Aldous and Bach 2014). Moreover, the proportion of wetlands that are fens diminished in the northern part of the basin where the Mazama pumice thins out. We interpret this as indicating that the glacial tills alone did not provide an environment for peat development. As little as a few tens of centimeters of pumice sand apparently created conditions necessary for peat development. We posit that the mantle of pumice may have transformed the landscape to favor peat accretion by any or all of the following: 1) increasing shallow groundwater storage, 2) providing a laterally extensive medium for movement of shallow groundwater, and 3) diffusing discharge of small springs from the pumice itself or from permeable zones in the underlying till. Moderate discharge velocity and diffusive discharge are identified as potentially important conditions for peat development (Almendinger and Leete 1998; Amon et al. 2002).

The basic hydrologic characteristics of a shallow aquitard overlain by a thin permeable surface deposit and appropriate meteorological conditions may occur elsewhere in Oregon or the Northwest. For example, alpine glacial deposits with substantial seasonal snow occur in the Blue and Wallowa Mountains of eastern Oregon. Young tephras that may have hydrologic characteristics similar to Mazama pumice occur throughout the volcanic Cascade Range from northern California to central Washington.

Many studies of fens isolated from larger peatland complexes discuss geomorphologic factors such as breaks in slope as important in the occurrence and distribution of fens (Winter 1992; Winter et al. 2001; Amon et al. 2002). These often are based on observations largely in midcontinental glaciated regions with relatively homogeneous hydrogeologic conditions (e.g., Gerla 1999). In the geologically complex mountain setting of the Oregon Cascades, we had limited success in differentiating fens from non-fens based on geomorphologic factors.

Proximity to springs and elevation (both of which are correlated to geology) were the only geomorphologic metrics that could be used reliably to differentiate fens from non-fen wetlands. Fens tend to be closer to springs, which is not surprising since many have small springs directly associated with them. However, many of the smaller discharge springs often are not mapped or included in commonly available geodatasets, and were only mapped in the field over the course of this study. Fens also were found at higher elevation than other wetland types in the study area. This is because they are largely restricted to glacial tills, which occur in a relatively narrow elevation band that is higher than the mean elevation of the study area as a whole.

Our findings suggest the vulnerability of fens to pumping stresses is small because of the geographic separation of fens from main centers of pumping, and the stratigraphic separation between the small aquifer systems feeding fens and the regional groundwater system from which major pumping occurs. Comparison of mapped fen locations with groundwater-level declines due to increased pumping over the past two decades simulated by Gannett and Lite (2013) show impacts of less than 0.3 m for 60 of the 67 fens identified; 0.3–0.6 m for six fens; and 0.6–1.5 m for one fen. Even small declines in groundwater levels can have deleterious effects on fens (Aldous and Bach 2014); however, the association between fens and glacial deposits serves to isolate them from pumping impacts. Most groundwater pumping is from permeable volcanic or fluvial deposits associated with the regional groundwater system. The low permeability of the glacial tills, in combination with the possible presence of an underlying unsaturated zone, would preclude or attenuate propagation of pumping-induced head changes to aquifers supporting fens. Fens could be vulnerable to pumping directly from glacial deposits or immediately-adjacent volcanic rocks, particularly if there is no unsaturated zone separating them. However, most of these areas are in public ownership with little possibility of significant groundwater development. The minor expected effect of groundwater pumping on fens is in contrast to potential declines in groundwater levels, streamflow, and spring discharge elsewhere in the basin (Gannett and Lite 2013), which could affect water levels in wetlands associated with surface waters.

In contrast to pumping, fens may be vulnerable to climate change based on their locations and expected changes in hydrology under projected future climate conditions. Warming in the Pacific Northwest is expected to result in shifts in the form of winter precipitation in the Cascade Range from snow to rain (Elsner et al. 2010; Mote and Salathé 2010). Snow in the Cascade Range is most sensitive to projected warming between elevations of 1000–2000 m (Nolin and Daly 2006; Sproles et al. 2013). This elevation range is projected to change from a seasonal snow zone, where snow accumulates all winter and melts in the spring, to a transient snow zone, where snow falls and melts multiple times throughout the winter, with decreases in basin-wide snow-water storage of up to 56 % (Sproles et al. 2013). The median elevation of fens we mapped is 1462 m (SD=229 m), near the middle of the elevation range of "at risk" snow. The largest regions of glacial till in the Cascade Range occur mostly between about 1300 and 1800 m. Simulations of the hydrologic response to projected climate conditions show that by the 2050s parts of the Cascades where fens occur may experience increases in recharge up to 23 cm during the December-February period (corresponding to an average increase of 56 % but as high as 100 %) (Waibel et al. 2013). Decreases in recharge up to 25 cm are projected to occur during the spring months (March-May) (corresponding to an average decrease of 28 % but as high as 66 %), with decreases of similar magnitude continuing through the summer. Due to the shift in the timing of recharge, the recession of groundwater discharge and water table elevations will start earlier in the year, and by summer will be lower than under historic conditions (Tague and Grant 2009; Waibel et al. 2013).

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