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Ecohydrology and stewardship of Alberta springs ecosystems

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ABSTRACT

We studied the role of ecological and anthropogenic impact gradients on ecosystem structure and composition of 56 freshwater springs among mountain, foothills, and prairie ecoregions in southern Alberta, Canada. A random stratified site selection from 2008 to 2012 was based on representation of characteristic springs types across elevation, ecoregions, and land use histories. Springs emergence varied over geomorphic contexts and was dominated by hillslope (28), helocrene (marsh, 13), and rheocrene (stream channel, seven) types, with fewer limnocrene (pool, four), cave (two), gushet (one), and hanging garden (one) springs. Among these springs, specific conductance of non-geothermal springs water was negatively related to elevation and groundwater temperature ($R^2 = 0.343$ and 0.336 respectively). Plant species richness was positively related to habitat area ($R^2 = 0.328$) and weakly to geomorphic diversity ($R^2 = 0.135$) and total alkalinity and specific conductance ($R^2 < 0.181$). We detected at least 444 higher native plant taxa on only 3.82 ha of springs habitat, equalling 25% of Alberta's flora on <0.001% of the provincial land area. Non-native plant species density was positively related to that of native plants ($R^2 = 0.36$). Human impacts on springs included livestock production and domestic water supplies, while beaver and other wildlife commonly influenced ecosystem function on protected lands. We conclude that the springs of Alberta are ecologically important but are understudied and inadequately protected, especially with increasing demand for groundwater as a result of extensive allocation and use of surface water in southern Alberta.

KEY WORDS Alberta; anthropogenic impacts; freshwater ecosystems; groundwater; springs; plant diversity; Rocky Mountains

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INTRODUCTION

Springs ecosystems occur where groundwater is exposed at, and usually flows from, the Earth's surface. These ecosystems occur in many forms and are commonly used for domestic, industrial, and livestock water supplies (Kodrick-Brown and Brown, 2007; Springer and Stevens, 2008). Springs are widely recognized as hot spots of biodiversity in both arid and mesic regions and often support rare and endemic taxa (Williams and Danks, 1991; Shepard, 1993; Minckley and Unmack, 2000; Hershler *et al*., 2014). Springs also may function as keystone ecosystems – small patches of habitat that play disproportionally large roles in landscape ecology (Perla and Stevens, 2008). Springs are of enormous significance to Native American and European people because of their natural and economic resources and their cultural, spiritual, and medicinal significance (Johansen, 1997; Phillips *et al*., 2006; Haynes, 2008; Kresic and Stevanovic, 2010). Springs are also sensitive indicators of anthropogenic impacts and probably climate change (Patten *et al*., 2008; Morrison *et al*., 2013). Despite their importance, springs are among the world's most highly threatened ecosystems, with estimates of impairment or loss exceeding 90% in some landscapes (Stevens and Meretsky, 2008).

Knowledge of the distribution and status of springs ecosystems in Alberta and throughout North America is limited but improving (Ceroici and Prasad, 1977; Borneuf, 1983; Williams and Danks, 1991; Toop and de la Cruz, 2002; Stevens and Meretsky, 2008). Although the subject of springs ecosystem ecology has long languished, springs may play important roles in the ecology and economics of the province. Recently, heightened interest in the distribution and status of Alberta's natural aquatic, plant, and animal resources prompted us to study the influences of ecological gradients on the array of springs ecosystems in southern Alberta. Such a study is warranted because southern Alberta contains a wide array of ecoregions and springs types. Also, the water supplies of the drier, southern half of the province have been extensively developed for agriculture and domestic purposes, uses to which springs are commonly subjected.

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Southern Alberta supports a broad array of habitats among a dozen natural regions within its Rocky Mountain, foothills, grasslands, and parklands ecoregions (Natural Regions Committee, 2006). Non-thermal springs are abundant across southern Alberta in areas with significant topographic relief, in montane and foothill zones and in river valleys. Geothermal springs are generally restricted to the east slope of the Canadian Rockies. Some of these are renowned natural features, such as the Cave and Basin springs complex in Banff National Park. Groundwater-dependent fens are abundant but poorly mapped on the northern Great Plains and in the adjacent aspen parklands. These fens support high concentrations of rare orchids, other wetland plants, invertebrates, and some amphibians (Moss and Packer, 1983; Clifford, 1991; Russell and Bauer, 2000; Lepitzki, 2002). The array of provincial springs types is related to topographic diversity, with hillslope, rheocrene, gushet, and, less commonly, geothermal and limnocrene springs emerging in the foothills and along the piedmont of the Canadian Rocky Mountains. Although poorly known and not studied here, springs in the muskeg-dominated northern half of Alberta in the boreal forest and Canadian Shield biomes are likely often seasonal, with shallow aquifers and short flow paths as a result of restriction of flow by frost and permafrost.

In this paper, we present the results of an ecohydrological inventory of southern Alberta springs, designed to address the following questions. (1) What is the relationship between intrinsic ecosystem variables and extrinsic physical and biological gradients, and how do geomorphology and biological complexity vary in relation to elevation, geochemistry, ecoregional influences, and habitat area? (2) Does the geomorphic configuration of springs influence vegetation composition, structure, and diversity? (3) Does land management strategy affect the ecological integrity of Alberta springs, and if so, how? We reviewed the existing literature on Alberta springs ecosystems and then undertook one of the first comprehensive, interdisciplinary field inventories and assessments to characterize springs in different regions and contexts. We discuss the utility of standardized springs mapping, inventory, and assessment protocols and the relevance of such information to improving springs and resource stewardship across the province and elsewhere in North America and worldwide.

METHODS

Study site selection

Springs study site selection, identification, and georeferencing for inventory are challenging because springs are inconsistently recognized, are poorly mapped, and often are only known by local stewards. Alberta initiated springs mapping on 1:50 000 hydrogeology maps (Borneuf, 1974; Tokarsky *et al*., 1974; Ozoray and Barnes, 1978). More recently, the Alberta Geological Survey digitized springs locations from these maps and published the data as a shapefile (Stewart, 2009). However, this dataset is incomplete and imprecise. We used provincial publications to identify potential study sites, including *Springs of Alberta* (Borneuf, 1983) and regional and project reports, such as that on the Canmore corridor (Toop and de la Cruz, 2002). We also contacted various private land owners, watershed organizations, park managers, and non-governmental organizations to obtain locations and other information about springs that were representative within regions and management units.

Few of the springs that we studied were depicted on provincial hydrogeology maps. This leads us to suspect that at least an order of magnitude more unmapped springs may exist in Alberta than are reported. Among the many springs located through our literature reviews and land and resource manager interviews, we selected 50 springs for inventory and assessment according to a stratified sampling design on the basis of springs types, elevation, ecoregion, geochemistry, and land use practices. In addition, we inventoried six other well-known springs of Alberta to ensure that we captured the full range of springs types known to occur in the province (Table I; Figure 1). Our study sites ranged from headwater springs in the Rocky Mountains and adjacent parklands to low-elevation prairie fens and from nearly pristine wilderness springs to highly developed springs in which ecological functionality had been nearly obliterated. The management units in which we inventoried springs were diverse and included Parks Canada (Waterton Lakes and Banff National Parks), provincial parks and protected areas (Cypress Hills Interprovincial Park, Bow Valley Wildlands Provincial Park, Spray Lakes Provincial Park, Big Hill Springs Provincial Park, and Kennedy Coulee Ecological Reserve), Alberta Environment and Sustainable Resources Department forest lands, Nature Conservancy of Canada preserves, and private lands that were used primarily for cattle ranching and to a lesser extent for crop production. We revisited one site (Grassi Lakes) to corroborate our methods and evaluate temporal shifts in site characteristics and our inventory team's data collection methods.

Inventory methods

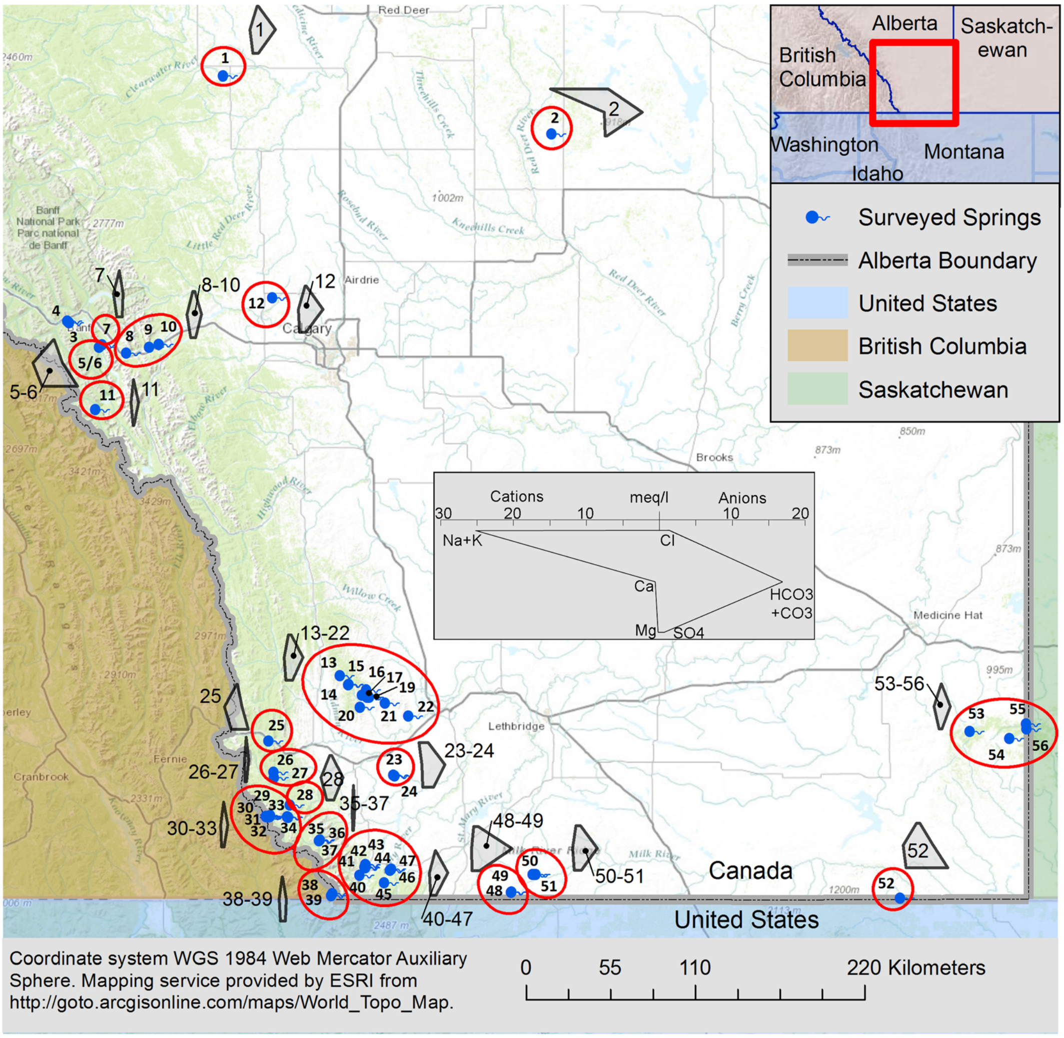
No single season is best for the characterization of all springs variables of interest, and among-season and among-year variation in springs characteristics is likely to be substantial (Stevens *et al*., 2011). We conducted single visit, rapid, comprehensive inventories of springs ecosystems at the height of the growing season (mid-July to mid-August) to best characterize vegetation composition and

Table I. Springs inventoried across southern Alberta from 2008 to 2012.

ID no.	Site name	Survey date	Spring type	N latitude	W longitude	Ecoregion	Elevation (m)	Area (m^2)	Flow ($L s^{-1}$)	Land use type
1	Raven Brood Trout Station Spring	17 July 2012	HI	52.0585	−114.6831	B	1033	239	74.25	C
2	Soap Hole 1	12 July 2012	HE	51.8503	−112.7636	G	822	227	0.08	Pr
3	Upper Middle Hot Springs	10 July 2012	C	51.1630	−115.5820	M	1603	215	4	C
4	Cave and Basin Upper Spring	10 July 2012	HI	51.1682	−115.5905	M	1420	101	*1*	C
4a	Cave Spring	10 July 2012	C	51.1694	−115.5908	M	1400	1365	*7*	C
5	Grassi Lakes Spring	28 July 2008	L	51.0722	−115.4072	M	1577	510	141	C
6	Grassi Lakes Spring	27 July 2009	L	51.0722	−115.4072	M	1577	510	189	C
7	Canmore Sulfur Spring	28 July 2008	R	51.0814	−115.3892	M	1403	156	1.27	Pu
8	Railside Spring	30 July 2008	L	51.0511	−115.2486	M	1292	3450	174.43	Pr
9	Many Springs 1	29 July 2008	HE	51.0717	−115.1142	M	1292	151	0.02	C
10	Willow Rock Campground Spring 1	29 July 2008	HE	51.0833	−115.0575	M	1296	198	1.9	Pr
11	Watridge Karst Spring	8 July 2012	HI	50.8431	−115.4273	M	1922	1034	3306	C
12	Big Hills Spring	11 July 2012	HI	51.2540	−114.3948	P	1240	4813	109	Pu
13	Heath Creek Cutbank Springs	23 July 2009	HI	49.8503	−114.0006	M	1505	130	1.11	Pu
14	Douglas-fir Coulee Springs	22 July 2009	HI	49.8161	−113.9500	M	1461	388	0.62	Pu
15	Beaver Creek Parsnip Spring	23 August 2009	HI	50.3500	−113.9478	M	1464	76.8	0.15	Pu
16	Carlton Springs	25 July 2009	R	50.3167	−113.8461	M	1354	370	3.82	Pr
17	The Big Spring	25 July 2009	HI	49.7769	−113.8711	M	1360	165	29.19	Pr
18	Nadeau House Springs	21 July 2009	HE	49.7686	−113.8410	G	1297	2542	3.33	Pr
19	Poplar Bluff Springs upper	21 July 2009	R	49.7686	−113.8303	G	1354	660	0.1	Pr
20	Price Hutterite House Springs	22 July 2009	HE	49.7319	−113.8825	G	1279	678	0.59	Pr
21	North Field Springs	24 July 2009	HI	49.7467	−113.7361	G	1250	539	1.11	Pr
22	Walker Farm Springs	24 July 2009	HE	49.6986	−113.5997	G	985	1494	0.07	Pr
23	Metzler Wall Spring	12 August 2011	HG	49.4738	−113.6884	G	1174	754	0.38	Pr
24	Metzler Ravine Spring	12 August 2011	R	49.4713	−113.6808	G	1191	100	0.01	Pr
25	Turtle Mountain Sulphur Spring	27 July 2009	L	49.6036	−114.4158	M	1273	2432.5	7.6	Pr
26	Adanac Owt Springs	30 July 2010	HI	49.4850	−114.3872	M	1638	66	0.01	Pu
27	Adanac Eno Springs	30 July 2010	HI	49.4649	−114.3860	M	1457	705	0.1	Pu
28	Beaver Mine Springs 1	27 July 2010	R	49.3600	−114.2928	M	1575	165	0.03	Pu
29	Red Chair springs	28 July 2010	HI	49.3177	−114.4311	M	1849	610	0	Pr
30	Jellyroll Springs	28 July 2010	HI	49.3157	−114.4199	M	1534	320	0.36	Pr
31	South Wetland Pond Springs 1	26 July 2010	L	49.3169	−114.4084	M	1406	3947	0.51	Pu
32	Moosejaw Springs	26 July 2010	HI	49.3196	−114.4072	M	1434	38	0.38	Pu
33	Sandboil Springs	27 July 2010	HI	49.3148	−114.3058	M	1468	92	0.09	Pu
34	BSNA Ephemeral Springs 1	27 July 2010	HI	49.3141	−114.3029	M	1509	540	0	Pu
35	Bovin Outlet Springs	29 July 2010	R	49.2254	−114.1207	M	2048	70	1.13	C
36	Bovin Cienega Springs	29 July 2010	HE	49.2276	−114.1170	M	2013	928	0.39	C
37	Bovin Cascade Springs	29 July 2010	HI	49.2285	−114.1159	M	2037	67	9.91	C
38	Cameron Hillslope Spring	16 August 2011	HI	49.0140	−114.0517	M	1664	140.5	0.15	Pu
39	Akamina Trail Spring	16 August 2011	HI	49.0218	−114.0432	M	1673	51.8	1.19	Pu
40	Blakiston Seep	17 August 2011	HE	49.0931	−113.8862	M	1290	228	0	Pu
41	Buffalo Springs	15 August 2011	HE	49.1236	−113.8549	P	1334	690	*0.04*	C
42	Waterton Spring Creek Spring	15 August 2011	HE	49.1213	−113.8499	P	1304	385	10.5	Pu

43	Waterton Willow Spring	16 August 2011	HE	49.1331	−113.8511	P	1320	1136	5	Pu
44	Waterton Camp 142 Spring	16 August 2011	HI	49.1327	−113.8492	P	1324	65.3	0.09	Pr
45	Wishing Well	15 August 2011	HI	49.0635	−113.7410	M	1521	22.3	0.75	C
46	Belly Gushet	14 August 2011	G	49.1109	−113.7078	P	1331	192	2.5	Pr
47	Birdseye Bench Spring	14 August 2011	HE	49.1166	−113.7004	P	1368	339.5	*0.02*	Pr
48	Whiskey Gap Meadow	13 August 2011	HE	49.0266	−112.9991	G	1282	205	0.02	Pr
49	Whiskey Gap Spring	13 August 2011	HI	49.0281	−113.0014	G	1289	802	3.29	Pr
50	Sandstone Ranch Spring	13 August 2011	HI	49.0951	−112.8741	G	1237	490	0.06	C
51	Sandstone Eyrie Spring	13 August 2011	R	49.0951	−112.8564	G	1241	1828	0.09	C
52	Kennedy Coulee Spring	24 July 2008	HI	49.0047	−110.7286	G	951	261	0.32	C
53	Nichol Spring	25 July 2008	HI	49.6403	−110.3208	M	954	330	0.04	Pr
54	CHPP Graburn Creek 2	26 July 2008	HI	49.6128	−110.0911	M	1367	150	1.86	Pu
55	Reesor Spring	26 July 2008	HI	49.6678	−109.9922	M	1259	304	1.34	Pr
56	Border Spring	25 July 2008	HI	49.6497	−109.9911	M	1260	168	0.2	Pu

Springs are sequenced from north-west to south-east, and ID numbers correspond to points plotted on Figure 1 (map). Spring types were classified according to discharge sphere: C – cave, G – gushet, HE – helecrene, HG – hanging garden, HI – hillslope, L – limnocrene, and R – rheocrene (Springer and Stevens, 2008). Ecoregions were assigned as B – boreal, G – grassland, M – mountain, and P – parkland (Natural Regions Committee, 2006). Flow rates in italics represent values that were estimated, not measured. Primary land use type was classified as C – conservation to retain and recover natural values, Pr – private management for direct or indirect use (e.g. campgrounds and ski areas), or Pu – public for passive management of wildlife or natural values.



Coordinate system WGS 1984 Web Mercator Auxiliary Sphere. Mapping service provided by ESRI from http://goto.arcgisonline.com/maps/World_Topo_Map.

Figure 1. Map of the 56 springs inventoried in Alberta, 2008–2012, displaying the array of major ions in water samples from select sites with Stiff diagrams. Anion meq/l is expressed on the right side of each diagram, and cation meq/l is expressed on the left side. Springs names and exact locations are presented in Table I.

structure and faunal presence and to minimize variation in anthropogenic use intensity. However, mid-summer is likely to be the period with the lowest discharge because of reduced inputs from snowmelt and rain and because of increased evapotranspiration. The purpose of this study was to compare a suite of ecohydrological variables across an array of Alberta springs, and while we do not provide monitoring data though repeated site visits, the data may provide guidance for future monitoring.

We sampled each springs ecosystem using the Level 2 rapid sampling methods of Stevens *et al.* (2011), which include quantification of a suite of variables to describe springs characteristics and functions and the extent of human impacts. A field team of four to six scientists and assistants visited each site to document and measure geography, water flow and geochemistry, geomorphology, habitat structure, vegetation composition and structure, fauna, ecological condition, and human influences. The area of springs habitat was measured as the landscape influenced directly by groundwater emergence, based on geomorphology and soils, in addition to vegetation cover. Information on the administrative context of the springs was collected through an interview with the springs steward(s) and, coupled with the inventory data, was used to conduct an ecosystem assessment of the site.

Physical, chemical, and geographic data were collected with standard techniques of the US Geological Survey and the US Environmental Protection Agency, which are detailed in Stevens *et al.* (2011) for specific application to the single-visit inventory method. Discharge measurements varied from small volumetric measurements to high-velocity stream channel surveys. Field parameters of water chemistry were measured *in situ*, and samples were collected for ion and isotope analyses. Published geological maps were used to determine the geological formations of the water-bearing units. The topographically based solar radiation budget was measured at the spring source using a Solar Pathfinder instrument (Solar Pathfinder, Inc., 2012), and a scaled, site sketch map was drawn to describe the general distribution and approximate size of geomorphic microhabitats and the locations where measurements and photographs were taken.

Vegetation composition and structure were quantified by visually estimating percent cover of each plant species detected in six cover strata, including aquatic, non-vascular (e.g. moss and liverwort), ground (deciduous herbaceous or graminoid), shrub (0–4 m woody perennial), middle canopy (4–10 m woody), and tall canopy layers (>10 m woody; Stevens *et al.*, 2011). We calculated plant species density by dividing the number of plant species by the area of the site. Plant species taxonomy and native versus introduced status are in accordance with the USDA-PLANTS database (2013). In addition, we collected aquatic and wetland invertebrates at each site and documented evidence of wildlife and livestock use.

All data, photographs, the sketch map, and other information about each springs ecosystem inventoried were entered into a relational database and quality controlled using standard methods (Ledbetter *et al.*, 2012) and are available at http://springstewardship.org/. Plant specimens are archived with SB Rood at the University of Lethbridge. LE Stevens coordinated aquatic invertebrate identification.

Analyses

Laboratory geochemistry analyses included determination of major ion and stable isotope concentrations, according to standard protocols (Stevens *et al.*, 2011). All laboratory geochemical and isotope analyses were conducted at the Colorado Plateau Stable Isotope Laboratory in the Merriam Powell Center for Environmental Research at Northern Arizona University using standard methods of the US Environmental Protection Agency. Stiff pattern diagrams (Stiff, 1951) were constructed for each spring and displayed on a regional map to show the distribution of major cation and anion concentrations among springs. A Piper plot of major ion chemistry was constructed with Rockworks v16 (RockWare, Inc, Golden, CO, USA). We calculated the geomorphic diversity of each springs ecosystem using the Shannon–Wiener diversity index (H′), with the proportional area of each geomorphic microhabitat. For vegetation analyses, we calculated total % cover, species density (number of species per m^2), plant species richness, and Shannon–Wiener diversity within strata and/or sites. At the site level, morphospecies richness (S_m) and diversity were used because a single taxonomic species may have been included in more than one stratum to account for its different ecological roles. For example, subalpine fir seedlings would be included in ground cover, saplings in shrub cover, and mature trees in the middle and tall canopies. We also calculated overall habitat structural diversity using raw proportional cover in each vegetation stratum, unadjusted for maximum possible cover (100% cover for each of six strata, or 600%). Relatively low Pearson correlation coefficients (below) were expected between vegetation and physical variables, given both the relatively small sample size and inclusion of springs that were subject to a wide array of human use intensity.

We calculated the sum of wetland and aquatic invertebrate species richness and a subset consisting of Ephemeroptera, Plecoptera, Tricoptera, and Turbellaria flatworm taxa (EPT + F), which is a slight modification of the US Environmental Protection Agency's commonly used rapid assessment metric of aquatic invertebrate diversity (Barbour *et al.*, 1999).

We used Pearson correlation analysis to determine the extent of correlation among predictor variables, and we considered all pairwise relationships to assess curvilinearity ($n = 56$ springs). We used linear regression and visual inspection of graphs to investigate the effect of physical variables on summary biological variables for the full set of springs and using the average of the two site visits at Grassi Lakes. To determine similarities among springs with respect to plant communities, we used PC-ORD, version 6 (McCune and Mefford, 2011) for non-metric multidimensional scaling (NMDS) of total plant species cover within vegetation strata, using Sorensen's distance measures on two axes with a maximum of 250 iterations, a stability criterion of 0.00001, and a step length of 0.2, with varimax rotation. We calculated one standard deviation of Axis 1 and 2 for springs types with sample sizes greater than four and plotted those standard deviations as boxes representing each springs type.

Various entities and agencies have created protocols for assessing the condition of springs ecosystems (Prichard *et al.*, 1998; Thompson *et al.*, 2002; Prichard *et al.*, 2003; Potyondy and Geier, 2011; USDA USFS, 2012). A recent review of springs ecosystem assessment methods revealed that methods relying on yes/no or true/false answers limited managers' ability to rank conditions and anthropogenic risks and were unable to generate prioritized stewardship action recommendations (Paffett, 2014). While many of those protocols include similar suites of variables, few were able to directly compare results across jurisdictional or aquifer boundaries or among springs types. This lack of concurrence among agencies and organizations over springs assessment approaches has limited research on and stewardship of springs ecosystems.

For the above reasons and to permit coordination of the Alberta study with springs studies across Western North America, we used the springs ecosystem assessment protocol (SEAP; Stevens *et al.*, 2011; Ledbetter *et al.*, 2012) to evaluate and compare the ecosystem condition (ecological integrity) and anthropogenic risk factors at each springs ecosystem that we inventoried. SEAP analysis incorporates data from the site inventory, expert opinion of the inventory team, and discussion with the site stewards to assess site condition, threats, and priorities. SEAP results provide guidance to managers about the ecological condition of the springs ecosystem (site 'naturalness') and the risks or threats to component and collective resources and processes. Ecosystem threats may occur locally, such as those as a result of flow regulation, geomorphic alteration, or wildlife population changes, as well as regionally from influences related to groundwater pumping, pollution, or climate change (e.g. Patten *et al.*, 2008). SEAP administrative context scoring does not presume a priori that the desired condition of a springs ecosystem is its pristine naturalness. Rather, it investigates whether or not the springs provide the desired amenities to the steward, the extent to which ecological integrity can be maintained and, if impaired, the ease with which its ecological functions and human goods and services could be rehabilitated.

SEAP condition and anthropogenic risk scores are both ranked from a low of 0 to a high of 6, and composite scoring of natural resource conditions against anthropogenic risk provides preliminary prioritization of management needs among springs within a landscape or a region. SEAP scoring criteria are provided online at the Springs Stewardship Institute website (Ledbetter *et al.*, 2012: http://springstewardship.org/). As an example relevant to this study, SEAP assessment and ranking of livestock herbivory impacts include consideration of microhabitat quality, vegetation cover, and evidence of ungulate use (grazing, browsing, trampling, and waste). SEAP can also be used for monitoring trend assessment, if repeated at a site. SEAP risk scores are inversely related to ecosystem rehabilitation potential and cost, allowing springs managers to more carefully consider ecosystem rehabilitation projects.

RESULTS AND DISCUSSION

Inventories

We inventoried 56 springs across four ecoregions in the southern third of Alberta between 2008 and 2012 (Table I; Figure 1). The springs were located between 49°1′41.17″N to 52°3′30.68″N latitude and −109°59′28″W to −115°35′26.8″W longitude and ranged in elevation from 822 to 2048 m. Only nine of our 56 springs were included in Borneuf's (1983) list of Alberta springs, and another six were included in Toop and de la Cruz (2002). Because springs in previous studies were rarely named and because the historic locations were often vague in the Dominion Land Survey system (1-mi sections), it was difficult to accurately relate unnamed historic springs to a precise field location. Most of the Alberta springs with high flow magnitude have been identified and described in existing literature, as have most of the province's substantial geothermal springs (van Everdingen, 1972; Borneuf, 1983). However, the majority of lower magnitude discharge springs have not been mapped or otherwise distinguished, especially those that are not thermal, those that discharge directly into stream channels, those on rangelands, and prairie helocrenes.

Hydrogeology

Springs types. All of the springs inventoried flowed from sedimentary rocks except one that emerged in metamorphic terrain. Limestone, sandstone, and unconsolidated sediments were the sedimentary units of discharge for 80% of the springs, followed by conglomerate, shale, mudstone, dolomite, and quartzite. We detected seven springs types based on sphere of discharge, as described by Springer and Stevens (2008), including hillslope springs (28, 54%), helocrene (low-gradient wetland springs; 13, 23%), rheocrene (channel springs; 7, 13%), limnocrene (pool-forming springs; 4, 7%), and cave (2, 4%), with one gushet spring pouring from a cliff face (2%), and one hanging garden (2%). Although the springs inventoried revealed a preponderance of hillslope springs, the prairies of central and eastern Alberta contain a great abundance of groundwater-dependent helocrenic fens (wet meadows). Based on our field observations, we believe that a more thorough inventory would demonstrate the dominance of helocrenes in the southern half of the province.

Flow and water quality. Flow and water quality measurement at each site was conducted during the mid-summer to standardize for the season of sampling. Springs discharge and water quality varied greatly across the province, from ephemeral hillslope seepage to large madicolous (whitewater) cascades (Table I). Flow among the springs inventoried ranged from $0\,\mathrm{L\,s^{-1}}$ at BSNA Seep, an ephemeral springs ecosystem, to $3306\,\mathrm{L\,s^{-1}}$ at Watridge Karst Spring, with a highly variable average of $71.89\,\mathrm{L\,s^{-1}}$ and a median of $0.59\,\mathrm{L\,s^{-1}}$. Grassi Lakes flow increased by one third from 2008 to 2009, an indication of interannual flow variation likely related to snowpack differences (Table I).

Flow varied among four springs types with sufficient data for comparison, with hillslope springs having the largest variability in flow. Although diffuse flow makes discharge difficult to accurately measure at helocrenes, flow was weakly positively related to area ($\log10A = \log10Q \times 0.143 + 2.527$; $R^2 = 0.104$), when limnocrene pool area was removed from the analysis. Larger springs support larger wetted areas, but decreased groundwater flow because of anthropogenic pumping, or climate change may reduce habitat quality and availability (e.g. Morrison *et al.*, 2013).

Geochemistry varied in relation to ecoregion and elevation (Figure 1). High-elevation Rocky Mountain springs had the lowest specific conductance and lowest water temperatures, although geothermal springs in the vicinity of Banff National Park and Cave and Basin National Historic Site had diverse geochemistry with generally higher solute concentrations (Figure 2). Parkland springs had variable ionic concentrations, and prairie springs derived from Cretaceous sedimentary aquifers generally had higher specific conductance and warmer temperature. These patterns are demonstrated both by increasing anion dominance and higher overall solute concentration in relation to longitude, with the eastward transition from the Rocky Mountains onto the prairies (Figure 1). Except for Soap Hole spring, which was Na–HCO_3-type water, all of the springs had Ca–Mg–HCO_3 or Ca–Mg–SO_4-type water chemistry (Figure 2).

Isotopic analyses of the spring water for ^{18}O and ^{2}H were consistent with previous provincial springs studies (Toop and de la Cruz, 2002). Springs water isotope ratios are similar to the isotope values of precipitation in the recharge basins and a Calgary local meteoric water line developed by Peng *et al*. (2004). We found a slight evaporation trend for ^{2}H in recharge waters, coupled with a strong elevation pattern, indicating that most springs are generally sourced from regional flow systems (Schaller, 2013). Springs more distant from their primary recharge areas have isotope ratios less characteristic of the local elevation and more characteristic of the elevation of the recharge area. Although we did not conduct seasonal analyses of the flow systems of the inventoried springs, previous studies support this interpretation (Borneuf, 1974; Tokarsky *et al*., 1974; Ozoray and Barnes, 1978; Borneuf and Pretula, 1980; Toop and de la Cruz, 2002).

As Borneuf (1983) indicated, there is a wide range of mineralization of spring waters across the province. High-elevation springs emerging from karst, or from fractured rock aquifers with isotopic values similar to local precipitation, indicating short groundwater flow paths have the lowest concentrations of dissolved solids, except for some geothermal springs (Figures 1 and 2). Some short-flow-path springs have specific conductance values as low as 97 µS cm^{-1}. Groundwater solute concentration is

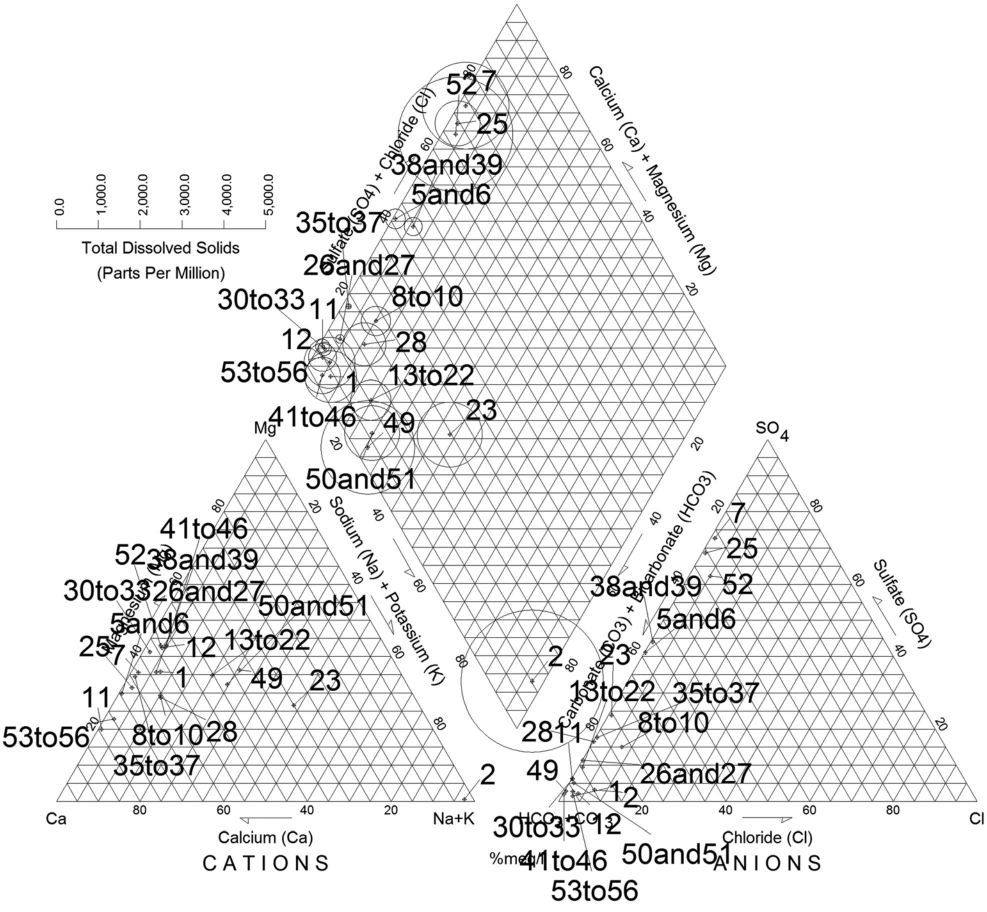


Figure 2. Piper geochemistry plot showing the type of major ion chemistry of each spring, or group of adjacent springs. Spring identifiers are listed in Table I, and locations of springs are shown in Figure 1.

positively related to distance from recharge area and flow path length [based upon isotopic analyses in Schaller (2013)] and is greater in springs emerging from mineral-rich sedimentary rocks or from the regional influence of glacial tills deposited by the continental Laurentide ice sheet (Grasby *et al.*, 2010). The specific conductance of non-geothermal springs water was negatively related to elevation and groundwater temperature ($R^2 = 0.343$ and 0.336 respectively). Cluster analysis of the major cation and anion concentrations revealed two main groups, and analysis indicated two additional smaller clusters related to the rock–water interactions of the general types of sedimentary rock aquifers of the region.

Vegetation

Diversity. We detected at least 444 native plant taxa at the 56 springs inventoried, on a total of 3.82 ha of springs habitat. We excluded from this analysis the large open-water pool areas of the four limnocrene springs because of the large area of that unvegetated microhabitat. Moss and Packer (1983) reported that Alberta supports 1775 native vascular plant species across 661 848 km^2; thus, we observed 25% of Alberta's flora on <0.001% of the provincial land area. This represents a native plant species density of 116.2 species ha^{-1}. While some of this remarkably high species concentration is because of species–area effects and colonization of springs by upland plant species, this finding attests to the importance of springs as biodiversity hot spots in relation to that of the surrounding habitats.

Plant species richness (S_m). S_m varied among strata, with at least five aquatic species, an unidentified number of non-vascular taxa, 390 herbaceous taxa, 32 shrub species, and 13 middle and tall canopy tree species. We evaluated several responses of S_m among strata and springs (Figure 3). Greater tree species richness occurs in hillslope as compared with helocrene springs ($P = 0.02$), but this may reflect an additional ecoregion difference: hillslope springs were more abundant in the montane and subalpine regions, and helocrenes were more abundant in the grassland and parkland ecoregions. Although the sample size of limnocrenes was low, ground and shrub cover were greater surrounding spring pools as compared with helocrene, hillslope, and rheocrene springs ($P < 0.036$). Ground cover S_m was proportionally equivalent among helocrene, rheocrene, and hillslope springs, although composition varied markedly among those springs ecosystem types.

Three factors obscured patterns of plant S_m among springs types. We detected an insufficient number of several springs types to allow for thorough comparison (i.e. gushets and hanging gardens). We detected high levels of variability among the attributes of hillslope springs. For example, flows at hillslope springs ranged from minor seepage (e.g. Adanac Eno Spring) to raging torrents (e.g. Watridge Karst and Raven Brood Springs). This variability indicates the need for a more refined description of hillslope springs to improve understanding of relationships between flow, geomorphology, and ecosystem ecology. Lastly, variability in vegetation response variables was also due, in part, to complex covariation among physical variables, including area, elevation, ecoregion, aspect, and land use. Such covariation creates additional dimensionality in multivariate analyses, which can only be resolved with a larger sample size.

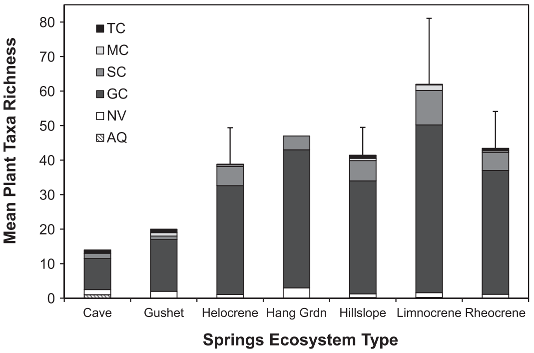


Figure 3. Mean plant morphospecies richness in six strata at seven springs types detected in southern Alberta. Cover codes: AQ – aquatic, GC – ground cover, MC – middle canopy cover, SC – shrub cover, and TC – tree cover. Error bars are 95% confidence intervals for total richness across all strata. Where only one or two springs within a spring type where sampled, error bars are not presented, and non-vascular and aquatic richness represents the presence of broader plant groups like moss, liverworts, and algae.

We tested for species–area effects by log10 transforming both total springs habitat area (A; m^2) and total plant S_m. We again excluded from this analysis the open-water habitat of the four limnocrene springs, as well as data for Cave Spring, which only supported algae. Linear regression demonstrated that species richness was greater at larger springs:

$$\log 10\, S_m = (0.184 * \log 10 A) + 1.142; R^2 = 0.328 \quad (1)$$

However, patterns of species richness varied among plant strata. Forb and graminoid species richness in the ground cover layer was positively related to area ($R^2 = 0.338$), while shrub species richness was not ($R^2 = 0.004$). Tree cover was more closely related to elevation and ecoregion than to habitat area. Therefore, the positive plant species–area relationship at springs appears to be driven primarily by ground-covering species.

Elevation also positively affected the plant species–area relationship. We regressed the ratio of $\log_{10} S_m : \log_{10} A$ against elevation (m). This species density metric was positively, linearly related to elevation ($R^2 = 0.303$). $\mathrm{Log}_{10} S_m$ by itself was not related to elevation ($R^2 = 0.002$), and the overall relationship appeared to be partially attributable to decreasing $\log_{10} A$ across elevation ($R^2 = 0.056$), increasing plant species density at higher elevations.

Geomorphic diversity also influenced springs plant S_m ($R^2 = 0.211$), which is consistent with previous analyses (Hallam, 2010). However, this finding was complicated by interactions among other physical variables. For example, the average area of springs habitats decreased with elevation, but geomorphic diversity was not related to elevation ($R^2 = 0.0003$) (Shannon, 1948).

Cover. Vegetation cover within strata broadly overlapped among the four springs types for which sufficient data were available for analysis. Helocrene, hillslope, limnocrene (excluding open-water habitat), and rheocrene springs supported 38–62% ground cover and 20–23% shrub cover. Tree canopy cover varied from 1.5 to 10.5%, with lowest values at helocrene springs. Rheocrenes had relatively low moss cover compared with other spring types. The high percent of ground cover at the single hanging garden spring inventoried (i.e. Metzler Wall Spring) was because of dense wetland ground cover on non-wall microhabitats associated with that spring ecosystem. Plant species diversity (H′, Shannon–Weiner diversity) within strata was similar to cover patterns among the four springs types for which sufficient sample sizes existed. Helocrene, hillslope, limnocrene (excluding open-water habitat), and rheocrene springs all had ground cover H′ values of 0.55–0.65 and shrub cover H′ values of 0.20–0.29. H′ for tree cover was approximately 0.2, except for the few limnocrene springs, where it averaged 0.29.

Non-native species. Non-native plant species commonly occurred at springs, particularly at sites managed for agricultural and domestic water supplies, but also at those conserved for natural resource values. The $\log_{10}$-transformed species density of non-native plants per m^2 was positively related to that of native plant species:

$$\mathrm{Log}_{10}\mathrm{S}_{\text{non-native}}\ \mathrm{m}^{-2} = \left(0.207{*}\mathrm{Log}_{10}\mathrm{S}_{\text{native}}\ \mathrm{m}^{-2}\right) - 0.011\left(R^2 = 0.435\right) \quad (2)$$

Thus, more non-native plant species were found at springs that had higher diversity of native plant species. Livestock grazing particularly influenced non-native plant species density; there were more than twice as many non-native plant species on sites grazed by livestock than at those that had not been grazed (Figure 4).

Ordination. NMDS of plant composition by cover revealed that vegetation varied among hillslope, helocrene, rheocrene, and limnocrene springs types (Figure 5). Sample sizes among these four springs types varied from 4 to 28 (Table I). Axis 1 was generally negatively related to disturbance (flooding/lotic to lentic aquatic habitats), velocity, and field-observed grain size. Axis 2 was negatively related to vegetation structural diversity, elevation, and the extent of herbivore impacts, and was positively related to site naturalness and water quality variables, particularly specific conductance. The considerable overlap in axis scores among springs types is partially attributable to the small sample size, the complex nature of hillslope springs, and also the great range of anthropogenic use intensity among study sites. While the NMDS results are strongly suggestive, further clarification of these patterns will require a larger sample size.

Fauna

Vertebrates. Survey crews detected 90 vertebrate species at the 56 springs, including livestock, (cattle and sheep), mule deer and whitetail deer (*Odocoileus hemionus* and

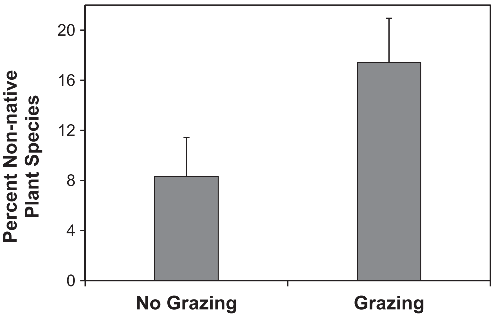


Figure 4. Percent of non-native plant species at springs that were grazed by domestic livestock in comparison with springs that were not subjected to livestock grazing. Error bars are 95% confidence intervals.

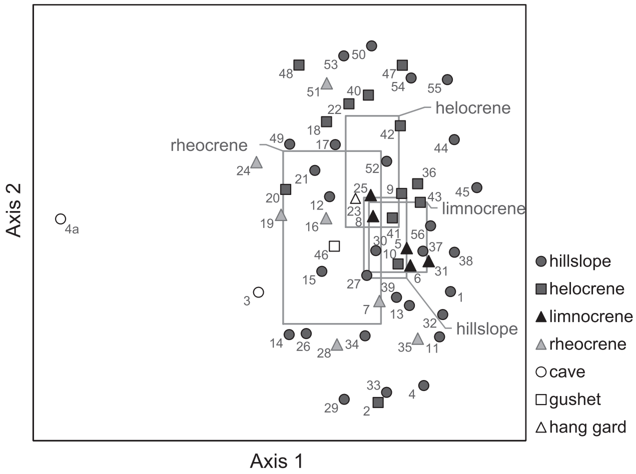


Figure 5. Non-metric multidimensional scaling of springs plant communities, with site numbers presented in Table I. Springs vegetation varied in relation to spring types, as demonstrated by the 95% confidence interval boxes around the four spring types with $n \geq 5$.

Odocoileus virginianus respectively), moose (*Alces alces*), buffalo (*Bison bison*), black and grizzly bear (*Ursus americanus* and *Ursus arctos*), and wolf (*Canis lupus*), as well as voles, numerous birds, and several amphibian species. However, vertebrate survey data represent evidence only from single visits, and additional surveys are needed to more fully describe springs habitat use by Alberta's vertebrate fauna. Fish strongly affect aquatic invertebrate assemblages, and the absence of fish in some springs promotes trophic complexity and endemism among invertebrates (Blinn, 2008). With the exception of the Raven Brood Fish Hatchery Spring, few of the Alberta springs supported fish.

Invertebrates. Aquatic and wetland invertebrate species richness was equivocal, weakly decreasing with temperature, with elevation, and on northerly aspects ($R^2 < 0.07$), and weakly increasing with geomorphic diversity ($R^2 = 0.023$). However, these patterns are strongly non-linear because habitat requirements vary greatly among taxa (Merritt *et al.* 2008). For example, the distribution of Banff Springs snail (*Physella johnsoni*) at Cave and Basin Hot Springs was strongly controlled by water temperature, with most snails occurring between 30 and 36 °C (Lepitzki, 2002), while Plecoptera species, Turbellaria flatworms, and many Trichoptera species occurred in cooler water springs. Ephemeroptera species were more broadly distributed with regard to temperature, with some found in warmer waters. Hence, warm springs supported compositionally different fauna as compared with coldwater springs, but not necessarily lower species richness. Non-thermal springs in Alberta support other rare and endemic insect species, such as the tiny *Sanfilippodytes bertae* diving beetle (Dytiscidae), which is known thus far only from a few springs emerging on the north bank of the Oldman River near Fort MacLeod (Larson *et al.*, 2000). Also, *Stygobromus secundus* is narrowly endemic, found at Many Springs and a few other springs on the east slope of the southern Canadian Rocky Mountains in Alberta (Clifford, 1991).

Assessment of spring ecosystem condition

We used the inventory data, expert opinion, and interviews with springs stewards to score 42 variables among 6 categories of information related to ecological integrity and management. We calculated the average of each of these SEAP category scores, an overall natural resource condition score, and human impact risk score for each springs ecosystem. While condition and risk scores within categories were expected to be strongly negatively related, few Pearson correlation coefficients greater than 0.7 ($R^2 \approx 0.5$) were detected among pairwise comparisons of category scores (Table II). In general, human impacts negatively affected geomorphology and native species habitat quality and population scores. These analyses demonstrate that the SEAP variables selected for analysis provide relatively discrete and independent guidance to spring stewards.

Human use of the springs varied from virtually no impact (pristine condition; scores >4.5) and low risk (scores <1.5) to heavy use for human goods and services (condition and risk scores <4.0 and >3.0, respectively; Figure 6). Primary anthropogenic uses included domestic or livestock water sources and recreation, and risks were also related to potential climate change impacts (Rood *et al.*, 2005). Simple linear regression of springs natural resource condition scores in relation to anthropogenic risk revealed a relatively strong negative relationship ($R^2 = 0.55$). Sites having a high ecological condition score and a high anthropogenic risk

Table II. Pearson correlation coefficients of SEAP category scores for 56 springs.

	AQWQ Cond.	AQWQ Risk	Geom. Cond.	Geom. Risk	Habitat Cond.	Habitat Risk	Biota Cond.	Biota Risk	Anthro. Cond.	Anthro. Risk	AC Cond.	AC Risk
AQWQ Cond.	1	0.083	0.014	0.133	−0.062	0.228	−0.069	0.089	−0.103	0.285	0.102	0.418
AQWQ Risk		1	−0.495	0.482	−0.008	0.398	−0.363	0.435	−0.176	0.35	0.102	0.478
Geom. Cond.			1	**−0.878**	0.416	−0.572	0.438	−0.426	**0.745**	−0.603	−0.35	−0.397
Geom. Risk				1	−0.297	**0.665**	−0.409	0.474	**−0.652**	**0.697**	0.411	0.503
Habitat Cond.					1	−0.418	0.052	−0.074	0.466	−0.371	−0.393	−0.254
Habitat Risk						1	−0.617	0.587	−0.578	**0.676**	0.223	0.415
Biota Cond.							1	**−0.823**	0.38	−0.329	−0.067	−0.397
Biota Risk								1	−0.538	0.596	0.191	0.355
Anthro. Cond.									1	**−0.837**	−0.293	−0.232
Anthro. Risk										1	0.38	0.361
AC Cond.											1	0.595
AC Risk												1

For each SEAP category, current condition (Cond.) and anthropogenic risks to the resource (inverse of restoration potential; Risk) were scored. Categories: AQWQ – aquifer and water quality, Geom. – geomorphic, Biota includes both plants and animals, Anthro. – anthropogenic, and AC – administrative context. Bold numbers indicate elevated covariation ($r > 0.65$ and $p < 0.05$).

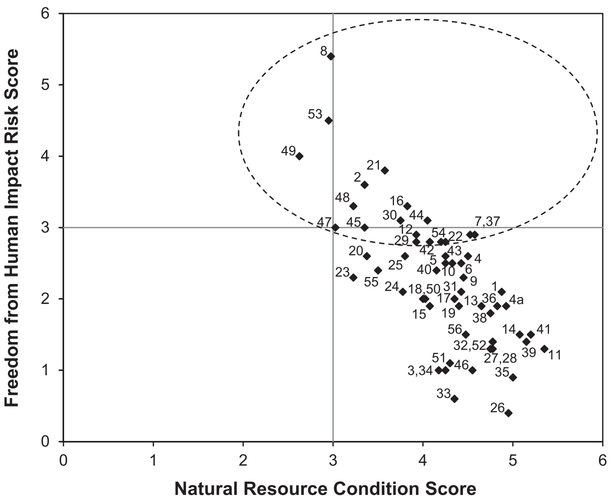


Figure 6. Springs natural resource SEAP scores in relation to freedom from anthropogenic risk scores. The circled area indicates springs that have relatively high ecological condition or value, as well as elevated risk, and therefore may warrant stewardship attention.

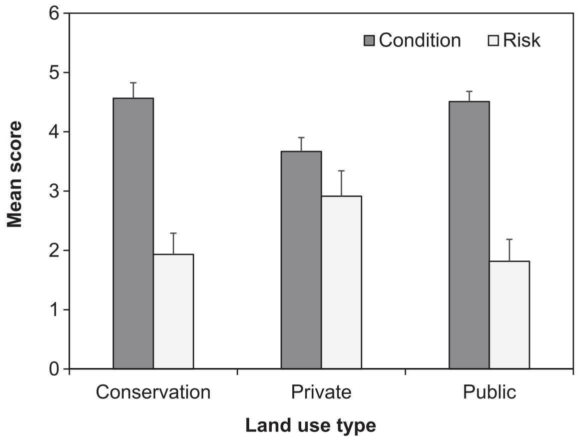


Figure 7. Average natural resource condition and anthropogenic risk scores at 56 springs in southern Alberta that were managed for their natural condition, conservation or rehabilitation, or private use. Error bars are 95% confidence intervals.

score may merit management attention (e.g. some springs in good condition that were used for livestock watering or domestic water supplies). In contrast, sites with a high condition score and a low risk score may simply merit maintenance of existing management conditions and require no active management (e.g. many wildland springs that are maintained in their natural condition). Improving the ecological functionality of springs with low ecological condition scores but elevated risk scores often is challenging because the ecosystem goods and services are intentionally exploited (e.g. use of hot springs for recreation) or because rehabilitation of such sites is likely to be uncertain and costly (e.g. springs that are used for domestic and livestock water).

We contrasted the SEAP-derived natural resource condition score with overall anthropogenic risk score by land ownership in three categories: springs that were privately managed for resource exploitation by the springs stewards (e.g. livestock or domestic water for private landowners or vegetation suppression at a spring in the middle of a commercial ski area), as compared with those managed passively for wildlife on public lands and those managed for specific conservation purposes (e.g. ecosystem rehabilitation; Figure 7). This analysis indicates that natural resource conditions were highest and risk scores were lowest on public and conservation lands as compared with springs under private management. However, natural resource scores were slightly higher, and risks were slightly lower on public wildlands, where springs were primarily passively managed for wildlife, as compared with springs that were subject to conservation actions or rehabilitation. We attributed this pattern to legacy impacts of past land management practices on conservation lands, where springs had not fully recovered from prior uses. Some of the wildlands and conservation springs that we visited may be useful as reference sites for several common Alberta springs types. These reference sites provide excellent opportunities for longer term monitoring and research, as well as useful guidance for spring ecosystem rehabilitation.

MANAGEMENT IMPLICATIONS AND CONCLUSIONS

Springs are abundant in Alberta and are ecologically and economically important but are underappreciated as natural resources. Many springs provide essential water supplies to ranches, farms, and recreational facilities, while others serve as important sources of clean water for recreation or fish hatcheries. The percentage of the provincial population reliant upon groundwater is estimated to be 23%, and most surface water in southern Alberta is intensively allocated (Government of Canada, 2013). This groundwater use estimate is primarily based on groundwater extracted from wells and not groundwater diverted from springs. It seems likely there will be increasing pressure on groundwater as a human water source to meet future water resource needs, further stressing the aquifers that discharge to springs. As Patten *et al.* (2008) determined for springs of the Great Basin and Mojave Deserts in the USA, increasing groundwater extraction has the potential to decrease springs discharge, reduce the wetted area that supports springs biota, and influence springs water quality as discharge decreases.

We found a remarkably high occurrence of nearly one quarter of the province's flora on <4 ha of springs habitat inventoried. We know of no ecosystem type other than springs that contains such a large concentration of regional flora. We also detected numerous invertebrate and wildlife species at the springs that we visited. Hanging garden, gushet, cave, and limnocrene springs appear to be rare springs types in Alberta and should be sought out for future inventory to better understand their distribution and natural resource characteristics. Alberta springs have not been extensively mapped or inventoried, and many thousand springs likely remain to be reported.

We found that the ecological integrity of most of the southern Alberta springs inventoried was relatively high (Figures 6 and 7). This was likely because many of the springs we inventoried were located in parks and protected areas and on lands managed for sustainable natural resource use (Table I). The surrounding catchments of wildland springs often are protected from development, resulting in well-functioning ecological conditions and reduced anthropogenic impacts and risks. Some of the springs that we visited were in sufficiently good ecological condition to serve as regional reference sites for comparative analyses and as models for rehabilitation of degraded springs (e.g. the Bovin Springs complex and Raven Brood Hatchery Springs).

Among the major human impacts on Alberta springs were water extraction, grazing, and recreation. Many provincial springs provide sole water supplies to private farms and ranches, and the loss or degradation of those water supplies as a result of mineral exploration and energy fuels extraction may pose considerable economic risk to private landowners. Although intentional management for extractive uses, particularly livestock and domestic water supplies, commonly resulted in lower condition scores and relatively high human impact scores, the management goals for springs under private management were generally being achieved. Further analysis of the economic value of springs to the province may be useful to regional resource planning and management.

Grazing differentially affects higher elevation riparian zones and may similarly affect springs. In southwestern Alberta, Samuelson and Rood (2011) found that grazing was associated with coarsening substrata, lower soil pH, reduced diversity and density of shrubs and trees, reduced vegetation cover overall, and increased percent cover and dominance of weedy species.

Alberta springs are predominantly helocrenes, rheocrenes, or hillslope types. While ditching, road construction, and diversion commonly reduce the ecological integrity of helocrenes (Cooper *et al.*, 1998), intensive grazing of rheocrene and hillslope springs by native and non-native ungulates is likely to exacerbate soil erosion and habitat loss. We observed degradation of springs ecological integrity by intensive livestock and wildlife grazing and browsing, particularly in ecologically sensitive source areas. Springs sources can be relatively easily protected from livestock grazing, while still providing water away from the sources. Thus, if the supporting aquifer is intact, springs ecosystems can be managed sustainably while still providing human goods and services.

Recreation impacts are, or have been, a major influence on springs function, and particularly on the geothermal springs in the Banff National Park area and at hiking destinations, such as Many Springs, Grassi Lakes, and Watridge Karst Springs. However, because recreational trails are well maintained at those sites, recreational impacts as a result of erosion are modest, perhaps mostly involving the disturbance of wildlife. Carefully considered efforts by springs stewards to rehabilitate geothermal springs in the Cave and Basin National Historic Park within Banff are improving the ecological integrity of those sites and better protect the associated rare, springs-specialist species, including endemic snails.

Numerous other human impacts affect springs ecosystem condition, and our SEAP analysis provides stewards with a means of prioritizing stewardship needs (e.g. through plotting cumulative natural resource condition scores against anthropogenic risk scores; Figure 6). Springs in the upper right quadrant are of high ecological value but also are at risk in relation to one or more anthropogenic influences. Therefore, springs in the upper right quadrant are more likely to warrant stewardship attention and are likely to respond favourably to such attention. Springs that score in the lower right quadrant of the plot are relatively pristine and may serve as reference sites, while those in the upper and lower left quadrants are of lower ecological importance, have low restoration potential, and would be more costly to rehabilitate.

Based on our observations, measurements, and analyses, several general recommendations appear relevant to springs ecohydrology and stewardship in Alberta.

1. We recommend an expanded program to map and inventory provincial springs – much remains to be accomplished, particularly in discovering, characterizing and protecting springs, and locating rare springs types and associated species.
2. We recommend development of regional groundwater flow models to interpret the groundwater contribution areas and to ascertain potential human influences in these areas.
3. Where practical, springs sources should be protected from overgrazing and other human impacts. Rare springs-dependent plant and faunal species are most numerous at springs sources, and livestock grazing may threaten some springs-dependent species populations.
4. Where hillslope springs sources are routinely accessed, trail construction may help minimize hillslope erosion.
5. Where springs are used for water sources, piping and infrastructure should be maintained.
6. More broadly, we recommend the development of education and outreach programs to communicate the importance of springs and groundwater in general and to provide direction on how to improve stewardship to optimize natural resources as well as human goods and services.

7. Expanding outreach about springs to First Nations will broaden intercultural discussion about springs and will provide a deeper understanding of the role of springs in cultural and landscape sustainability.
8. Finally, we recommend the deliberate establishment of a series of Alberta reference springs for research and monitoring and to provide comparison for ecosystem rehabilitation efforts.

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