OREGON ATLAS OF GROUNDWATER-DEPENDENT ECOSYSTEMS

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COVER PHOTO: Unnamed spring on Broken Top Mountain © Z. Freed/TNC

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Executive Summary

Groundwater-dependent ecosystems and species (GDEs) rely on groundwater for their structure, composition, or function. GDEs include a broad range of aquatic habitat types such as springs, rivers, wetlands, lakes, as well as individual species that utilize groundwater for all or part of their lifecycle. GDEs are characterized by their disproportionate biodiversity, their resilience to short- and long-term climate variation, and their ecological importance as they are often the only perennial sources of water in semi-arid or arid regions. Despite their climate resilience, GDEs are vulnerable to hydrologic alterations and anthropogenic impacts.

This study builds upon a prior effort led by The Nature Conservancy in 2009 to map GDEs across Oregon[1]. The 2009 effort developed a precedent for mapping GDEs which has been replicated in other states, countries, and regions. This study—the Oregon Atlas of Groundwater-Dependent Ecosystems 2022—builds upon that prior effort. This study includes all-new analyses and updated input data to identify GDEs throughout the state as well as assess stressors and threats that are known to impact GDE condition. This effort was undertaken in response to Oregon's 2017 Integrated Water Resources Strategy[2] Recommended Action 3.b, which identified a need to characterize GDEs across the state.

The distribution and abundance of five GDE types were assessed: springs, rivers, wetlands, lakes, and species. All springs were considered to be groundwater dependent. Twelve indicators of groundwater dependence were used to determine whether rivers, wetlands, and lakes were GDEs. Groundwater-dependent vegetation, called phreatophytes, were mapped using a specific set of indicators dependent upon vegetation type[3].

This report also mapped stressors and threats to GDEs (Table ES-1). A **stressor** *is any physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that reduces the viability of an individual, population, or a species, or the viability of its habitat*. A **threat** *is a potential (or impending) physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that is reasonably likely to negatively affect an organism, population, species, or its habitat*[4]. Four themes of stressors and threats were assessed: groundwater withdrawals, invasive species, ungulates, and climate. Five total stressors and eleven total threats were mapped among those themes.

Results of the analyses identified 29,379 springs across the state. A total of 59,349 km of rivers were determined to be groundwater dependent (33.1% of all river km in Oregon). Groundwater-dependent wetlands comprise 3,479 km^2 of area (45.4% of total wetland area in Oregon). Groundwater-dependent lakes cover 1,458 km^2 (62.9% of total lake area in Oregon). Finally, 3,103 observations of groundwater-dependent species and a total phreatophyte area of 6,821 km^2 are distributed across the state. The abundance of all GDE types as well as the confidence based on number of indicators were combined into one bivariate statewide map (Figure ES-1).

GDEs were exposed to up to five stressors: three separate stressors related to groundwater withdrawals, one invasive species stressor, and one ungulate stressor. The GDE types most associated with one or more stressors were groundwater dependent lakes (92.3% with at least one stressor) and phreatophyte communities (95.4% with at least one stressor) (Table ES-2). Non-phreatophyte groundwater-dependent species were the least exposed to stressors. Aside from other groundwater-dependent species, the substantial majority of all GDE types co-occurred with the five stressors. The most widespread stressor was ungulate impacts in active grazing allotments.

Eleven threats also affected or will affect GDEs: two threats related to groundwater withdrawals, two invasive species threats, and seven climate threats. Groundwater demand is expected to increase throughout the state while available summer streamflow decreases, which will cause added pressure on aquifers and affect GDEs. Mean August stream temperature is expected to increase in most streams by 10-20%, emphasizing the importance of protecting groundwater inputs as cold-water refugia for anadromous fish and other species. Invasive annual grasses combined with increased drought will change the fire regime in eastern Oregon, which will particularly impact springs, groundwater-dependent rivers, and phreatophyte communities.

This report and associated appendices demonstrate the ubiquitous presence of GDEs throughout Oregon. This statewide analysis can inform the prioritization of groundwater monitoring, the deployment of instream water rights, and the implementation of management actions to protect these important habitats. The stressors and threats mapped within this report and associated appendices will require careful management to ensure the continued function of GDEs. Resource managers and legislators in Oregon must continue to invest capacity and funding to understand how to effectively conserve these climate-resilient groundwater-dependent ecosystems.

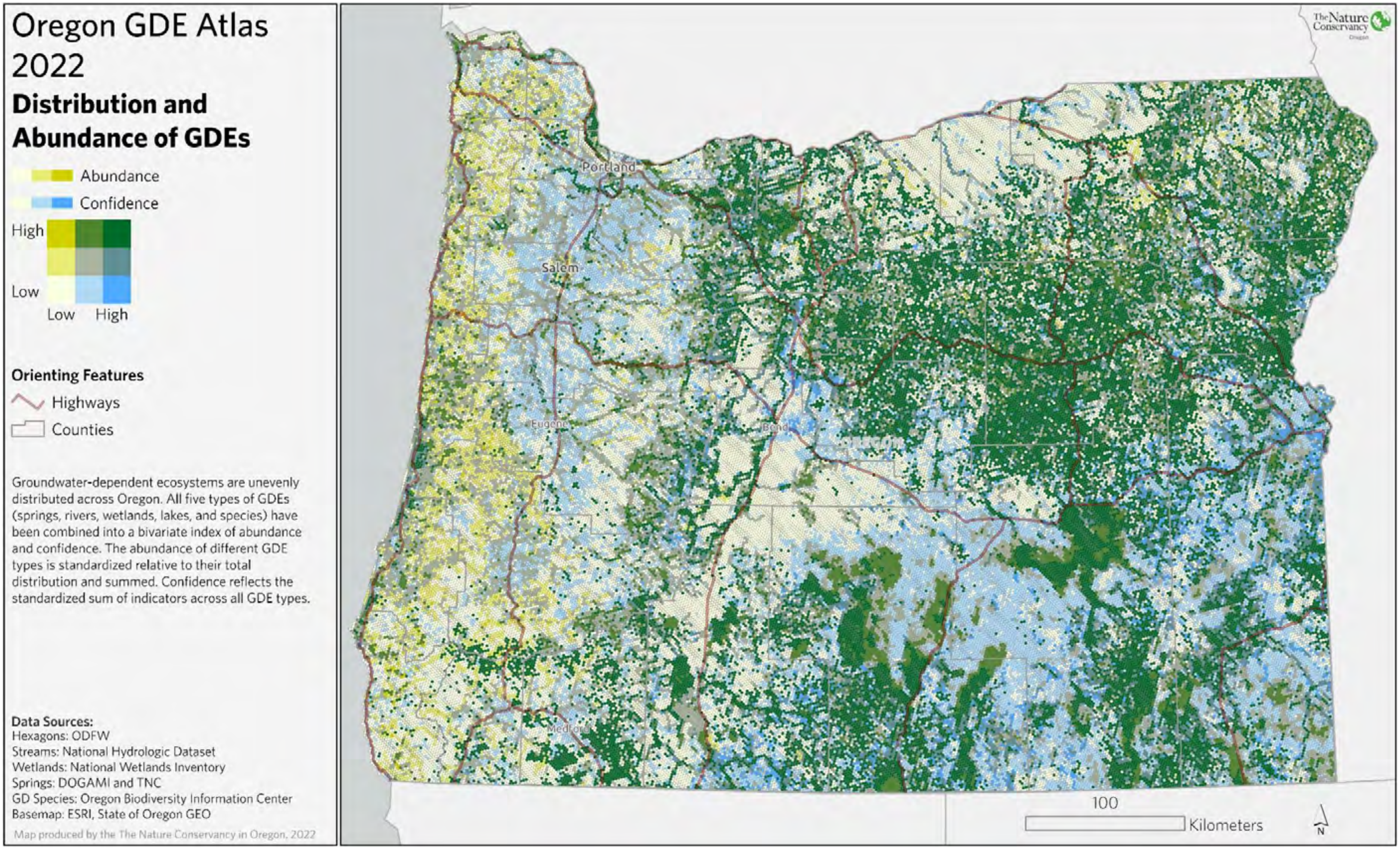

Figure ES-1: Map of Groundwater-Dependent Ecosystems of Oregon.

Table ES-1: Stressors and threats to groundwater-dependent ecosystems in Oregon.

Class	Description	Stressor	Threat
Groundwater withdrawals	Groundwater level declines	X	
	Concentrations of permitted groundwater use	X	
	Presence of Groundwater Administrative Areas	X	
	Future projected irrigation demand		X
	Future projected irrigation reliance		X
	Lack of instream flow protection		X
Invasive species	Presence of aquatic invasive species	X	
	Presence of invasive annual grasses		X
	Road density		X
Ungulates	Active grazing allotments on public land	X	
Climate	Future projected precipitation		X
	Future projected actual evapotranspiration		X
	Future projected air temperature		X
	Future projected snow-water equivalent		X
	Future projected stream flow		X
	Future projected stream temperature		X

Table ES-2: Summary of GDE types potentially affected by number of stressors. The percent of GDEs at risk of stressors is listed as a proportion of all GDEs within that type. Units are count (number of springs), km (length of groundwater-dependent rivers), km^2 (area of groundwater-dependent wetlands, groundwater-dependent lakes, and phreatophytes) and observations (surveyed groundwater-dependent species).

Number of Stressors	Springs (% count)	Rivers (% length)	Wetlands (% area)	Lakes (% area)	Groundwater-dependent Species	
					Phreatophtyes (% area)	Other Species (% observations)
0	37.3%	31.1%	22.3%	7.7%	4.6%	53.7%
1	56.5%	53.7%	45.9%	31.5%	50.6%	35.7%
2	5.4%	12.7%	20.7%	56.0%	27.5%	8.7%
3	0.8%	2.1%	5.8%	4.2%	11.2%	1.8%
4	0.03%	0.3%	1.5%	0.0%	4.9%	0.1%
5	0.0%	0.004%	3.7%	0.6%	1.3%	0.01%

[1] Brown JB, Wyers A, Bach LB, and Aldous AR. 2009. Groundwater-dependent biodiversity and associated threats: a statewide screening methodology and spatial assessment of Oregon. The Nature Conservancy. 175 p.

[2] Oregon Water Resources Department. 2017. Oregon's 2017 Integrated Water Resources Strategy. 190 p. Salem, OR. https://www.oregon.gov/owrd/WRDPublications1/2017_IWRS_Final.pdf

[3] Garcia, C.A., Haynes, J.V., Herrera, N.B., and Gingerich, S.B. 2021. Select phreatophytic shrub and grass species of Oregon, the estimated distribution of phreatophytic shrubland and grassland across Oregon, and field observations used to constrain mapped species distributions. U.S. Geological Survey data release, https://doi.org/10.5066/P901GNIX.

[4] Saito L, Byer S, Badik K, Provencher L. 2022. Stressor and Threat Assessment of Nevada Groundwater Dependent Ecosystems. The Nature Conservancy. https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/nevada/water/Documents/gde_stress_threat_rpt_noapp_may22.pdf

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Introduction

Groundwater is a vital resource for people and nature. It will become increasingly important as a changing climate intensifies water demand for economic, domestic, cultural and recreational uses (Siebert et al. 2010; Haddeland et al. 2014). Groundwater supports more than 48% of irrigation needs in the United States (Siebert et al. 2010). As Oregon's population grows and its climate changes, demand for groundwater is likely to increase (OWRD 2015) even as supply decreases due to more frequent drought (Ahmadalipour et al. 2016) and shifts in precipitation (Nolin & Daly 2006). Reliance on groundwater is already increasing rapidly in Oregon where agriculture represents 85% of statewide water demand (OWRD 2015) and is expected to increase due to prolonged growing seasons and increased rates of evapotranspiration from climate change (OWRD 2017). Surface water in Oregon during the irrigation season is almost fully allocated (OWRD 2017), so future increases to water demand or decreases to surface water supply will likely result in additional groundwater development. The increased utilization of groundwater has resulted in accelerating rates of aquifer depletion (Konikow 2013).

Groundwater forms the hydrologic basis for many aquatic ecosystems throughout Oregon (Brown et al. 2009). These groundwater-dependent ecosystems and species (GDEs) are reliant on a supply of groundwater for their structure, composition, and function (Kløve et al. 2011). Due to their unique functional characteristics, GDEs provide disproportionate contributions to regional biodiversity (Perla and Stevens 2008), including rare and endemic species (Murphy et al. 2015). About 17% of all species on the United States Endangered Species List are groundwater-dependent (Blevins and Aldous 2011). GDEs also serve as cold water refugia in a warming climate (Power et al. 1999; Cartwright et al. 2020) and can act as hydrologic refugia during drought (Cartwright et al. 2020). Despite their ecological importance, GDEs remain understudied and their distribution and abundance are poorly understood. Oregon's Integrated Water Resources Strategy includes the statewide characterization of GDEs as a recommended action (Recommended Action 3.B; OWRD 2017).

To address this knowledge gap, the Atlas of Groundwater-Dependent Ecosystems in Oregon (GDE Atlas) utilizes existing spatial data to estimate groundwater dependence among five GDE types: springs, rivers, wetlands, lakes, and species. The GDE Atlas also provides a spatial assessment of water quantity stressors and water quantity threats to GDEs. The objectives of this study are to:

1. Identify indicators to assess the groundwater dependence of four of the five GDE types: rivers, wetlands, lakes, and species, and compile a map of springs
2. Determine the abundance and distribution of GDEs in Oregon
3. Map stressors and their overlap with GDEs
4. Map current and future threats and their overlap with GDEs

Oregon has the benefit of being one of a few geographic regions with a precedent study on the abundance of groundwater-dependent ecosystems (Brown et al. 2009; but see also Byer et al. 2019,

Doody et al. 2017, Howard and Merrifield 2010, and Gou et al. 2015). These previous efforts resulted in a major advancement in the understanding of the distribution of GDEs throughout the state and helped prioritize further studies (e.g., Aldous and Freed 2018). However, over the past decade, substantial improvements in the coverage and quality of available data have made it possible to build on this foundational knowledge through greater accuracy and precision in the assessment of groundwater dependence. The state of the science related to water quantity stressors and threats has also improved in the prior decade, leading to a new focus to their impact on GDEs. While this study addresses the primary stressors and threats known to impact GDEs, there are some threats not covered in this analysis. Notably, groundwater quality remains a concern for GDEs. However, Brown et al. (2009) provided a thorough review of likely groundwater quality stressors and threats and that assessment has not been repeated here.

This GDE Atlas is intended to be used to prioritize conservation, protection, management, and monitoring of GDEs, including targeted actions to reduce threats to groundwater quantity and/or preserve refugial capacity in a changing climate. Only four governmental entities in the world currently have GDEs explicitly listed as a water management consideration (Rohde et al. 2017). Oregon is not yet one of them, but there is increasing recognition of their ecosystem services. A better understanding of GDEs and the factors influencing their function will be critical to ensuring the effective long-term management of these habitats and species.

Background

Groundwater-dependent ecosystems and species

There are at least seven ecosystems that rely on groundwater: springs, phreatophytes, subterranean ecosystems, rivers, wetlands, lakes (Eamus and Froend 2006), and estuarine or marine habitats that rely on subaquatic groundwater discharge (Paytan et al. 2006). These GDE types can be classified into two types of groundwater dependence: *obligate GDEs* which can only persist in the presence of groundwater, and *facultative GDEs* which situationally utilize groundwater depending on climate, hydrogeologic setting, and/or lifecycle stage. Springs and subterranean ecosystems are obligately groundwater dependent, while rivers, wetlands, lakes, most marine habitats, phreatophytes, and many other species are facultatively groundwater dependent. Although marine and estuarine GDEs can provide locally important ecosystem services (Swarzenski et al. 2017), they were not addressed in this study due to lack of supporting data to evaluate groundwater dependence in Oregon. Subterranean GDEs including stygofauna, also called subsurface GDEs (Tomlinson and Boulton 2008), may also exist in Oregon but their assessment is also hindered by data scarcity.

GDEs are often perennial sources of habitat and forage for fish and wildlife, and these perennial resources become disproportionately important to support regional biodiversity as annual precipitation decreases (Perla and Stevens 2008). Oregon has a varied climatic, geologic, and hydrologic landscape with seasonal precipitation patterns: less than 10% of precipitation occurs during summer months (Western Regional Climate Center 2013). Annual precipitation in Oregon ranges from almost 200 inches per year near the Cascade Crest to 6 inches per year in the eastern Basin and Range province (30-year normal; OSU 2014).

Springs are obligate GDEs regardless of location or context (Brown et al. 2009). Springs are surface expressions of groundwater often characterized by their hydrogeologic setting and are classified into 12 spring types (Springer and Stevens 2009). Each spring type supports up to 13 distinct microhabitats depending on the spring type and characteristics (Springer et al. 2008) and springs are known to contribute disproportionate amounts of biodiversity over large geographic areas (Davis et al. 2017). Endemism is common in springs (Cantonati et al. 2012), and the single greatest known concentration of endemic species in North America is found in a spring in central Arizona (Stevens 2007), leading to springs being described as "museums of biodiversity" (Murphy et al. 2015). The abundance of biodiversity and endemism found in springs is likely due their ability to act as ecological or evolutionary refugia (Cartwright et al. 2020) which can support spring-associated relict species like pupfish (e.g., Turner 1973). In addition, springs provide temporally or regionally scarce resources to migratory and wide-ranging birds and wildlife (Davis et al. 2017).

Rivers, wetlands, lakes, phreatophytes, and other species are facultative GDEs—all of which can rely on varying proportions of groundwater and surface water for flow, inundation, or hydroperiod depending on their hydrogeologic setting (Brown et al. 2009). Therefore, groundwater dependence for these potential GDEs is typically assessed either through direct field measurements (Kalbus et al. 2006) or by using a suite of indicators that suggest groundwater influence (e.g., Brown et al. 2009). Groundwater dependence for these GDE types is spatially and temporally dynamic. Most facultative GDEs have hydrographs (i.e., inundation periods or discharge) that benefit from both surface water and groundwater contributions depending on where the GDE is measured. For example, a stream may be primarily supported by surface runoff until it intersects with a groundwater-producing feature like a fault, at which point the streamflow is supported primarily by groundwater. The groundwater contribution of facultative GDEs can change over time: some ecosystems are proportionately groundwater dependent during dry seasons, droughts, or even decadal climate cycles, whereas the groundwater contribution during unusually wet years may be proportionately less compared to the surface water runoff (Scanlon et al. 2002).

Groundwater contributions can be essential to maintaining the hydrologic regime of rivers and streams (Barlow and Leake 2012). Groundwater dependence in rivers can also vary on a reach-by-reach basis, as *gaining reaches* increase in flow due to groundwater discharge while *losing reaches* recharge the aquifer (Kalbus et al. 2006). The distinction between groundwater and surface water in the context of rivers is further complicated by the presence of the hyporheic zone, the interface where surface water mixes with soil moisture and groundwater in pore space adjacent to the stream channel (Boulton et al. 1998). Groundwater input to rivers provides hydrologic resilience through baseflow (Wahl and Wahl 1995) during low-flow seasons or drought years, as well as an important source of nutrient exchange (Findlay 1995). Finally, groundwater input to rivers can mediate thermal stresses by providing cold water refuge during seasonally hot weather, heat waves, or drought (Torgersen et al. 2012).

Groundwater-dependent wetlands include fens and slope wetlands (Bedford and Godwin 2003) as well as other palustrine emergent wetlands with groundwater contributions (Brown et al. 2009). Fens, which occur where peat accretes due to groundwater discharge, provide habitat for unusually rich species assemblages which rely on their unique hydrogeologic, edaphic, and geochemical conditions (Aldous et al. 2015). The accumulation of peat requires the consistent hydrology associated with groundwater, and the amount of peat accretion is related to access to the water table (Aldous and Bach 2014). However, groundwater dependence in wetlands is not unique to fens, and can include slope wetlands (Bedford and Godwin 2003) or other perennially-wet areas supported by groundwater. Like other facultative GDE types, the hydroperiod of many wetlands is likely dependent upon shifting proportions of groundwater and surface water inputs (Custodio 2000). Wetlands are partially defined by the presence of "a prevalence of vegetation typically adapted for life in saturated soil conditions" (FICWD 1989). Federal wetland indicator species (and therefore wetlands) may be supported by surface water or groundwater; however, the most consistent presence of wetland species in climate zones with highly seasonal precipitation patterns tend to be groundwater-supported (Cartwright and Johnson 2018, Albano et al. 2020) and many indicator species are associated with groundwater depths less than 70 cm (Aldous and Bach 2014). Riparian wetlands are sometimes considered innately groundwater dependent (e.g., Klausmeyer et al. 2018) as the functional hydrology and associated plant response to soil water dynamics in riparian settings can be closely related to groundwater dynamics (Hultine et al. 2010, Abdallah et al. 2017).

Lakes can be perennially or seasonally groundwater dependent (Anderson and Munter 1981, Winter 1999), and in some cases groundwater dominates the water balance for lakes (Petermann et al. 2018). In addition to supporting inundation, groundwater discharge into lakes can play an important role in their geochemical budgets due to the input of nutrients (Nakayama and Watanabe 2008). Even when the groundwater contribution to lakes is proportionately small compared to surface water, lake-adjacent springs or lacustrine groundwater discharge can support microhabitats conducive to fish (King County DNR 2000) or vegetation (Sebeysten and Schneider 2004) that benefit from the groundwater. Naturally-occurring lakes in Oregon nearly always interact with groundwater to some degree (Brown et al. 2009).

Phreatophytes are plants with deep roots that can access groundwater instead of soil moisture, especially in arid or semi-arid conditions (Mata-Gonzalez et al. 2012). Phreatophytes are defined by their use of groundwater but will also utilize soil moisture if groundwater is not available and are thus facultatively groundwater dependent. Mesic phreatophytes access near-surface groundwater, such as springs or seeps (Thomas 2014). Xeric phreatophytes access deeper water tables through root systems that can reach up to 15 meters depth (Robinson 1958). Phreatophyte communities provide critical habitat for many sensitive species in arid and semi-arid environments (Huntington et al. 2016). The deep roots of xeric phreatophytes may directly exploit groundwater or may facilitate root-mediated hydraulic redistribution of groundwater where it is taken up by a more extensive shallow root system (Smith et al. 1997; Ryel et al. 2002; Ryel et al. 2010; Provencher et al. 2020).

Non-phreatophytic groundwater-dependent species tend to be associated with GDEs for a subset of life stages (Murray et al. 2003), often related to the ability of GDEs to provide thermal or hydrologic refuge. Many anadromous fish and salmonids utilize groundwater as cold-water refuge (Torgersen et al. 2012) and qualify as facultatively groundwater dependent. Similarly, other species require warm water refuge, such as trumpeter swans which rely on thermal springs as their only source of open water during cold winter months (USFWS 2013).

Both obligate and facultative groundwater-dependent ecosystems provide crucial ecosystem services, including ecological contributions of increased biodiversity; economic production via fisheries, forestry, and agriculture; and socio-cultural values such as outdoor recreation, tourism, and habitat for indigenous First Foods like salmon (Brown et al. 2011, Kath et al. 2018). Groundwater-dependent ecosystems may provide buffering from climate impacts depending on the flow system length (Aldous and Gannett 2021), residence time of water, and relative protection from evapotranspiration (Davis et al. 2017). Identifying the distribution and abundance of GDEs can indicate where these ecosystem services, biodiversity potential, and climate buffers exist on the landscape. An assessment of the likely water sources for facultative GDEs offers resource managers a greater understanding of their vulnerability to anthropogenic stressors and threats.

Stressors and threats to groundwater-dependent ecosystems and species

Despite their ability to act as hydrologic or thermal refugia, GDEs are often susceptible to anthropogenic disturbances. The overall spatial distribution of stressors and threats to GDEs is poorly understood in Oregon, and that information gap hinders the ability of resource managers to effectively deploy resources. In this report, **stressors** are defined as *a physical, chemical, or biological alteration of the GDE that reduces the viability of the habitat or species therein*, and **threats** are defined as *potential (or impending) physical, chemical, or biological alteration of the GDE that is reasonably likely to negatively impact the viability of the habitat or species therein* (*sensu* Saito et al. 2022). Stressors and threats in Oregon can be grouped into four themes: groundwater withdrawal, climate change, invasive species, and ungulates.

Groundwater withdrawal

The functional hydrology of GDEs is governed by connectivity to groundwater (Boulton et al. 2014), which can be described by the hydrogeologic regime (Kath et al. 2018). Connectivity between the aquifer and GDEs is a function of timing, frequency, magnitude, rate of change, and duration of water table depths, groundwater volume, and groundwater flow rates (Kath et al. 2018). Groundwater extraction by pumping directly impacts the hydrogeologic regime and can disrupt connectivity between groundwater and GDEs. Globally, groundwater extraction has drastically altered groundwater regimes (Gleeson et al. 2012) and frequently exceeds natural recharge rates of the aquifer (Gleeson et al. 2015).

Groundwater extraction is "balanced by a loss of water" from other sources (Theis 1940), including water that would otherwise reach springs or other GDEs. The cumulative impact from groundwater withdrawal over time causes an immediate removal of storage from the aquifer as well as eventual capture from groundwater that otherwise would have reached GDEs (Barlow and Leake 2012). Small amounts of capture will reduce groundwater discharge to a GDE—for example, a perennially-gaining river reach may become a seasonally-gaining reach. Capture of sufficient magnitude or duration can reverse the flow of groundwater, causing a GDE to contribute water to an extraction well—for example, changing a gaining river reach to a losing reach, and therefore disrupting the groundwater regime that would otherwise support a GDE (Barlow and Leake 2012).

Policy protections such as instream water rights may moderate the impacts of groundwater extraction. The ability of the Oregon Water Resources Department to regulate groundwater uses in favor of surface water has been hindered (*Brooks v Byler et al*. 2020) but could still be relevant within certain management designations. Outside of the context of streamflow capture, instream water rights are still useful for mitigating or preventing impacts from surface water diversions that may otherwise affect groundwater-dependent rivers. Oregon does not currently have a groundwater corollary to instream water rights (often called an *in-situ* water right) (Amos and Burke 2018). Some management designations in Oregon, such as "Critical Groundwater Areas," have not proven to be effective at stabilizing groundwater extraction (OWRD 2021) but are useful as spatial delineators of areas with substantial groundwater declines.

On a state scale, groundwater extraction is likely the most widespread and impactful cause of hydrologic alteration. Direct data on groundwater declines and surrogate data for groundwater use are sparsely available, but sufficiently widespread to draw conclusions from. However, there are other types of hydrologic alteration such as spring developments that can affect GDE function but are too data-scarce for statewide mapping efforts. Spring developments are common in the western United States, and prior studies have shown evidence widespread alteration: 97% of rheocrene springs surveyed in central Oregon were developed (Freed et al. 2019), 60% of surveyed springs in northern Nevada were developed or diverted (Sada et al. 1992), and 78% of surveyed springs in southern Nevada were developed or diverted (Sada et al. 2005).

This report assesses three stressors and three threats related to groundwater withdrawal in Oregon. The stressors are observed declines in groundwater levels, presence of groundwater management designations, and the distribution and abundance of permitted water use. The threats are the absence of in-stream flow protections, future increased irrigation demand, and future increased irrigation reliance.

Climate change

Future projected climate conditions in Oregon will likely cause substantial impacts to aquatic ecosystems, including GDEs. A significant portion of snowpack in the Pacific Northwest region accumulates close to the freezing point under current conditions (Nolin and Daly 2006), indicating that increasing air temperature can drastically affect snowpack (Sproles et al. 2013). In addition to decreasing snowfall, warmer temperatures can reduce the longevity of snowpack, all of which is likely to shift the magnitude and timing of aquifer recharge (Waibel et al. 2013) because snowmelt is a disproportionately effective contributor to recharge (Siirila-Woodburn et al. 2021). Although long-term climate impacts to groundwater recharge are less understood than those on surface water (Green et al. 2011), climate variability has been demonstrated to affect groundwater recharge and GDEs on multidecadal time scales (Kløve et al. 2014).

In addition to decreased annual aquifer recharge, changes to the timing and type of precipitation will shift the timing of streamflow peaks earlier in the year, especially in snowpack-dominated watersheds (Fritze et al. 2011). Late-season low flow conditions for surface water are already in decline (Luce and Holden 2009) and likely to decrease further (e.g., Liebowitz et al. 2014), increasing the importance of groundwater-fed baseflows for climate resilience in streams. Decreased surface water availability during the summer is expected to increase water demand for groundwater to meet human needs (OWRD 2017). The increasing synchrony between late season low flows and maximum temperatures will negatively impact cold-water fishes (Arismendi et al. 2013) and will emphasize the ecological importance of the cold water refugia provided by groundwater. Facultative GDEs that rely on a combination of groundwater and surface water, such as groundwater-dependent wetlands, rivers, or lakes with upslope runoff or upstream surface water contributions, may be indirectly impacted by the warmer temperatures and decreased flows.

Evapotranspiration from both crops and natural vegetation is expected to increase as the climate warms, which will affect groundwater and GDEs (Condon et al. 2020). Agricultural water use accounts for 86% of Oregon's water demand (OWRD 2015). Total annual crop water demand is expected to increase due to prolonged growing seasons and increased rates of evapotranspiration (Mucken and Bateman 2017), adding further pressure on aquifers to meet demand. Increased evapotranspiration by riparian vegetation, mesic phreatophytes, and xeric phreatophytes may affect local water tables or GDE water availability (Kløve et al. 2014). Changes in evapotranspiration are expected to indirectly affect groundwater availability by shifting groundwater recharge rates (Condon et al. 2020).

There has been significant climate-caused desiccation of GDEs around the world (UNESCO 2022). Climate impacts to GDEs in Oregon are likely moderated by the length and contributing area of flow paths known as flow systems. Flow systems affect the relative vulnerability of groundwater-dependent species to climate and groundwater withdrawal (Aldous and Gannet 2021). Shorter or shallower flow systems are likely to be more vulnerable to climate influence and groundwater withdrawal than longer or deeper flow systems. The hydrogeologic setting of GDEs affects their vulnerability to anthropogenic and climate stressors (Godwin et al. 2002) and is defined by subsurface geology, flow system and discharge, topography, and precipitation and evaporation. The hydrogeologic setting of GDEs in Oregon varies substantially (Aldous et al. 2015, Freed et al. 2019), so climate resilience and vulnerability of GDEs is nonuniform. This spectrum of GDE resilience affects their ability to act as climate refugia on ecological and evolutionary scales. The most resilient GDEs will provide stable refugia because their flow systems will persist on a decadal or millennial timescales without crossing significant ecological thresholds (McLaughlin et al. 2017). The least resilient GDEs, or transient refugia, will create ecological traps for obligate groundwater-dependent species because their water table elevation or groundwater discharge will be sufficiently altered to cross ecological thresholds under future climate conditions (Cartwright et al. 2020). Many GDEs will likely fall somewhere in between stable and transient refugia and may shift into new stable states. For example, a groundwater-dependent wetland may change from having perennial inundation into a mesic depression supported by near-surface groundwater (Cartwright et al. 2020). Even relatively minor changes in groundwater connectivity may result in substantial changes to habitat availability (e.g., Morrison et al. 2013, deGraaf et al. 2019).

This report assesses six climate threats for GDEs in Oregon. The threats include future projections related to decreased stream flow, increased stream temperature, changes to precipitation, increased evapotranspiration, increased air temperature, and decreased snow-water equivalence.

Invasive species

Groundwater-dependent ecosystems can suffer altered physical and ecological characteristics due to invasive species. Invasive species directly affect ecosystem services through altered community dynamics, changes to the physical environment, and impacted biogeochemical function (e.g., Pejchar and Mooney 2009, Weidenhamer and Callaway 2010, Bauer 2012). Aquatic invasive species in Oregon are widespread and include plant, fish, mollusk, and reptile species (ODFW 2016). Although there have been few statewide surveys of aquatic invasive species, studies have shown the ubiquity of invasives in waterbodies in general (e.g., Miller and Sytsma 2014), GDEs like springs (Freed et al. 2019), and phreatophyte communities (Albano et al. 2020). Invasions of non-native plants may also be partly mediated by depth to groundwater (Mata-Gonzalez et al. 2012).

Invasive species can also indirectly impact GDE function. Increased or altered evapotranspiration from invasive plants can affect shallow groundwater (e.g., Pongkijvorasin et al. 2020, Dzikiti et al. 2013). Across the American West, invasive annual grasses like cheatgrass (*Bromus tectorum*), medusahead (*Taeniatherum caput-medusae*), and ventenata (*Ventenata dubia*) have established across vast portions of rangeland (Chambers et al. 2014). Due to their increased fine fuel load compared to native vegetation, invasive annual grasses increase the frequency, severity, and size of wildfires (Balch et al. 2014). Areas with invasive annual grass cover exceeding 15% were twice as likely to burn and four times more likely to have multiple wildfires as areas with low abundance of invasive annual grasses (Bradley et al. 2017). Although fire impacts to groundwater-dependent ecosystems are relatively poorly understood

(Burch 2021), increasing severity of wildfires can affect riparian ecosystem function (Dwire et al. 2018) and therefore is likely to have similar impacts to GDEs. Although wildfires can disrupt ecosystem services of GDEs, some types of GDEs such as springs (Tsinnajinnie et al. 2021) can provide local refuge from wildfire impacts. If their access to groundwater is impeded due to other stressors or threats, phreatophyte communities like black greasewood are at risk of transitioning to a disturbed state dominated by invasive annual grasses with high fire risk (Provencher et al. 2020), exacerbating this threat. The presence of roads influences the establishment of invasives species (Deeley and Petrovskaya 2022). Road density is correlated to disturbance severity in GDEs (Sada and Nachlinger 1998).

Invasive species comprise one stressor and two threats to GDEs. The stressor is observed occurrences of invasive species in relation to GDEs. The threats are the presence of invasive annual grasses and road density.

Ungulates

Livestock grazing is the most widespread land management practice in western North America and affects a broad diversity of ecosystem types (Fleischner 1994). These impacts are especially pronounced near perennial sources of water (Kauffman and Krueger 1984). While ungulates vary by species in terms of their environmental requirements, it has been well documented that cattle in particular demonstrate a preference for riparian areas around a wide variety of freshwater ecosystems as a way to manage their low heat tolerance and high water demand (Steuter and Hidinger 1999; Allred et al. 2013). Cattle, sheep, and other ungulates affect groundwater-dependent ecosystems through physical disturbance (e.g., herbivory, compaction, or trampling) or water quality impacts due to nutrient inputs (Dwire et al. 2018) and increased sediment concentrations (Grudzinski et al. 2018). Herbivory and trampling of emergent or riparian vegetation reduces native plant abundance in GDEs like spring-fed wetlands (Burdick et al. 2021) and affects vegetative shading in inundated GDEs (Kauffman and Krueger 1984). Terrestrial GDEs like phreatophytes that are heavily grazed can have reduced ecosystem function (Boyd et al. 2017). Compaction by livestock can affect some GDEs, such as fens, by altering wetland soil structure (USFS 2012). Nutrient inputs from livestock can cause eutrophication and water quality degradation (Hooda et al. 2000). Surveys of 2,213 springs in Nevada documented ungulate disturbance in over 50% of the springs (Sada and Lutz 2016). The interactions between livestock grazing impacts and other GDEs have not been well studied. However, there is evidence that grazing impacts near wetlands negatively affect migrant shorebird nesting areas by reducing invertebrate prey and overall habitat diversity (Powers and Glimp 1996).

Ungulates are considered a stressor in this analysis that directly impact GDEs where they co-occur.

Methods

This section describes the methodology used to identify potential groundwater-dependent ecosystems and species (GDEs) and the stressors and threats that impact them. Potential GDEs were mapped using existing spatial data sets and literature references. Five types of potential GDEs (referred to as “GDE types”) were assessed for groundwater dependence: springs, rivers, wetlands, lakes, and species. Existing information on the distribution and abundance of GDEs in Oregon is scarce (but see Brown et al. 2009), and many existing datasets used in this analysis did not have full statewide or ecosystem-wide coverage. Therefore, the determination of groundwater dependence for many indicators is proof-positive—in other words, presence of an indicator suggests groundwater dependence, but absence of an indicator does not suggest lack of groundwater dependence. Furthermore, groundwater dependence is both spatially and temporally dynamic (Kath et al. 2018). Therefore, multiple indicators are used for each facultative GDE type to increase confidence in the assessment of groundwater dependence. The number of positive indicators for groundwater dependence are considered to represent the degree of confidence that the ecosystem is a GDE. Ecosystems with more indicators have greater confidence of groundwater dependence than ecosystems with fewer indicators. For example, we used five indicators for assessing groundwater-dependence in rivers. A river reach that met three indicators of groundwater-dependence is more likely to be groundwater-dependent than a river reach that only met zero, one, or two indicators. All indicators are considered equal, and no weighting was used to assess confidence.

Study extent

The analyses described in this report are confined to the state of Oregon. Comprehensive datasets at the state scale were used when possible, but data limitations precluded this in many cases. When watershed boundaries cross state lines (e.g., Klamath and Walla Walla watersheds), analyses were constrained to Oregon only. Data availability varies substantially on a state-by-state basis, and it was outside the scope of this study to incorporate input data from neighboring states.

A general overview of the processing steps for each GDE type are presented below. Further detail can be found in the embedded metadata for each GDE dataset.

Groundwater-dependent ecosystems and species

Springs

1) Spring compilation

Springs by definition are groundwater dependent (Brown et al. 2009, Springer and Stevens 2009), so indicators are not needed to assess groundwater dependence. This study synthesized, de-duplicated, and combined three primary sources: National Hydrography Dataset maps (NHD; USGS 2020b), the second release of the Geothermal Information Layer for Oregon thermal springs maps (GTILO-2; DOGAMI 2013), and The Nature Conservancy's staff located and field-verified spring data in Oregon (Freed et al. 2019 and unpublished field surveys). Mapped springs in multiple datasets were considered duplicates if they either (1) had the same place name and were within 250 meters of each other, or (2) unnamed springs mapped within 10 meters of each other. When duplicative locations were found, only one spring was retained.

Springs mapped within GTILO-2 were identified as geothermal using DOGAMI's "Designation" field.

2) Assumptions and limitations of spring mapping

While this is the most comprehensive known synthesis of mapped springs in Oregon, we recognize that many springs are not yet mapped. Field verification of mapped springs in central Oregon, for example, found that approximately 30% of ground-located springs were not documented in NHD (Freed et al. 2019). Similarly, springs that are included may no longer exist due to fluctuations in water tables, land alterations and/or changes in precipitation (Cartwright et al. 2020).

Rivers

Rivers can receive water inputs through several mechanisms including runoff from precipitation events, direct discharge from other waterbodies (such as lakes and wetlands), and from groundwater sources. The latter group are germane to this analysis and occur as either gaining reaches, which receive direct groundwater inputs within the stream channel, or indirect input from channel-adjacent (within 100 m), upslope springs. The National Hydrography Dataset High Resolution Plus v2.1 (USGS 2020b) was used as the source for river and stream locations. Groundwater dependence for rivers was assessed using five indicators.

1) Perennial flow east of the Cascades

Perennial streamflow in mapped rivers and streams (NHD attribute fcode = 46006) is considered an indicator of groundwater dependence in semi-arid or arid regions (Saito et al. 2020). Therefore, perennial streamflow is considered an indicator to the east of the Cascade Mountains. Perennial streamflow in the more temperate region of the state west of the Cascade Mountains could be supported by runoff, so it was not included as an indicator of groundwater dependence in those areas.

2) Hydrologic classification

Random forest classifications of gaged streams in the United States have grouped hydrographs into 30 clusters (McManamay and DeRolph 2019). The most consistent hydrograph cluster by flow, "super-stable groundwater" was used as an indicator of groundwater dependence in Oregon. The hydrologic classification data (McManamay and DeRolph 2019) were mapped onto NHD flowlines to perform this analysis.

3) Baseflow separation

In non-regulated rivers without glacial inputs, the amount of groundwater influence in a river is reflected in the base flow component of its hydrograph (Wahl and Wahl 1995). Baseflow analysis separates a hydrograph into two components: a more responsive and transitory component that represents runoff from storm events, and a persistent baseflow component that represents groundwater input or glacial melt (Wahl and Wahl 1995).

To determine the appropriate gage data for this analysis, only "reference gages" were used (as defined in GAGES-II dataset; Falcone et al. 2010) which were further restricted to unregulated gages. Upstream regulation was determined by compiling a dataset of flow-regulating dams using the National Anthropogenic Barrier Dataset (2012), Oregon Large Dams dataset (OWRD 2014), National Inventory of Dams (2004), and the Oregon Department of Fish and Wildlife Barrier database (ODFW 2014). Flow networks were computed for streams and rivers that intersected reference gages. If flow-regulating dams were found within the flow networks, the gages were omitted from this analysis. The remaining gages were assessed and validated using expert opinion and review of the USGS Annual Data Report comments written for each gage. A final dataset of 95 reference gages was developed for analysis.

Baseflow separation was calculated using the "BFI Standard" method (Wahl and Wahl 1995) at five- and eight-day intervals. Streams that were upstream and within the same flow network of gages were considered groundwater dependent if baseflow evaluated at five-day intervals exceeded 50% of the total annual flow (Sear et al. 1999, Boulton and Hancock 2006), which is a conservative estimate of groundwater dependence and likely underestimates the amount of groundwater-dependent stream reaches detected by this analysis.

4) Gaining reaches

Where available, field measurements from published reports were used to identify the presence and distribution of gaining reaches. Seepage runs to assess groundwater dependence were evaluated by a review of 16 relevant USGS reports among six basins: Columbia, Deschutes, Goose Lake, Umatilla, and Willamette (Table 1). Because existing spatial data were not available—especially in older reports—the locations of gaining reaches were manually transcribed onto NHD flow lines. When studies repeated seepage runs on the same reaches, only reaches that were gaining during all seepage runs were included.

Table 1: U.S. Geological Survey reports for Oregon with seepage runs or other measurements of gaining reaches.

Basin	Reference
Columbia	Kahle et al. 2011; Burns et al. 2012
Deschutes	Gannett et al. 2001; Gannett et al. 2004; Gannett et al. 2017
Goose Lake	Morgan 1988
Klamath	Gannett et al. 2007; Gannett et al. 2012
Umatilla	Herrera et al. 2017
Willamette	Morgan and Weatherby 1992; Laenen and Risley 1997; Woodward and Gannett 1998; Lee and Risley 2002; Conlon et al. 2005; Lee and Snyder 2009; Lee 2011

5) Proximity to springs

Springs that discharge directly into rivers directly add groundwater and indicate the possibility of additional subsurface groundwater discharge within the river channel. For spring proximity to be a meaningful indicator of groundwater dependence in rivers, a spring must be at a higher elevation than the feature, allowing water to flow into the river reach. Springs were considered likely to discharge into adjacent reaches if they were within 100 meters of the reach based on field observations of spring flow entering rivers in Oregon. Due to evapotranspiration and infiltration, springs beyond that distance may not support the flow of the nearest river.

Spring elevation was extracted to each mapped spring point from the statewide 30m DEM (USGS 2020a). River elevation was defined at the midpoint of the reach. Euclidean distance was then applied to filter out upslope springs greater than 100 meters from each river reach.

6) Assumptions and limitations of indicators

Groundwater dependence is evaluated at the reach scale for rivers, but ignores the groundwater-dependency of immediately adjacent upslope reaches. This was a conscious analysis decision intended to assess reach-specific groundwater inputs without attempting to create a subjective threshold for the inertia of groundwater dependence, which would likely require flow modeling to track.

The selection of only using the hydrograph class "super-stable groundwater" to indicate groundwater dependence likely underestimates the actual amount of groundwater-dependent stream reaches. Other hydrograph classes described by McManamay and DeRolph (2019) may also indicate groundwater dependence; however, the super stable groundwater cluster corresponded with the highest likelihood of groundwater influence. Given the relatively coarse resolution of the data in the nationwide classification, only the most reliable class was used as an indicator.

The use of a 50% baseflow index threshold is very cautious compared to other attempts to assess groundwater dependence in rivers, such as a 15% threshold (Howard and Merrifield 2010) and any perennial flow (Saito et al. 2020). Because baseflow is assessed on a continuous scale, the selection of a threshold value is necessary to distinguish between groundwater-dependent and surface water-dominated rivers. Assuming the baseflow component of a hydrograph is primarily comprised of groundwater (Winter et al. 1998), a simple majority was used as the indicator threshold.

Springs which occur upslope and within 100 meters of a river reach are assumed to discharge into the river. However, due to the scarcity of spring flow data, it is unknown whether a given spring supports sufficient discharge to develop a spring brook that flows into the river without being lost evapotranspiration or infiltration. Additionally, the estimation of elevation is coarse given the resolution of the DEM data, and therefore may not account for the presence of intervening landforms that may deflect spring flow away from the reach and/or cause pooling prior to entering the reach.

Wetlands

Groundwater dependence in naturally-occurring, palustrine wetlands in Oregon was assessed using four indicators: wetland type, soil type, presence of direct spring input, and proximity to adjacent springs. The National Wetlands Inventory dataset (NWI V2; USFWS 2018) was used as the source for wetland locations.

1) Wetland type

Wetland type was used both to evaluate eligibility of wetlands for this analysis and as an indicator of groundwater dependence (following Byer et al. 2019), because perennial palustrine emergent wetlands often interact with groundwater or—in regions with less precipitation—are perennial because of groundwater. Naturally-occurring wetlands were selected from the NWI dataset using attribute "first modifier name" to exclude diked, impounded, or excavated wetlands (NWI V2; USFWS 2018). Only palustrine wetlands with a permanent, semi-permanent, or seasonally-flooded water regime were considered potentially groundwater dependent. Riparian wetlands are sometimes considered innately groundwater dependent without the need for further indicators. However, due to a lack of clarity around presence or absence of phreatic inputs to the hyporheic zone, riparian wetlands that did not meet at least one other indicator of groundwater dependence were not considered innately groundwater dependent. Similarly, the functional hydrology of estuarine wetlands is affected by tidal dynamics and marine inputs which obscure potential groundwater influence, so estuarine wetlands were omitted from the analysis.

2) Soil indicators

Histosol soils form in areas of permanent saturation, and are therefore presumed to be present in areas with shallow groundwater. The coincidence of mapped Histosols with natural wetlands are an indicator of groundwater dependence. These soils were identified through a combination of two soil survey maps.

The USDA Natural Resource Conservation Service has produced two scales of soil survey maps:

a) STATSGO, mapped at 1:250,000 across the entire coterminous United States
b) SSURGO, mapped at 1:12,000 in select areas, primarily in locations with crop potential

The finer-scaled SSURGO data are typically mapped county by county. Consequently, there exist numerous discontinuities across county boundaries. However, these are the best soil data available to date. Following Buttrick et al. (2015), SSURGO & STATSGO information were stitched together, favoring the finer SSURGO data where available. Map units classified as "Histosols" were selected as an indicator of wetland groundwater dependence.

3) Direct spring input

Wetlands with mapped springs intersecting their delineated boundary were assumed to be receiving direct groundwater input via spring discharge. Natural wetlands were selected that overlapped one or more springs to map this indicator.

4) Proximity to springs

This indicator was assessed using the 30m Oregon DEM (USGS 2020a), NWI wetlands in Oregon, and the compiled spring dataset described above. Springs with an elevation greater than or equal to a wetland's minimum elevation and within 100 meters of the delineated wetland boundary were used as positive indicators of groundwater dependence.

5) Assumptions and limitations of indicators

The higher resolution SSURGO data are available for most areas of the state that support some form of agriculture. For all other areas the lower resolution STATSGO data were used. This constrains the detection of soil types with limited and/or small-patch distribution, such as Histosols, in those areas.

Similar to the spring proximity analysis in rivers, it is assumed that upslope springs within 100 meters of a wetland edge discharge into that wetland. However, spring flow must be greater than losses to evapotranspiration or infiltration for the water to reach the wetland, and local topography must allow water to flow from the spring point to the wetland.

Lakes

The groundwater dependence of lakes was assessed using three indicators: natural occurrence, direct spring input, and proximity to adjacent springs. Lakes with the greatest confidence of groundwater dependence met all three indicators, while lakes with zero indicators are not considered to be groundwater dependent.

1) Natural occurrence

The natural occurrence of lakes is by default an indicator of likely groundwater dependence (*sensu* Brown et al. 2009; Saito et al. 2020). Naturally-occurring lakes were defined as NWI lacustrine wetlands that lacked modifiers indicating that they were diked, impounded, excavated, or artificial.

2) Direct spring input

Lakes with one or more mapped springs intersecting their delineated boundary were assumed to be receiving direct groundwater input via springs. This indicator was assessed by determining the number of springs found within each natural lake boundary.

3) Proximity to springs

This indicator was assessed using the Oregon 30m DEM (USGS 2020a), NWI lake polygons in Oregon, and the compiled spring dataset described above. Springs with an elevation greater than or equal to the lake's minimum elevation and within 100 meters of the delineated lake boundary were used as a positive indicator of groundwater dependence.

4) Assumptions and limitations of indicators

Natural lakes are assumed to be groundwater dependent because they support, and interact with, a local groundwater table. However, it is likely that some lakes lose more water to infiltration than they gain from groundwater discharge, and that relationship may vary by season, microclimate, and water year. The groundwater dependence of large lakes probably varies spatially as well, with certain portions of the lake receiving more surface water runoff than groundwater, and other portions of the lake receiving more groundwater than surface water runoff.

The distinction between lakes and riparian wetlands is blurred in some cases, especially in playas or large shallow saline lakes. The input data from NWI sometimes assigns multiple different wetland types to the same lake, partitioning a single lake into multiple polygons. Therefore, on an individual lake scale, some assessments of groundwater dependence may incorrectly appear to only correspond to one part of a lake but not other parts due to the partitioned input data.

Similar to the spring proximity analyses for both wetlands and rivers, discharge from springs within 100 meters of the edge of the lake is assumed to reach the lake. In reality, lake extents can vary widely on a seasonal or interannual basis, especially for playas and large shallow saline lakes where relatively small differences in lake stage correspond to significant differences in lake area (e.g., Freed et al. 2021). Therefore, the influence of nearby adjacent springs on lake levels can be site-specific and temporally variable.

Species

Over 1,200 plant and animal species in Oregon have been identified as obligately or facultatively dependent upon groundwater (Brown et al. 2009); however, most do not have published spatial data of their range or observations. Thirty-one of these groundwater-dependent species have documented occurrences in the Oregon Biodiversity Information Center Biotics database (ORBIC 2020), and another forty-three phreatophyte species were mapped by the U.S. Geological Survey (Garcia et al. 2021).

1) Phreatophyte communities

The USGS has mapped phreatophyte communities across southeast Oregon (Garcia et al. 2021). A total of 43 potentially-phreatophytic species have been mapped into communities of 45 unique combinations. Phreatophyte communities were sorted into three classifications: greasewood (*Sarcobatus vermiculatus*) communities, saltgrass (*Distichlis spicata*) communities, or other phreatophytes. All greasewood communities were assumed to be groundwater dependent. Saltgrass communities without greasewood were considered groundwater dependent if they were found in relatively flat topography consistent with field observations (Garcia et al. 2021). All other phreatophytes communities were considered groundwater dependent if they occurred in relatively flat landscapes with poorly drained soils (Garcia et al. 2021). Although all communities that met these criteria are likely to be groundwater dependent, a distinction was made between all other phreatophyte communities and the greasewood or saltgrass communities. Greasewood and saltgrass communities have a very high confidence of groundwater dependence, whereas other phreatophyte communities are conditionally groundwater dependent.

2) Assumptions and limitations of phreatophyte mapping

Many phreatophytes will opportunistically utilize groundwater at different life stages, during different times of year, or during drought. Therefore, although communities that meet the criteria described above are considered groundwater-dependent ecosystems, they may not continuously be utilizing groundwater.

3) Other groundwater-dependent species

Other non-phreatophytic species were considered groundwater dependent if identified as such in Brown et al. (2009). Species occurrence data were collected from a wide range of researchers and institutions and across many years in the Biotics dataset (ORBIC 2020). No attempt has been made to assess the current status of these occurrences; however, observations that met the criteria required for inclusion in the Brown et al. (2009) dataset met rigorous standards. Although Brown et al. (2009) identified hundred of other groundwater-dependent species that likely occur in Oregon, only 31 species had verified observations within the Biotics dataset through the year 2020.

4) Assumptions and limitations of other groundwater-dependent species

Data in the Biotics dataset (ORBIC 2020) are mapped with uncertainty buffers which can be quite large. They were also initially collected at different times and during surveys which may have targeted different taxonomic groups, potentially introducing survey bias. The data are likely to be spatially and temporally skewed based on available surveys, rather than representing a comprehensive distribution of each species. Some taxa like anadromous fish or flowering plants are much more well-surveyed than other taxa like invertebrates. These observations should be considered a substantial underestimate of the actual distribution of groundwater-dependent species, but comprise the best currently-available data.

Observations of groundwater-dependent species may have been made under historical conditions, and land use, climate, habitat availability, or other variables affecting species distribution may have changed since they were surveyed. No additional attempt was made to verify the observations under current conditions.

Atlas Map

1) Analysis units

To map the abundance and distribution of GDE types across the state, all GDE data were summarized to 640 acre hexagonal polygons. The statewide hexagon dataset was originally produced by Oregon Department of Fish and Wildlife as the reporting units for their contribution to the Crucial Habitat analysis for the Western Governors' Wildlife Council and as the base analysis and reporting units for their statewide 2015 Wildlife Action Plan. Additionally, The Nature Conservancy used a subset of these hexagons to portray various threats and stressors to Sage-grouse for the state Sage-grouse Action Plan.

Aligning these data with these other official ODFW projects will streamline the use of these data in future agency planning efforts.

2) Standardization

All GDE data summarized to hexagons were first standardized to allow data to be combined across GDE types expressed as different units (i.e., count, length, and area). Two separate standardized indices were created; one for the abundance of GDEs within the hexagon, another for the number of indicators of groundwater dependence for the GDEs. The two indices were named 'Abundance' and 'Confidence' respectively. Abundance represents the standardized amount of a given GDE type. A hexagon with a high GDE abundance means that it contains some combination of many springs; many river kilometers of groundwater-dependent river reaches; a large area of groundwater-dependent lakes, wetlands, and/or phreatophytes; and/or a large number of other groundwater-dependent species observations. Confidence is the standardized number of indicators for a given GDE type. A hexagon with high GDE confidence means that it contains some combination of springs; river reaches, wetlands, or lakes that meet most or all of their respective indicators of groundwater dependence; phreatophyte communities with greasewood or saltgrass; and/or many observations of other groundwater-dependent species.

The calculation of abundance was a two-step process. First, the total amount (count, length, or area) of a GDE type within the hexagon was standardized by dividing the total amount of that GDE type by the maximum amount of that GDE type found across all hexagons. The resulting standardized value for each GDE type within a given hexagon ranges from 0 (no GDEs of that type are within the hexagon) to 1 (the maximum amount of GDEs of that type found within any hexagon). All groundwater-dependent species observations from both phreatophyte data and non-phreatophyte data were combined to achieve a single value of abundance of groundwater-dependent species. Secondly, the standardized abundance for all GDE types within the hexagon were summed, resulting in a final index value for all GDEs within a hexagon ranging from 0 (no GDEs of any type found within the hexagon) to 5 (a theoretical hexagon which simultaneously contains the maximum number of springs, river kilometers, wetland area, lake area, and groundwater-dependent species). These summed, standardized abundances for each GDE type were used to calculate an index of abundance for each hexagon analysis unit.

$$Abundance_n = \frac{Spring_n}{Spring_{max}} + \frac{River_n}{River_{max}} + \frac{Wetland_n}{Wetland_{max}} + \frac{Lake_n}{Lake_{max}} + \left(\frac{\frac{Phreatophyte_n}{Phreatophyte_{max}} + \frac{Species_n}{Species_{max}}}{All\ Species_{max}}\right)$$

Where $Abundance_n$ is the standardized GDE abundance in hexagon *n*;
$Spring_n$ is the number springs in hexagon *n*;
$Spring_{max}$ is the maximum number of springs found in any hexagon;
$River_n$ is the summed length (km) of groundwater-dependent rivers in hexagon *n*;
$River_{max}$ is the maximum summed length (km) of groundwater-dependent rivers found in any hexagon;
$Wetland_n$ is the summed area (km^2) of groundwater-dependent wetlands in hexagon *n*;
$Wetland_{max}$ is the maximum summed area (km^2) of groundwater-dependent wetlands found in any hexagon;
$Lake_n$ is the summed area (km^2) of groundwater-dependent lakes in hexagon *n*;
$Lake_{max}$ is the maximum summed area (km^2) of groundwater-dependent lakes found in any hexagon;
$Phreatophyte_n$ is the summed area (km^2) of phreatophytes in hexagon *n*;
$Phreatophyte_{max}$ is the maximum summed area (km^2) of phreatophytes found in any hexagon;
$Species_n$ is the number of observations of any groundwater-dependent species in hexagon *n*;
$Species_{max}$ is the maximum number of observations of any groundwater-dependent species found in any hexagon; and

$All\ Species_{max}$ is the maximum value of $\frac{Phreatophyte_n}{Phreatophyte_{max}} + \frac{Species_n}{Species_{max}}$ found in any hexagon.

Confidence was calculated as the scaled sum of indicators per hexagon. Similar to the abundance calculation, the index of confidence is a two-step process. First, the maximum number of indicators for a particular GDE type within a hexagon was standardized by the maximum number of possible indicators for that GDE type. The resulting value ranges from 0 (there are no features with indicators of groundwater dependence for that GDE type, so no GDEs of that type found within the hexagon) to 1 (at least one feature met the maximum number of indicators for that GDE type). The occurrence of springs are innately an indicator of groundwater dependence and are expressed as presence (1) or absence (0). Standardized values for phreatophytes and other groundwater-dependent species are again combined into one single value for all groundwater-dependent species. Secondly, the standardized confidence for all GDE types within the hexagon were summed, resulting in a final index value for all GDEs within a hexagon ranging from 0 (no indicators for any GDEs are within the hexagon) to 5 (a theoretical hexagon which simultaneously contains springs and at least one feature with the maximum indicator values for each of rivers, wetlands, lakes, and species). These summed, standardized confidences for each GDE type were used to calculate an index of confidence for each hexagon analysis unit.

$$Confidence_i = Spring_i + \frac{River_i}{River_{conf}} + \frac{Wetland_i}{Wetland_{conf}} + \frac{Lake_i}{Lake_{conf}} + \left(\frac{\frac{Phreatophyte_i}{Phreatophyte_{conf}} + \frac{Species_i}{Species_{conf}}}{All\ Species_{conf}}\right)$$

Where $Abundance_i$ is the standardized GDE abundance in hexagon *i*;
$Spring_i$ = 1 if there are one or more springs in hexagon *i* and otherwise equals 0;
$River_i$ is the maximum number of indicators met by any groundwater-dependent river reaches in hexagon *i*;
$River_{conf}$ is the maximum number of indicators met by a groundwater-dependent river reach found in any hexagon;
$Wetland_i$ is the maximum number of indicators met by any groundwater-dependent wetlands in hexagon *i*;
$Wetland_{conf}$ is the maximum number of indicators met by a groundwater-dependent wetland found in any hexagon;
$Lake_i$ is the maximum number of indicators met by any groundwater-dependent lakes in hexagon *i*;
$Lake_{cpnf}$ is the maximum number of indicators met by a groundwater-dependent lake found in any hexagon;
$Phreatophyte_i$ is the maximum number of indicators met by any phreatophyte community in hexagon *i*;
$Phreatophyte_{conf}$ is the maximum number of indicators met by a phreatophyte community found in any hexagon;
$Species_i$ is the species richness of groundwater-dependent species in hexagon *i*;
$Species_{conf}$ is the maximum species richness of groundwater-dependent species found in any hexagon; and

All $Species_{conf}$ is the maximum value of $\frac{Phreatophyte_i}{Phreatophyte_{conf}} + \frac{Species_i}{Species_{conf}}$ found in any hexagon.

The calculated values of 'Abundance' and 'Confidence' were then used to portray the statewide distribution of GDEs using a bivariate color ramp.

Stressors and Threats to groundwater-dependent ecosystems and species

The evaluations of risk factors to GDEs in this section use terms defined in Saito et al. (2022):

- A **stressor** is *any physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that reduces the viability of an individual, population, or a species, or the viability of its habitat*.
- A **threat** is *a potential (or impending) physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that is reasonably likely to negatively affect an organism, population, species, or its habitat*.

Four classes of stressors and threats were assessed: groundwater withdrawals, invasive species, ungulates, and climate. Within those four classes, a total of sixteen individual stressors and threats were mapped in Oregon (Table 2). In all cases, best available data for Oregon were synthesized from existing sources.

Table 2: Stressors and threats to groundwater-dependent ecosystems in Oregon.

Class	Description	Stressor	Threat
Groundwater withdrawals	Groundwater level declines	X	
	Concentrations of permitted groundwater use	X	
	Presence of Groundwater Administrative Areas	X	
	Future projected irrigation demand		X
	Future projected irrigation reliance		X
	Lack of instream flow protection		X
Invasive species	Presence of aquatic invasive species		X
	Presence of invasive annual grasses		X
	Road density		X
Ungulates	Active grazing allotments on public land	X	
Climate	Future projected precipitation		X
	Future projected actual evapotranspiration		X
	Future projected air temperature		X
	Future projected snow-water equivalent		X
	Future projected stream flow		X
	Future projected stream temperature		X

Identifying and mapping stressors

Groundwater withdrawals

1) Groundwater level declines

Groundwater level trends were assessed in monitoring wells and production wells measured by state and federal agencies in Oregon (Garcia et al. 2021). Monitoring well data were obtained from the Oregon Water Resources Department Groundwater Information System (OWRD, 2020) and the U.S. Geological Survey National Water Information System (USGS, 2020). Trend analyses were performed for all monitoring wells with 5 or more years with measurements among 5 and 30-year periods of record. To account for seasonal pumping effects when detecting interannual trends, water level data used in the analysis were restricted to the highest pre-irrigation (February to April) water level measurements. Trends were described using the Sen Slope, which is the median of all possible pairwise slopes for a given well analysis, and trends were statistically tested using the Kendall-tau test for monotonic trends (Kendall, 1975; Lorenz, 2016). Following Hirsch and others (2015), positive and negative trends were categorized using a likelihood value calculated as the functional equivalent of a two-sided p-value (alpha = 0.1). Trends were categorized as very likely (greater than 0.9), likely (0.9 to 0.66), or no trend (less than 0.66). Groundwater level trends were summarized by well for each possible period of record, and some wells had trend analyses for both 5- and 30-year periods. Wells with either likely or very likely negative water level trends were indicative of aquifer declines. Monitoring wells are not well distributed across the range of GDEs within Oregon. Some GDE types are less well matched to the distribution of monitoring wells than others.

A GDE within 1 km of a well with a likely or very likely negative trend for either a 5-year or 30-year period was considered to be affected by groundwater declines. Although this analysis was split into two time periods to increase understanding of long-term vs. recent well trends, it is considered a single stressor to GDEs to avoid double-counting in cases where monitoring wells were assessed for both time periods.

2) Concentrations of permitted groundwater use

Groundwater rights themselves are not perfectly reliable surrogates for actual water use: many water right holders may use less water in reality than their permit allows leading to overestimates, whereas other water rights may underestimate water use due to accidental overuse, leaking equipment, or illegal use. However, actual measurement data for water use is rare in Oregon and only found on fewer than 17% of all water rights (OWRD 2019).

Permitted groundwater rights were obtained from the Oregon Water Rights Information System (OWRD 2020). The number of rights and their combined rate were summed by 36 square mile Townships and Ranges (hereafter referred to as "Townships") as defined in the Public Land Survey System (PLSS). Cumulative rate (permitted volume per time, usually in cubic feet per second) was chosen as the metric of groundwater use rather than duty (total permitted volume per year or per irrigation season) because a substantial proportion of water rights found within the Water Rights Information System are missing information about duty. Duty is likely a more appropriate metric to assess long-term water demand because rate is influenced by the permitted season begin and end dates, but due to data availability, rate is the best available surrogate for concentrations of water use. Although the impact of a water right's rate on nearby GDEs may vary based on actual use and irrigation season, the spatial distribution and approximate amounts of permitted groundwater use is a surrogate for actual groundwater use.

Due to overall data scarcity around both water use and the hydrogeologic setting of individual GDEs, it is outside the scope of this analysis to determine specific thresholds of groundwater use that will impact GDEs. Even small amounts of groundwater use may have a disproportionately large effect on GDEs. Due to this uncertainty, the median permitted groundwater use was chosen as a threshold to standardize relative risk among GDEs in Oregon. GDEs were at risk of impacts due to groundwater extraction if they fell within a Township with greater than median permitted groundwater use.

3) Presence of Groundwater Administrative Areas

The state of Oregon has several administrative tools to manage groundwater. These vary in degree of restriction, from limiting new uses of groundwater to restrictions on existing uses to curtail over-appropriation. Groundwater Administrative Areas are regions where demonstrated groundwater declines have led to the establishment of management boundaries. Groundwater Administrative Areas were obtained from Oregon Water Resources Department (OWRD 2021) and were spatially intersected with GDE locations. Several areas across the state show negative groundwater trends from monitoring well data that are outside of existing Groundwater Administrative Areas, so this stressor underestimates regional groundwater declines. There are five types of Groundwater Administrative Area designations in Oregon: Limited, Critical, Classified, Withdrawn, and Mitigation. In all cases, the presence of any formal groundwater management designation indicates potential over-use of groundwater and subsequent stress to GDEs.

GDEs within any Groundwater Administrative Area designation were therefore considered potentially stressed.

Invasive species

Invasive species displace native biota and can alter hydrologic processes. Records of aquatic invasive species are subject to similar limitations as records of groundwater-dependent species. Aquatic species—especially motile ones—are notoriously difficult to comprehensively survey. Surveys are patchily distributed, nonuniform, and are subject to widely varying levels of resource investment. Bias due to survey effort is also a limitation.

Two data sources were used to map aquatic invasive species: the Non-Indigenous Aquatic Species Database (USGS 2021) and iMap Invasives (NatureServe 2021). Data were obtained from each source and records were edited to remove: all records from the year 1999 and older, records listed as brackish or marine, or records labeled as "extirpated", "eradicated", and "failed." A small suite of attributes were standardized between the two datasets and all records were merged into a single layer. A total of 10,719 discrete invasive species observations were mapped across the state.

For the purposes of this analysis, no distinction was made among taxa groups of invasive species in terms of their potential impact. Presence/absence of invasive aquatic species was the only metric considered. Given the innate ability of invasive species to spread to nearby habitats, a GDE could be at risk of invasion if it is located near an observed invasive species.

A GDE was considered potentially stressed if it was within 1 km of one or more invasive species observations.

Ungulates

Ungulates impact GDEs through trampling and compaction of mesic soils, over-grazing of vegetation, water quality impacts, and likely presence of hydrologic alteration for livestock drinking sources. Domestic livestock, primarily cattle, are the only group of ungulates for which reasonably comprehensive data exist. Boundaries of grazing allotments on public lands managed by the USFS and BLM were obtained from the agencies. Grazing allotments were used as surrogates for the impacts associated with ungulates to GDEs. Many allotment managers take action to reduce grazing impacts within allotments. Grazing intensity and measures to protect aquatic resources vary from allotment to allotment. These differences could not be accounted for in this analysis.

A GDE was considered potentially stressed if it fell within an active grazing allotment managed by a public land agency.

Identifying and mapping threats

Groundwater withdrawals

1) Future projected irrigation demand

Irrigation demand is the mean annual volume of water consumptively used by crops. Increasing irrigation water demand corresponds to increased consumptive use and decreased return flow from crops irrigated with both surface and groundwater. Future projections of irrigation demand for the year 2050 (OWRD 2015) were downloaded at the county level for two climate scenarios to assess results among a spectrum of likely conditions. The scenarios chosen are the "Central Tendency" (CT) scenario, which approximates the average of multiple climate scenarios, and the "Hotter/Drier" (HD) scenario, which represents the greatest change in agricultural water demand. In both scenarios, future projections are displayed as a relative percent change compared to 2015 conditions.

This threat was mapped across Oregon to show the relative magnitude for any area of interest, but was not summarized to GDE types due to the coarse resolution of the threat and indirect nature of its impact to GDEs.

2) Future projected irrigation reliance

Irrigation reliance is the amount of crop water demand met by irrigation as opposed to precipitation or runoff. Changes to irrigation reliance will occur as a combined consequence of changes to irrigation water demand, evapotranspiration, runoff, and precipitation. Changes in irrigation water reliance will impact both surface water and groundwater utilization; however, because surface water is nearly fully allocated in Oregon during the irrigation season (OWRD 2017), they may be expected to disproportionately affect groundwater use. Future projections for irrigation reliance for the year 2050 (OWRD 2015) were downloaded at the county level for both the CT and HD scenarios, and displayed as relative percent change compared to 2015 conditions.

This threat was mapped across Oregon to show the relative magnitude for any area of interest, but was not summarized to GDE types due to the coarse resolution of the threat and indirect nature of its impact to GDEs.

3) Lack of in-stream flow protections

Oregon's water laws are typical of western states - the first person to obtain a water right on a stream has seniority and will be the last person to be shut off in times of water scarcity. The Oregon Instream Water Right Act (ORS 537.332 through 537.360) was adopted in 1987, so many instream water right priority dates are junior to other uses; however, they are still critically important tools for protecting instream flows from human overuse. Rivers and streams which lack an instream water right are vulnerable to hydrologic alteration during drought years or low-flow periods. Spatial data for all noncancelled instream water rights as of 2021 were acquired directly from Oregon Department of Fish and Wildlife for this analysis, but all data are also available through the Oregon Water Rights Information System (OWRD 2022). Instream water right spatial data were joined to the dataset of groundwater-dependent rivers (rivers with at least one indicator of groundwater dependence) to assess the proportion of groundwater-dependent rivers with and without in-stream flow protections.

Invasive species

1) Invasive Annual Grasses

Invasive grass data were taken from the Rangeland Analysis Platform's (RAP) vegetation biomass product (RAP 2020), which provides annual and 16-day aboveground biomass from 1986 to present of: annual forbs and grasses, perennial forbs and grasses, and herbaceous (combination of annual and perennial forbs and grasses). All non-cultivated annual grasses in eastern Oregon are invasive.

For counties east of the Cascades Mountain Range, annual grass biomass (band 1) for 2020 was extracted from the RAP dataset and masked using NLCD (National Land Cover Data, 2019) to exclude agricultural, developed, and forested land cover types. This representation of invasive annual grasses was used in two ways to derive grass cover areal estimates for each GDE type: 1) pixel-based cover estimates, and 2) a focal statistic function was used to calculate mean grass cover within 500 meters of each focal pixel.

The focal statistic dataset was used to impute an annual grass cover value to springs. As springs are mapped as points, the slightest positional error in either the spring location or the RAP vegetation data could result in an inaccurate cover value. For all other GDE types, the pixel-based cover estimates were used. For linear river reaches, the annual grass cover was estimated as the mean of the pixel-based cover values along each reach. For lakes and wetlands less than 20 acres in size, the mean of the pixel-based cover values was imputed to each feature. Lakes and wetlands larger than 20 acres were given the mean value of the cells within a shoreline buffer (interior 40m of the shore) to minimize the influence of open water on proximity to annual grasses.

2) Road Density

Road density data from the 2014 U.S. Census TIGER dataset (USCB 2021) were obtained from ESRI's Living Atlas. These data display road density calculated as kilometer of road per 1 km raster cell.

For springs, mapped as points, the road density value was taken directly from the raster cell at the spring location. For river reaches, mapped as lines, the value was calculated as the mean of the raster values along each reach. For lakes and wetlands less than 20 acres in size, the mean value of overlapping raster cells was imputed to each feature. Lakes and wetlands larger than 20 acres were given the mean value of the cells within the interior 40m of the shore to minimize the influence of open water cells far interior from the shore zone.

Climate

1) Future projected precipitation, actual evapotranspiration, air temperature, and snow-water equivalent

Statistically downscaled datasets from the latest Coupled Model Intercomparison Project phase 5 (Naz et al. 2016) were summarized to the NRCS 4th level (8-digit) hydrologic unit boundaries for both intermediate- and high-emissions scenarios (RCP 4.5 and 8.5, respectively) (Garcia et al. 2021). Projected future climate anomalies for the period 2070-2099 were summarized to better understand potential threats to GDEs due to climate variability. Anomalies are represented as percent change in future climate and hydrological metrics relative to the historical mean of the years 1971-2000. Anomalies summarized for our analyses included: mean annual precipitation, mean annual actual evapotranspiration, mean annual air temperature, and April 1st snow-water equivalent.

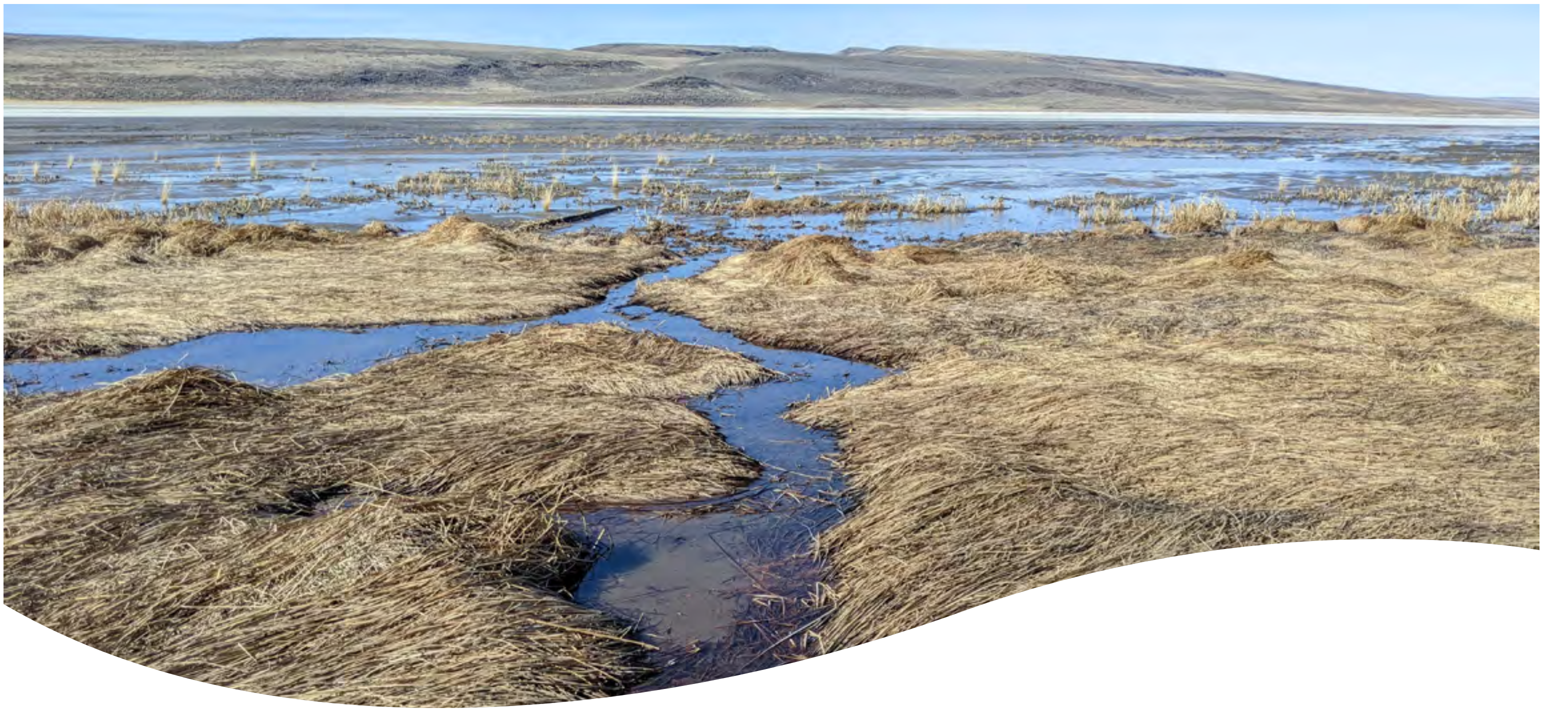
These threats were mapped across the state of Oregon to show their relative magnitude for any area of interest, but were not summarized to GDE occurrences because of the scarcity of GDE-specific data describing their hydrogeologic setting and ecological thresholds that may be crossed due to changing climate conditions. Given that lack of information, any assessment of threat to GDEs across the state in response to climate data would require arbitrary or subjective thresholds. Additionally, climate projections may change with improved models or changes to conditions the models are predicated upon.

2) Future projected streamflow

Mean annual and mean summer streamflow projections for the years 2070-2099 were computed for the high emissions scenario RCP 8.5 using daily modeled data from a Variable Infiltration Capacity model (USFS 2022). Streamflow projections are displayed as percent change relative to historical (1997-2006) conditions. The projections for groundwater-dependent rivers (any river or stream with at least one indicator of groundwater dependence) were assessed to forecast flow declines to groundwater-dependent rivers and streams.

3) Future projected stream temperature

Future projected August stream temperature for the years 2070-2099 were computed as the mean values of a ten-model global climate ensemble that represents the A1B emissions scenario, which approximates RCP 6.0 (Isaak et al. 2017). August stream temperatures were selected because they are representative of likely lowest-flow and warmest conditions, and therefore are ecologically important for the growth and survival of aquatic species. Projections are displayed as percent change relative to historical (1993-2011) August stream temperatures. The projections for groundwater-dependent rivers were assessed to forecast the threat of future warming.



Results

Groundwater-dependent ecosystems and species

Atlas Map

Groundwater-dependent ecosystems in Oregon are abundant and unevenly distributed across the state (Figure 1). Distinct regional patterns emerge in the confidence and abundance of GDEs. The most abundant and most likely GDEs are found in the central and eastern part of the state, especially at higher elevations like in the Cascade, Ochoco, Blue, and Wallowa mountains and in the more arid south-central Oregon. The large extent of phreatophytes tend not to co-occur with other GDE types in the relatively lower-elevation valley bottoms of south-central and southeast Oregon which leads to many analysis units with a high-confidence of GDEs, but low-abundance. Finally, parts of the state west of the Cascade Mountain Range have lower abundance and confidence of GDEs other than high-baseflow rivers and groundwater-dependent wetlands.

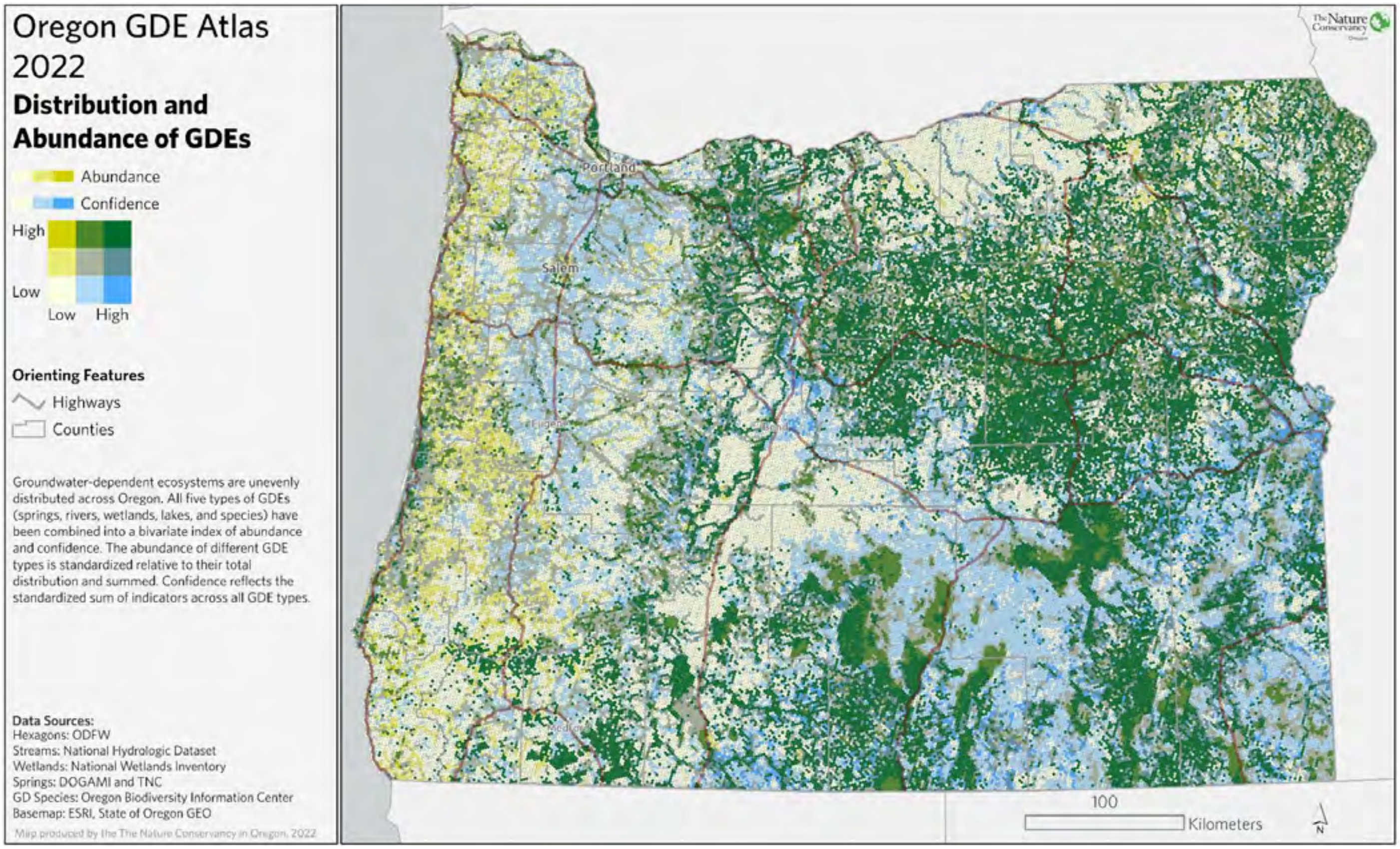


Figure 1: Atlas Map of Groundwater-Dependent Ecosystems of Oregon

Springs

A total of 29,379 springs were mapped throughout Oregon (Figure 2), including 140 springs classified by the Oregon Department of Geology and Mineral Industries as thermal, warm, or hot. Springs are most abundant at high absolute elevations (mean: 1,341 m MSL NAVD88; median: 1,379 m MSL NAVD88) and appear most dense in mountain ranges compared to valley bottoms. The ten densest clusters of springs (> 0.08 springs per ha in a given 640-acre hexagon; not shown on map) occur in southwest Oregon in the Rogue (4 spring clusters) and Klamath (2 spring clusters) basins; in southeast Oregon in the Closed Lakes (2 spring clusters) and Owyhee (1 spring cluster) basins; and in eastern Oregon in the Upper John Day basin (1 spring cluster).

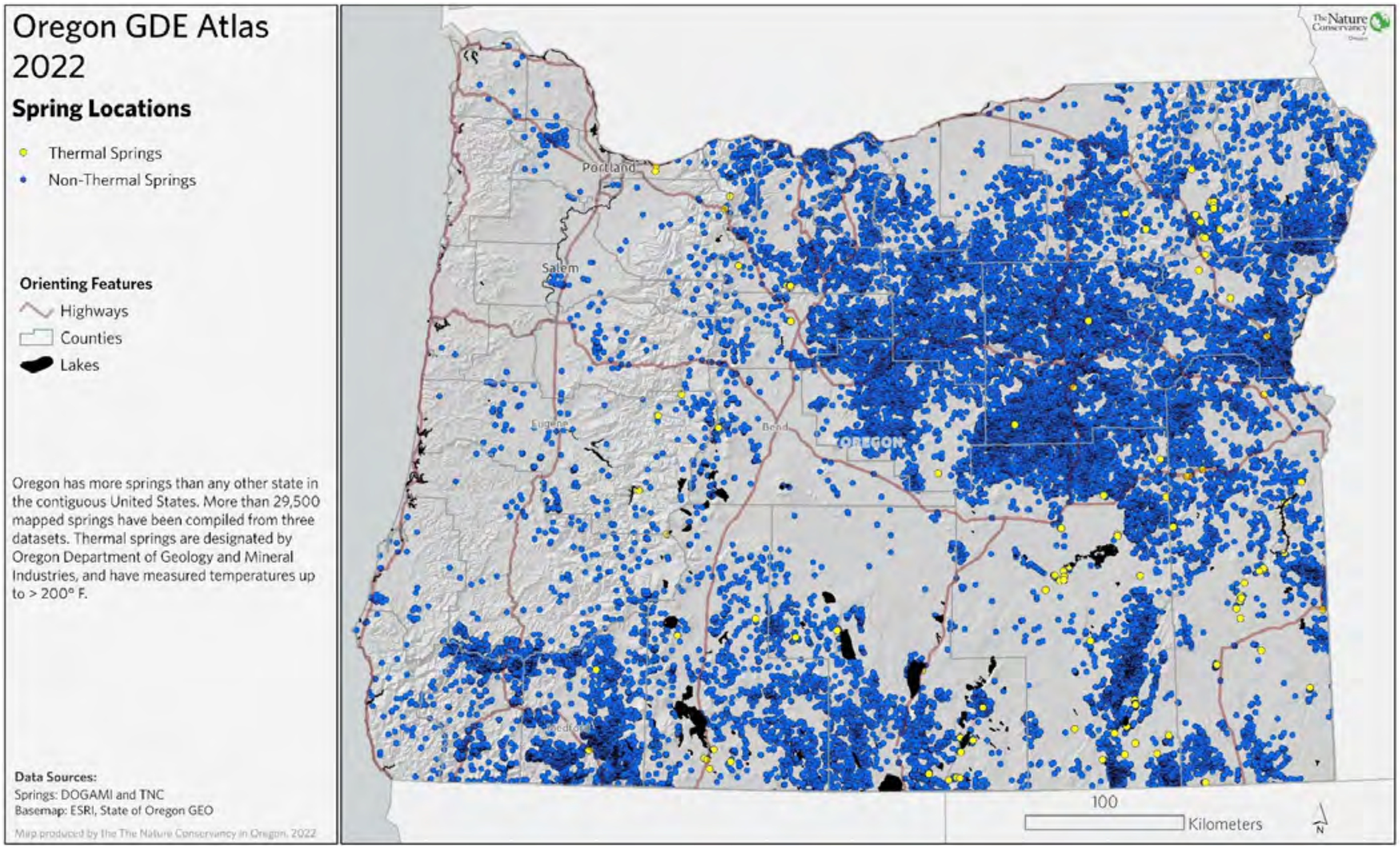


Figure 2: Springs of Oregon

Rivers

This analysis identified 59,349 km of groundwater-dependent rivers in Oregon (33.1% of the total 179,000 km of mapped rivers in the state) that met at least one indicator of groundwater dependence (Figure 3). Among groundwater-dependent rivers, more than 12,900 km (21.7%) met two indicators of groundwater dependence, and about 2,700 km (4.5%) met at least three indicators. Very few rivers (0.2%) met four indicators and none met all five. The most common indicator of groundwater dependence was perennially-flowing rivers and streams in the semi-arid regions east of the Cascade Mountain Range (Table 3).

Rivers that met four indicators are most common in the west side of the Deschutes Basin, and are scarce but present in the Lower John Day, Umatilla, and Upper Malheur basins. All major river basins with headwaters in the Cascade Mountain Range and all major river basins east of the Cascade Range have groundwater-dependent reaches. Coastal rivers met fewer indicators of groundwater dependence overall, but all coastal basins south of the Siletz River had some evidence of groundwater dependence. Maps of individual indicators of groundwater dependence for rivers can be found in Appendix A.

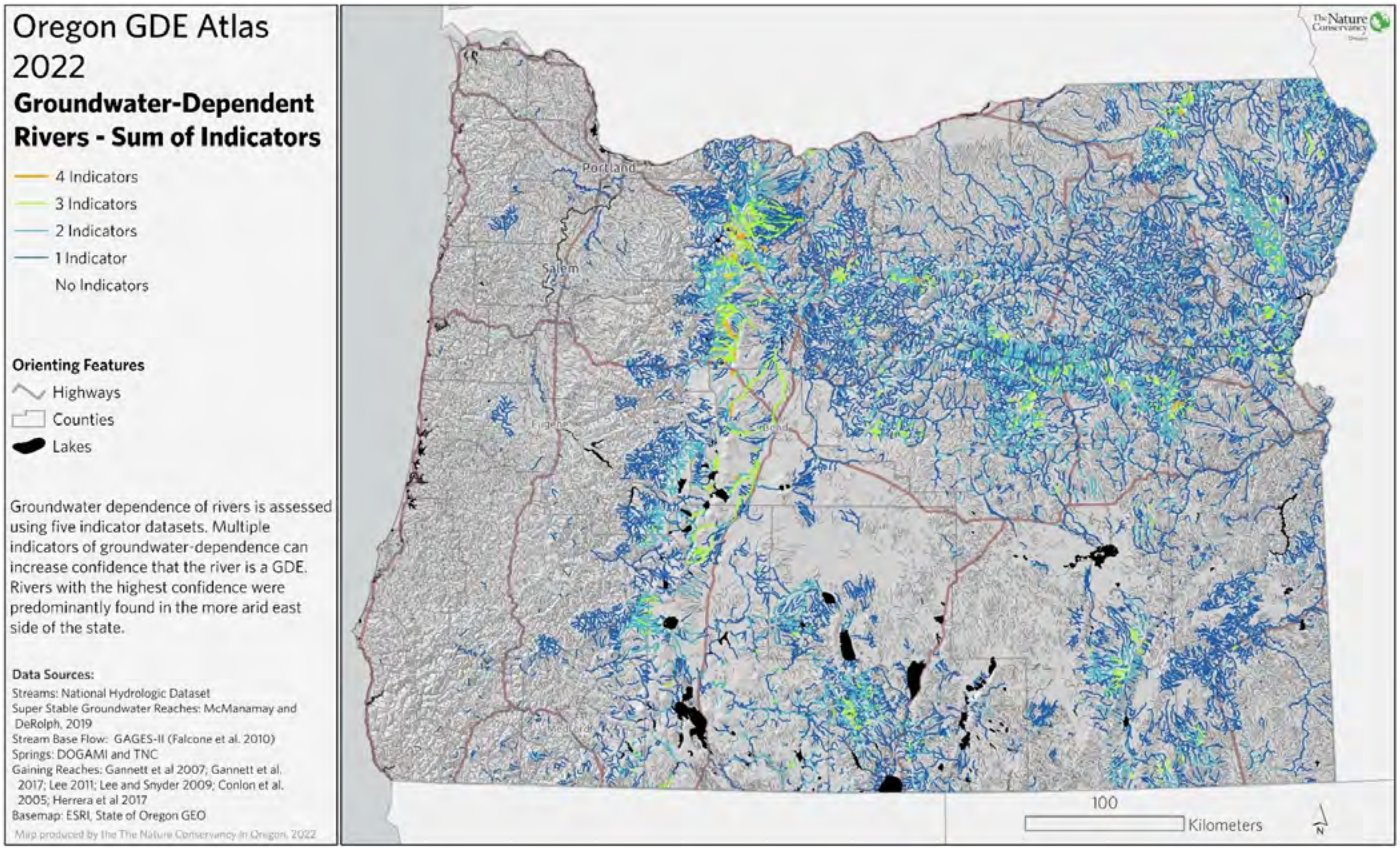


Figure 3: Groundwater-Dependent Rivers of Oregon

Table 3: Abundance and relative proportion of indicators of groundwater dependence for rivers in Oregon.

Indicator Type	Abundance (river length)	% of Groundwater-dependent Rivers
Perennial flow east of Cascades	35,344 km	59.6%
Hydrologic classification	22,762 km	38.4%
Baseflow separation	10,201 km	17.2%
Proximity to springs	7,513 km	12.7%
Gaining reaches	2,157 km	3.6%

This is a conservative estimate of groundwater-dependent rivers in Oregon. The reach-by-reach methodology to determine groundwater dependence ignores upstream groundwater inputs which may contribute a substantial source of groundwater. For example, an upstream reach that met four indicators of groundwater dependence will confer groundwater to the immediately-adjacent downstream reach; however, our analysis assesses each reach independently of upstream and downstream reaches. Additionally, some indicators for groundwater dependence are unsuited to major rivers west of the Cascades because they are often flow-regulated systems. For example, although the headwaters and many tributaries to the Willamette River are considered groundwater dependent, the mainstem Willamette only has a few reaches that this assessment would consider groundwater dependent.

Wetlands

There are 3,479 km^2 of groundwater-dependent wetlands in the state, which is about 45.4% of the 7,660 km^2 total wetlands mapped in Oregon (Figure 4). Among groundwater-dependent wetlands, 77% met one indicator of groundwater dependence, 12.6% met two indicators, 10.0% met three indicators, and 0.06% met four indicators. Groundwater-dependent wetlands are widely distributed across the state, including floodplain wetlands likely supported by hyporheic flow in the Willamette basin, interdunal wetlands along the coast, playas in the closed basins, and fens or spring-supported wetlands in many mountain ranges. Wetland type was used as both an eligibility criterion and an indicator of groundwater dependence. Therefore, 100% of groundwater-dependent wetlands meet that indicator (Table 4). Maps of individual indicators of groundwater dependence for wetlands can be found in Appendix A.

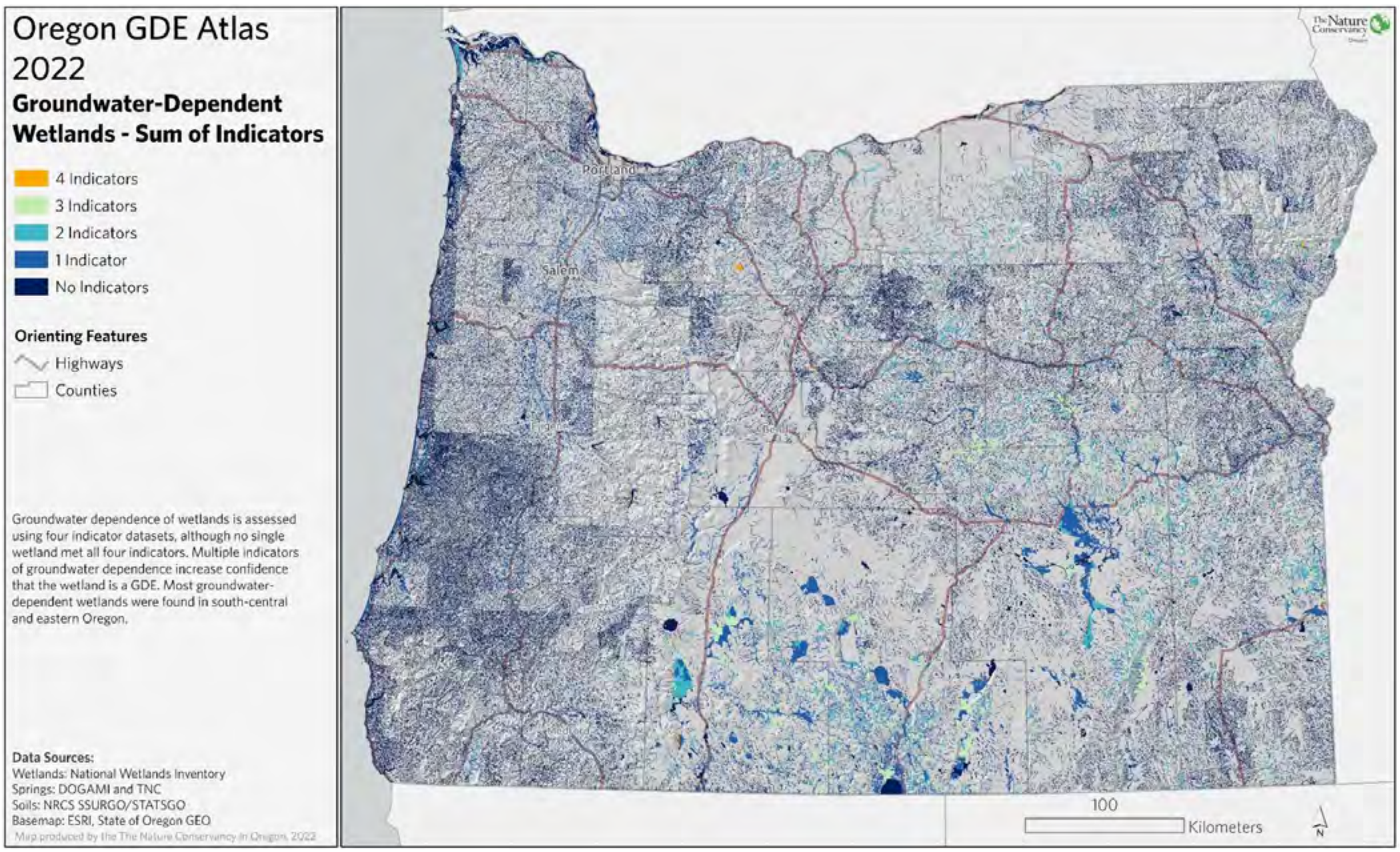


Figure 4: Groundwater-Dependent Wetlands of Oregon

Table 4: Abundance and relative proportion of indicators of groundwater dependence for wetlands in Oregon.

Indicator Type	Abundance (wetland area)	% of Groundwater-dependent Wetlands
Wetland type	3,479 km^2	100%
Proximity to springs	572 km^2	16.4%
Direct spring input	341 km^2	9.8%
Soil indicators	229 km^2	6.5%

Lakes

A total of 1,458 km^2 lake area in Oregon met at least one indicator of groundwater dependence, which is 62.9% of the 2,319 km^2 of total lake area in the state (Figure 5). Among groundwater-dependent lakes, 67.6% met one indicator, 3.6% met two indicators, and 28.7% met all three indicators. The unusual distribution of indicator counts by lake area is driven by the largest lakes in Oregon, which have a disproportionate impact on area-weighted percentages. These large lakes tend to either be located near abundant springs, in which case they meet both adjacent spring input and direct spring input indicators (e.g., Harney, Abert, and Alvord Lakes) or not meet either spring indicators (e.g., Malheur, Summer, or Crater Lakes). The spring indicators tend to co-occur: while 28.7% of groundwater-dependent lakes had both direct and adjacent spring inputs, only 0.2% of groundwater-dependent lakes had direct spring inputs without adjacent and 3.1% of groundwater-dependent lakes had adjacent spring inputs without direct. Following Brown et al. (2009), all naturally-occurring lakes are assumed to be groundwater dependent, so 100% of groundwater-dependent lakes meet that indicator (Table 5). Maps of individual indicators of groundwater dependence for lakes can be found in Appendix A.

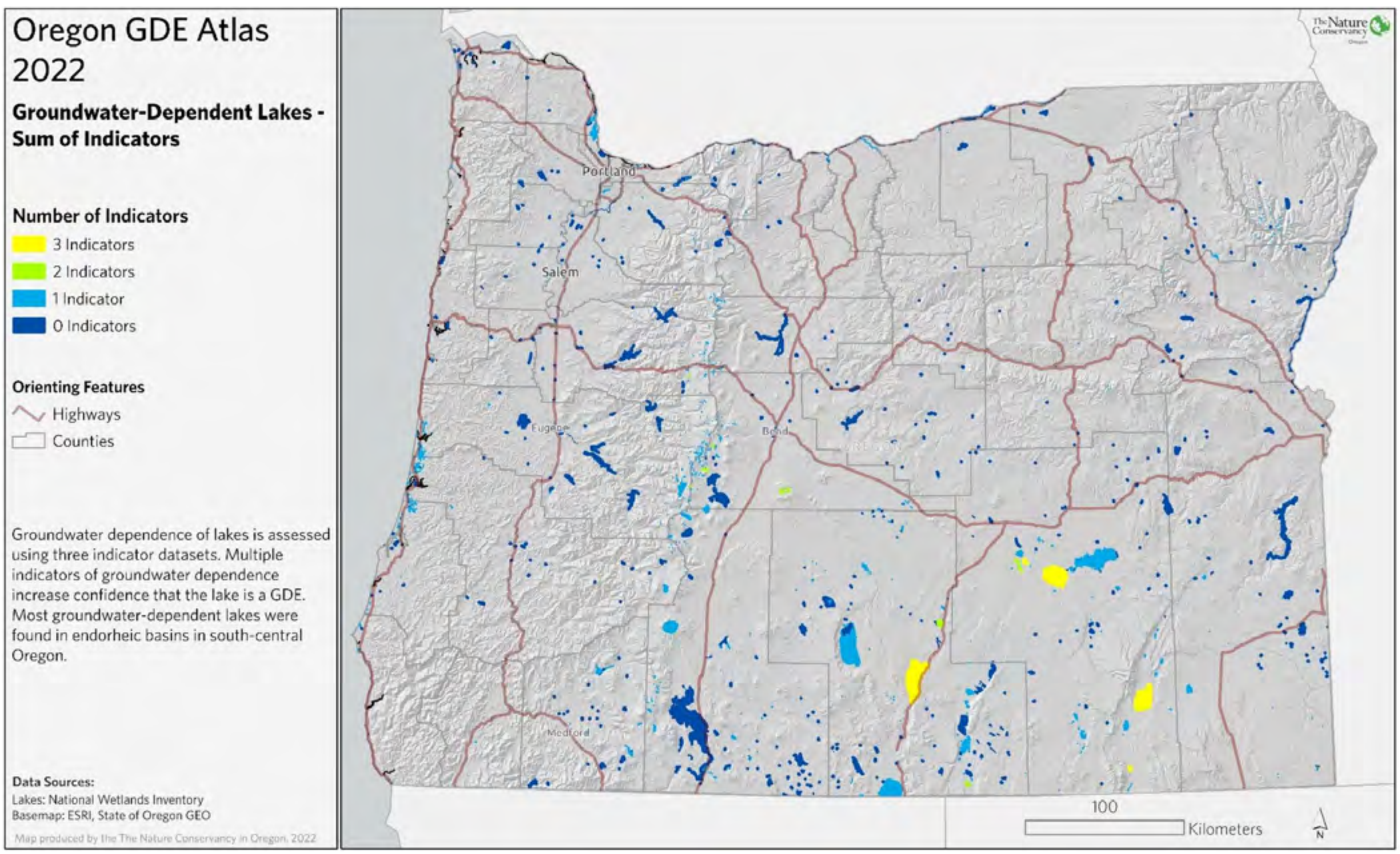


Figure 5: Groundwater-Dependent Lakes of Oregon

Table 5: Abundance and relative proportion of indicators of groundwater dependence for lakes in Oregon.

Indicator Type	Abundance (lake area)	% of Groundwater-dependent Lakes
Natural occurrence	1,458 km^2	100%
Proximity to springs	472 km^2	32.4%
Direct spring input	453 km^2	31.1%

Species

This analysis divides groundwater-dependent species into two groups: phreatophytes and all other species (Figure 6). A total of 6,821 km^2 of phreatophytes were mapped in Oregon (Garcia et al. 2021). The majority of phreatophyte area (81.8%) is associated with greasewood, while 12.0% is desert saltgrass communities, and the remaining 6.2% contains other phreatophyte communities without either greasewood or desert saltgrass. The substantial majority of xeric phreatophytes were mapped in the most arid parts of the state, primarily in the southeast quarter of Oregon.

In addition to phreatophyte communities, there were 31 other groundwater-dependent species observed a combined total of 3,994 times throughout Oregon, including four species that had multiple populations or runs (Chinook salmon, Coho salmon, Bull trout, and Steelhead). The three species with the most observations in the state were Coho salmon (1193 observations across two populations), marbled murrelet (779 observations), and Steelhead (571 observations across six populations). Western snowy plover, despite only having 40 observations, has the largest areal distribution of any non-phreatophytic groundwater-dependent species and is found throughout the coast and in lakes or playas in southern and eastern Oregon.

The mapping of non-phreatophytic groundwater-dependent species is limited by a lack of understanding of groundwater dependence at different life stages and scarce data regarding obligate and facultative groundwater-dependent species. Because these data rely on recorded observations, they are a substantial underestimation of actual groundwater-dependent species abundance and are biased towards charismatic species like Coho salmon or marbled murrelet populations. Despite this, the data compiled for this study represent the most modern dataset of groundwater-dependent species in Oregon.

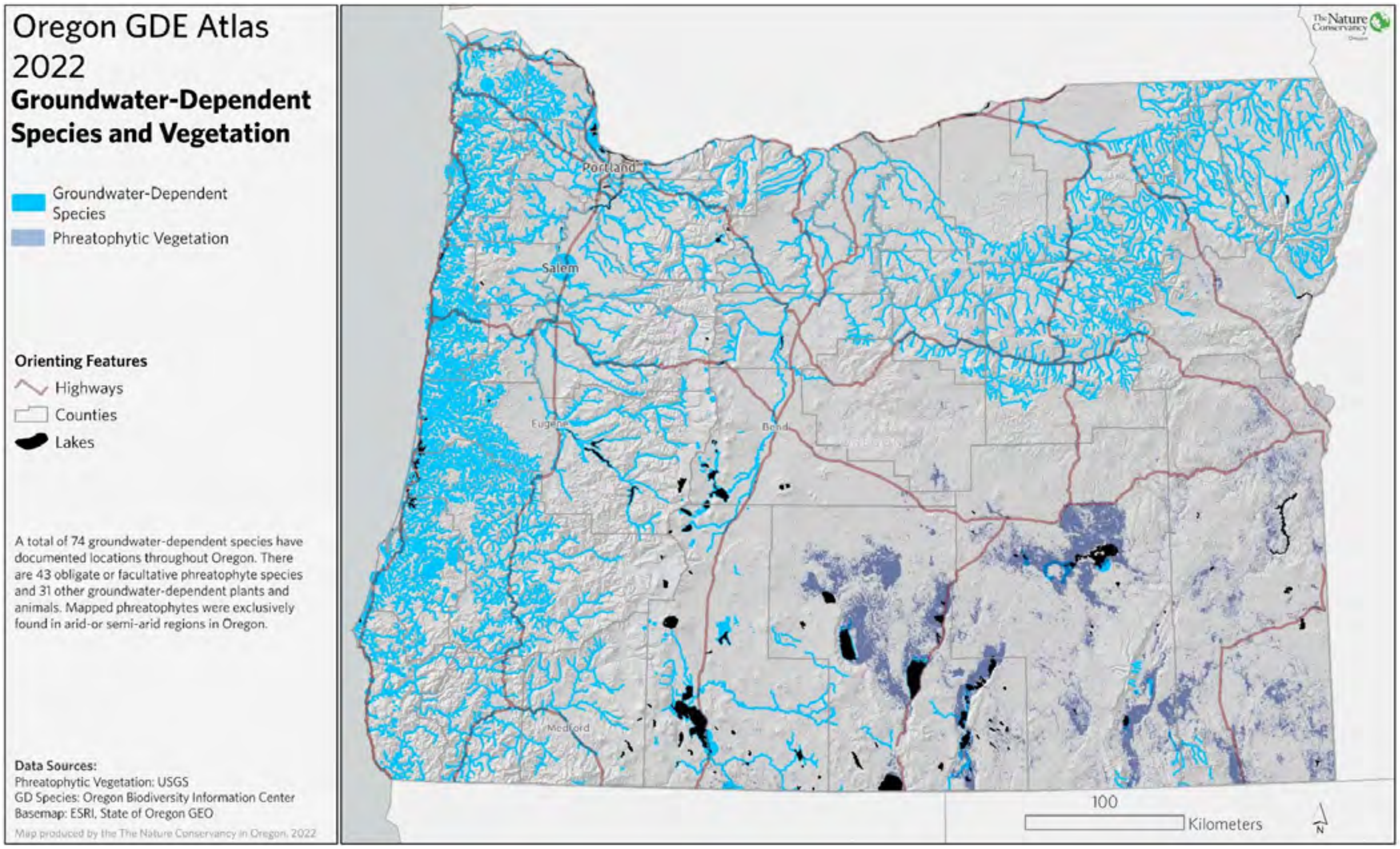


Figure 6: Groundwater-Dependent Species of Oregon

Stressors and threats to groundwater-dependent ecosystems and species

Stressors

Five stressors were assessed across Oregon across three categories: groundwater withdrawal, ungulate disturbance, and invasive species impacts. The five stressors included declining groundwater levels, concentration of permitted groundwater use, presence of Groundwater Administrative Areas, active grazing allotments, and observations of invasive species. All GDE types were at risk of each of the five stressors. Some ecosystems of each GDE type except springs were exposed to all five stressors simultaneously, while springs were exposed to a maximum of four concurrent stressors (Table 6). Other than non-phreatophytic groundwater-dependent species, the majority of all ecosystem types were exposed to at least one stressor (springs = 62.7%; rivers = 68.9%; wetlands = 77.7%; lakes = 92.3%; phreatophytes = 95.4%; other groundwater-dependent species = 46.3%). Only one groundwater-dependent species, the Hutton tui chub, was not found to be at risk of any stressors across all observations. Maps of all individual stressors can be found in Appendix B.

Table 6: Summary of GDE types potentially affected by number of stressors. The percent of GDEs at risk of stressors is listed as a proportion of all GDEs within that type. Units are count (number of springs), km (length of groundwater-dependent rivers), km^2 (area of groundwater-dependent wetlands, groundwater-dependent lakes, and phreatophytes) and observations (other groundwater-dependent species).

Number of Stressors	Springs (% count)	Rivers (% length)	Wetlands (% area)	Lakes (% area)	Groundwater-dependent Species	
					Phreatophtyes (% area)	Other Species (% observations)
0	37.3%	31.1%	22.3%	7.7%	4.6%	53.7%
1	56.5%	53.7%	45.9%	31.5%	50.6%	35.7%
2	5.4%	12.7%	20.7%	56.0%	27.5%	8.7%
3	0.8%	2.1%	5.8%	4.2%	11.2%	1.8%
4	0.03%	0.3%	1.5%	0.0%	4.9%	0.1%
5	0.0%	0.004%	3.7%	0.6%	1.3%	0.01%

Groundwater withdrawals

1) Groundwater level declines

Groundwater level trends were calculated for the last five and/or thirty years among 1,458 total wells, depending on the period of record of available data and data quality. Five-year trends were interpreted as recent or modern groundwater level trends, while thirty-year trends reflect long-term rates of change.

Of the total 1,167 wells analyzed for five-year groundwater level trends, water levels were declining in 43% of wells, increasing in 22% of wells, and the remaining 35% of wells did not have a statistical likelihood of increasing or decreasing. A total of 291 wells were analyzed for thirty-year groundwater level trends, among which 71% were declining, 23% were increasing, and 5% did not show a statistically significant trend. Shallow wells (< 200 ft deep) were less likely to have a declining trend in both the five- and thirty-year periods, and more likely to not have a trend, compared to deep wells (≥ 200 ft). The greatest Sen slope rate of decline in a five-year period was 22.25 feet per year in a deep well. The greatest Sen slope rate of decline in a thirty-year period was 6.1 feet per year in a deep well.

All GDE types were found near declining well trends based on combined five- and thirty-year period trends (Table 7). However, the sparse distribution of monitoring wells across the state led to substantial data gaps for all GDE types: only between 0.2% and 12.1% of any GDE type were within 1 km of qualifying monitoring wells. Although a 1 km radius is a conservative indicator of surrounding groundwater level trends, this analysis nevertheless reveals the scarcity of reliable monitoring wells compared to the distribution of GDEs.

Table 7: Summary of GDEs likely affected by declining five- and thirty-year well trends. Abundance is measured in the native units for each GDE type, which are number of springs, km of groundwater-dependent rivers, km^2 of groundwater-dependent lakes, groundwater-dependent wetlands, and phreatophytes; and number of observations of other groundwater-dependent species. GDEs within 1km of a monitoring well describes the amount of GDEs among each type included in the analysis and the percentage of all GDEs of that type across the state. GDEs within 1 km of a declining well trend describes the amount of GDEs potentially impacted by declining aquifer levels and the percentage of all GDEs of that type included in the analysis. For example, there are 120 springs within 1 km of monitoring wells with a 5-year trend, which is 0.4% of the total 29,379 springs in the state. Of the 120 springs that are within 1 km of monitoring wells with a 5-year trend, 65 springs (54.0% of 120 qualifying springs) are associated with a well with a significantly declining trend.

Period of Record	GDE Type	GDEs within 1 km of monitoring well Abundance (% of all GDEs of that type statewide)	GDEs within 1 km of declining well trend Abundance (% of GDEs of that type within 1 km of well with declining trend as proportion of all GDEs of that type within 1 km of well)
5 year	Springs	120 springs (0.4%)	65 springs (54.0%)
	Rivers	1,357 river km (2.3%)	536 river km (39.5%)
	Wetlands	423 km^2 (12.2%)	241 km^2 (57.0%)
	Lakes	17.0 km^2 (1.2%)	14.7 km^2 (86.6%)
	Phreatophytes	522 km^2 (7.7%)	457 km^2 (87.6%)
	Other Species	116 observations (2.9%)	58 observations (49.8%)
30 year	Springs	48 springs (0.2%)	34 springs (70.8%)
	Rivers	489 river km (0.8%)	317 river km (64.9%)
	Wetlands	221 km^2 (6.4%)	181 km^2 (81.9%)
	Lakes	9.4 km^2 (0.6%)	9.4 km^2 (100%)
	Phreatophytes	477 km^2 (7.0%)	386 km^2 (81.0%)
	Other Species	20 observations (0.5%)	8 observations (39.3%)

2) Concentrations of permitted groundwater use

In addition to monitoring well trends, spatial concentrations of groundwater rights are an indicator of potential stress to GDEs. There were 36,927 non-cancelled groundwater rights included in this analysis which were split into six use classifications: agricultural, municipal, commercial, domestic, wildlife, and all other uses. The total cumulative statewide permitted rate across all use classifications was 61,701 CFS. Agricultural groundwater rights represented the majority of both total number of rights and total rate of groundwater use (Table 8). The Township (36 mile2 land division) with the highest rate of groundwater use included groundwater rights for 2,398 CFS in the Willamette Basin. The median rate of groundwater use among all Townships with at least one groundwater right was 6.44 CFS.

Table 8: Distribution of non-cancelled groundwater rights and cumulative sum of their rates by water use classification in Oregon.

Water Use Classification	# of Groundwater Rights	% of Groundwater Rights	Cumulative Sum of Rate (CFS)	% of Total Rate (CFS)
Agriculture	30,043	81.4%	38,820 CFS	62.9%
Municipal	2,600	7.0%	8,271 CFS	13.4%
Commercial	1,716	4.6%	4,998 CFS	8.1%
Domestic	888	2.4%	333 CFS	0.5%
Wildlife	282	0.8%	960 CFS	1.6%
Other	1,398	3.8%	8,320 CFS	13.5%
Total	36,927		61,701 CFS	

GDEs that fell within Townships with permitted groundwater rates exceeding the median were considered potentially stressed. All GDE types had some co-occurrence with high concentrations of permitted groundwater use. A total of 2,842 springs (9.7% of all springs) were at risk of concentrations of permitted groundwater use. There were 10,730 km of groundwater-dependent rivers (18.0% of all groundwater-dependent rivers) exposed to concentrations of groundwater use, along with 1,678 km^2 groundwater-dependent wetlands (48.2% of all groundwater-dependent wetlands), and 931 km^2 groundwater-dependent lakes (63.9% of all groundwater-dependent lakes). About 2,977 km^2 of phreatophytes (43.6% of all phreatophytes) and 867 observations of other groundwater-dependent species (21.7% of all observations) were also potentially stressed by permitted groundwater use.

3) Presence of Groundwater Administrative Areas

There are 28 groundwater administrative areas in Oregon split amongst five designations: 12 "Limited" areas, 7 "Critical" areas, 6 "Classified" areas, 2 "Withdrawn" areas, and one "Mitigation" area. The two largest groundwater restricted areas are the Upper Deschutes Groundwater Mitigation Area in central Oregon and the Greater Harney Valley Classified groundwater area in southeast Oregon. In part due to the size of those two areas, the "Classified" designation contributes the greatest amount of groundwater restricted area across the state (47.4%) and the "Mitigation" designation takes up the second largest area (40.2%). The presence of a groundwater restricted area is an indicator of a legacy of stressors, but does not necessarily mean present stress. Some groundwater restricted areas have achieved stability in groundwater level trends, but many continue to have ongoing groundwater level declines (OWRD 2021).

All GDE types were found within groundwater restricted areas across Oregon (Table 9). Among groundwater-dependent species, the most-affected species were Oregon spotted frog (34% of all Oregon spotted frog observations), bull trout (26% of all bull trout observations), Howellia (20% of all Howellia observations), and western snowy plover (18% of all western snowy plover observations).

Table 9: GDEs within Groundwater Administrative Areas.

GDE Type	GDEs Found Within Groundwater Administrative Areas	% of GDEs per Type Found Within Groundwater Administrative Areas
Springs	1,245	4.2%
Groundwater-dependent Rivers	6,062 river km	10.2%
Groundwater-dependent Wetlands	804 km^2	23.1%
Groundwater-dependent Lakes	409 km^2	28.1%
Phreatophytes	2,254 km^2	33.0%
Other GD-Species	160 observations	4.0%

Invasive species

Statewide there are 10,720 confirmed observations of 114 invasive exotic species recorded in the iMap Invasives and USGS NAS databases since the year 2000. Most records of invasive species are fish, mammals, mollusks, and amphibians. The majority of observations of aquatic invasive species in Oregon are found along the coast, in the Columbia River, and in the Willamette Valley, which may be due to a biased distribution of surveys for invasives. All GDE types co-occurred with invasive species, but especially groundwater-dependent lakes and non-phreatophytic groundwater-dependent species (Table 11). Springs were only rarely mapped near invasive species, which may be a result of the scarce spring survey data in Oregon or an under-representation of springs surveyed for invasive species. Almost all groundwater-dependent species had some exposure to invasive species, but it was generally a low percent of total observations. Only the Hutton tui chub, Lahontan cutthroat trout, Borax Lake chub, and Foskett Spring speckled dace did not co-occur with this stressor. This may be due to survey bias if information on invasive species was collected concurrently with observations of native groundwater-dependent species in a given survey.

Table 10: Number and proportion of GDEs potentially affected by invasive species.

GDE Type	# of GDEs with observed invasive species	% of GDEs with observed invasive species
Springs	278	0.9%
Groundwater-dependent Rivers	3,013 river km	5.0%
Groundwater-dependent Wetlands	299 km^2	8.6%
Groundwater-dependent Lakes	251 km^2	17.2%
Phreatophytes	105 km^2	1.5%
Other GD-Species	715 observations	17.9%

Ungulates

Active grazing allotments on public land are widespread across Oregon, encompassing a massive 196,009 km^2. About 28.1% of the active allotments are managed by the U.S. Forest Service and the remaining 71.9% are managed by the U.S. Bureau of Land Management. The presence of an active grazing allotment does not innately indicate damage to GDEs from ungulates, and the absence of an allotment does not preclude damage to GDEs from ungulates. However, surveys in Oregon (e.g., Freed et al. 2019) and Nevada (e.g., Sada and Lutz 2016) indicate a high prevalence of ungulate impacts to GDEs in grazing allotments. Many GDEs among all types were found within active grazing allotments (Table 10). The majority of all phreatophytes, springs, and groundwater-dependent rivers are found within allotments, suggesting that ungulates are among the most widespread stressors to GDEs in Oregon. Efforts from land managers to manage risk of ungulates on grazing allotments are likely to be especially impactful for GDEs but are not reflected in this analysis due to lack of data. Therefore, this is likely to be an overestimate of actual GDEs at risk of ungulate grazing and compaction. These results indicate the importance of responsible ungulate management in grazing allotments throughout Oregon. Among groundwater-dependent species, 89.5% of all Lahontan Cutthroat trout observations and 100% of all Fosket Spring speckled dace observations were within active grazing allotments.

Table 11: GDEs within active grazing allotments.

GDE Type	GDEs Found Active Grazing Allotments	% of GDEs per Type Found Within Active Grazing Allotments
Springs	16,046	54.6%
Groundwater-dependent Rivers	31,264 river km	52.4%
Groundwater-dependent Wetlands	1,293 km^2	37.2%
Groundwater-dependent Lakes	715 km^2	49.0%
Phreatophytes	5,119 km^2	75.1%
Other GD-Species	551 observations	13.8%

Threats

Eleven threats were assessed across Oregon among three categories: climate, groundwater withdrawals, and invasive species. Unlike the discrete spatial location of stressors, six of the eleven threats are distributed across the entire state: future projections of evapotranspiration, air temperature, precipitation, snow-water equivalent, irrigation demand, and irrigation reliance. Therefore, these six threats do not have GDE type-specific analyses because 100% of all GDE types are affected by them. Three of the remaining five threats are relevant only to groundwater-dependent rivers: future projected streamflow, future projected stream temperature, and absence of instream flow protections. The final two threats, invasive grasses and road density, do have GDE type-specific analyses. Maps of all individual threats can be found in Appendix B.

Groundwater withdrawals

1) Future projected irrigation demand

Irrigation demand represents the mean annual volume of water required to irrigate crops. Among both Central Tendency (CT) and Hotter/Drier (HD) scenarios, irrigation demand increases throughout most of the state by 2050 compared to 2015. The only exception is the coastal Lincoln County, where irrigation demand is expected to decrease by 3.6% in the CT scenario. The county with the greatest increase in the CT scenario is Clatsop County with a 26% increase on the north coast. This substantial percent increase translates to a small magnitude increase: Clatsop County has the second-lowest current irrigation demand of all counties in Oregon at 0.8 thousand acre-feet per year and is projected to increase to just over 1.0 thousand acre-feet per year in 2050 (OWRD 2015). The greatest magnitude increase in irrigation demand in the CT scenario is in Lake County with a projected 68.6 thousand acre-feet per year increase in addition to its current 418.0 thousand acre-feet per year demand. More than 40% of counties in Oregon will experience increased irrigation demand of greater than 10% in the CT scenario, mostly in the Willamette Valley and south-central Oregon. All counties in Oregon will experience at least 5.6% increased irrigation demand under the HD scenario. Counties in the northwest, south-central, and northeast parts of the state will experience the greatest increases to demand, ranging from 20 – 49% by the year 2050 in the HD scenario. GDEs tend to have higher abundance and confidence in the northeast and south-central parts of the state, indicating that these are potential focal areas for management actions intended to conserve GDEs in the face of increasing irrigation demand.

2) Future projected irrigation reliance

Irrigation reliance is the amount of crop water demand met by irrigation as opposed to precipitation or runoff. Trends in future projected irrigation reliance are uneven throughout the state, with some counties experiencing little or no changes and other counties expected to increase substantially. Under the CT scenario, there is effectively no projected change to irrigation reliance in mid-coast counties, north-central Oregon, and Harney County in southeast Oregon. However, the Willamette Valley, Klamath County in south-central Oregon, Wallowa County in northeast Oregon, and the northwest coast are expected to increase irrigation reliance by up to 5% under the CT scenario. Irrigation reliance in 2050 under the HD scenario project increases throughout the state with the exception of southeast Oregon. Similar to the CT scenario, the Willamette Valley, Klamath County, and northeast Oregon are expected to have the most substantial increases of 4%–9%.

3) Lack of in-stream flow protections

Only 2,118 river km of groundwater-dependent rivers and streams (3.6% of the length of all groundwater-dependent rivers) have an instream water right protecting ecologically-important flows. Instream rights are an important tool that allow water managers to conserve flow within streams and rivers. However, these protections are affected by priority date, so instream rights only reduce the ecological impact of water uses junior to the instream right. The vast majority of instream rights in Oregon have a priority date between 1989 and 1993 (median = 1990) which corresponds with the passage of Oregon's Instream Water Rights Act of 1987. The most senior priority date protecting a groundwater-dependent river reach is 1959. Despite their innate climate resilience, the lack of instream rights in 96.4% of groundwater-dependent streams and rivers highlights human water demand as a key vulnerability and threat for these GDEs.

Invasive species

Invasive Annual Grasses:

Invasive annual grasses were assessed east of the Cascade mountain range, where their presence is most problematic in altering the historical fire regime. The highest concentrations were found in arid or semi-arid valley bottom habitats throughout north-central and southeast Oregon. Springs, groundwater-dependent rivers, and phreatophytes have abundant invasive annual grass threats, while groundwater-dependent wetlands, lakes, and non-phreatophyte species are overall less at risk of impact (Table 12).

Table 12: GDEs potentially impacted by invasive annual grasses.

GDE Type	# of GDEs associated with >15% invasive annual grass cover	% of GDEs associated with >15% invasive annual grass cover
Springs	6,772	23.0%
Groundwater-dependent Rivers	35,401 river km	19.8%
Groundwater-dependent Wetlands	101 km^2	1.3%
Groundwater-dependent Lakes	20 km^2	1.3%
Phreatophytes	1,412 km^2	20.7%
Other GD-Species	12 observations	0.3%

Among the eight phreatophyte community types that were exposed to mean annual grass cover exceeding 15%, five of them were greasewood *(Sarcobatus* spp.*)* communities, two were desert saltgrass *(Distichlis* spp.*)* communities, and the remaining was a wildrye community. The only non-phreatophyte groundwater-dependent species that was observed in habitats with mean annual grass cover exceeding 15% was Lahontan cutthroat trout *(Oncorhynchus clarkii henshawi)*. All observations of Lahontan cutthroat trout co-occurred with invasive annual grasses. Several other groundwater-dependent species did not co-occur with invasive annual grasses due to their location on the west side of the Cascade mountains, such as Oregon silverspot *(Speyeria zerene hippolyta)*, Howellia *(Howellia aquatilis)*, and western lily *(Lilium occidentale)*.

Road Density:

The distribution of roads across Oregon is extremely uneven. The greatest road density is in the urban centers of the Willamette Basin and the Oregon coast along the major interstate routes. Roads in the remainder of the state are scarce, although an abundance of dirt access roads managed by public land management agencies increase road density in south-central and northeast Oregon.

Mean and median road density is low across all GDE types (Table 13), indicating that the threat is highly localized and not broadly distributed across the state. The only groundwater-dependent species strongly at risk of impact due to road density was water Howellia (*Howellia aquatilis*) which had observations in areas with a mean road density of 5.2 km/km^2.

Table 13: Mean and median road density for each GDE Type.

GDE Type	Mean road density (km/km²)	Median road density (km/km²)
Springs	1.1	0.9
Groundwater-dependent Rivers	1.4	1.1
Groundwater-dependent Wetlands	1.7	1.3
Groundwater-dependent Lakes	0.8	0.2
Phreatophytes	1.2	0.9
Other GD-Species	1.9	1.5

Climate

Despite spatial variability in future projected climate anomalies and the uneven distribution of GDEs across Oregon, statistical analysis did not reveal any significant relations between climate variables and GDE types. Therefore, no single GDE type was disproportionately affected by climate threats compared to other GDE types.

1) Future projected precipitation

The amount, timing, and type of precipitation all affect recharge and ecological importance of GDEs. The discharge of GDEs themselves relies on aquifer recharge from rain and snow. As precipitation type shifts from snow to rain, the relative proportion of runoff to recharge will increase. As timing of precipitation events becomes more seasonal and drought becomes more frequent, GDEs will become more important to maintaining hydrologic function during the dry seasons and could serve as hydrologic refugia during drought. Understanding total annual precipitation anomaly is one component of understanding overall projected changes to hydrology.

Total annual precipitation in the years 2070–2099 is projected to either stay the same or increase compared to historical mean annual precipitation from 1971–2000. The spatial trends are consistent between emissions scenarios: in both RCP 4.5 and RCP 8.5, the smallest projected change occurs in southwestern Oregon while the greatest projected increase is in southeastern Oregon. In RCP 4.5, there is effectively no projected change in total annual precipitation in southwestern Oregon and up to a 7.9% increase in southeastern Oregon. Under RCP 8.5, southwestern Oregon may have between 2.4–3.9% increased annual precipitation while southeastern Oregon will experience up to 15% increases.

2) Future projected actual evapotranspiration

Actual evapotranspiration has both direct and indirect impacts to GDEs. Water demand from evapotranspiration affects water availability and community composition for all GDE types, but especially lakes, wetlands, and phreatophytes. Increased water demand can decrease or alter the timing of inundation hydroperiods, change perennially-inundated ecosystems to intermittent or ephemeral, or alter the habitat type entirely from open water to a soil moisture zone to dry. Phreatophytes in particular are at risk despite their deep rooting depths if water demand begins to exceed available recharge. Declining water table depths may lead to changes in community composition as relatively shallow-rooted phreatophytes are competitively excluded by deeper-rooted phreatophytes. Indirectly, increased evapotranspiration will also result in increased human water demand, exacerbating other threats to GDEs.

Actual evapotranspiration in the years 2070–2099 is projected to increase throughout the state relative to historical mean evapotranspiration from 1971–2000. Under the intermediate-emissions scenario RCP 4.5, annual actual evapotranspiration is expected to increase at least 2% throughout the state. The greatest increases (up to 18.9%) will occur in the Cascades Range, the Coast Range, and northeastern Oregon. These spatial trends are generally the same as projections under the high-emissions scenario RCP 8.5 with the addition of southeastern Oregon as another area of substantial increases to actual evapotranspiration. The magnitudes of projected increases are higher in the RCP 8.5 scenario: all parts of Oregon are projected to increase actual evapotranspiration by at least 3%, and the greatest increases are up to 24.5%.

3) Future projected air temperature

Air temperature affects water temperature in GDEs and is a key determinant of actual evapotranspiration. Although groundwater inputs to springs, rivers, wetlands, and lakes will likely buffer the impacts of air temperature changes on water temperature, projected alteration of air temperature still affects the thermal diversity of GDEs. Warming air temperatures will likely have the greatest effect on lentic GDEs with significant surface area exposed to air, such as lakes, some wetlands, and some spring types like limnocrene springs. Projected air temperature increases will emphasize the importance of protecting and conserving sources of climate-buffered, consistent water temperatures as cold water refugia.

Annual air temperature in the years 2070–2099 is projected to increase throughout the state relative to historical mean annual air temperatures from 1971–2000. In both RCP 4.5 and RCP 8.5, projected future air temperature anomaly manifests a clear east-to-west gradient with the greatest increases in eastern Oregon adjacent to Idaho and the smallest increases along the Oregon coast. Projected temperature increases range from 4% to 5.7% under RCP 4.5 and 8% to 11.4% under RCP 8.5.

4) Future projected snow-water equivalent

The slow melt of snowpack is among the most impactful contributors to aquifer recharge and supports late-season streamflow in headwater streams. Changes to snowpack will affect the amount of recharge that benefits GDEs, but will also emphasize the ecological importance of GDEs for late-season streamflow and perennially available water. Snow water equivalent (SWE) is the amount of water found within snowpack. Decreases to SWE will likely affect the resilience and ecosystem services provided by GDEs dependent upon it, especially those with short or shallow flow systems.

Total April 1st SWE is expected to dramatically decrease throughout the state under both emissions scenarios by the 2070–2099 period relative to historical means. Under the RCP 4.5 scenario, all watersheds throughout the state have at least a 66% decrease in April 1st SWE and up to a 100% decrease in April 1st SWE, which indicates the total elimination of late-spring snowpack. The areas with the greatest SWE declines include the Coast Range, eastern Oregon, and the John Day and Crooked basins of north-central Oregon. Under the RCP 8.5 scenario, more than 60% of all watersheds in Oregon will experience > 95% decreases in April 1st SWE. The only watersheds with less than 90% decreases in April 1st SWE are the furthest southeastern watersheds and a few watersheds in northeastern Oregon.

5) Future projected streamflow

The vast majority (99.6%) of all groundwater-dependent streams and rivers are projected to decrease in summer flow by the year 2080 by a maximum of 96.7% of historical mean summer flow. The greatest decreases occur in the headwater streams of Oregon's mountain ranges, such as the Cascades, Wallowas, and Steens range. The 0.4% of groundwater-dependent streams with increasing projected summer flows are tributaries of the South Fork Crooked River in central Oregon and some small streams in southeastern Oregon north of the Alvord Desert. The persistence and presence of summer flow is especially important to aquatic ecosystems in Oregon due to the state's seasonal precipitation patterns. Decreased projected summer flow is a threat to the ecosystem function of groundwater-dependent streams, but it should primarily be interpreted as decreases to the runoff and surface water component of the hydrographs. The flow projections rely on the Variable Infiltration Capacity (VIC) model, a land surface hydrologic model that does not incorporate an explicit groundwater component. VIC is also intended for use at a regional scale, whereas the indicators of groundwater dependence in this study were assessed at a reach scale. It is likely that the groundwater portion of the hydrographs of these streams and rivers will experience relatively less impact than projected. Despite this, the modeled flow projections provide valuable information about where the groundwater component of a river's hydrograph will become disproportionately important during low flows in future climate projections.

Mean annual flow projections for the year 2080 indicate that the flow of about two-thirds (65.7%) of groundwater-dependent streams and rivers will increase by up to 32% of historical flow. The mean annual flow of the remaining 34.3% of groundwater-dependent streams and rivers are projected to decrease by up to 33% of historical flow. Projected annual flow increases are generally in northern Oregon and eastern Oregon, especially including the Silvies, Umatilla, and Grande Ronde basins.

Projected annual flow decreases occur in central and southern Oregon, with the greatest decreases in the Deschutes, John Day, and Klamath basins and the closed basins of Lake County. The majority trend of increasing annual flows combined with the near-ubiquitous trend of decreasing summer flows by the year 2080 indicates a shift in precipitation type and timing, with increased rainfall and decreased snowfall during winter months and decreased precipitation overall in summer months.

6) Future projected stream temperature

Stream temperature in August is an important indicator of habitat quality for cold water fishes and other temperature-sensitive species. Stream temperatures tend to be highest in late summer months in Oregon, so August stream temperatures may be limiting factors of ecosystem viability for perennial and anadromous fish that inhabit the streams in the summer. Mean August stream temperature is expected to increase throughout the state by the year 2080. The vast majority of temperature projections for groundwater-dependent streams and rivers are between 10% and 20% increased August temperatures. However, some outlier streams (0.03% of total groundwater-dependent river kilometers) have mean August temperature projections for 50% to 125%. Similarly, some outlier groundwater-dependent streams (0.26% of total groundwater-dependent river kilometers) had effectively no projected change.

Mean August stream temperature increases were greatest in headwater streams of the Cascades, Wallowas, Blues, Ochocos and Steens mountains. The smallest mean August temperature increases are in valley-bottom streams, especially in southeast Oregon within Harney, Lake, and Klamath counties. The spatial pattern of projected stream temperature increases may be partially explained because headwater streams have cooler historic means than valley-bottom streams in southeast Oregon, so similar absolute magnitude increases in temperature will manifest as greater percent differences in headwater streams than valley-bottom streams. The projected temperature increases were greater in streams and rivers with more indicators of groundwater dependence, ranging from a mean temperature increase of 15% in streams with only one indicator of groundwater dependence to a mean temperature increase of 22% in streams with four indicators of groundwater dependence.

Conclusions

Groundwater-dependent ecosystems are abundant throughout Oregon. More than 33% of all mapped rivers in the state met indicators for groundwater dependence, along with 45% of all wetlands and 63% of all lakes and reservoirs. Over 29,000 springs are distributed across the state along with nearly 7,000 km^2 phreatophytic plant communities. These GDEs will contribute to landscape-scale resilience for Oregon's fish and wildlife in a changing climate. However, groundwater must be managed appropriately to protect these biodiverse and climate-resilient habitats.

The majority of all GDEs among each GDE type are at risk of the five stressors related to groundwater withdrawals, ungulates, and invasive species. Groundwater withdrawals were particularly important for groundwater-dependent wetlands, lakes, and phreatophytes, all of which are predominantly found at relatively lower-elevation positions within a watershed alongside the majority of water use. Ungulates were the most ubiquitous stressor affecting springs and groundwater-dependent rivers, emphasizing the importance of good rangeland management practices for those GDE types. The potential impact of invasive species was most apparent in groundwater-dependent lakes and non-phreatophyte groundwater-dependent species. Understanding the distribution of these stressors in relation to the position and type of GDE is necessary to developing management practices to mitigate these stressors and conserve GDEs.

Eleven threats of groundwater withdrawals, climate, and invasive species affected GDEs throughout the state. Irrigation demand is expected to increase while late-season surface water availability decreases, which will shift total water demand to groundwater sources. Future projected climate conditions such as decreasing snow-water equivalent will threaten the availability of groundwater to support GDEs while concurrently highlighting their importance as sources of hydrologic and thermal refugia. Changes to the fire regime due to invasive annual grasses in Oregon threaten the ecosystem function of GDEs and especially phreatophytes.

This report and associated appendices summarize the most rigorous and modern analysis of groundwater dependence in facultative GDEs and the most complete mapping of obligate and facultative GDEs in Oregon.

Increasing the understanding of Oregon's GDEs is identified as Recommended Action 3.B in the 2017 Oregon Integrated Water Resources Strategy. However, local and site-specific information about the condition and function of GDEs remains extremely scarce. A continued and increased investment in research and management practices is necessary for Oregon to conserve its most charismatic, biodiverse, and resilient groundwater-dependent ecosystems.

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Appendix A

Oregon Atlas of Groundwater-dependent Ecosystems 2022

Zach Freed, Michael Schindel, Claire Ruffing, Shonene Scott

Figures

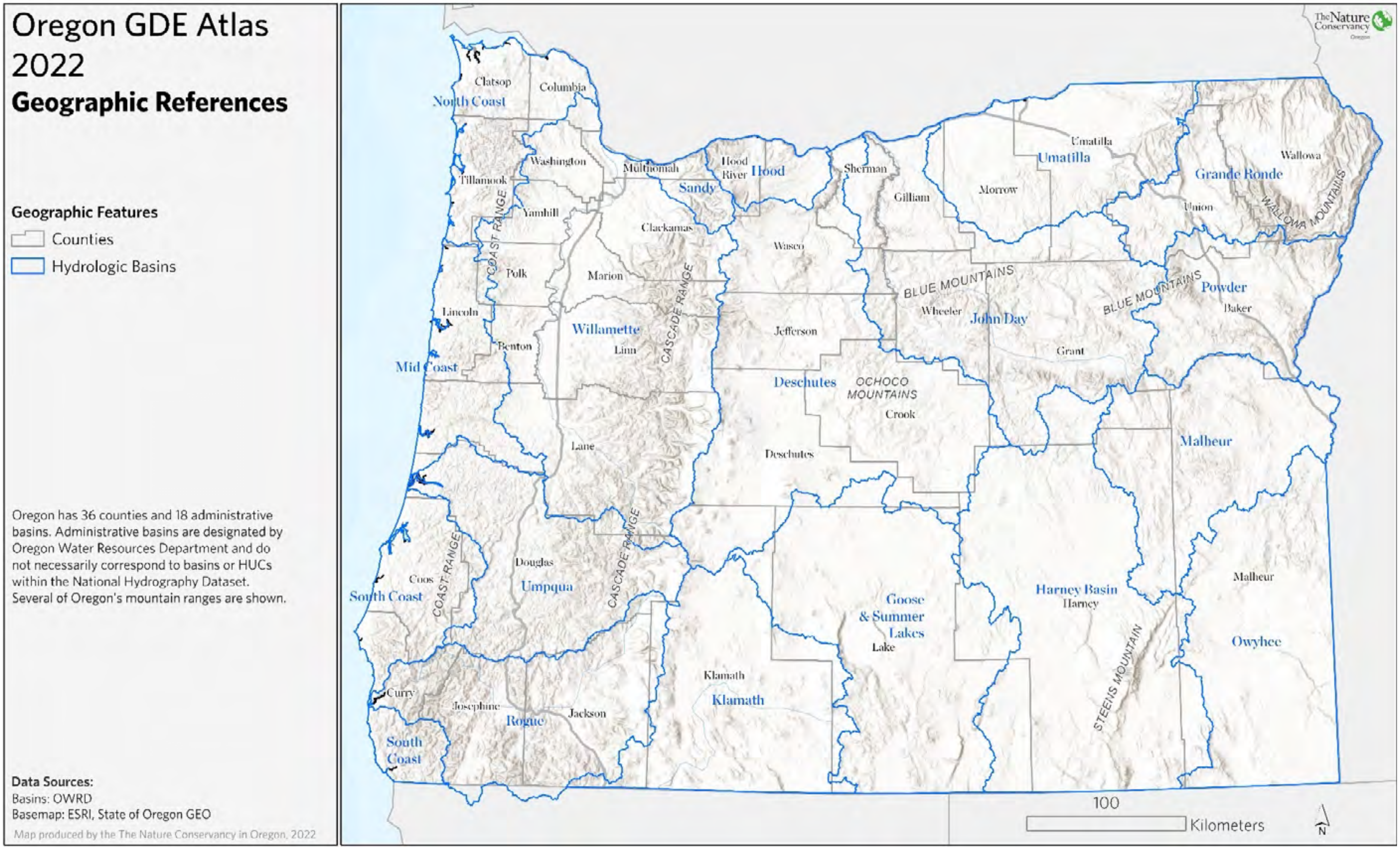

Figure A1: Study area and geographic reference map

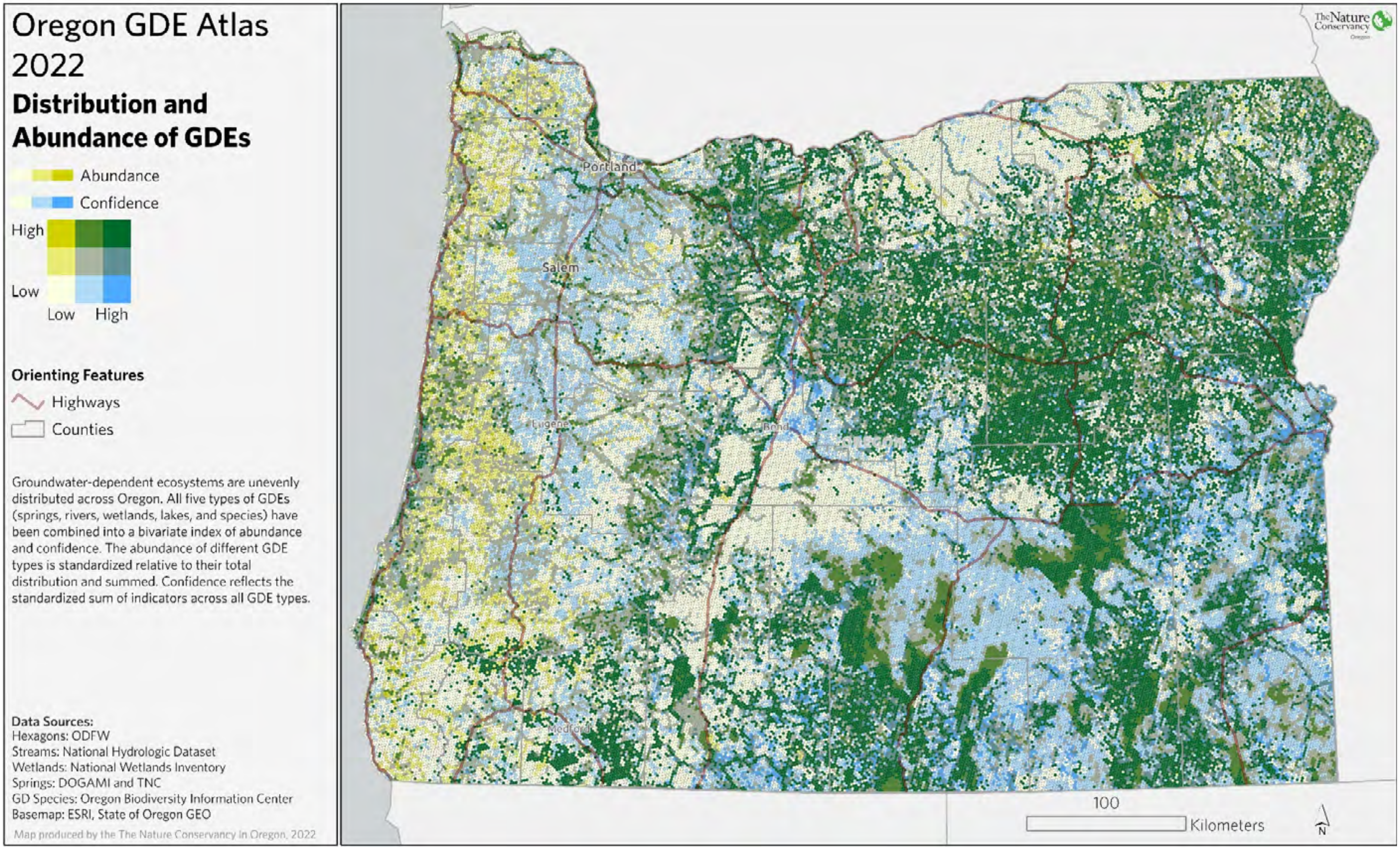

Figure A2: Atlas of groundwater-dependent ecosystems and species of Oregon.

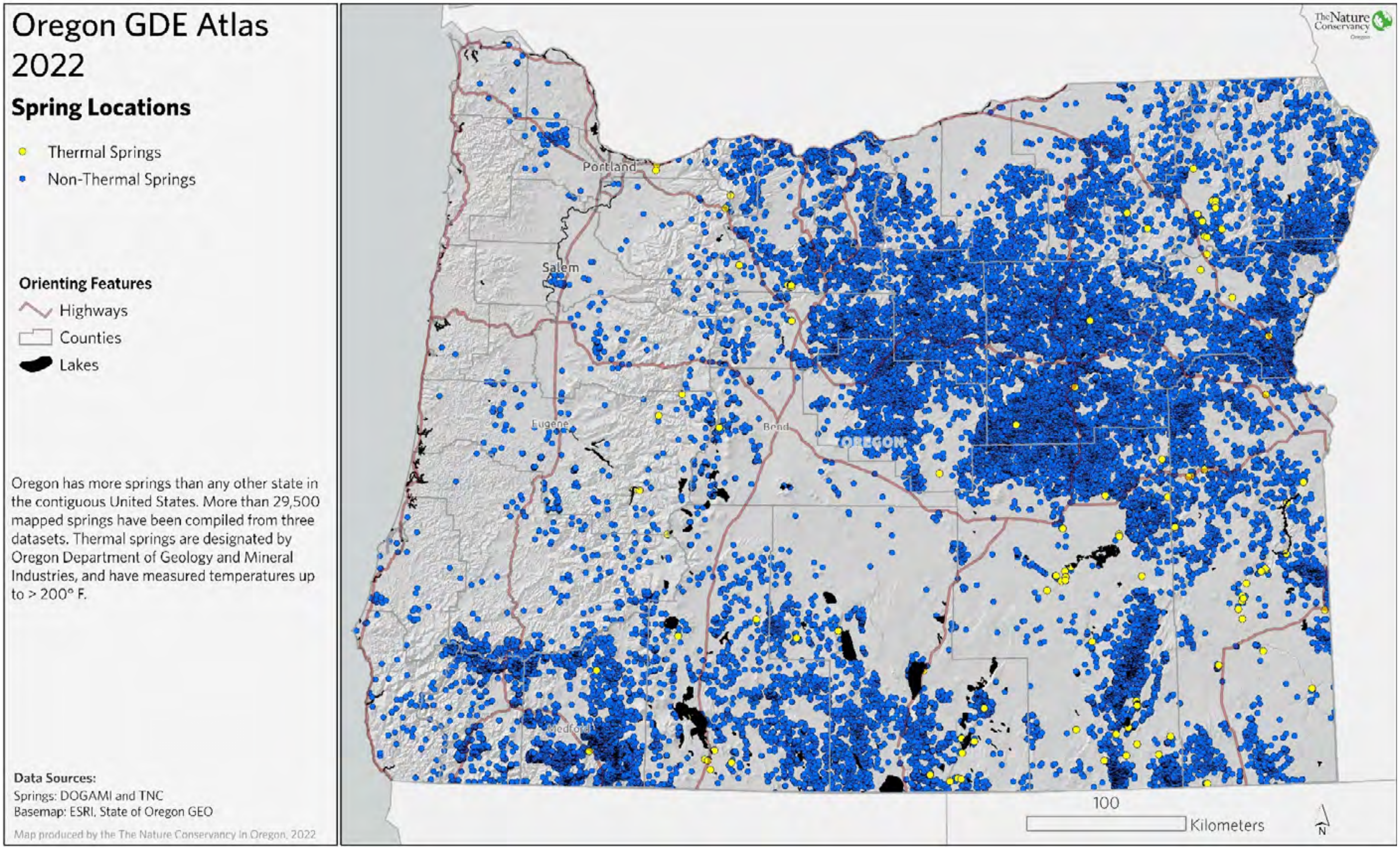

Figure A3: Springs and geothermal springs

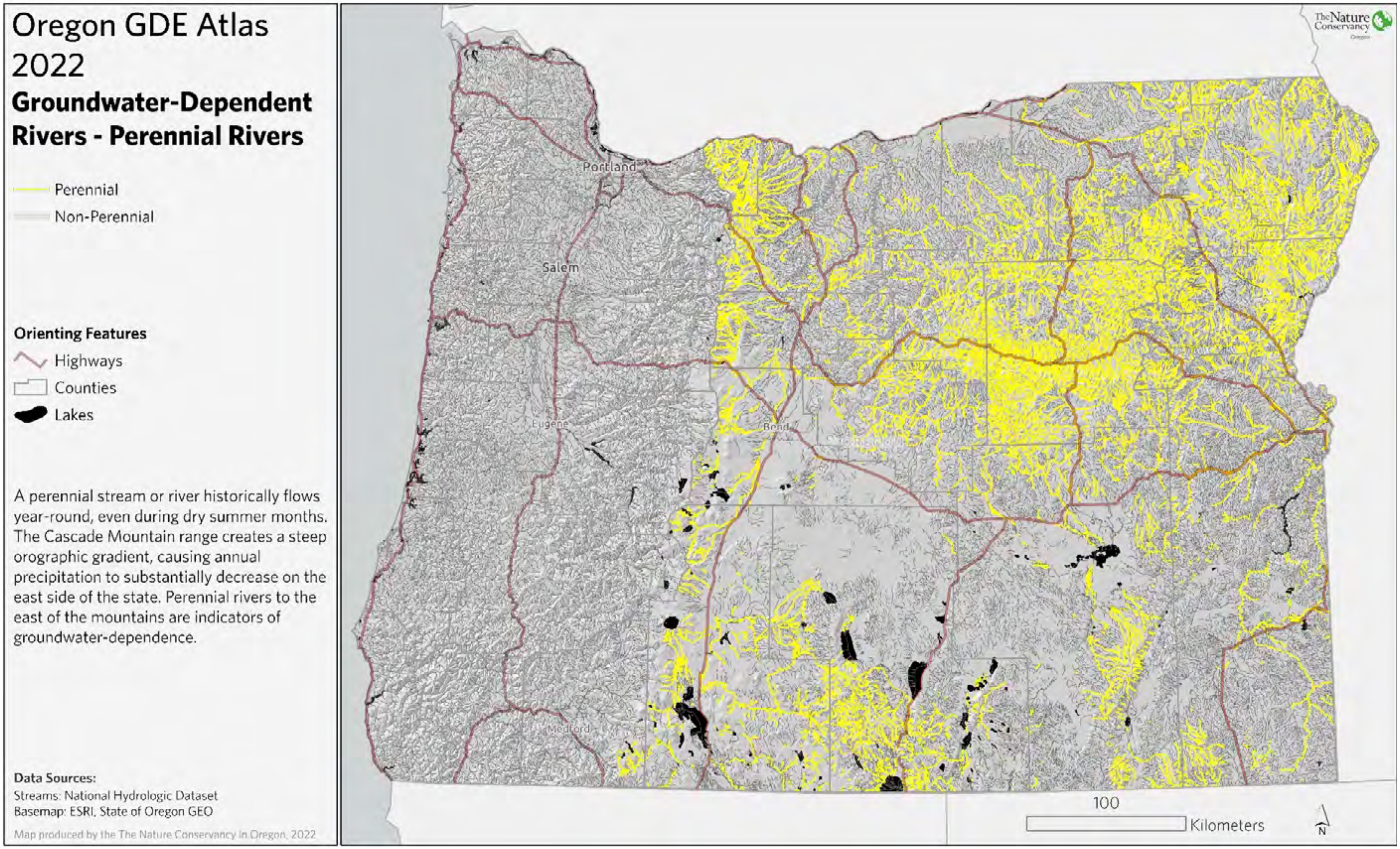

Figure A4 i: Groundwater-dependent rivers and streams: flow regime

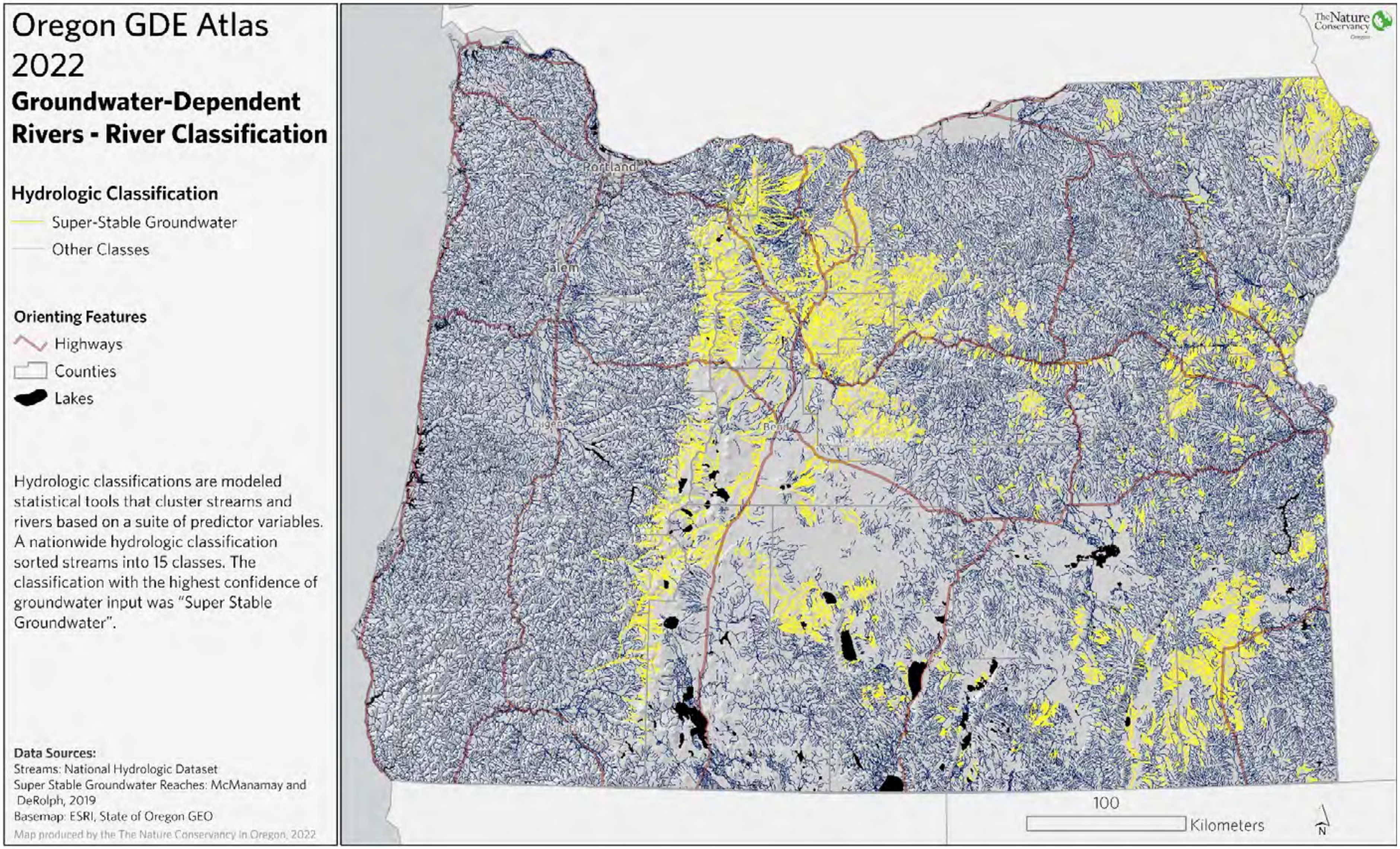

Figure A4 ii: Groundwater-dependent rivers and streams: hydrologic classification

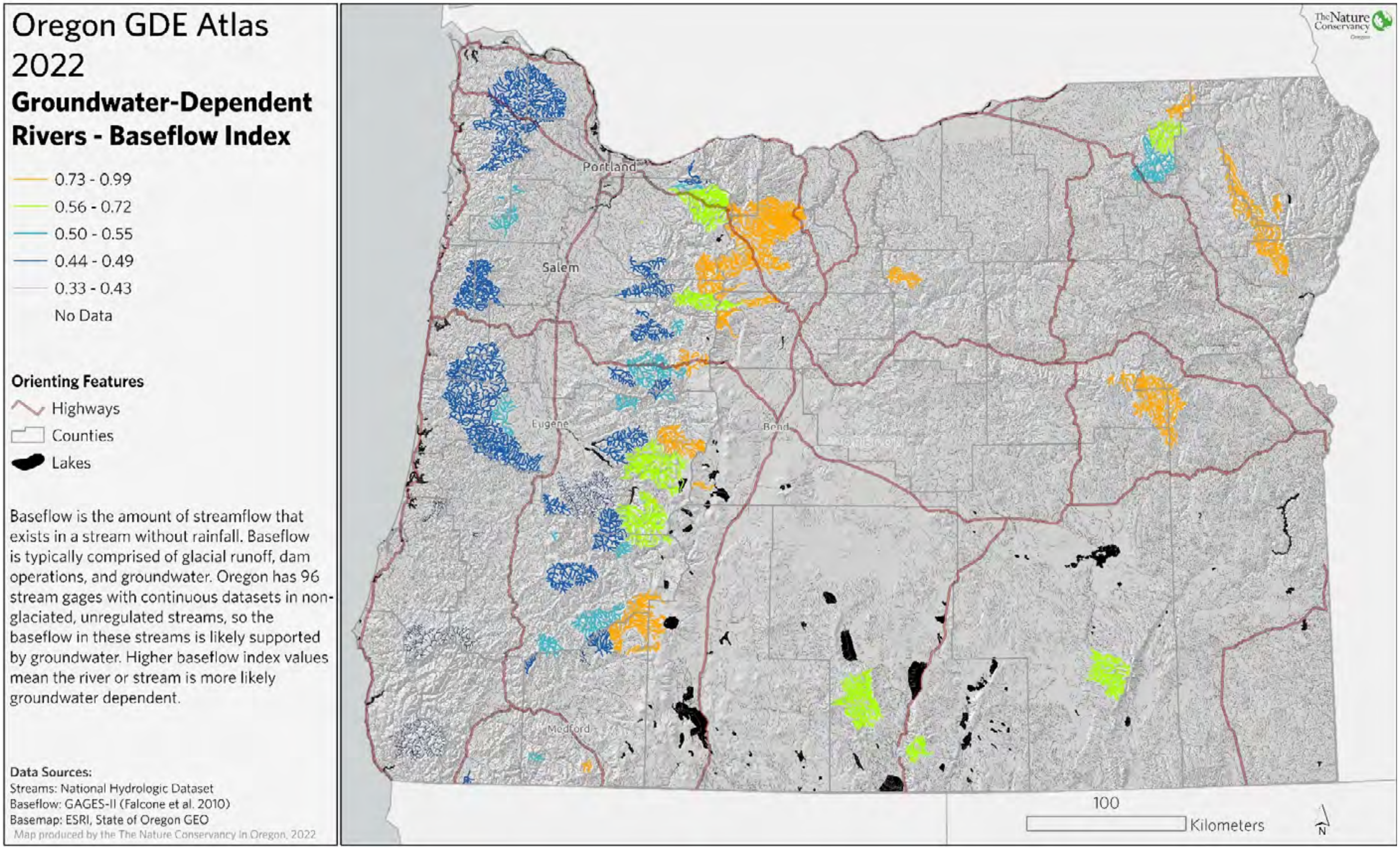

Figure A4 iii: Groundwater-dependent rivers and streams: baseflow index

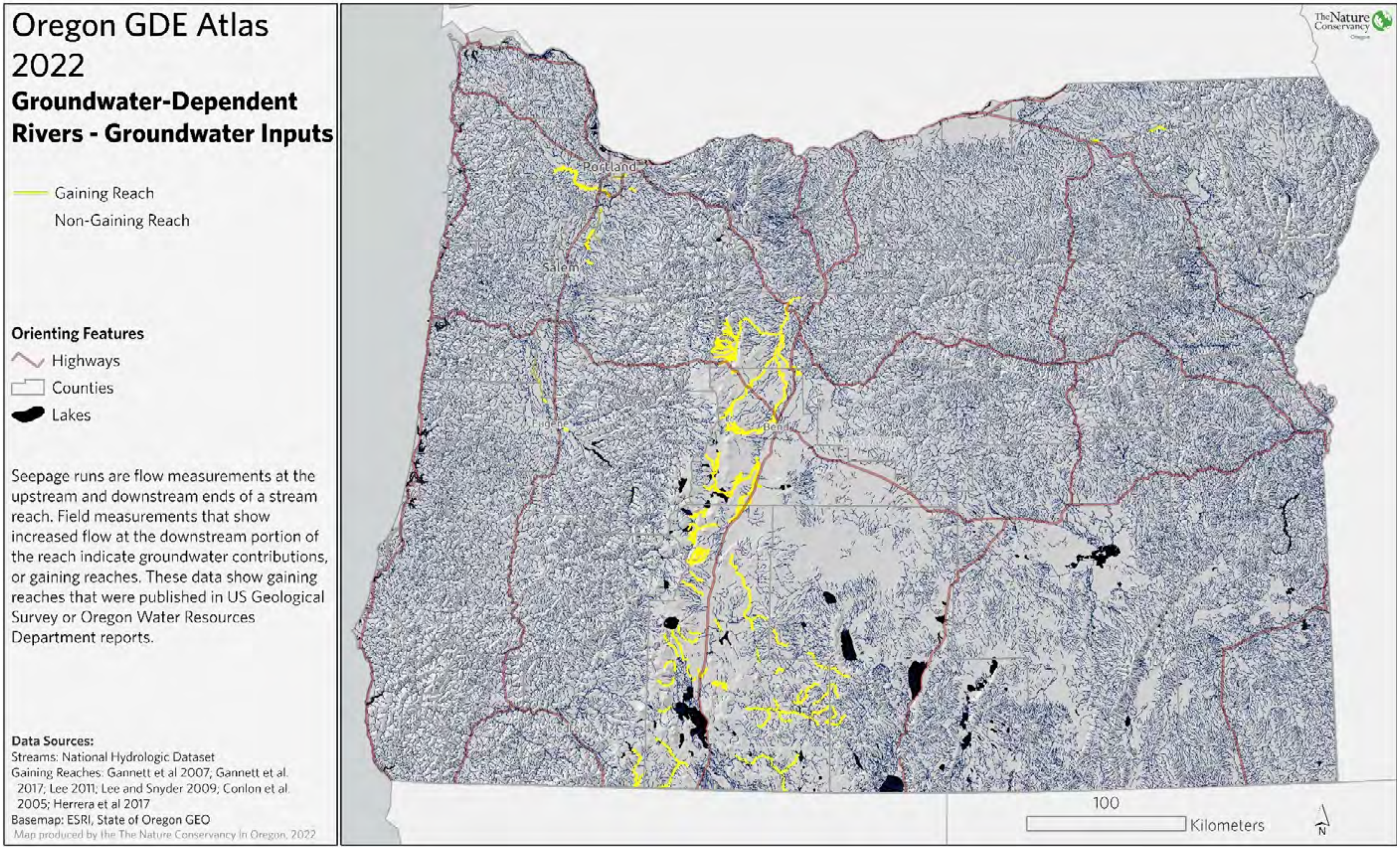

Figure A4 iv: Groundwater-dependent rivers and streams: gaining reaches

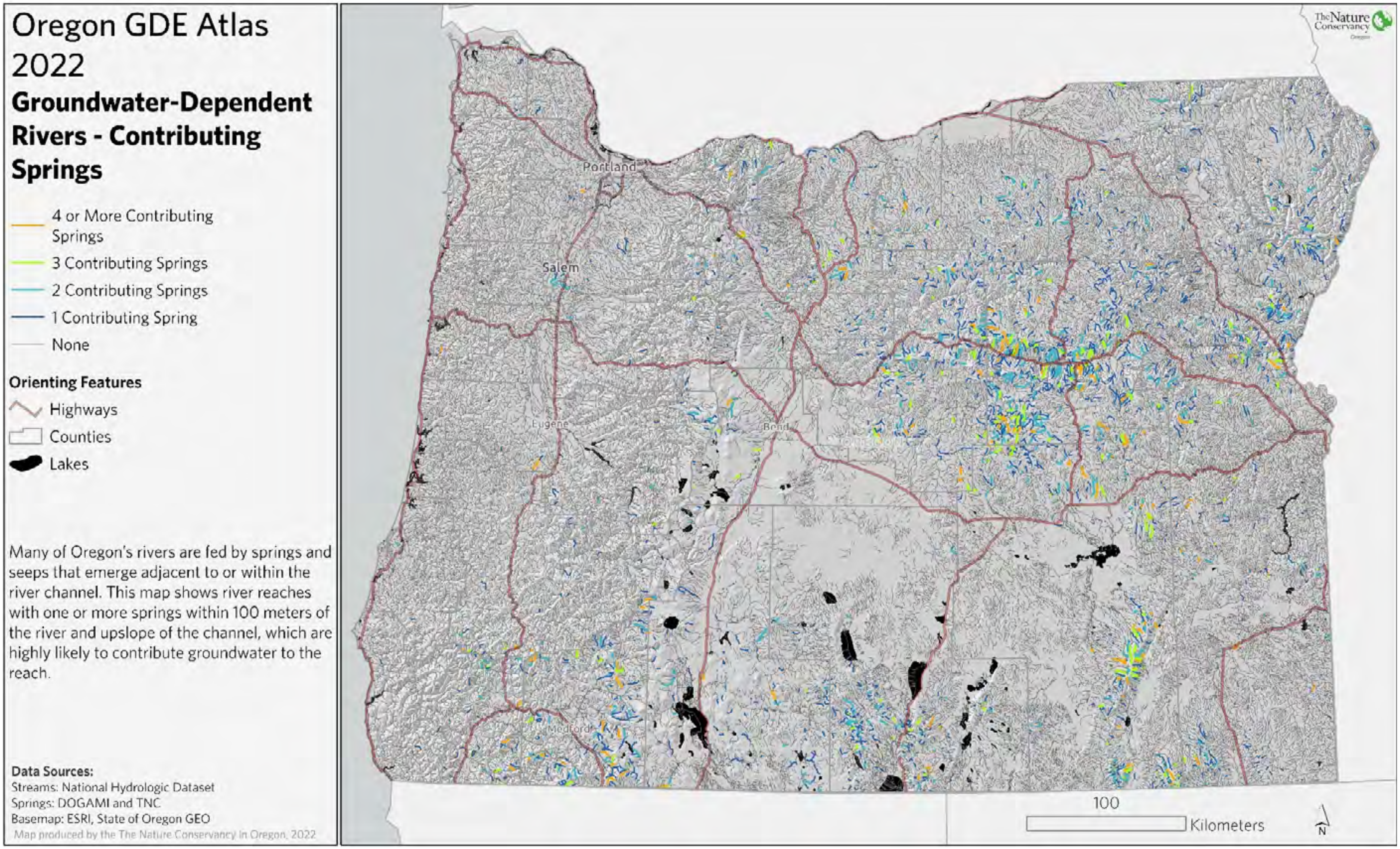

Figure A4 v: Groundwater-dependent rivers and streams: proximity to springs

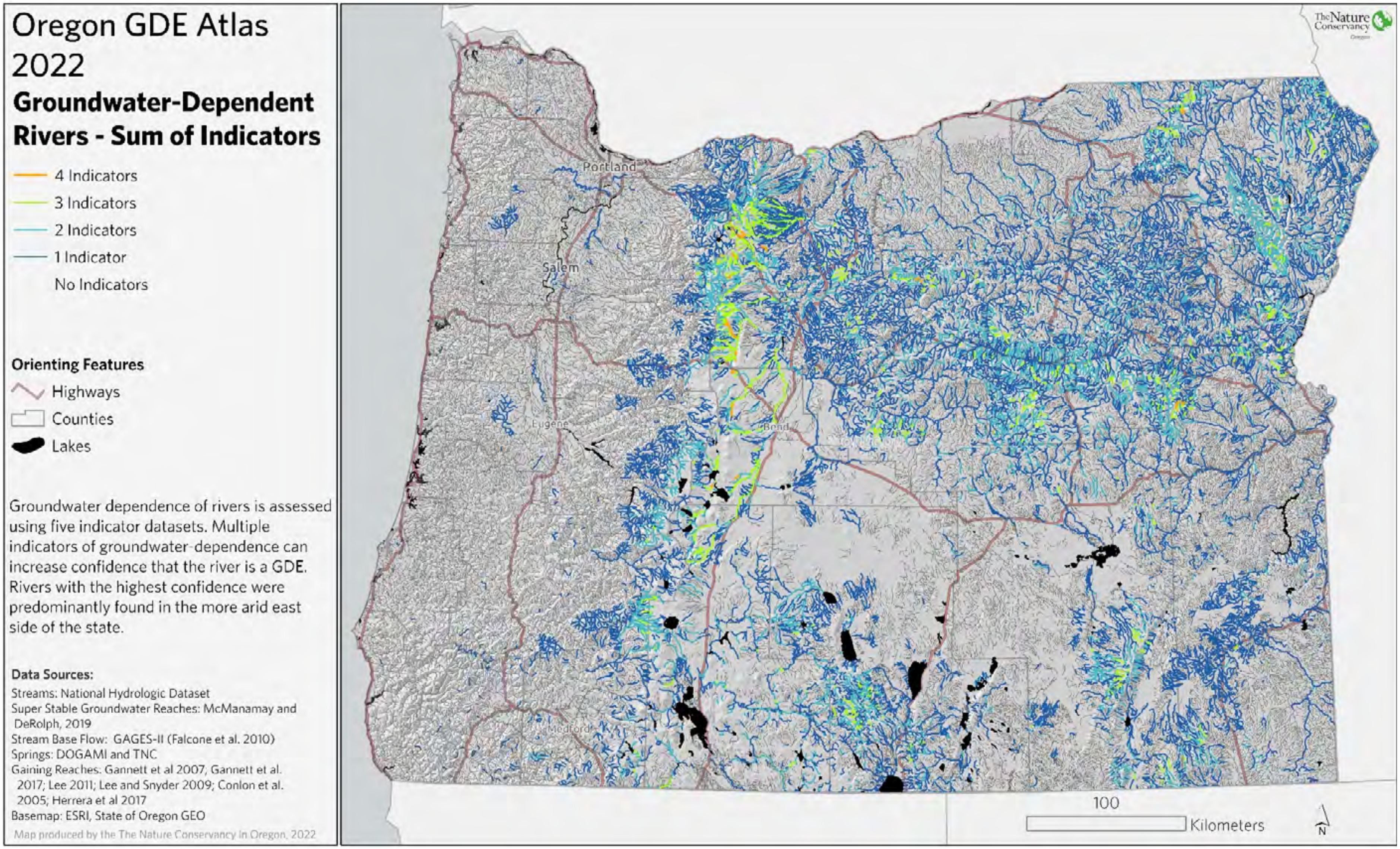

Figure A4 vi: Groundwater-dependent rivers and streams: sum of indicators

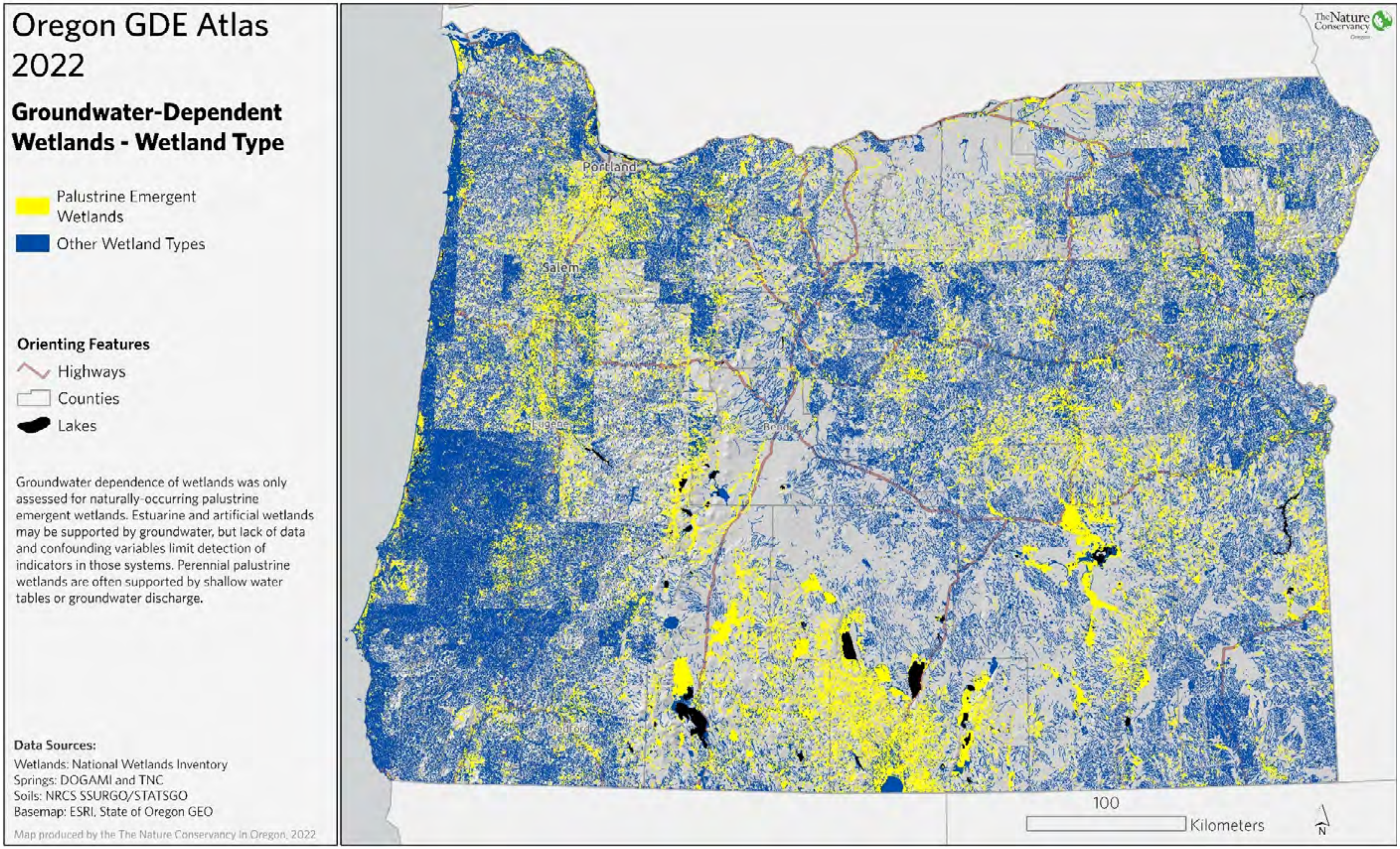

Figure A5 i: Groundwater-dependent wetlands: wetland type

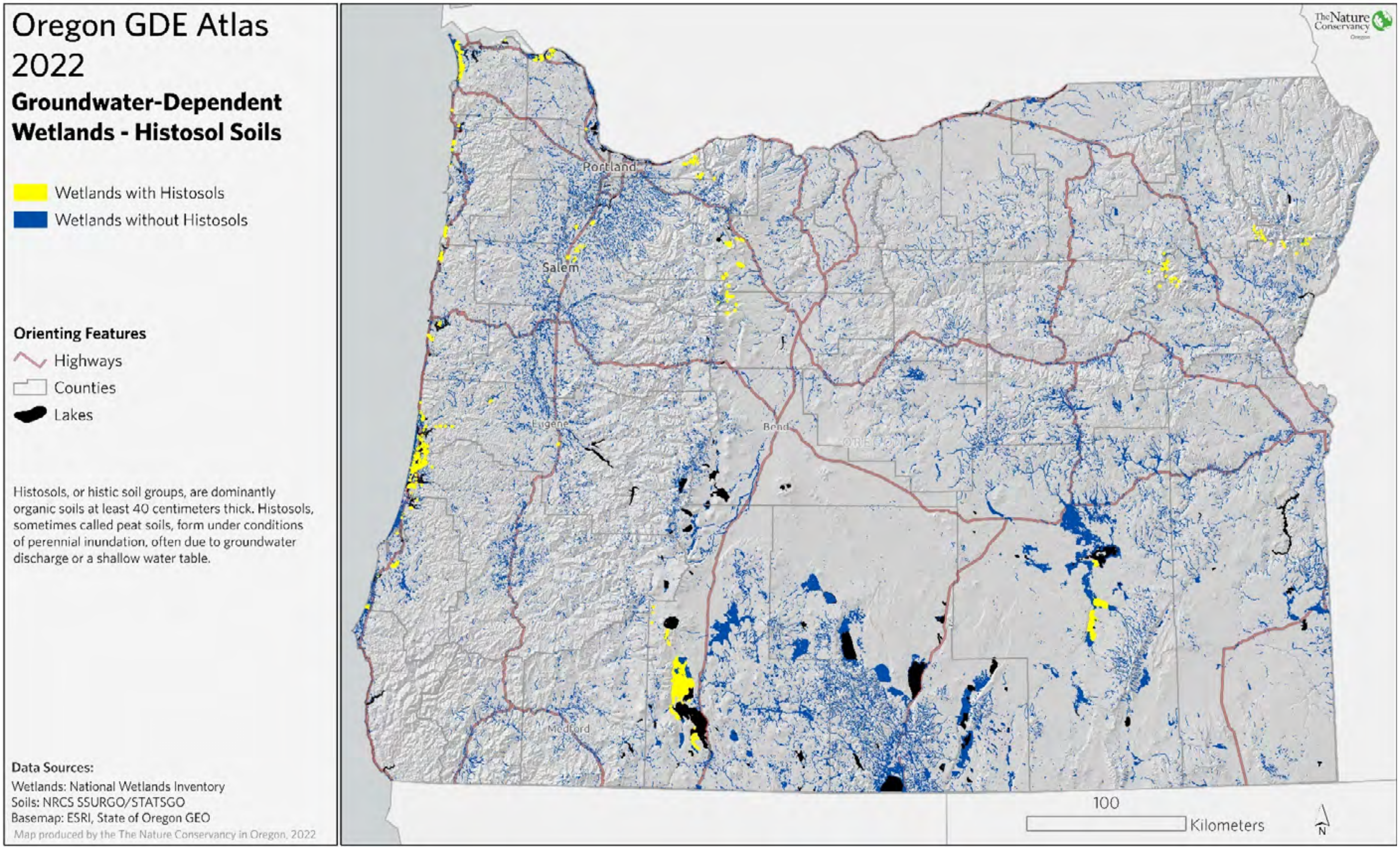

Figure A5 ii: Groundwater-dependent wetlands: histosols

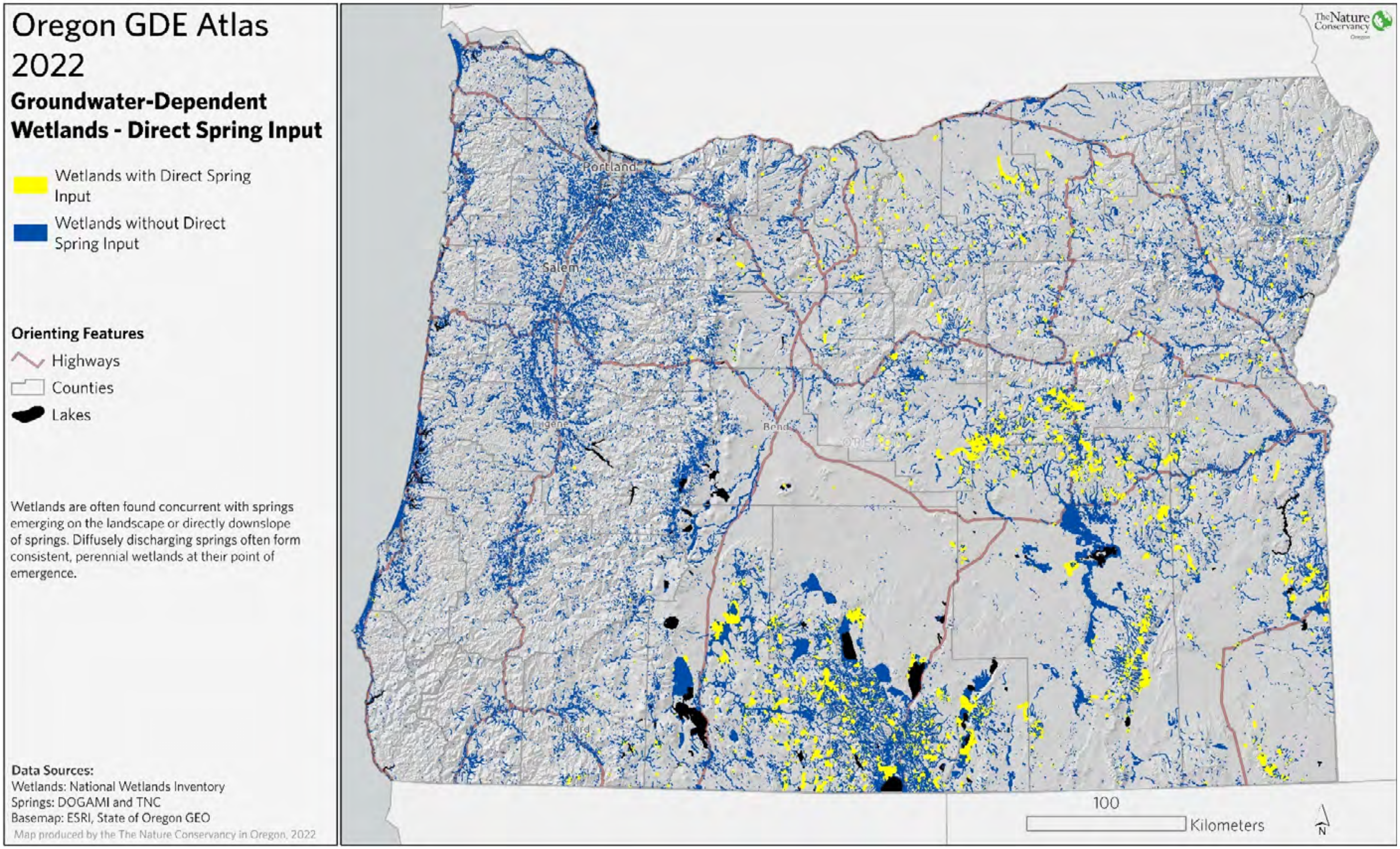

Figure A5 iii: Groundwater-dependent wetlands: direct spring input

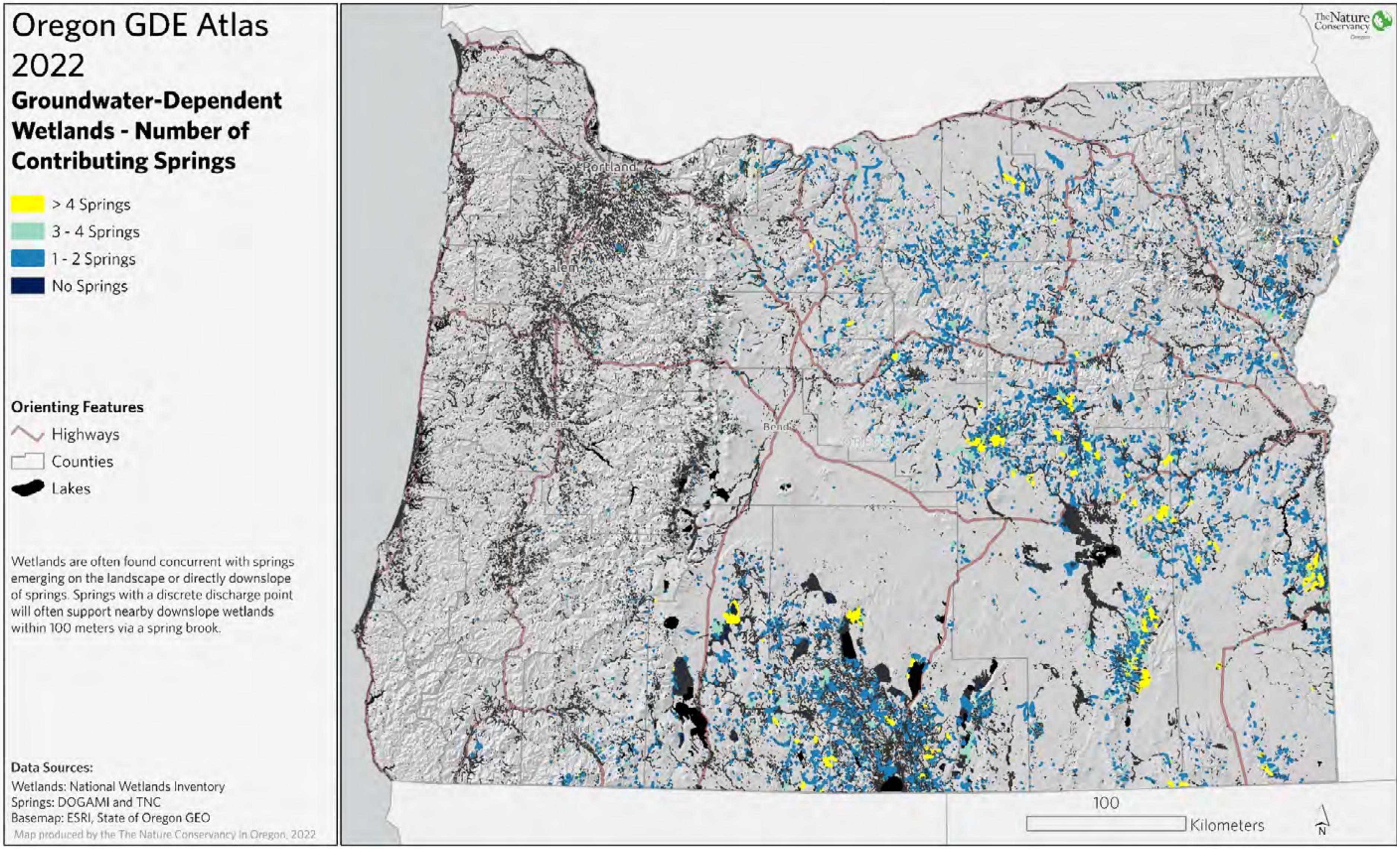

Figure A5 iv: Groundwater-dependent wetlands: proximity to springs

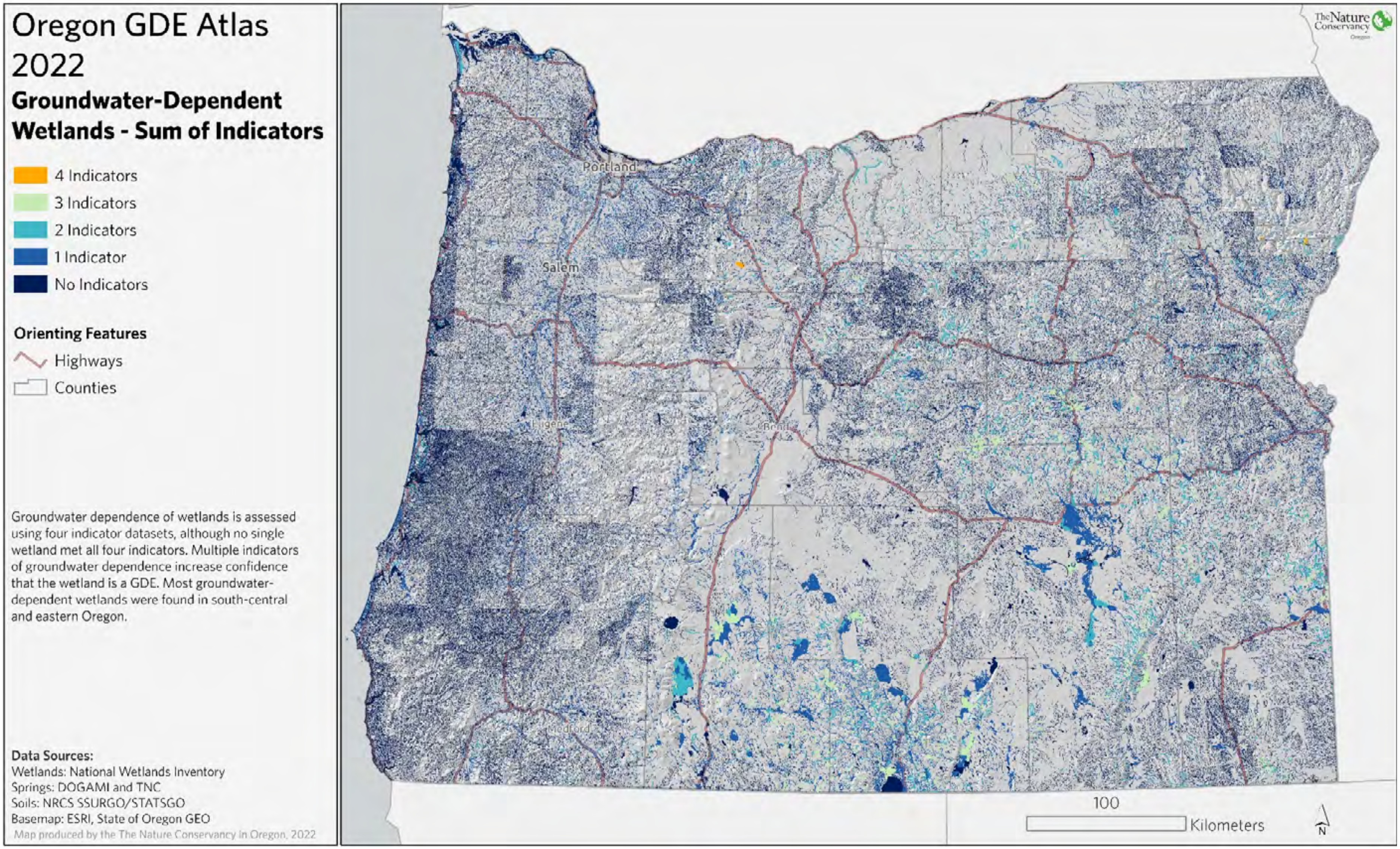

Figure A5 v: Groundwater-dependent wetlands: sum of indicators

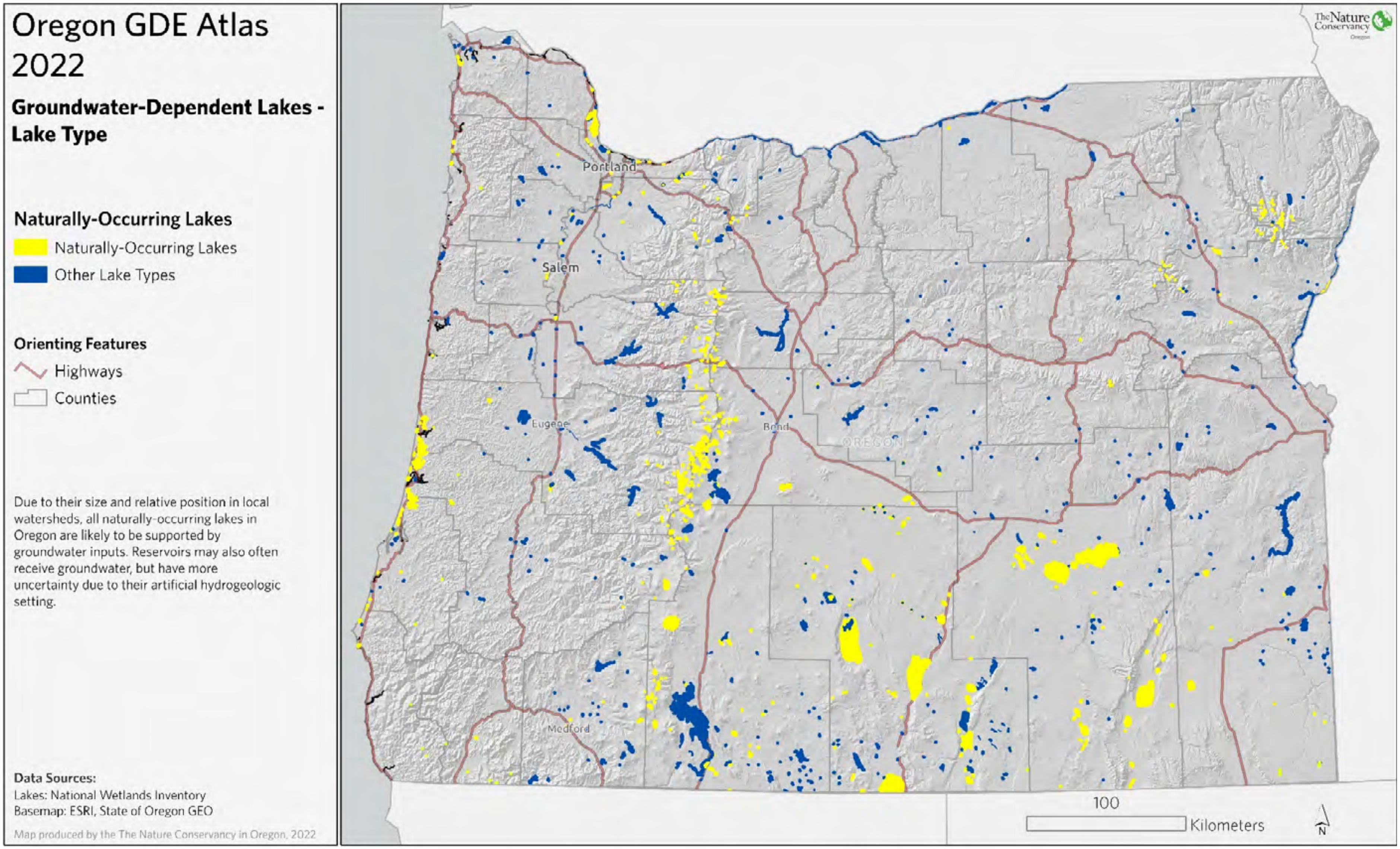

Figure A6 i: Groundwater-dependent lakes: naturally-occurring lakes

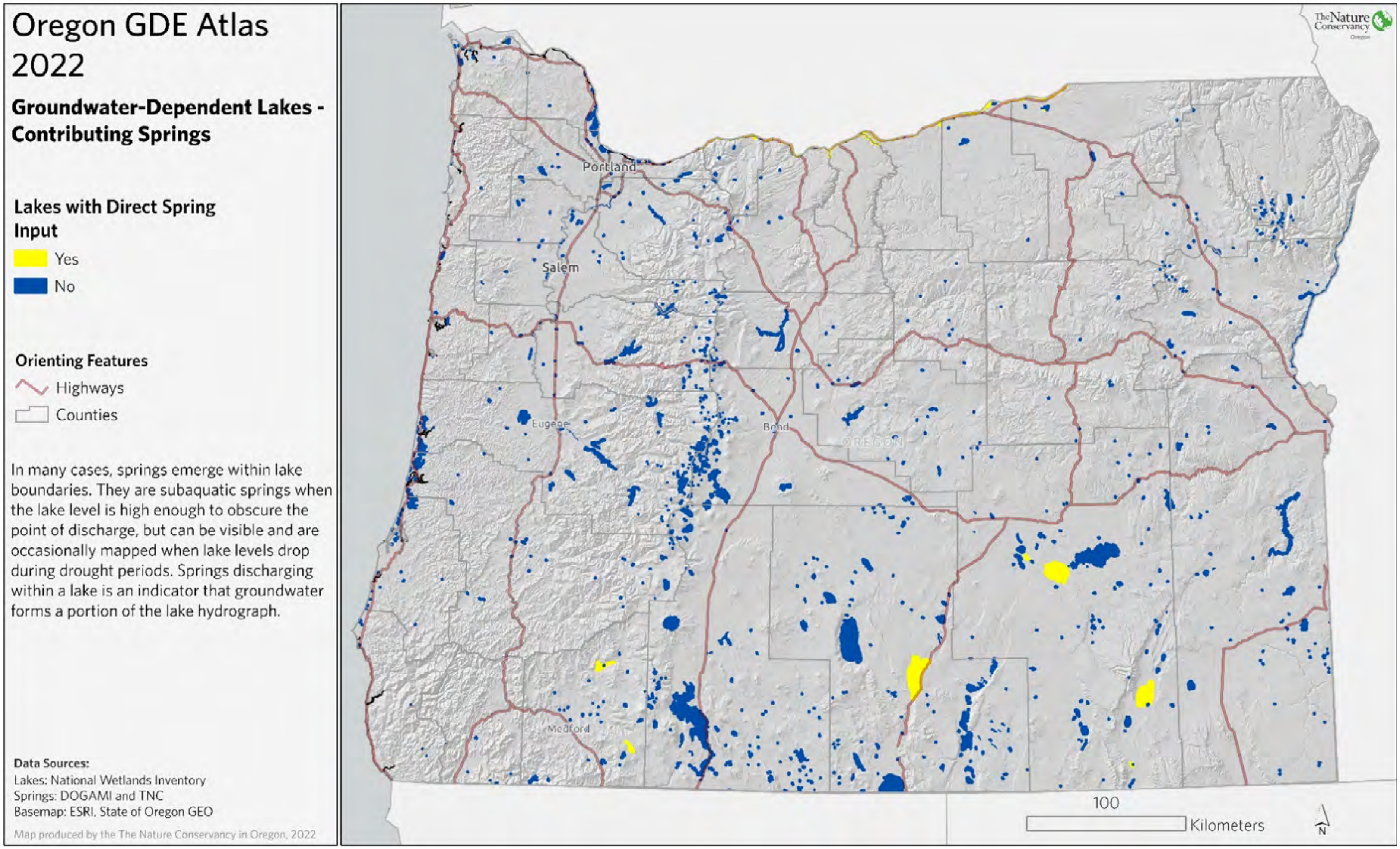

Figure A6 ii: Groundwater-dependent lakes: direct spring input

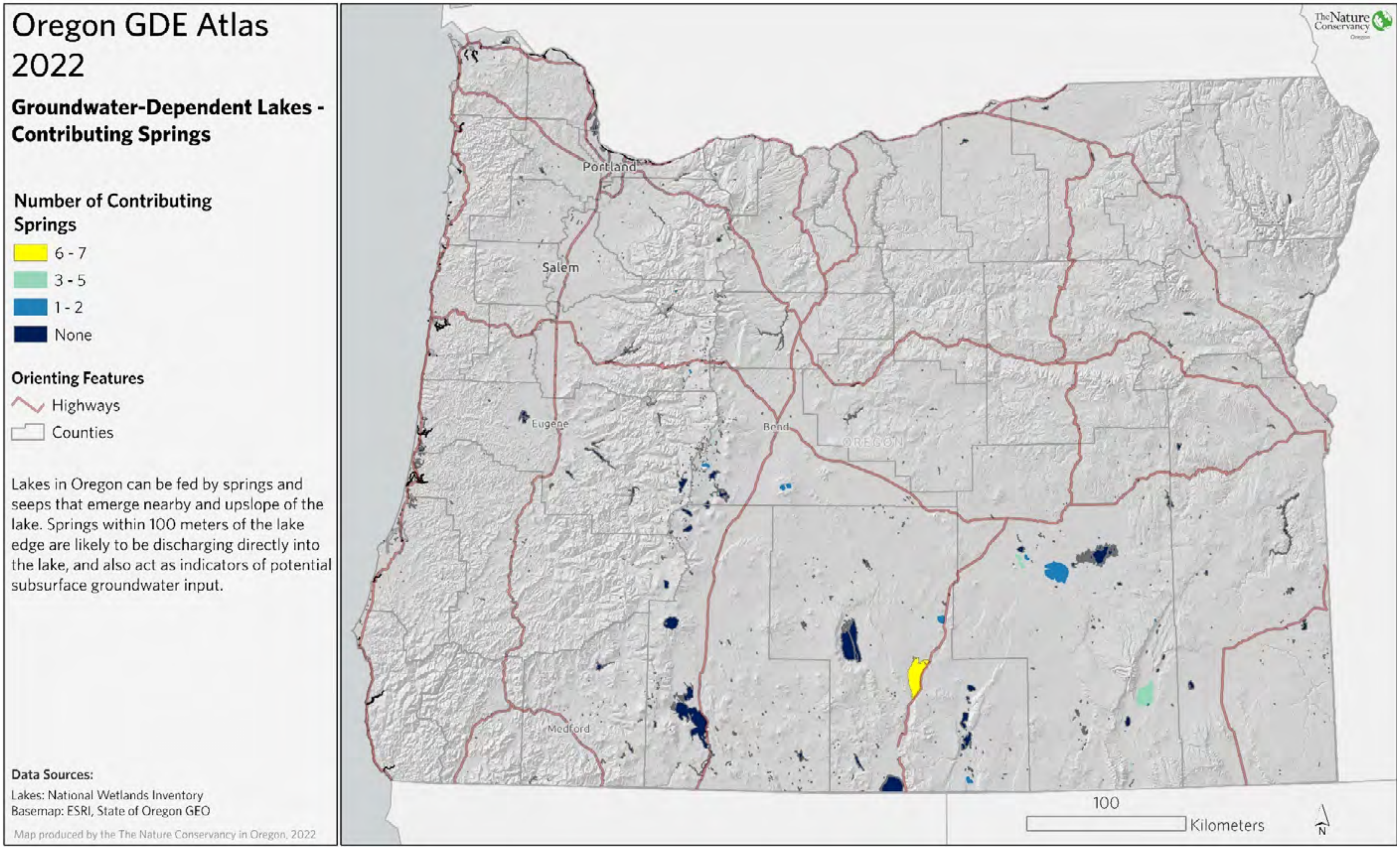

Figure A6 iii: Groundwater-dependent lakes: proximity to springs

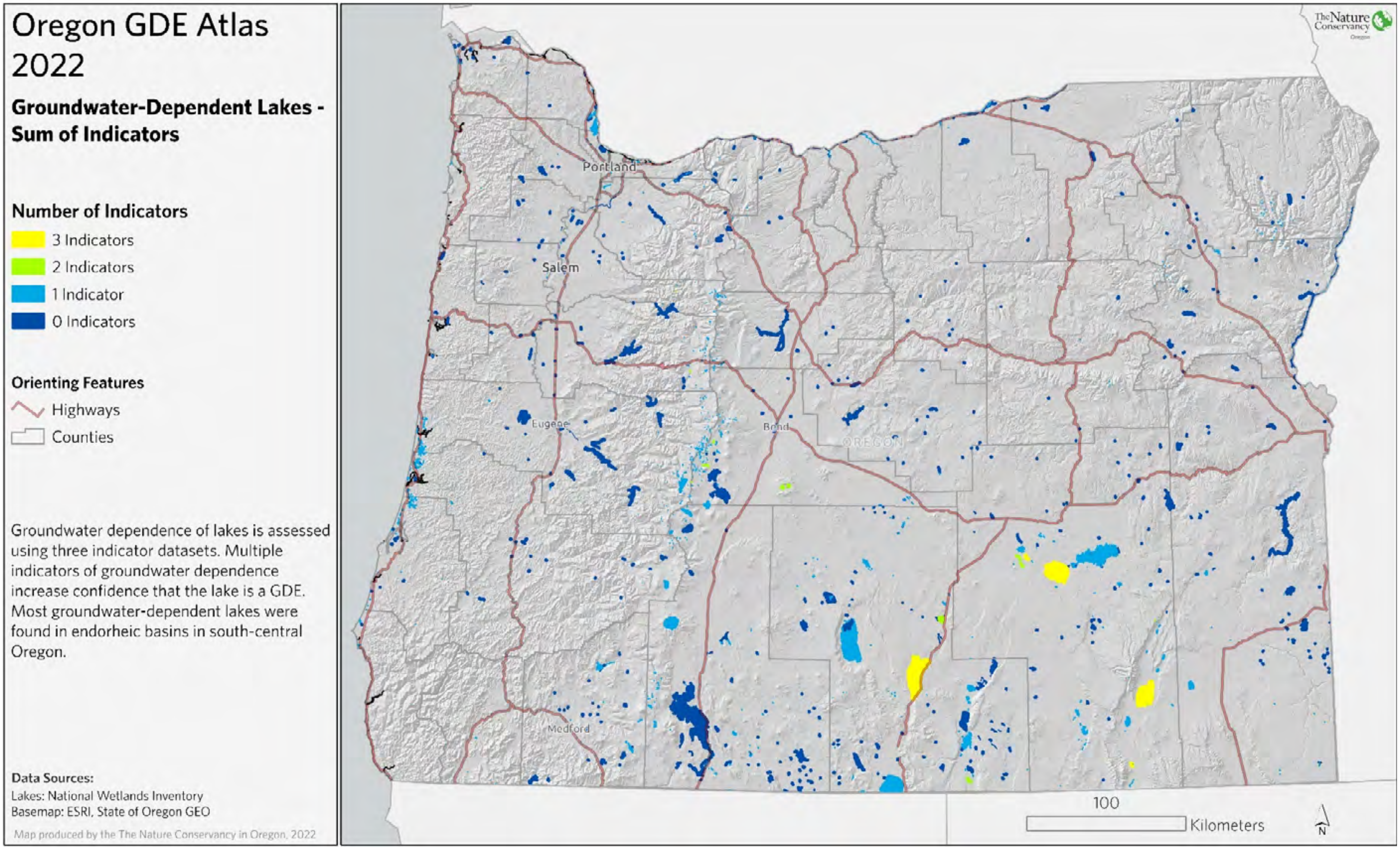

Figure A6 iv: Groundwater-dependent lakes: sum of indicators

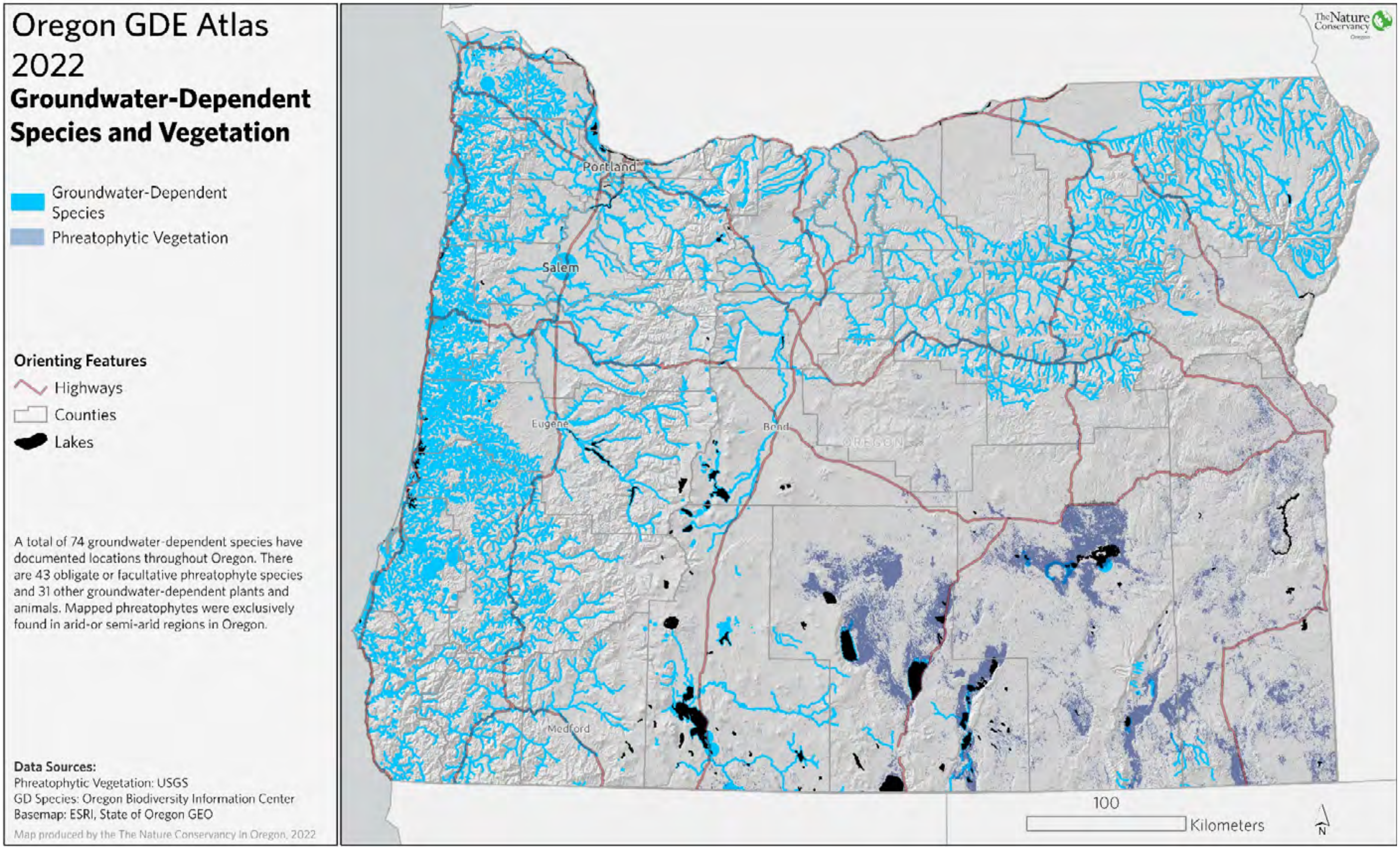

Figure A7: Groundwater-dependent species

Appendix B

Oregon Atlas of Groundwater-dependent Ecosystems 2022

Zach Freed, Michael Schindel, Claire Ruffing, Shonene Scott

Figures

ii. Invasive species
   a. Road density
   b. Invasive annual grasses
iii. Climate
   a. Precipitation anomaly (RCP 4.5)
   b. Precipitation anomaly (RCP 8.5)
   c. Actual evapotranspiration anomaly (RCP 4.5)
   d. Actual evapotranspiration anomaly (RCP 8.5)
   e. Air temperature anomaly (RCP 4.5)
   f. Air temperature anomaly (RCP 8.5)
   g. April 1st snow water equivalent anomaly (RCP 4.5)
   h. April 1st snow water equivalent anomaly (RCP 8.5)
   i. Projected future mean summer streamflow
   j. Projected future mean annual streamflow
   k. Projected future August stream temperature

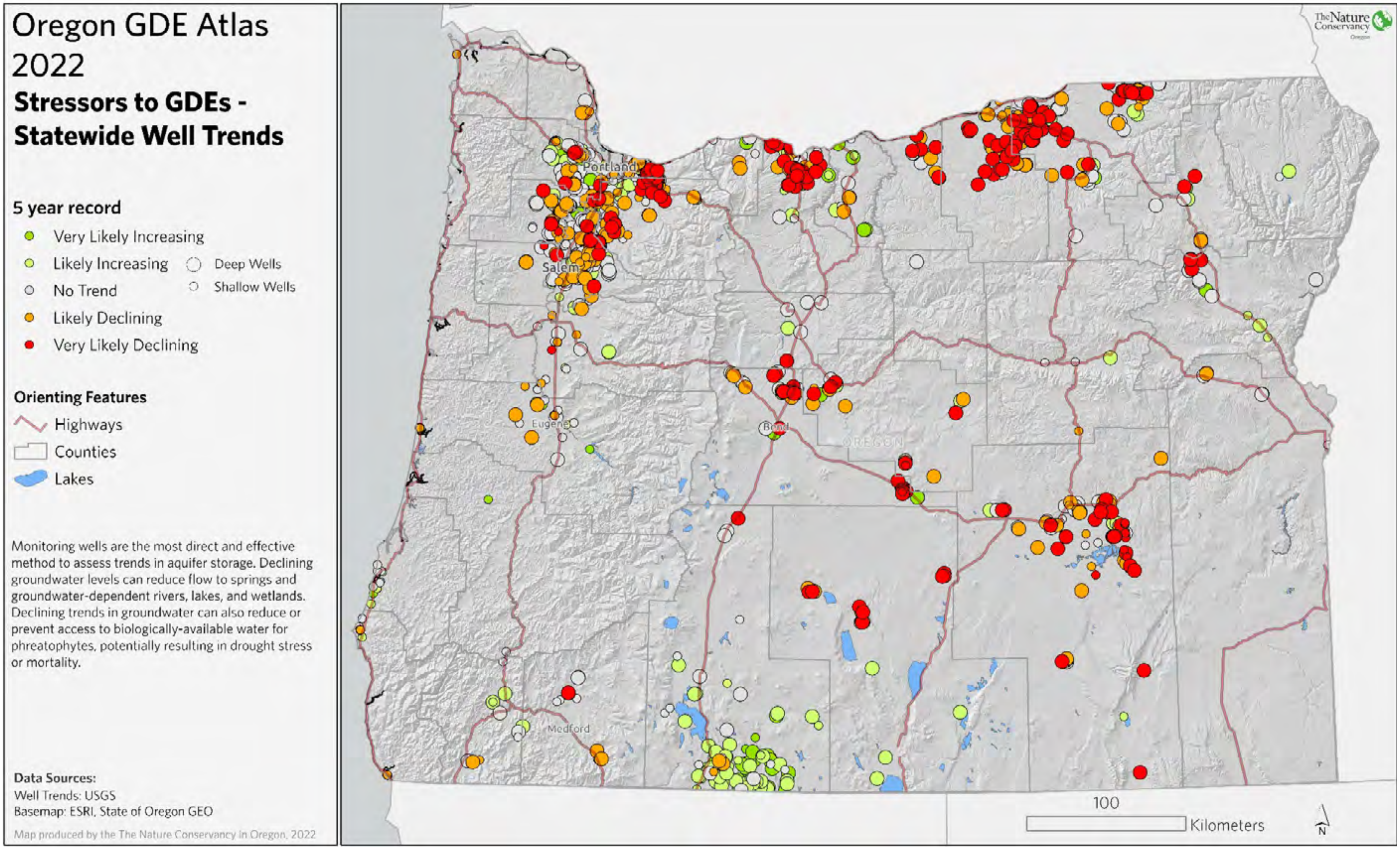

Figure B1 i a: Groundwater withdrawals: observed monitoring well declines with a five-year period of record

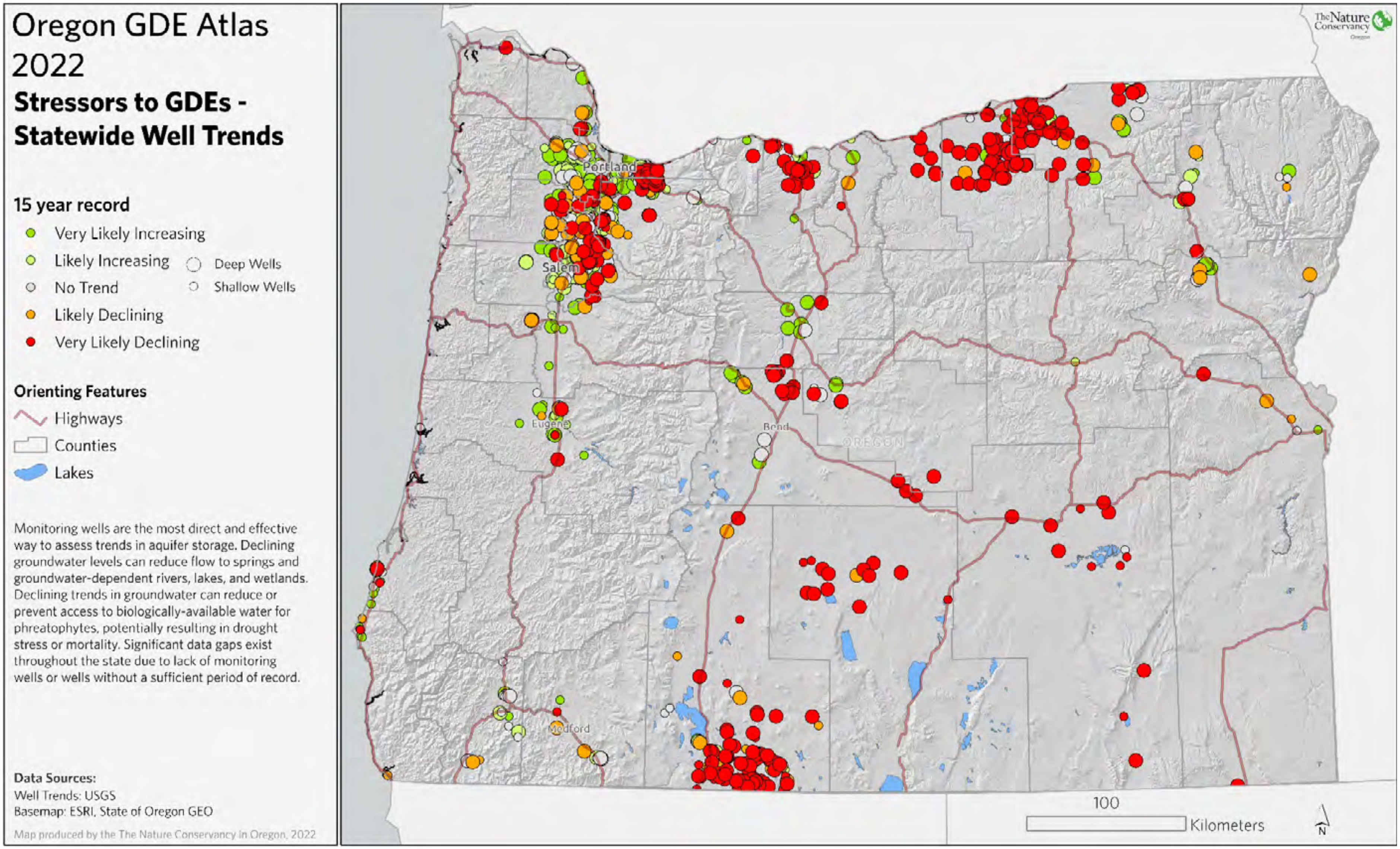

Figure B1 i b: Groundwater withdrawals: observed monitoring well declines with a fifteen-year period of record

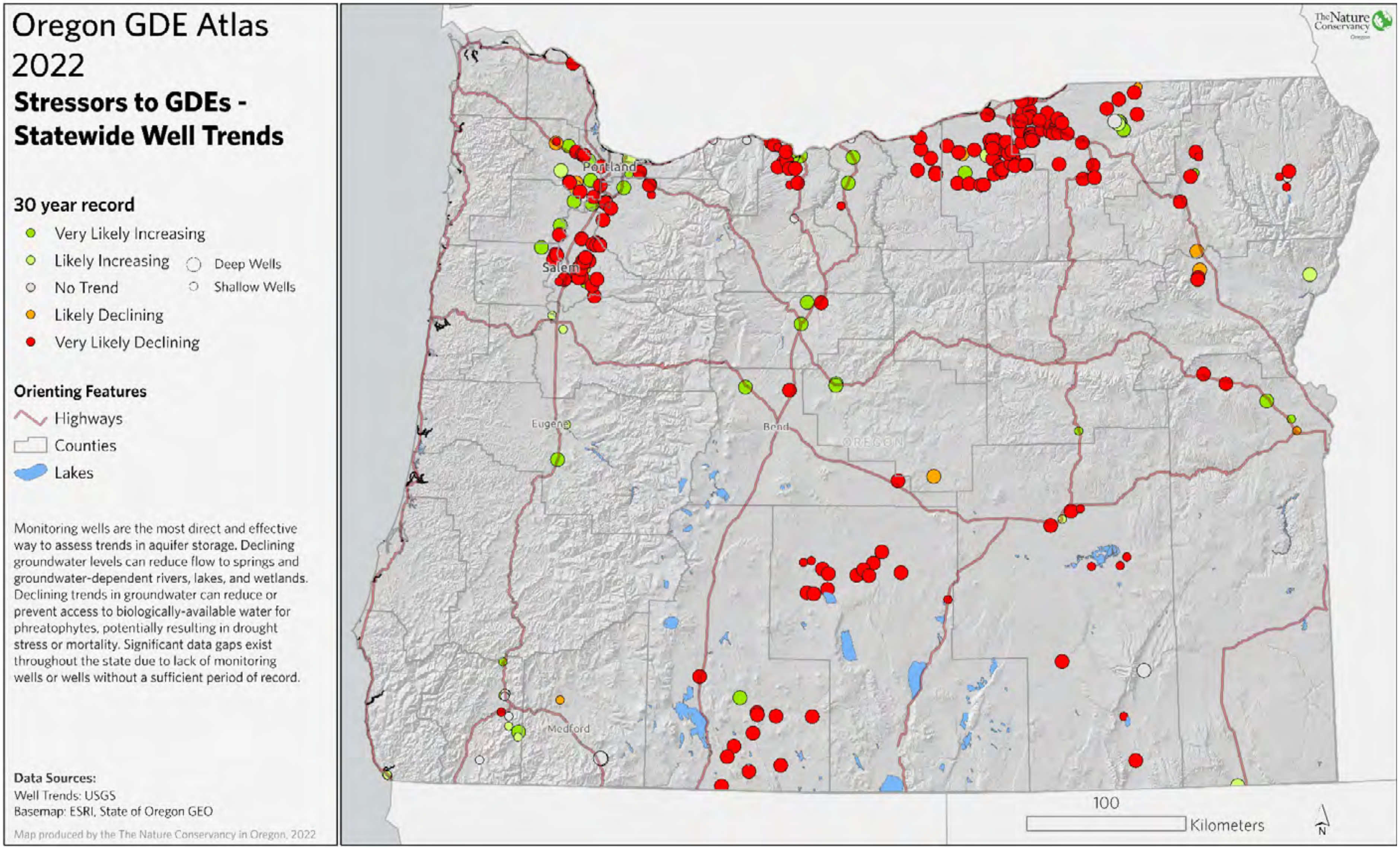

Figure B1 i c: Groundwater withdrawals: observed monitoring well declines with a thirty-year period of record

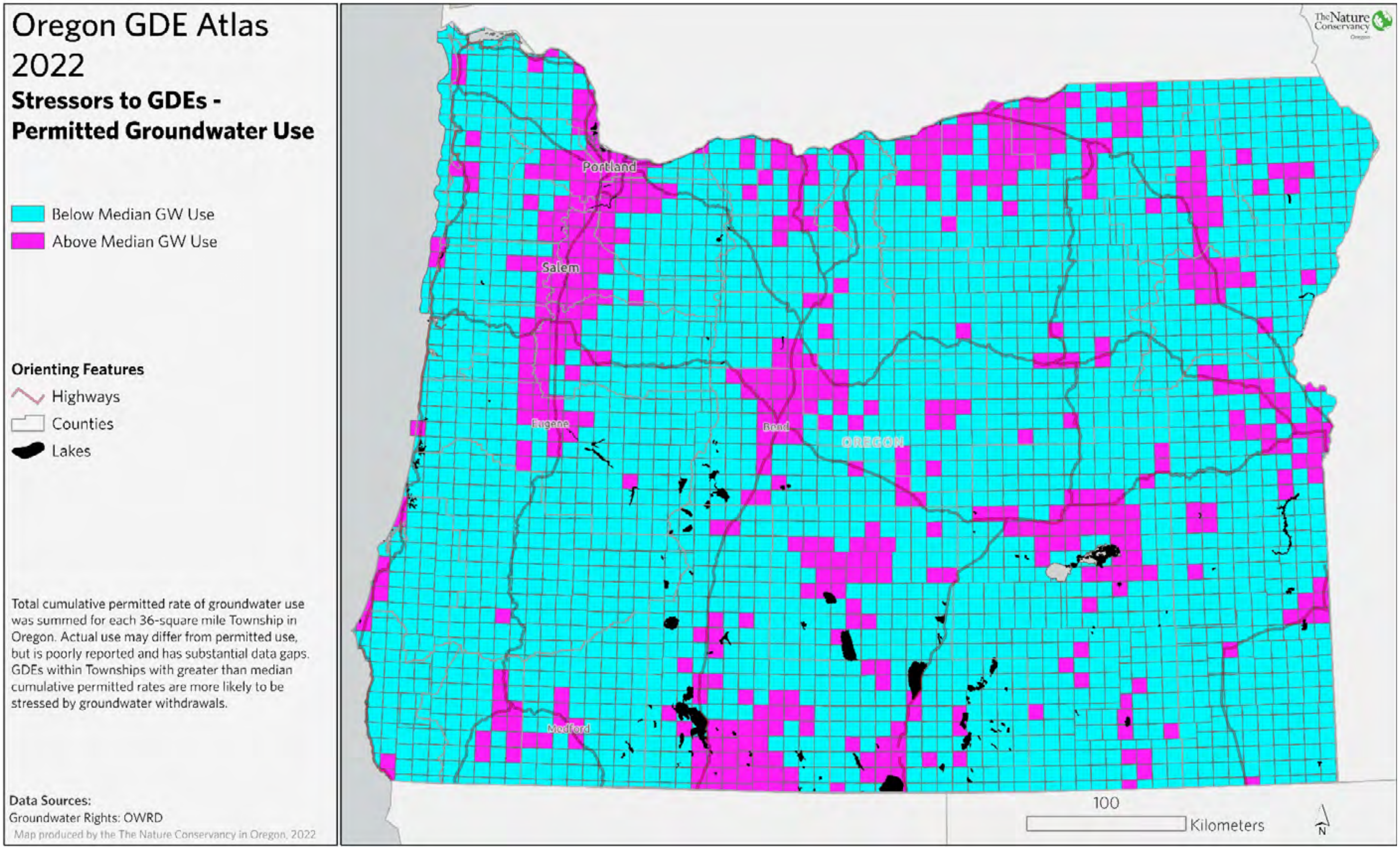

Figure B1 i d: Groundwater withdrawals: concentrations of permitted groundwater use

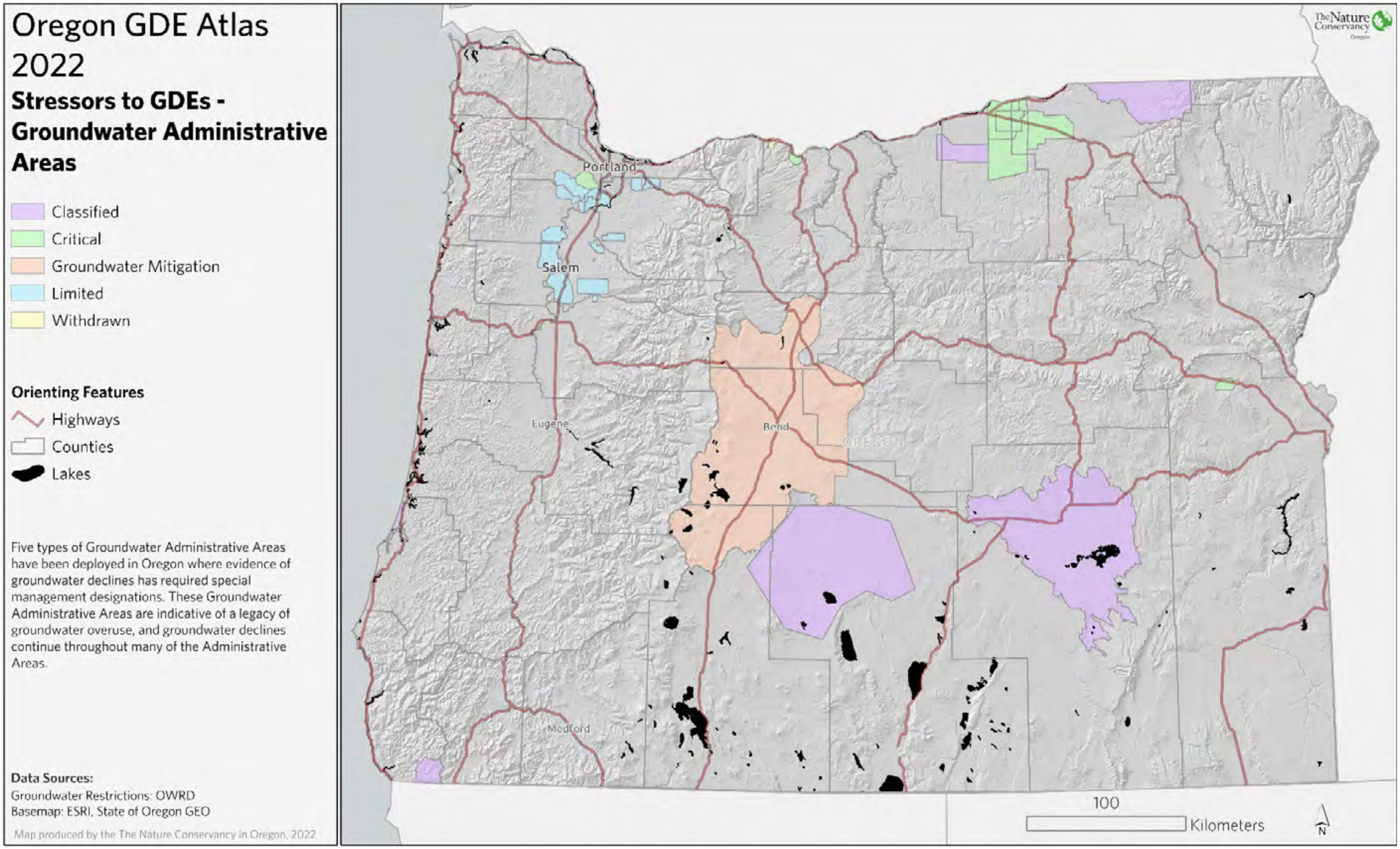

Figure B1 i e: Groundwater withdrawals: Groundwater Administrative Areas

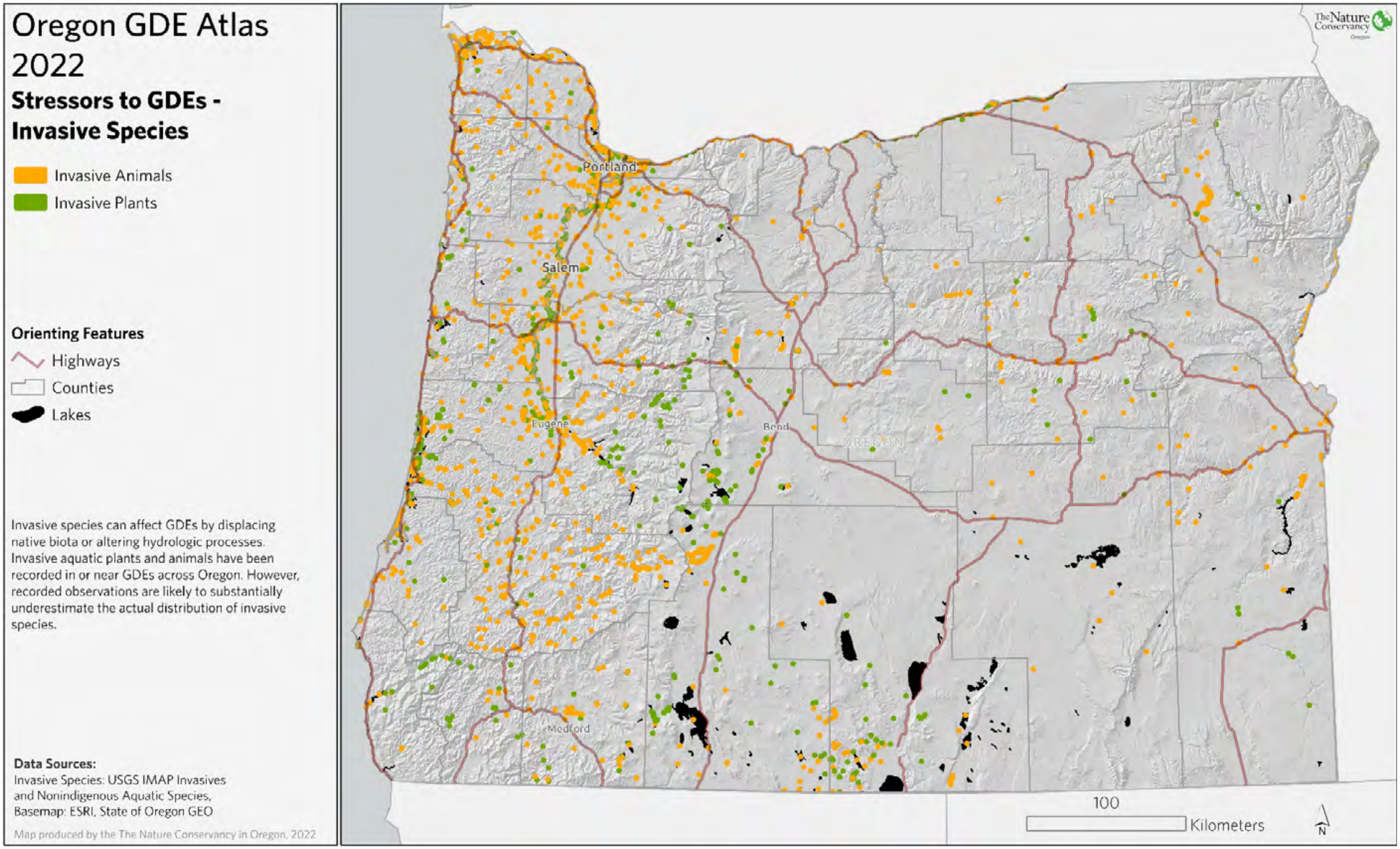

Figure B1 ii a: Invasive species: distribution of aquatic invasive species in GDEs

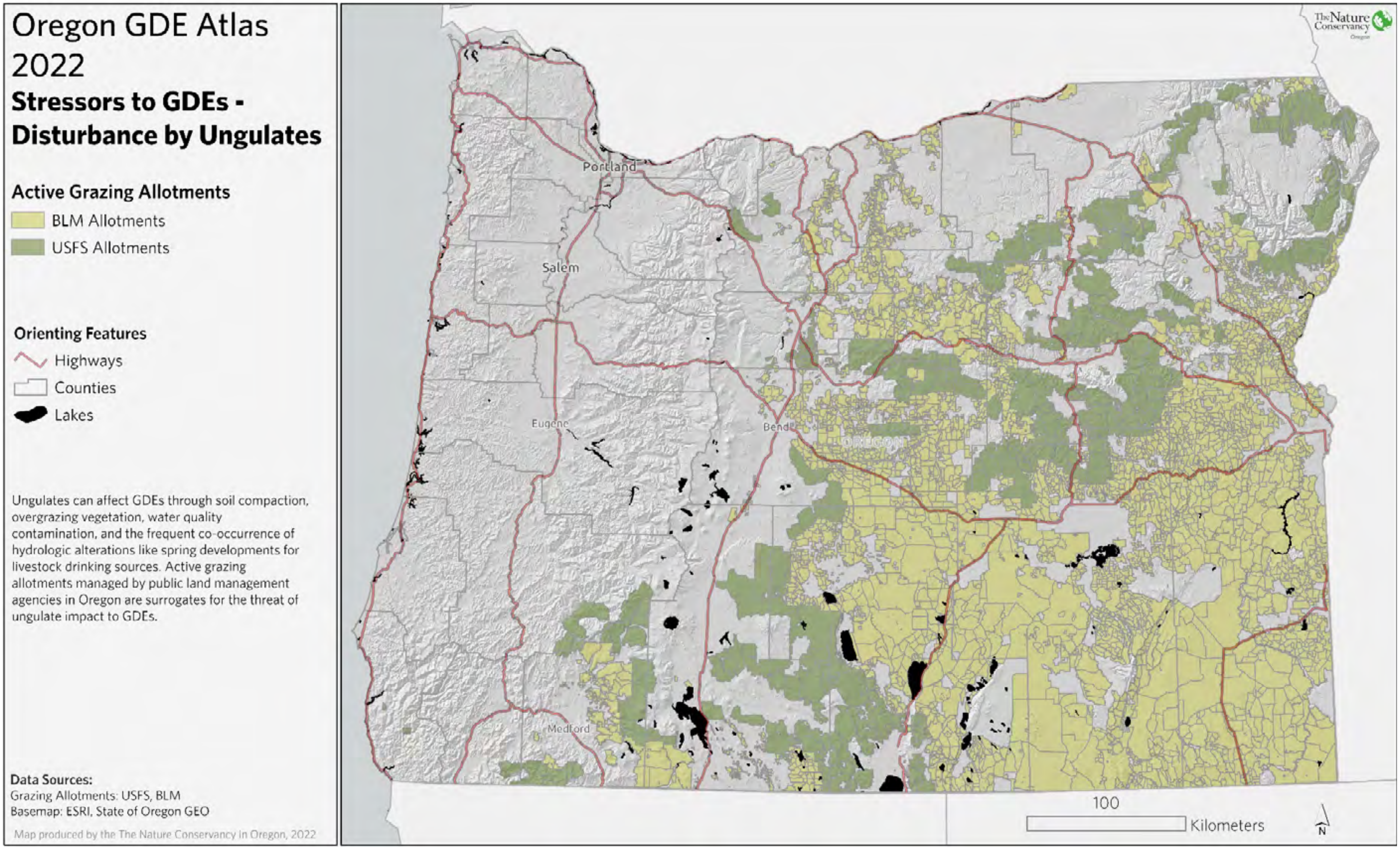

Figure B1 iii a: Ungulates: GDEs within active grazing allotments.

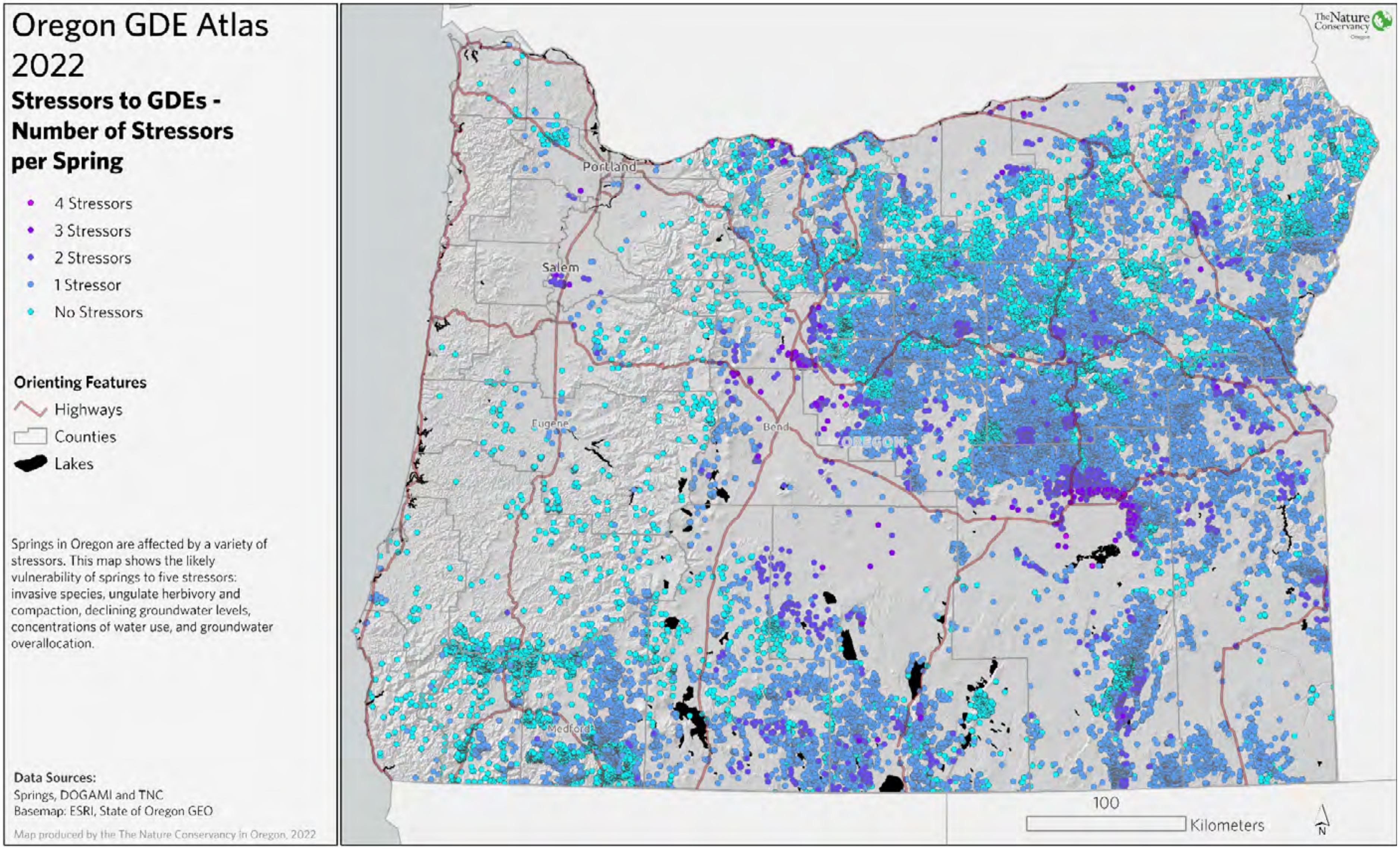

Figure B1 iv: Stressors to springs

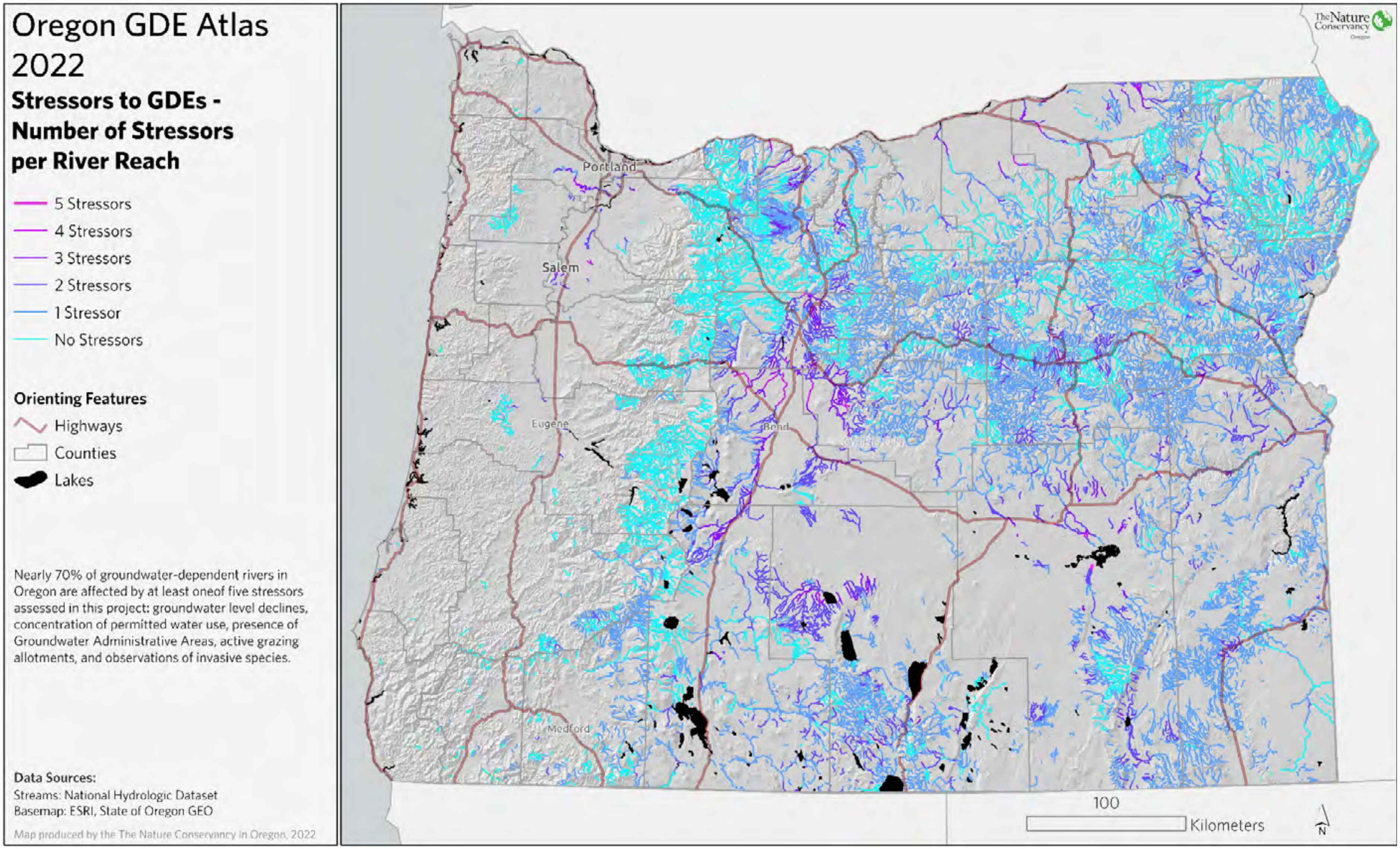

Figure B1 v: Stressors to groundwater-dependent rivers

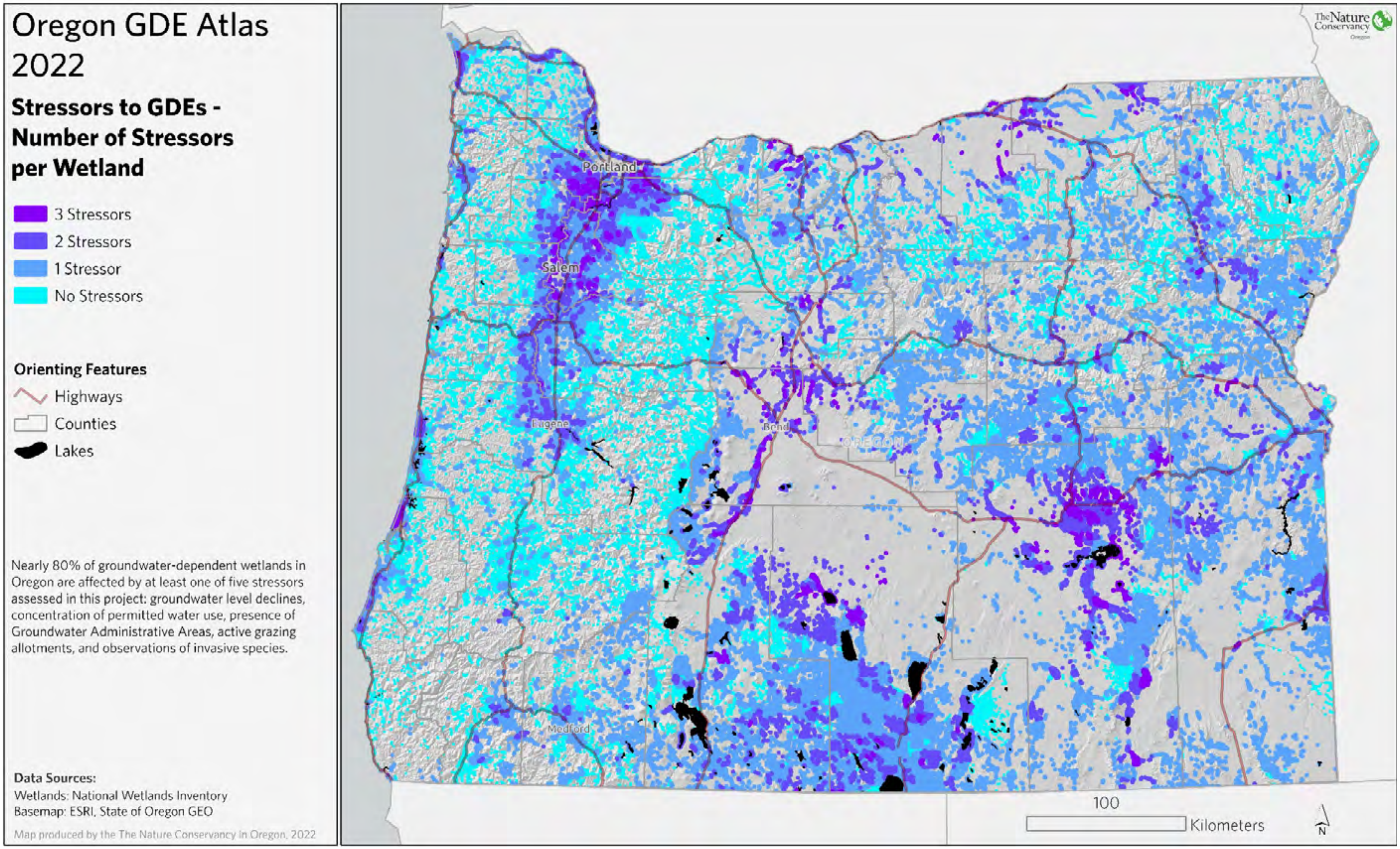

Figure B1 vi: Stressors to groundwater-dependent wetlands

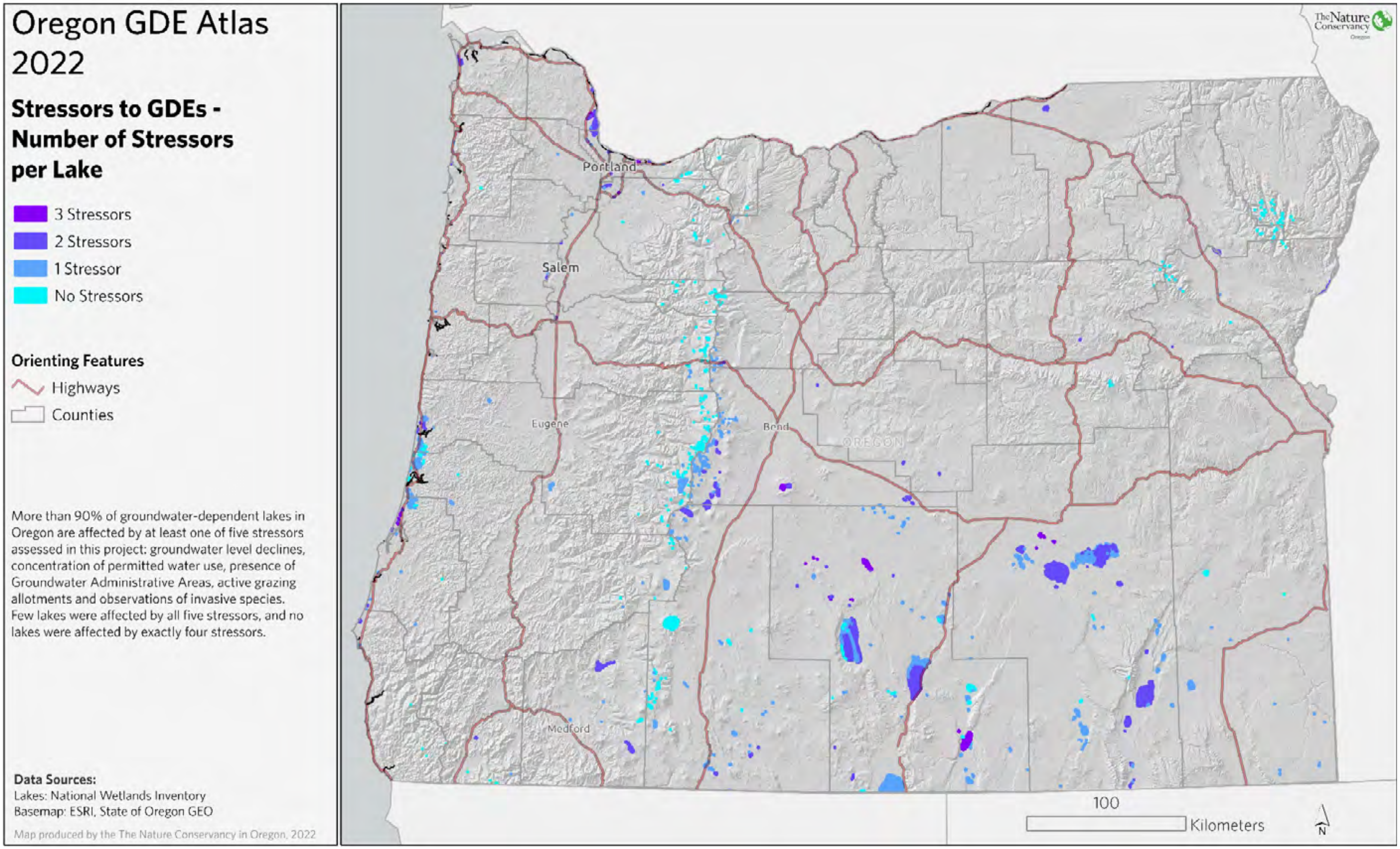

Figure B1 vii: Stressors to groundwater-dependent lakes

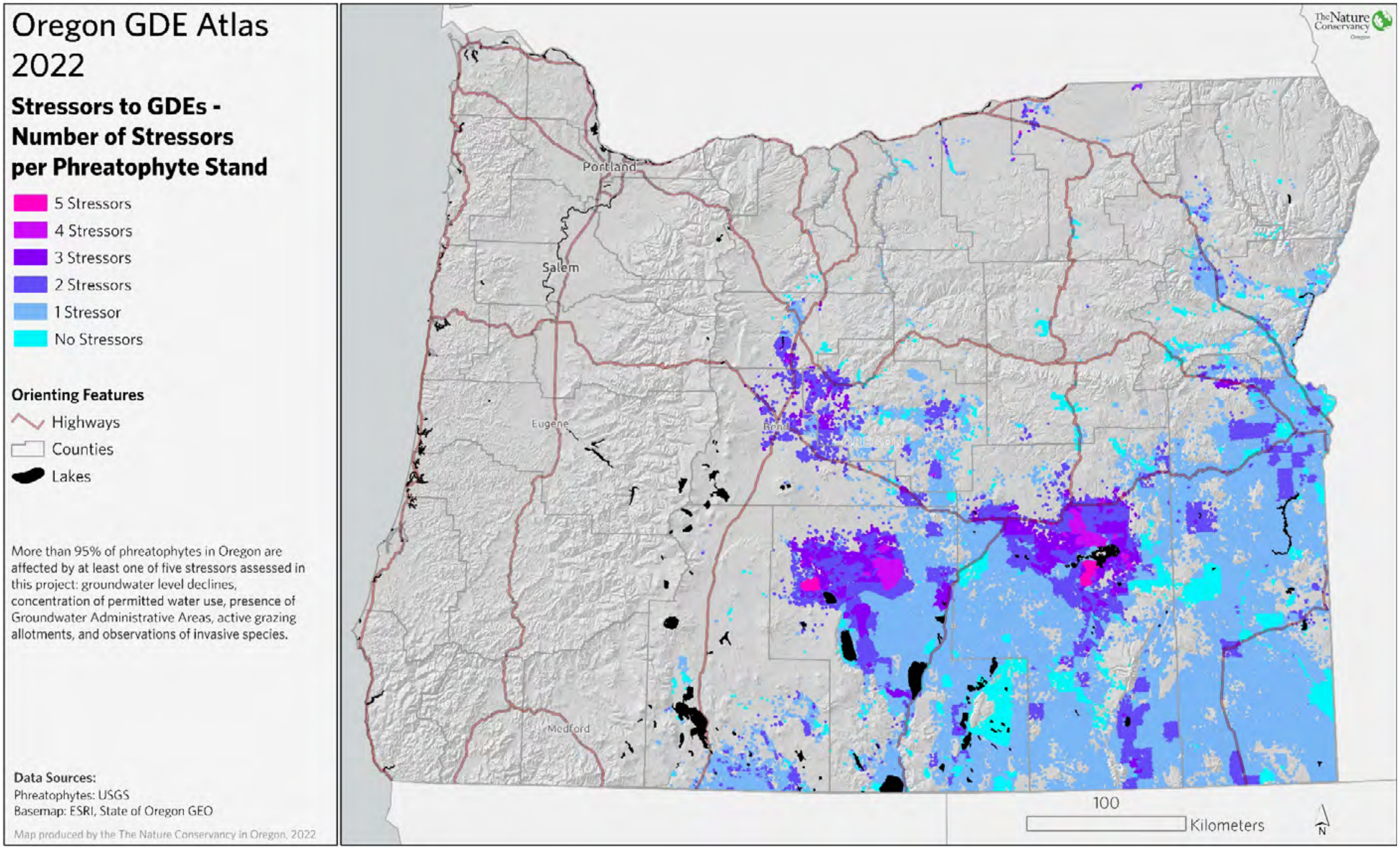

Figure B1 viii: Stressors to phreatophytes

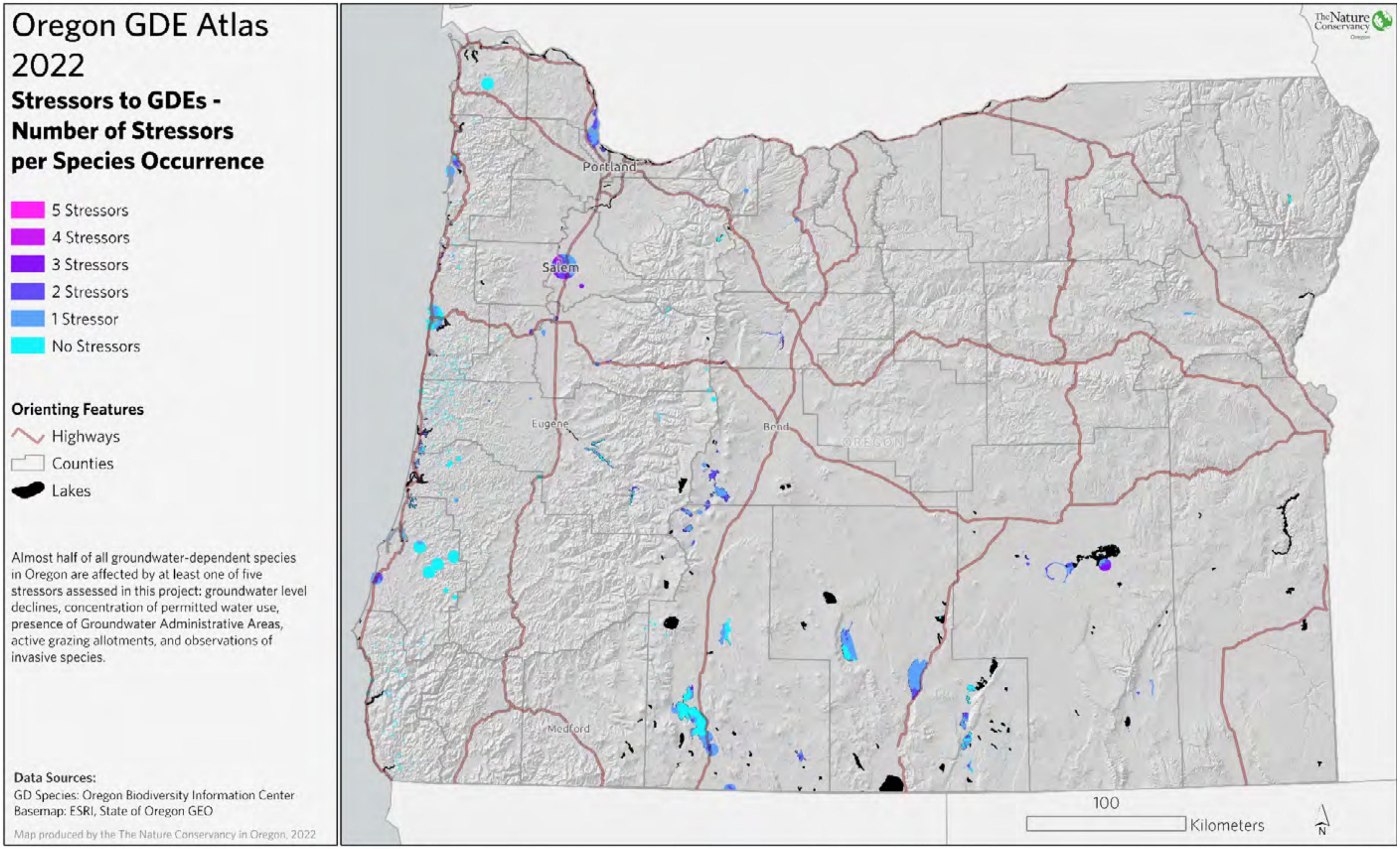

Figure B1 ix: Stressors to non-phreatophytic groundwater-dependent species

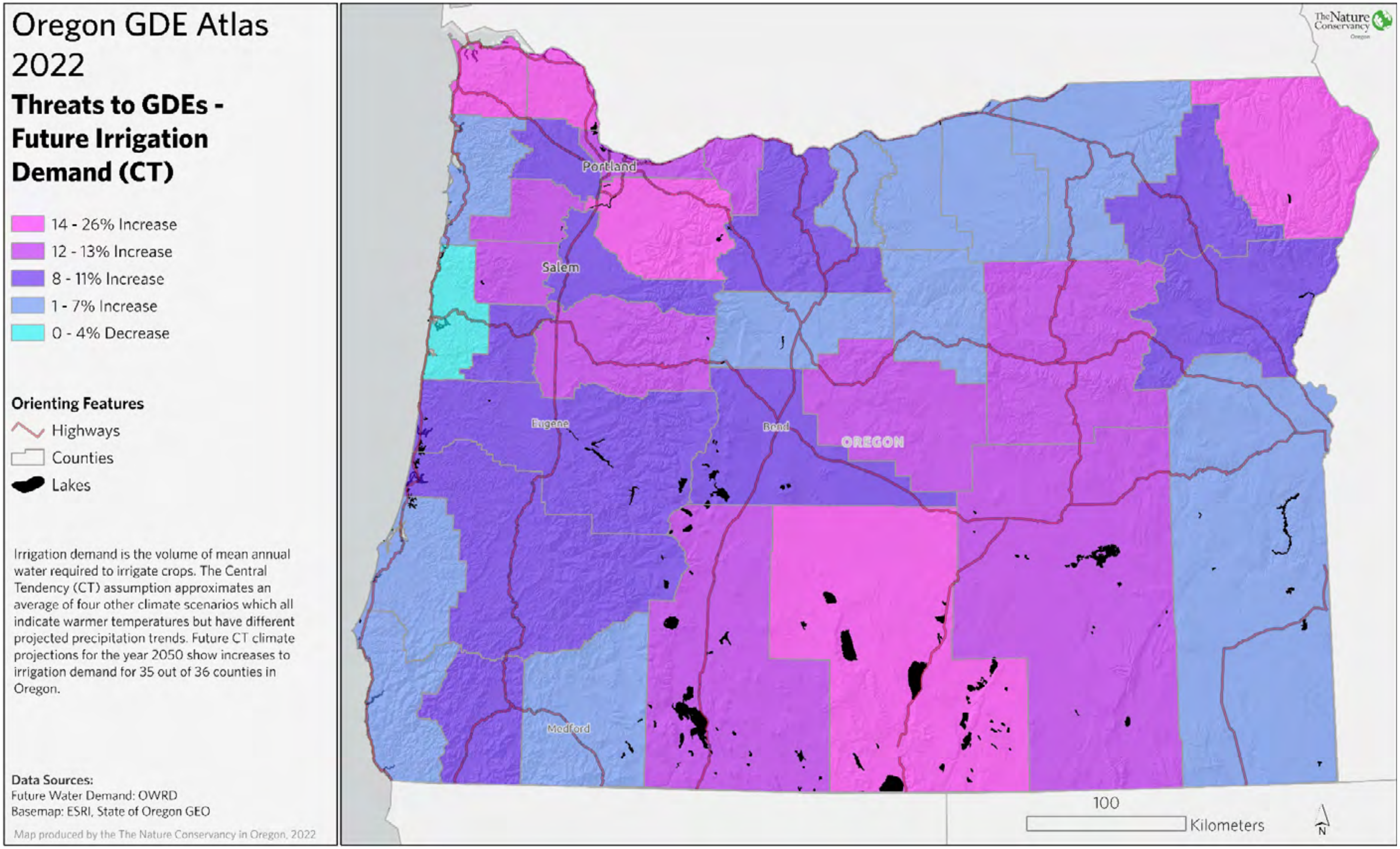

Figure B2 i a: Groundwater withdrawals: change in irrigation demand (central tendency scenario)

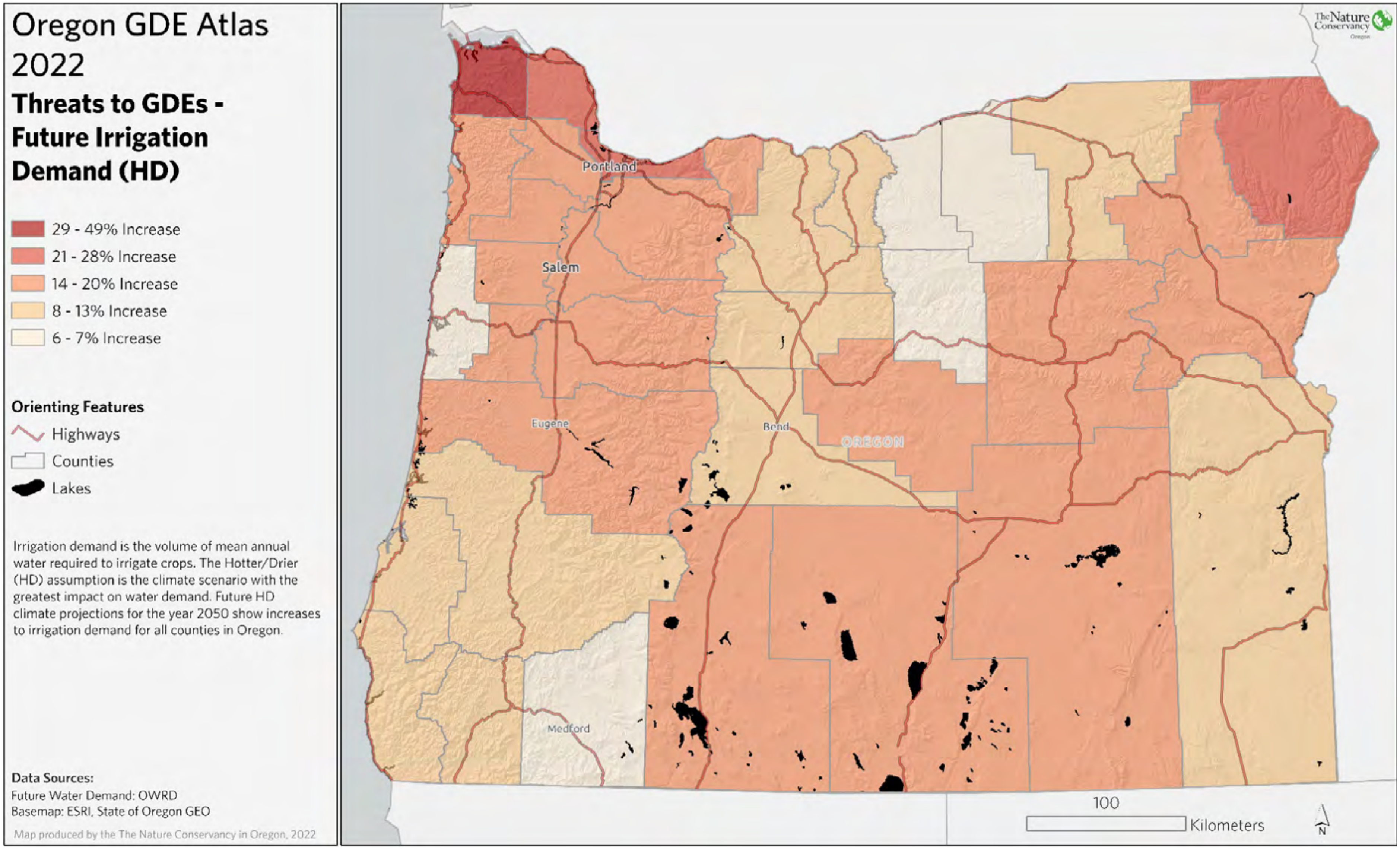

Figure B2 i b: Groundwater withdrawals: change in irrigation demand (hotter/drier scenario)

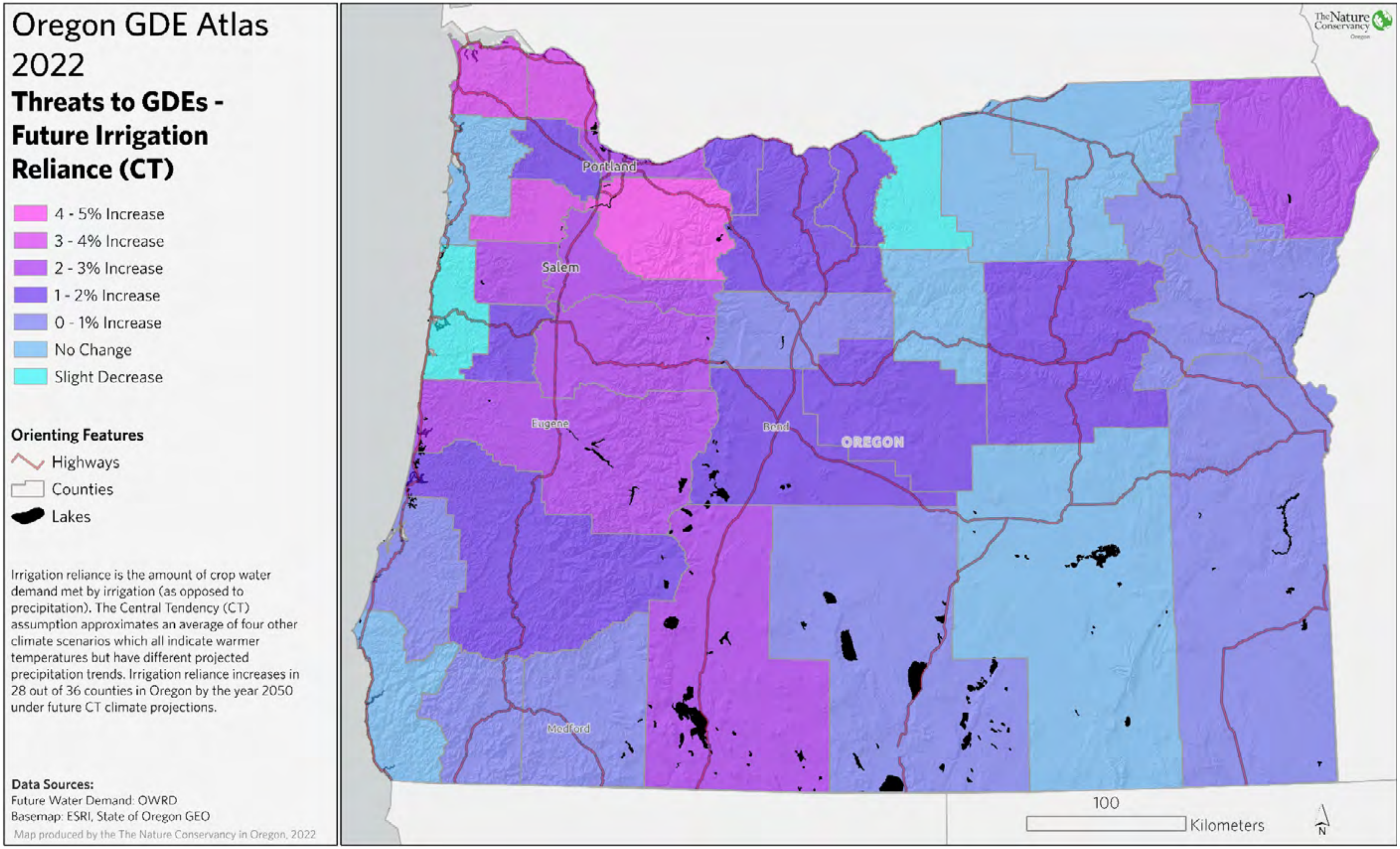

Figure B2 i c: Groundwater withdrawals: change in irrigation reliance (central tendency scenario)

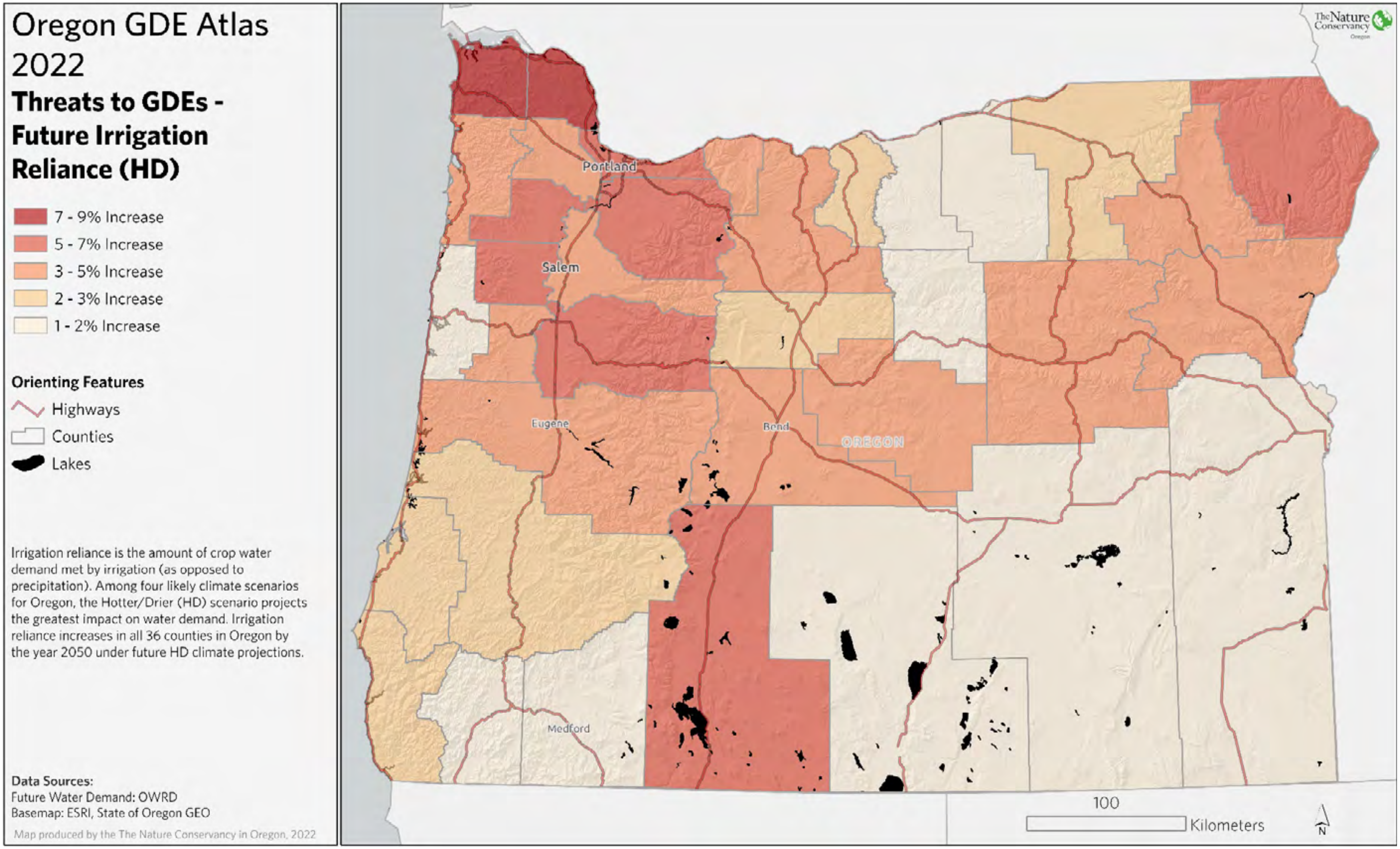

Figure B2 i d: Groundwater withdrawals: change in irrigation reliance (hotter/drier scenario)

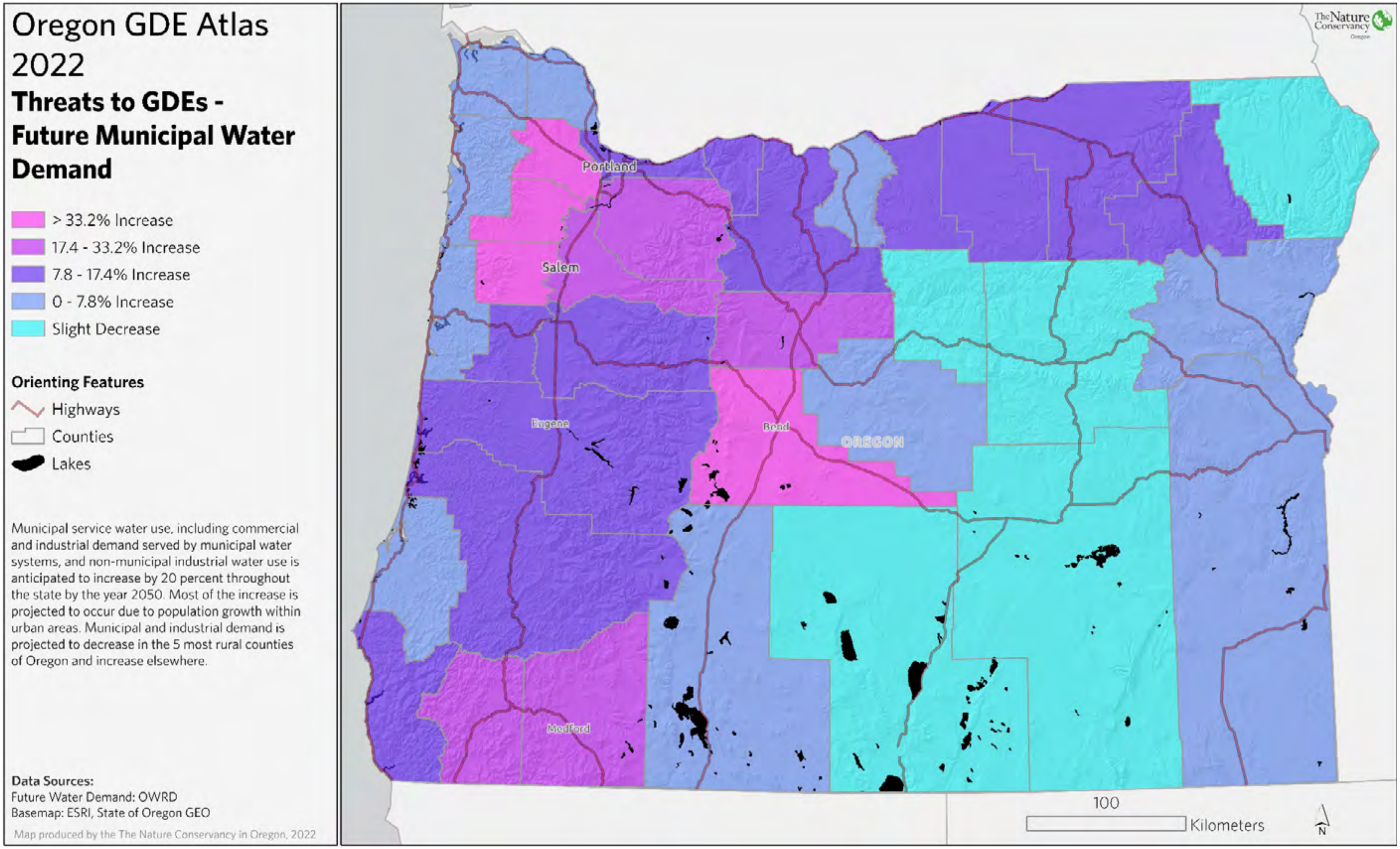

Figure B2 i e: Groundwater withdrawals: change in municipal water demand

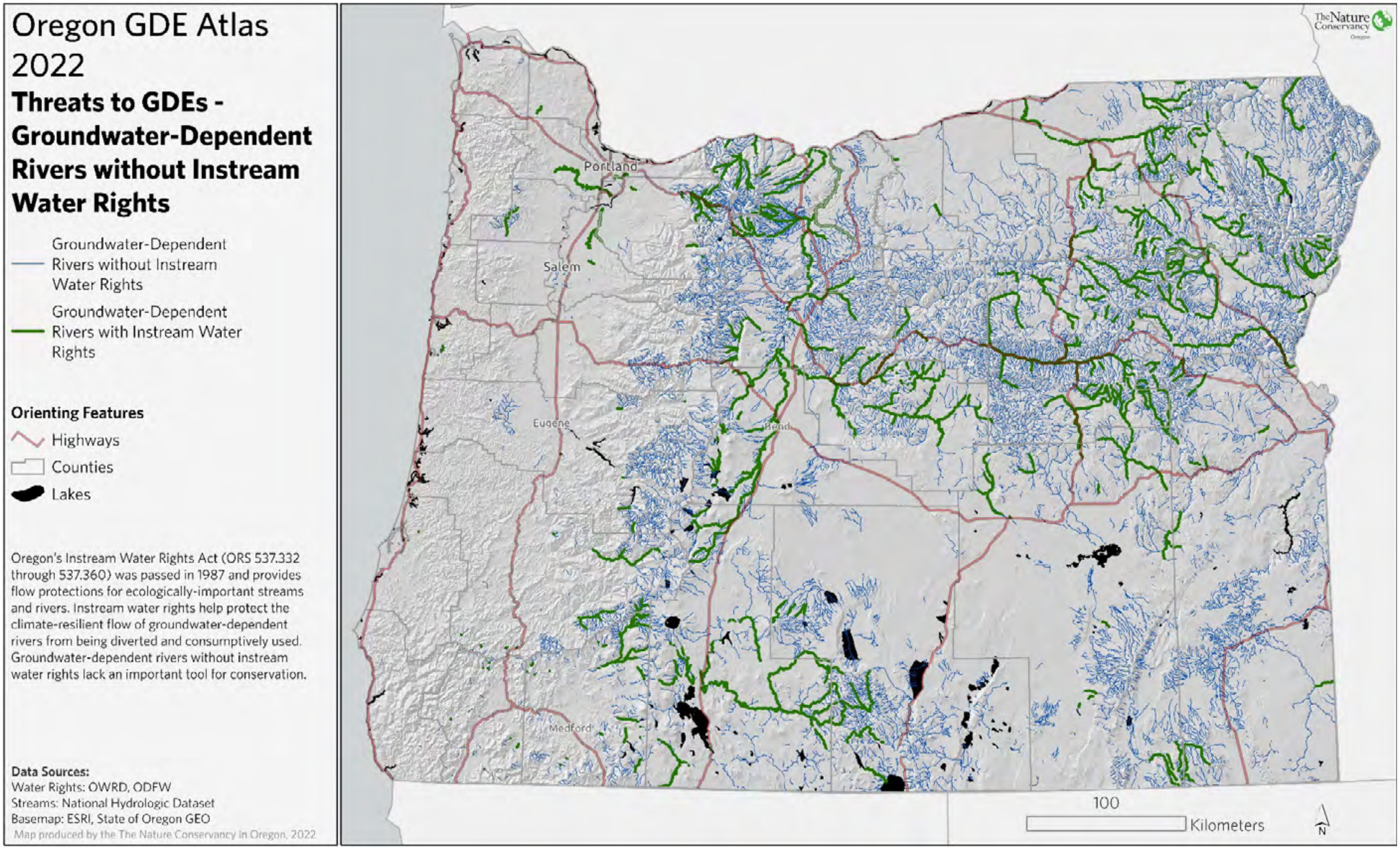

Figure B2 i f: Groundwater withdrawals: groundwater-dependent rivers lacking instream water right protections

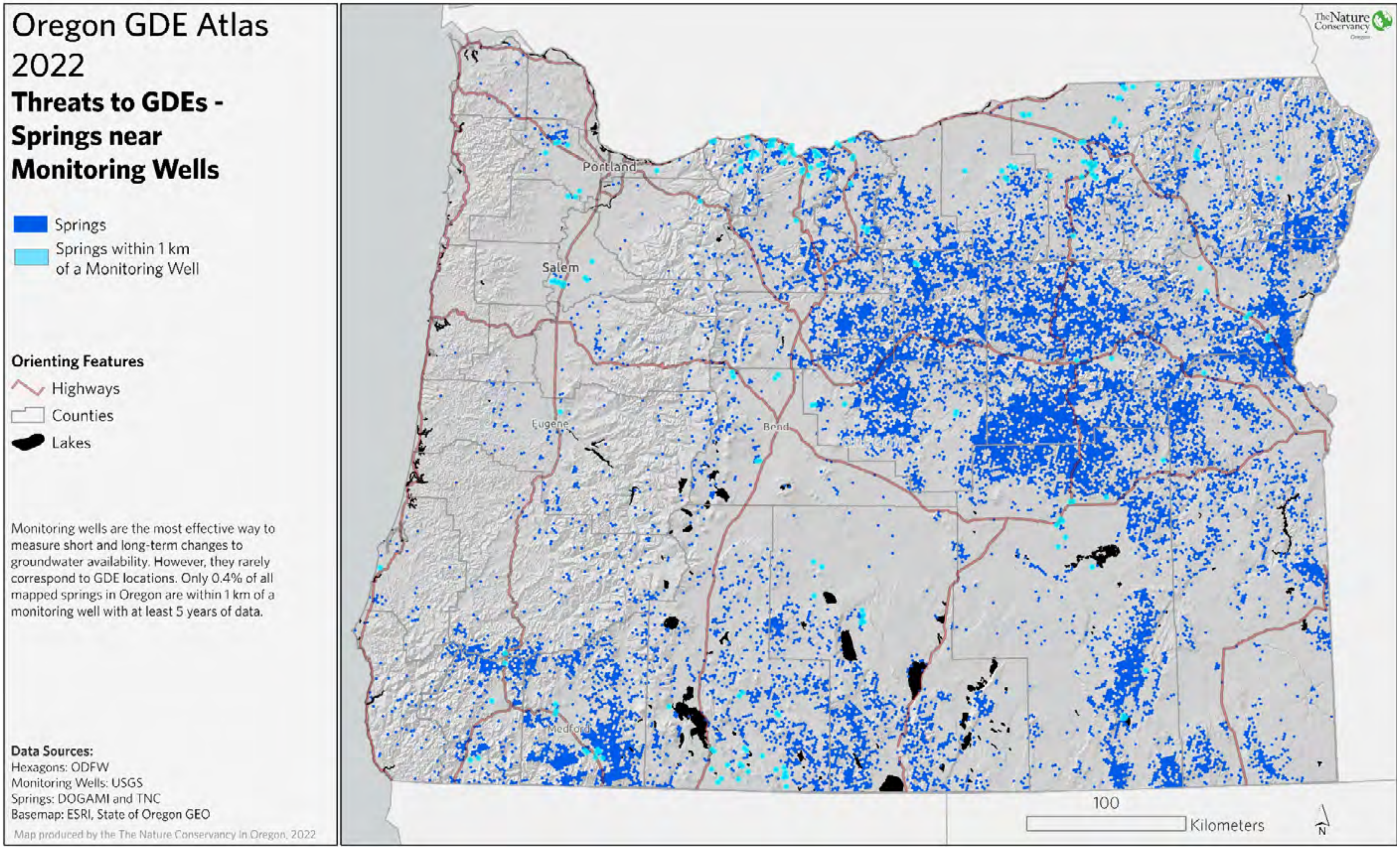

Figure B2 i g: Groundwater withdrawals: springs near monitoring wells

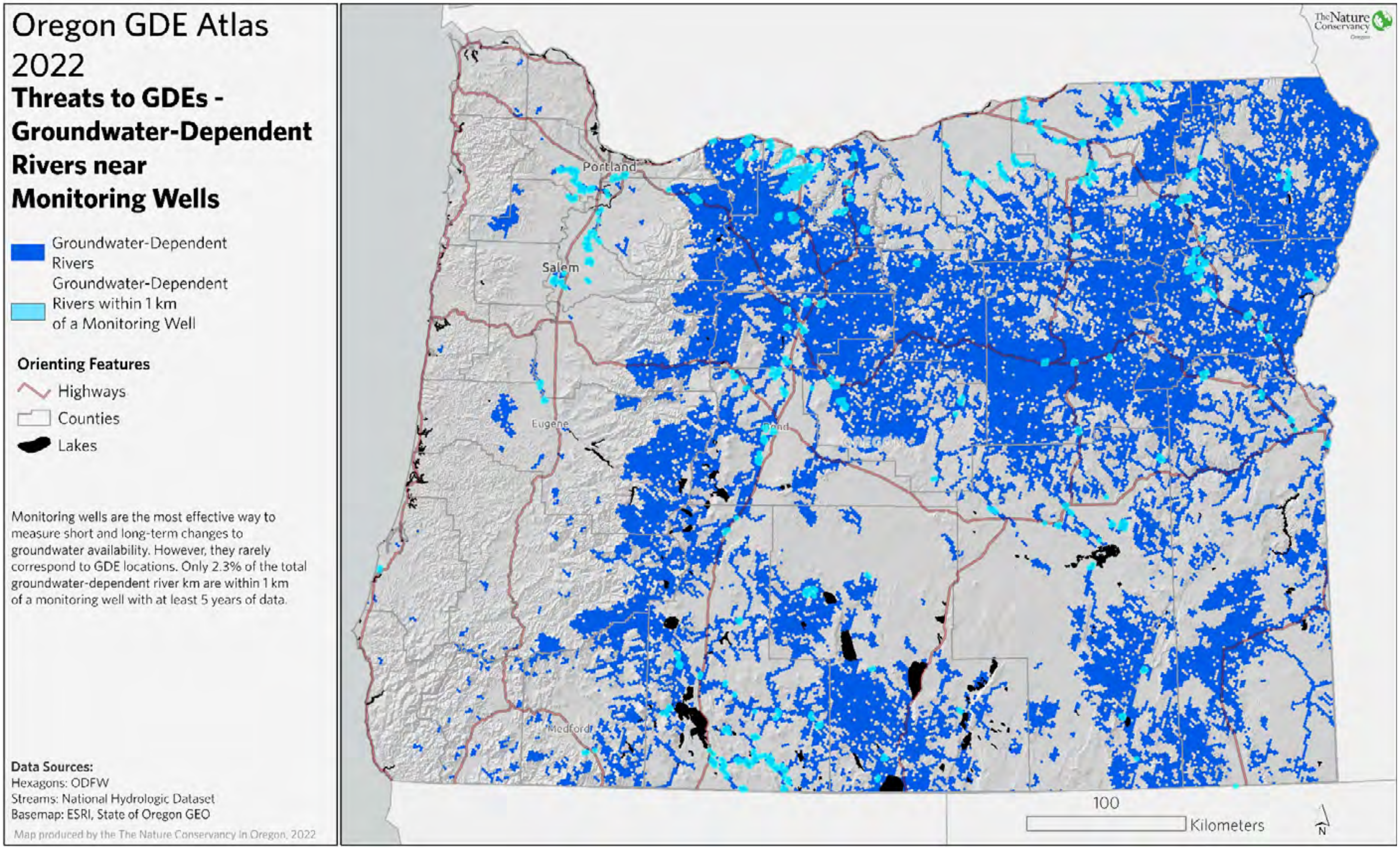

Figure B2 i h: Groundwater withdrawals: groundwater-dependent rivers near monitoring wells

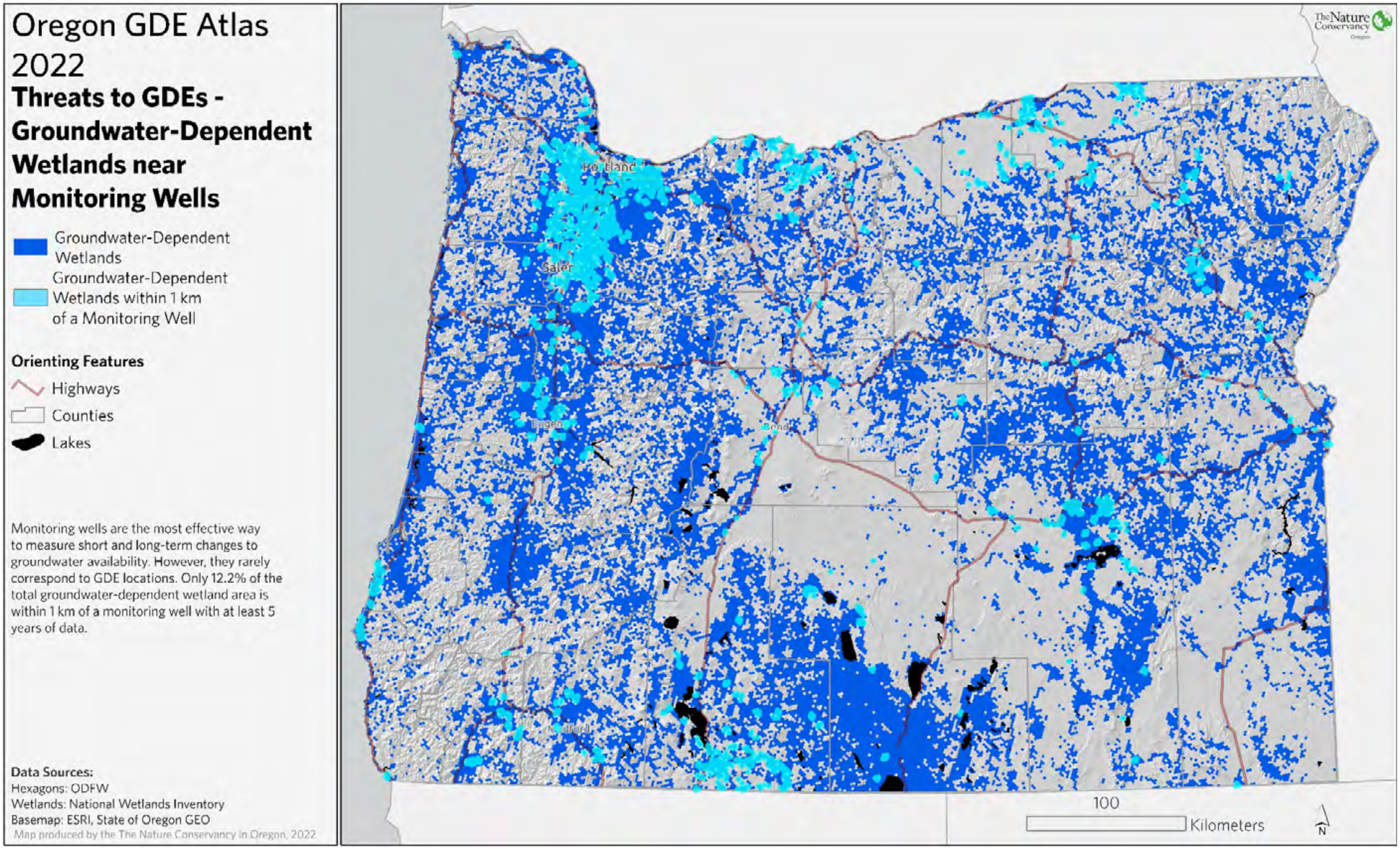

Figure B2 i i: Groundwater withdrawals: groundwater-dependent wetlands near monitoring wells

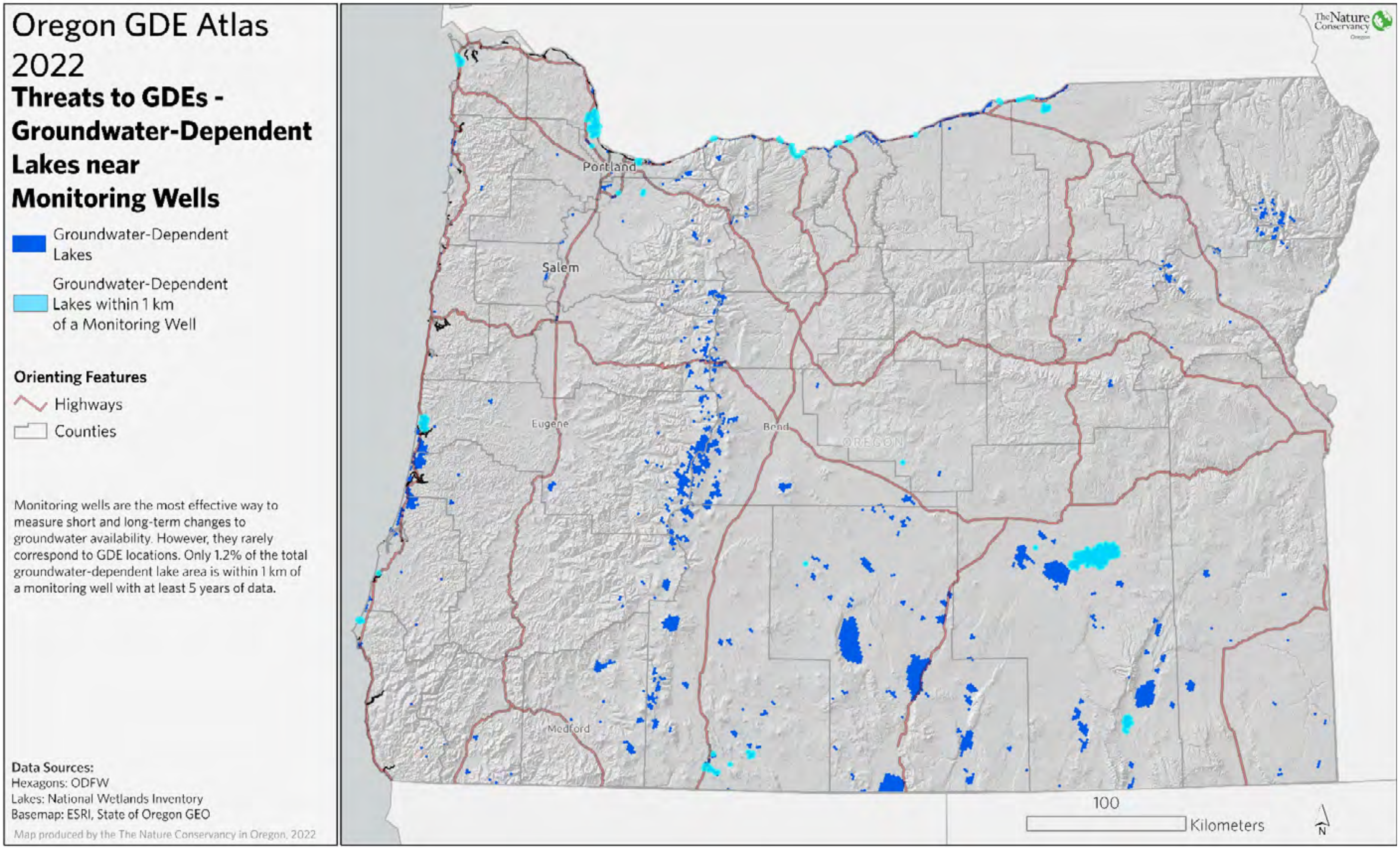

Figure B2 i j: Groundwater withdrawals: groundwater-dependent lakes near monitoring wells

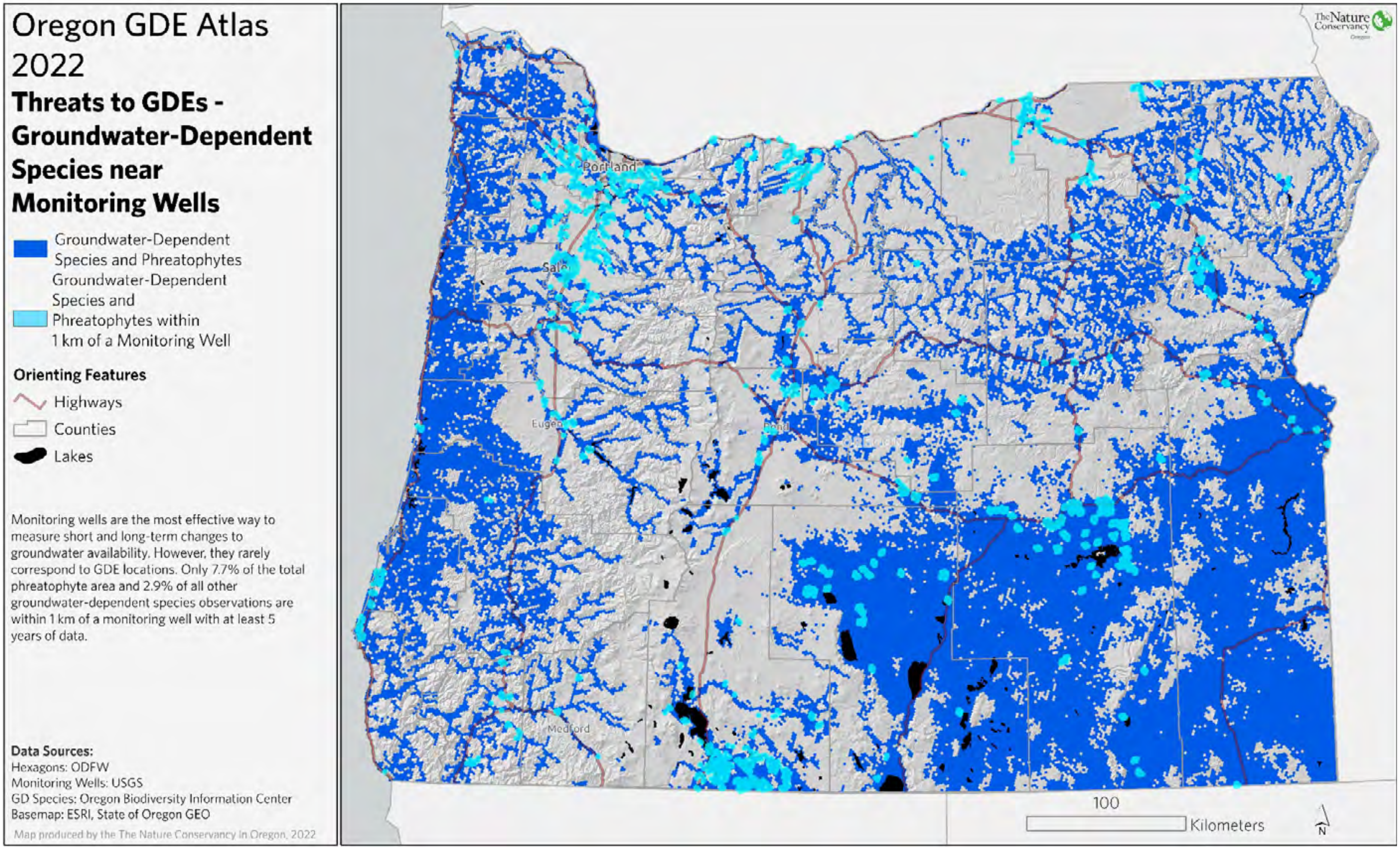

Figure B2 i k: Groundwater withdrawals: groundwater-dependent species and phreatophytes near monitoring wells

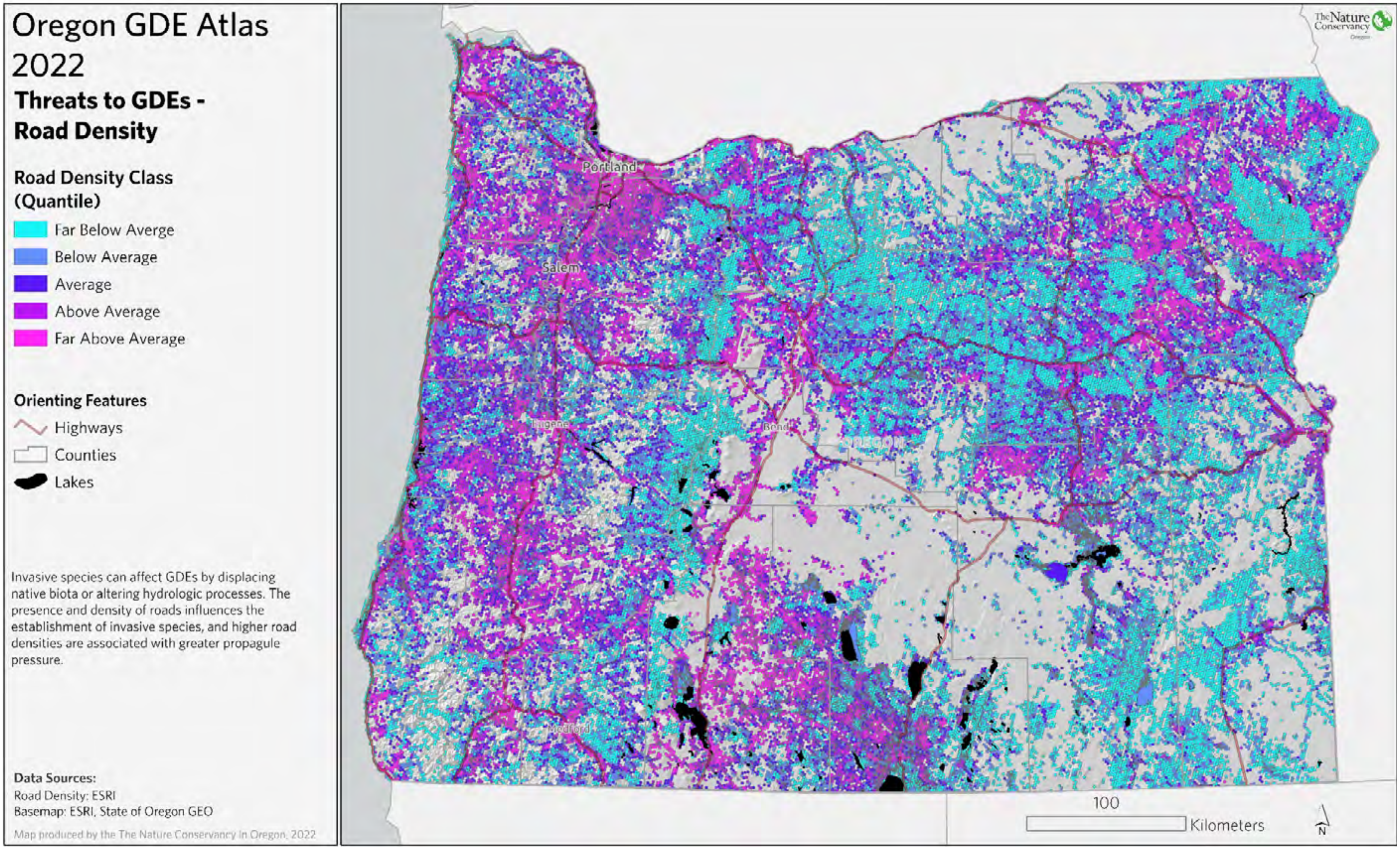

Figure B2 ii a: Invasive species: road density

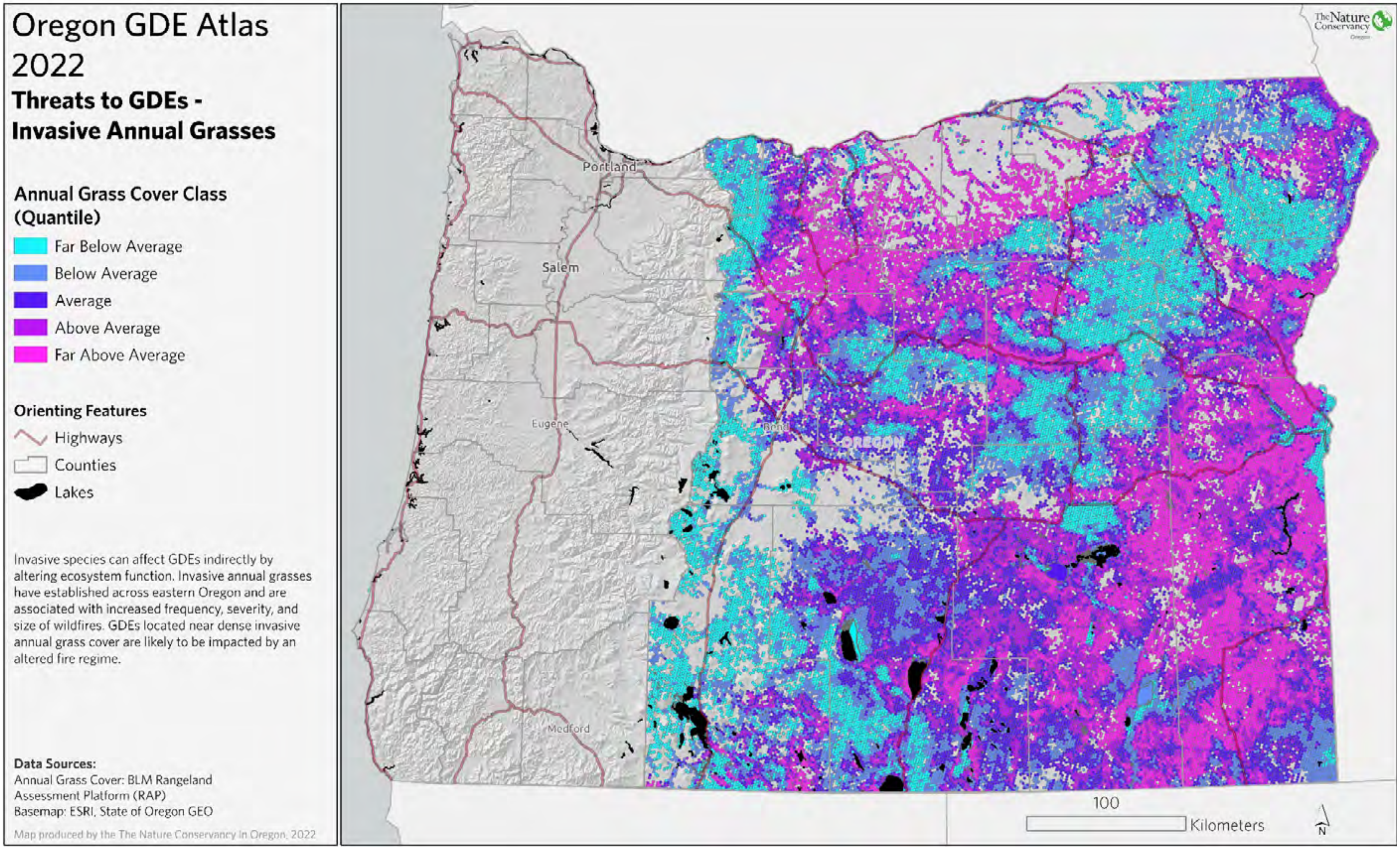

Figure B2 ii b: Invasive species: invasive annual grass cover

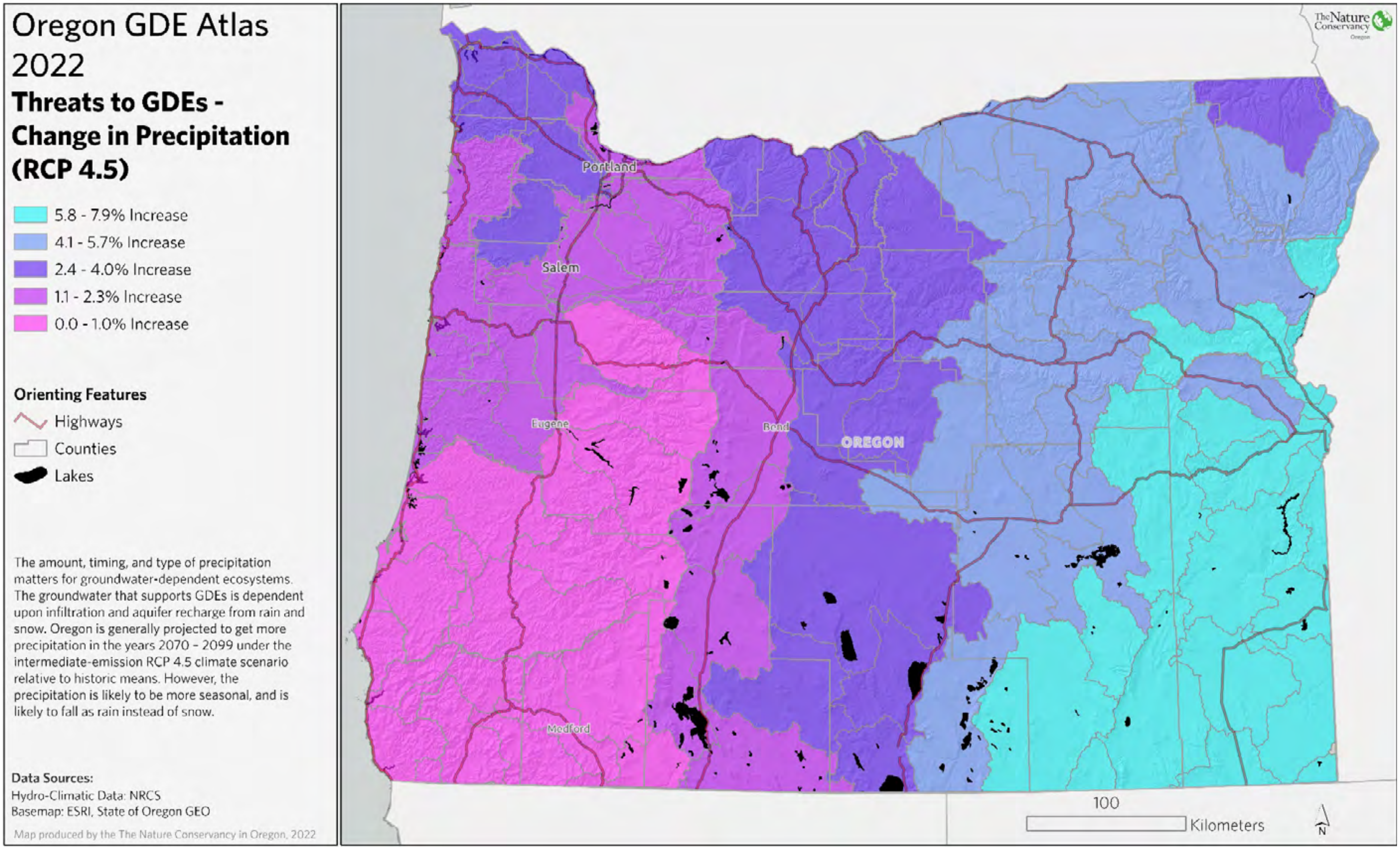

Figure B2 iii a: Climate: precipitation anomaly (RCP 4.5)

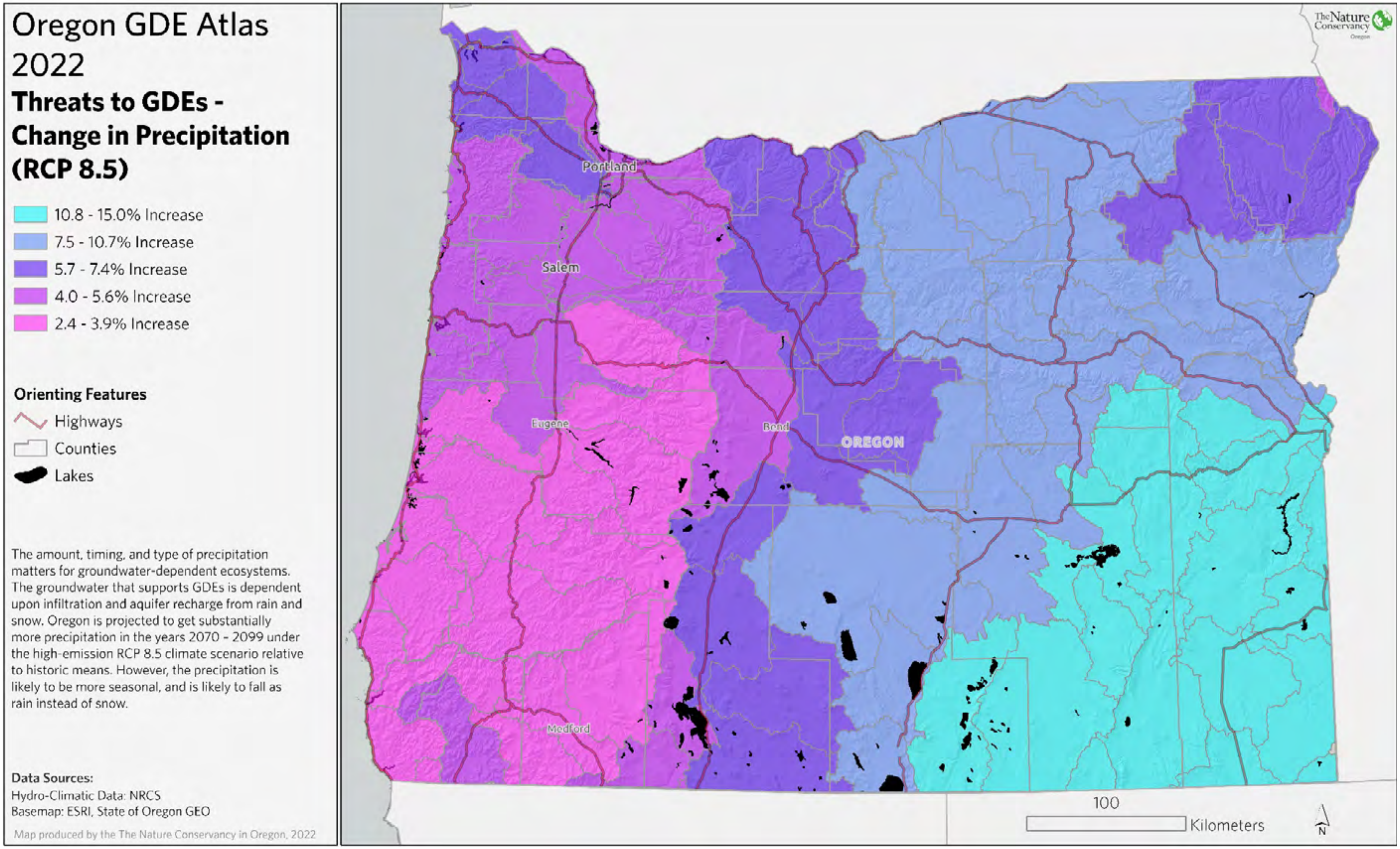

Figure B2 iii b: Climate: precipitation anomaly (RCP 8.5)

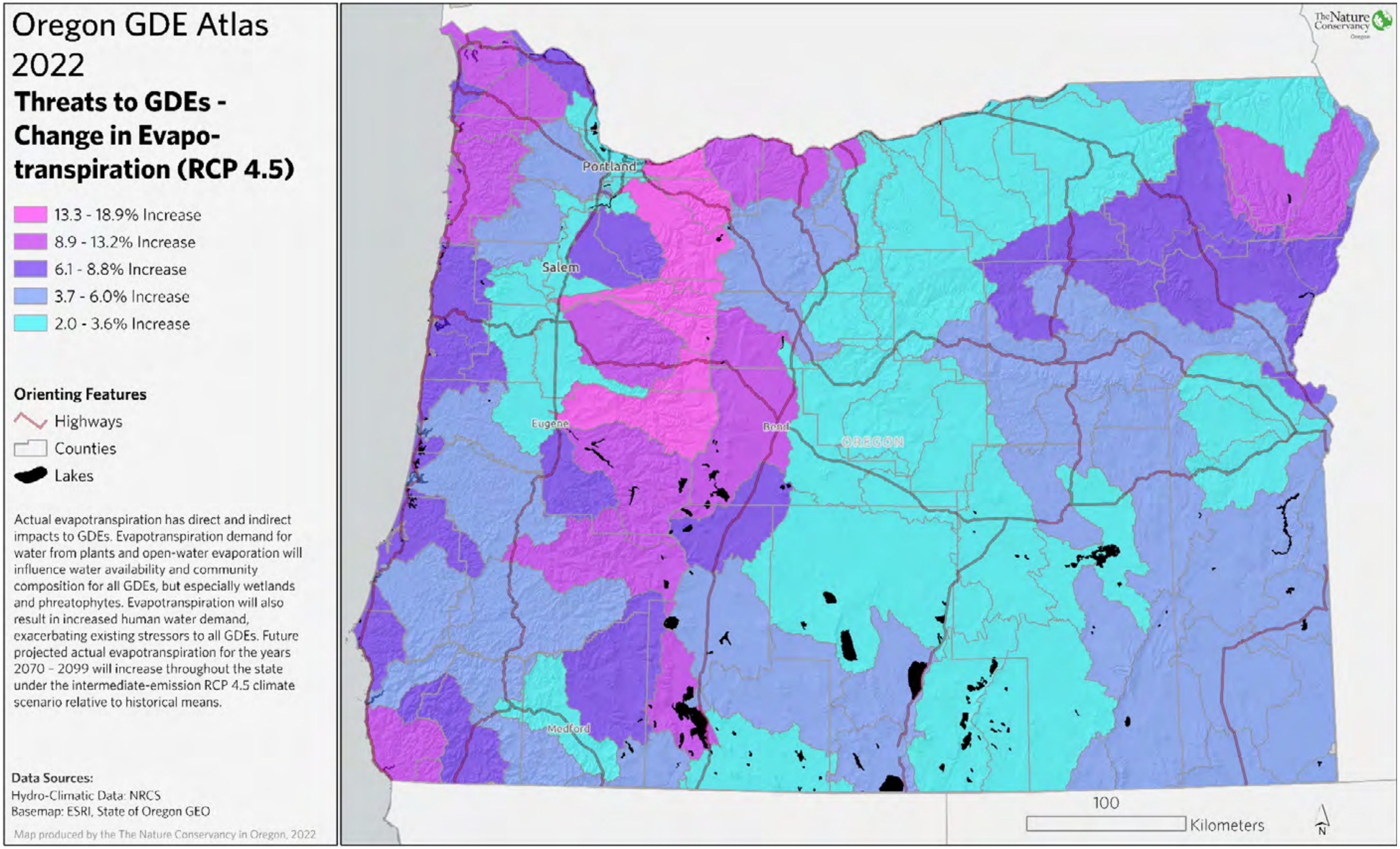

Figure B2 iii c: Climate: actual evapotranspiration anomaly (RCP 4.5)

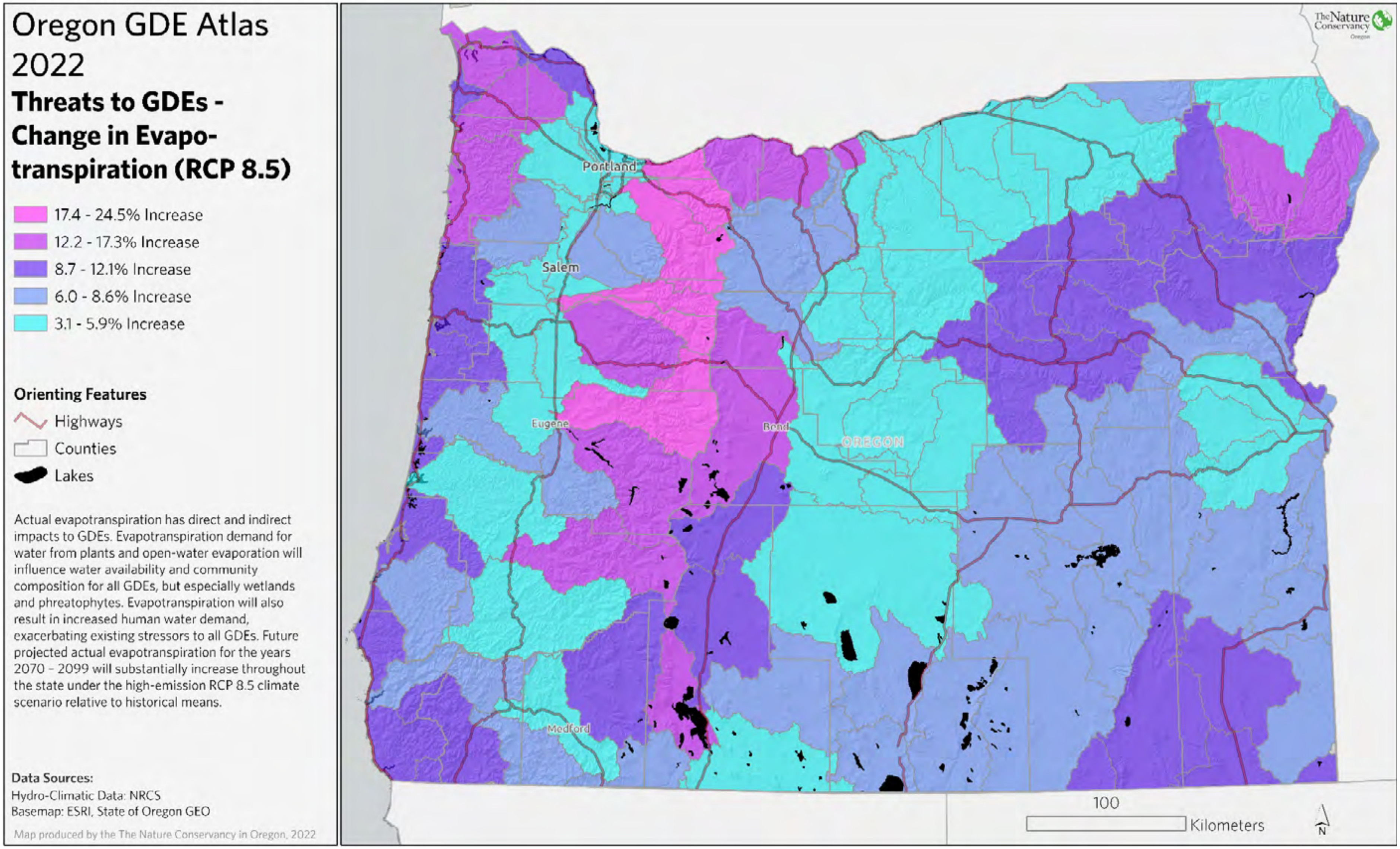

Figure B2 iii d: Climate: actual evapotranspiration anomaly (RCP 8.5)

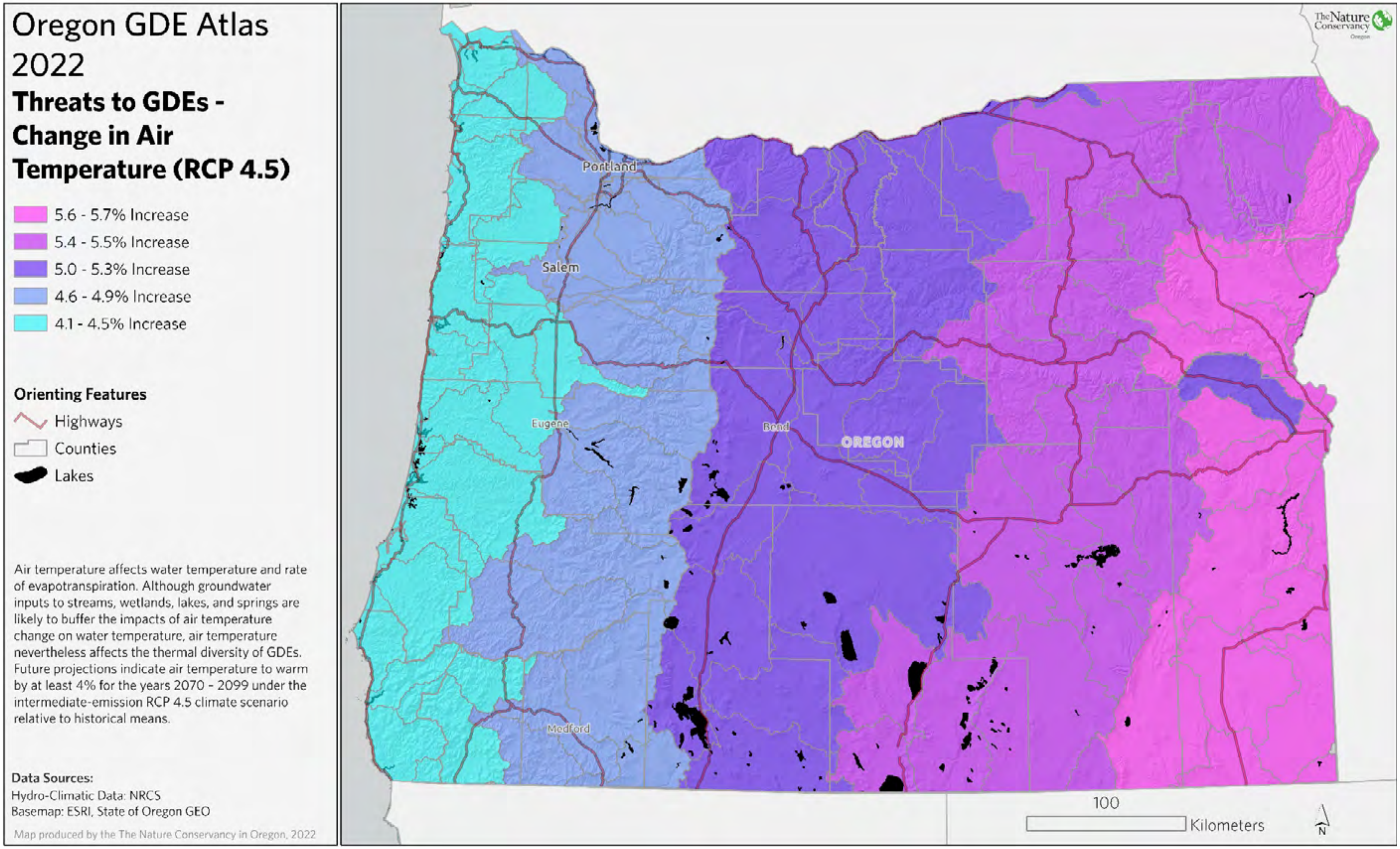

Figure B2 iii e: Climate: air temperature anomaly (RCP 4.5)

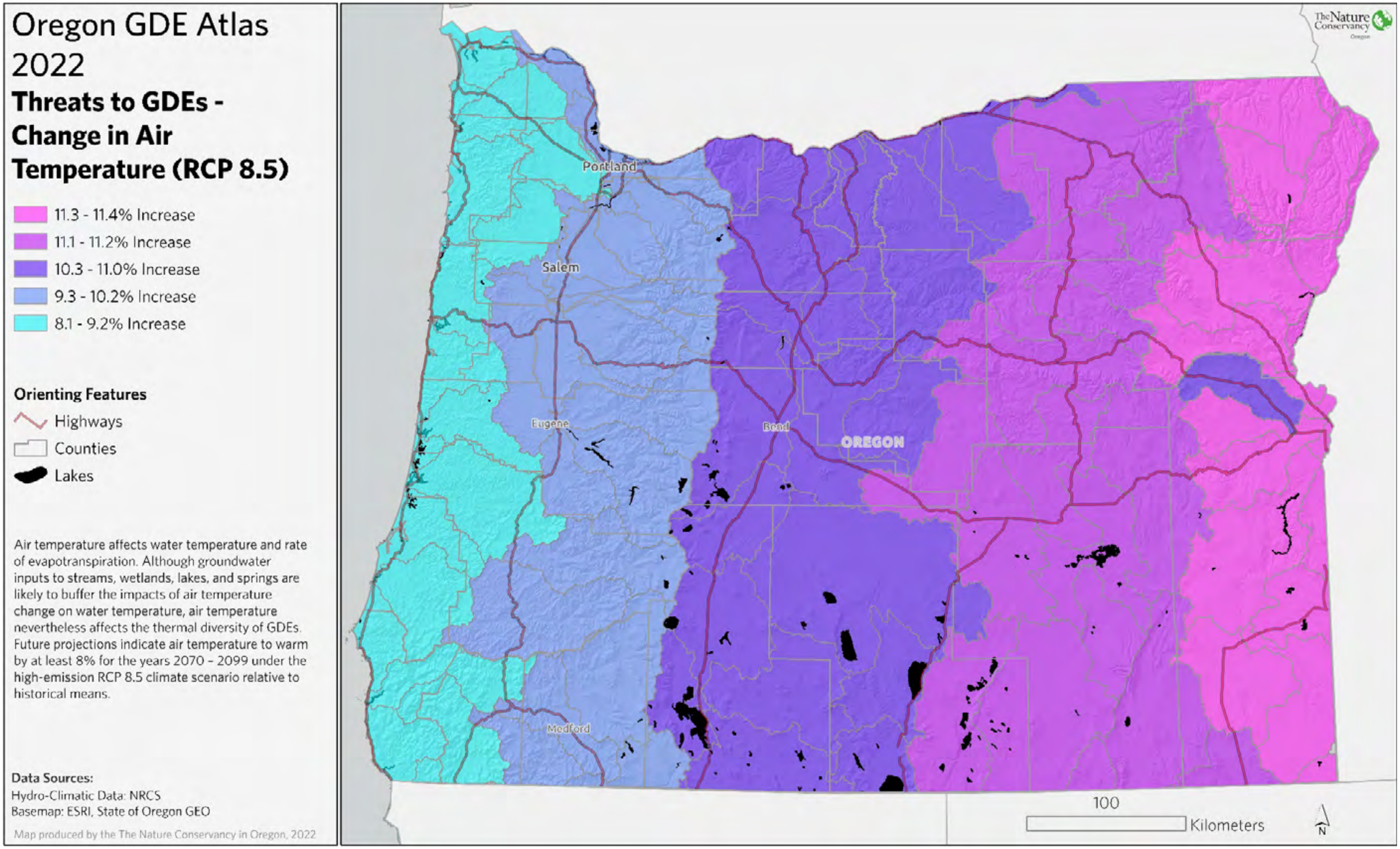

Figure 2B iii f: Climate: air temperature anomaly (RCP 8.5)

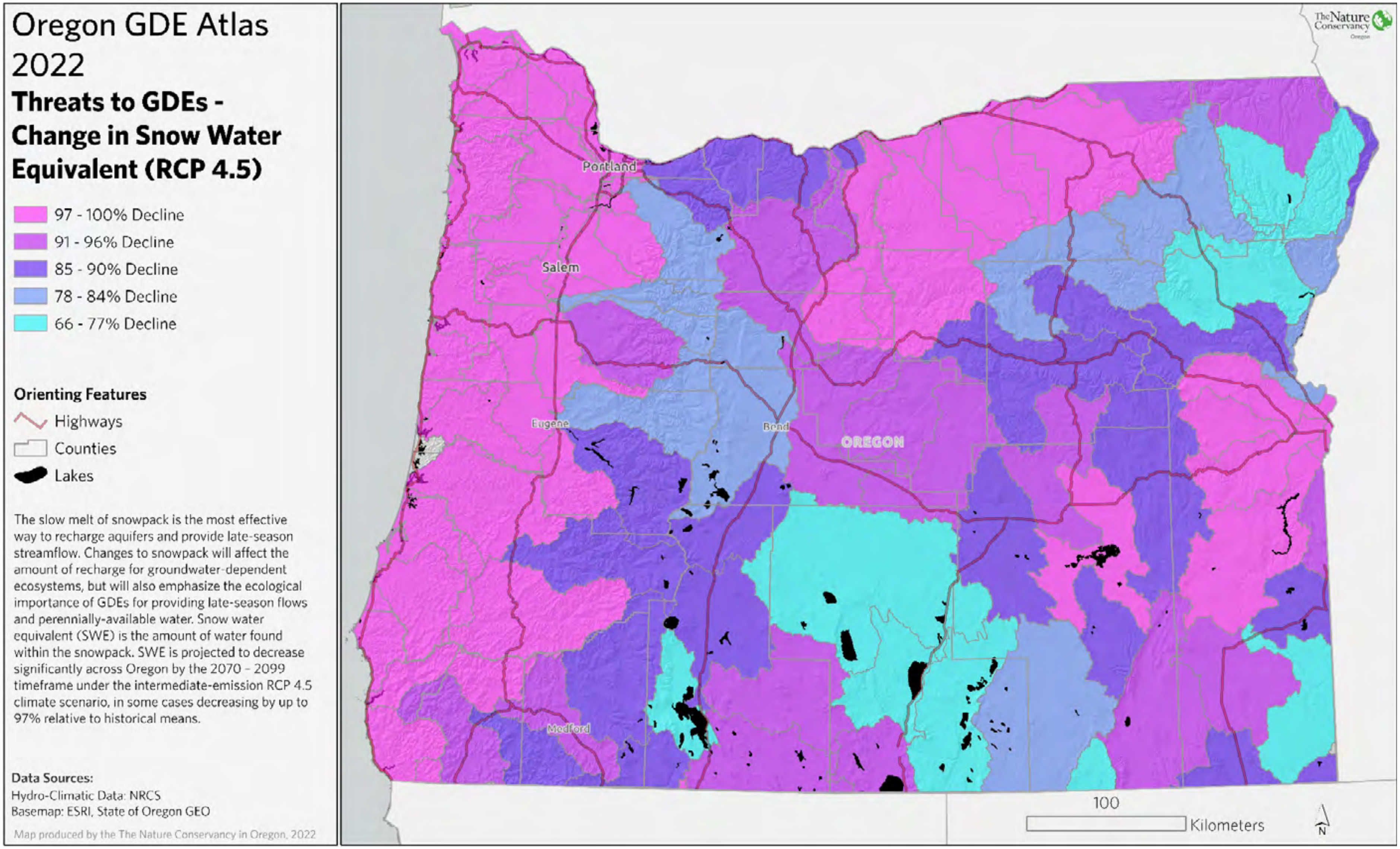

Figure B2 iii g: Climate: snow water equivalent anomaly (RCP 4.5)

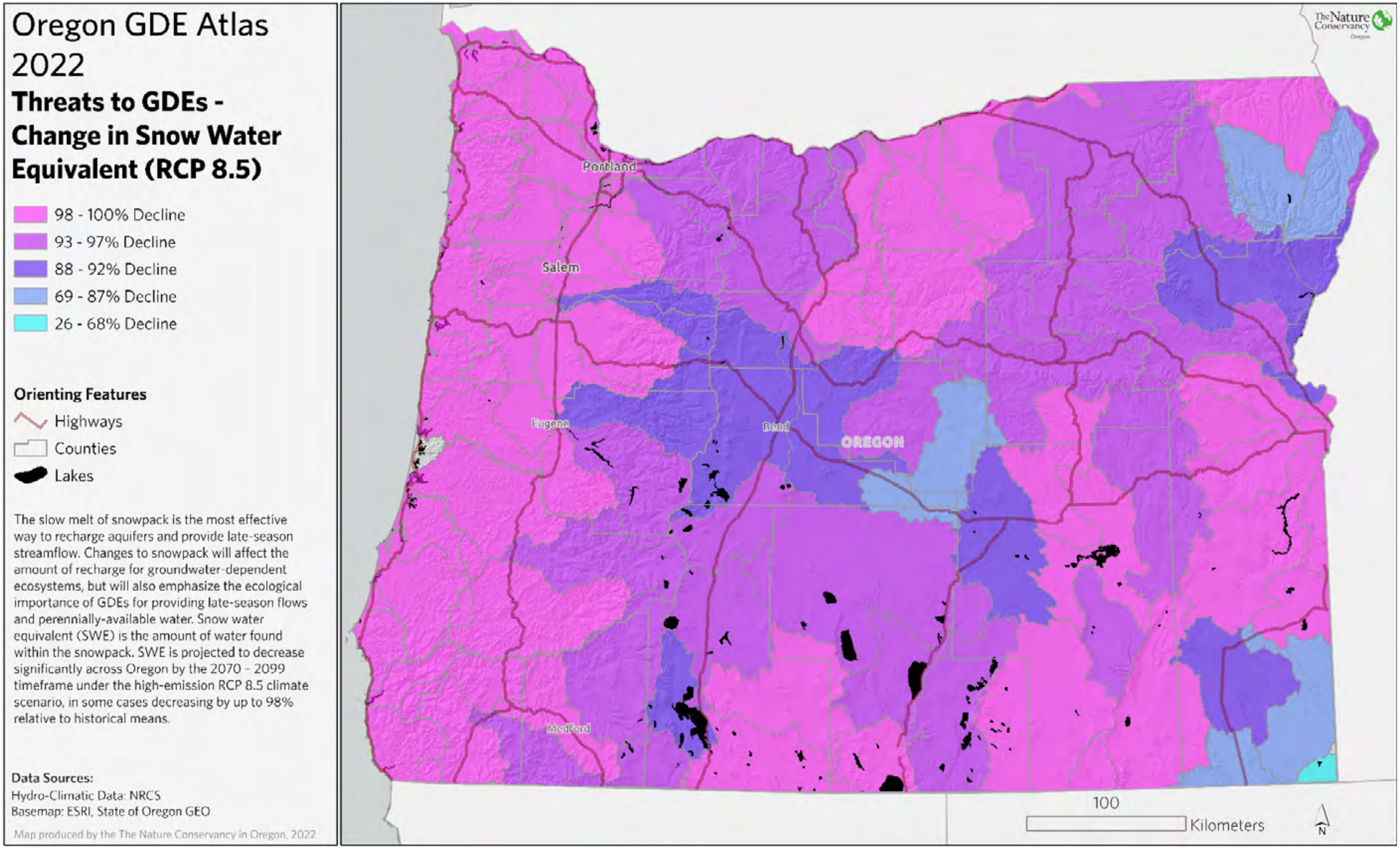

Figure B2 iii h: Climate: snow water equivalent anomaly (RCP 8.5)

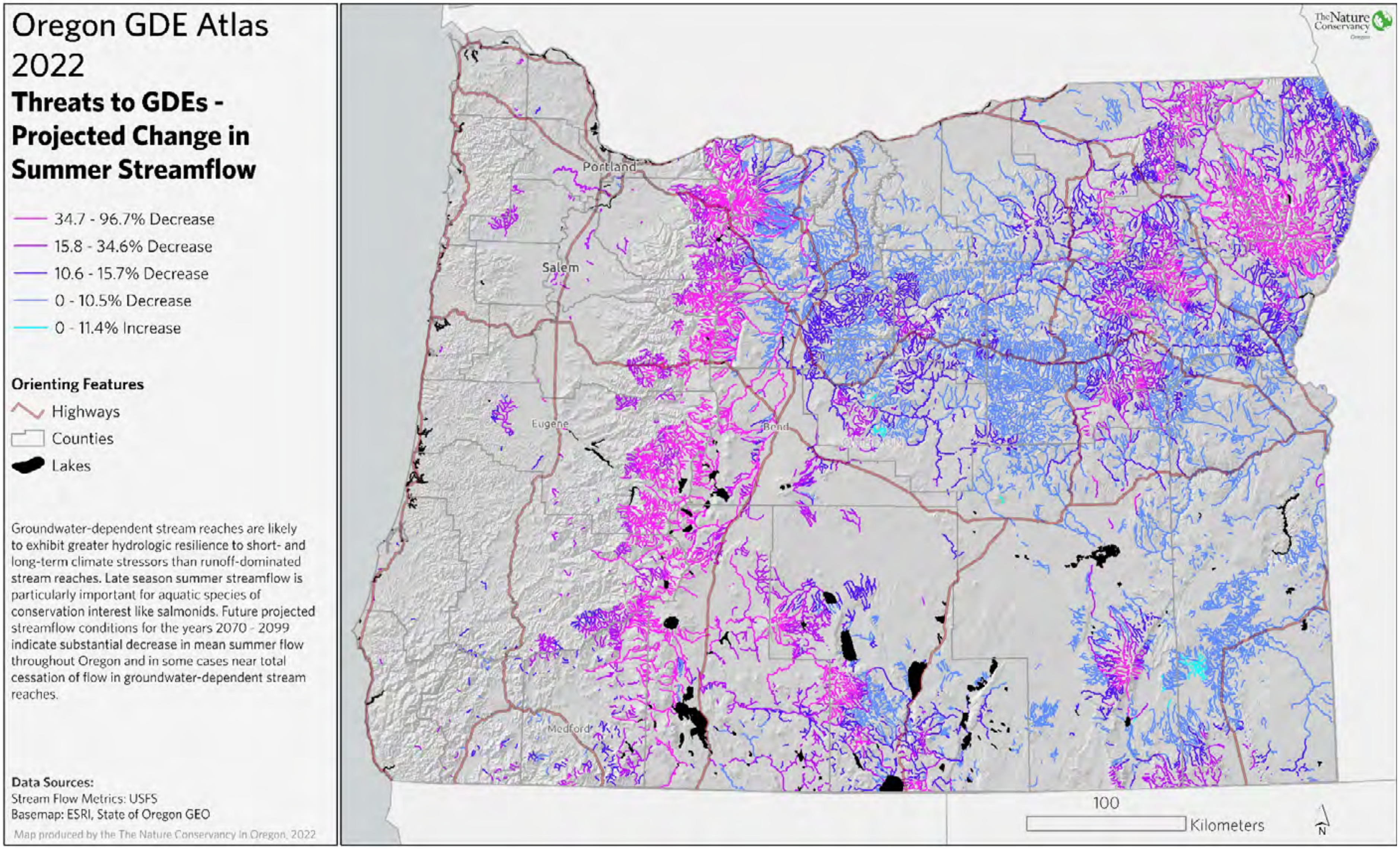

Figure B2 iii i: Climate: projected future mean summer streamflow

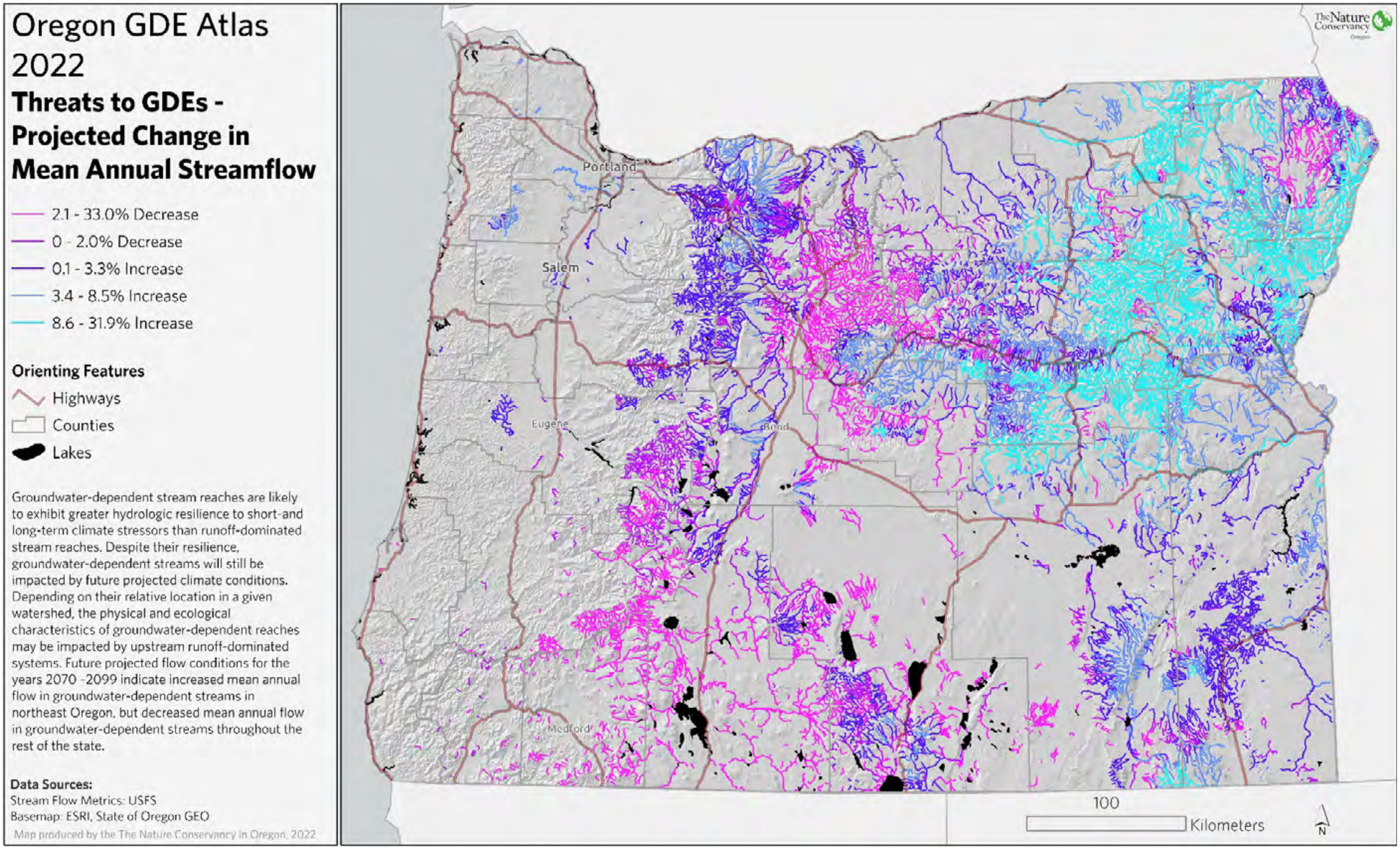

Figure B2 iii j: Climate: projected future mean annual streamflow

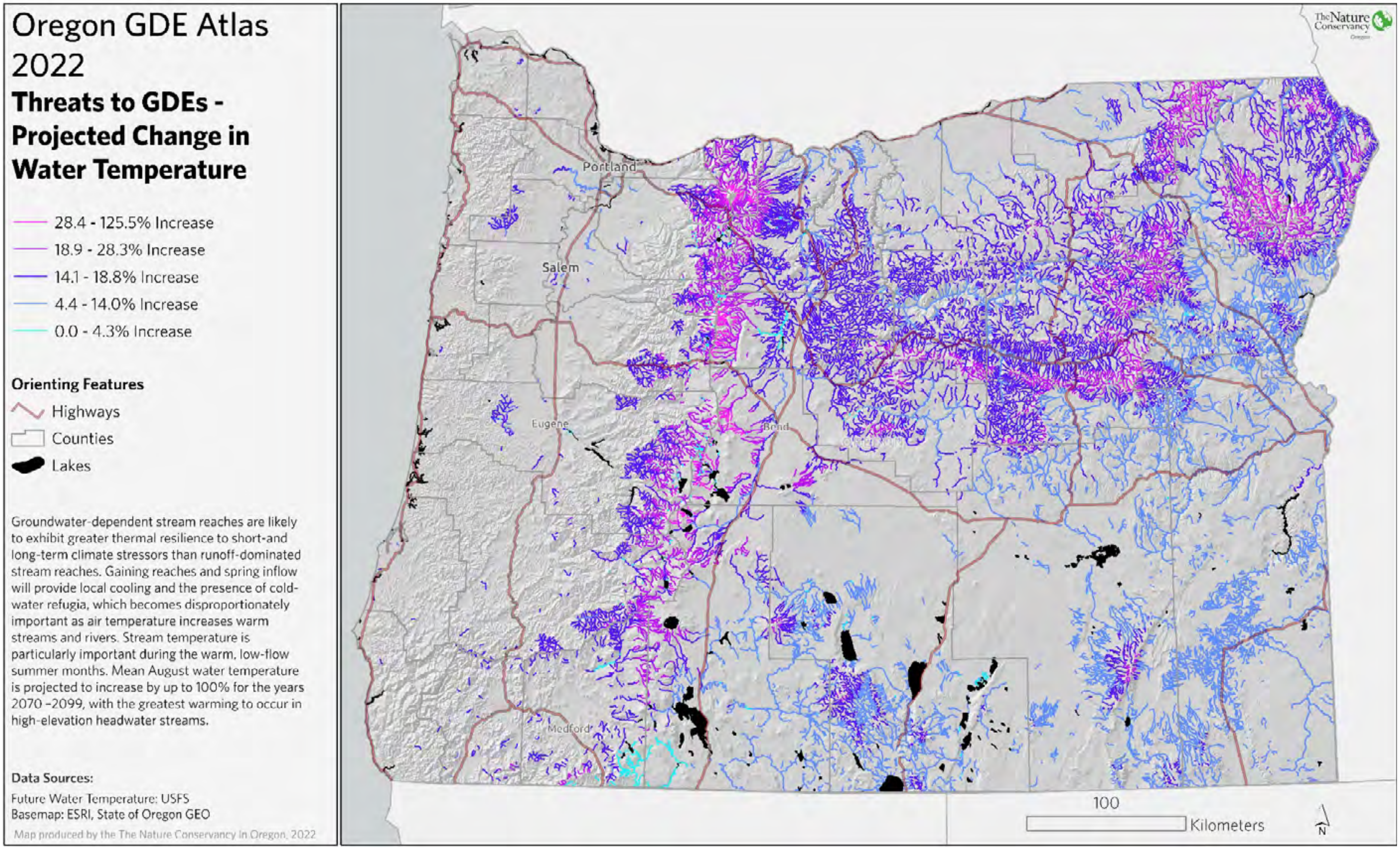

Figure B2 iii k: Climate: projected future August stream temperature

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