CLASSIFICATION OF WETLANDS IN THE READER CREEK BASIN USING REMOTE SENSING AND WATER CHEMISTRY, UINTA MOUNTAINS, USA

Marek Matyjasik[1], Michael W. Hernandez[1], Sonya Welsh[2], Richard L. Ford[1], and James Arnold[3]

ABSTRACT

Our research characterizes wetlands of the Reader Creek basin in the Uinta Mountains, which are typical for many alpine wetlands in the Rocky Mountains (including the Uinta Mountains of Utah) and similar to boreal peatlands of Canada and Northern Europe. The Reader Creek basin wetlands are characterized by the presence of flark and strings which have formed, based on the oldest radiometric dates obtained in our study area, during at least 9,670 years of post-glacial activities. We developed a set of Uinta Mountain alpine plant community classes for use in characterizing the geochemistry of the wetlands and in developing a remote-sensing based multispectral classification of wetland regions. We identified 14 distinct plant communities within the wetland obligate communities that are composed of one or more of the following wetland indicator species: *Carex aquatilis, Carex limosa, Carex saxatlis, Eriophorum polystachion (syn. E. angustafolium),* and *Eleocharis quinqueflora*. After analysis of 22 quadrat sites representative of the prominent plant communities, corresponding imagery, and preliminary image classifications, 13 distinct land cover classes were identified as suitable for image classification. The overall classification accuracy was 73% with a kappa coefficient 0.70. In our proposed classification, we have used six parameters: pH, dissolved oxygen (DO), oxidizing-reducing potential (ORP), pH/DO, DO/ORP, and NO_3- / $PO_4{}^3$-. This system is based on the correlation between observed water properties and established vegetation classes. Results from 15 continuous temperature profiles obtained from the lower meadow and the sloping fen shared average annual temperatures between 36.3 and 39.6ºF. This indicates that the Uinta alpine wetland systems are characterized by long-term near freezing temperatures and thus are sensitive to climate change similarly to their boreal counterparts from the northern latitudes of Europe and North America. Overall, areas of faster rate of flow, caused by a steeper topographic gradient and sufficient meadow permeability (strings), have sufficient kinetic energy to prevent the water from freezing in the winter months. Water generally freezes in fens during October and stays below freezing until late January, when developed snow cover provides sufficient thermal blanket to melt the ice below the snow cover.

INTRODUCTION

Most of the world's peatlands (>90%) occur in low-relief boreal regions of North America and Eurasia (Cooper and others, 2012). However, wetlands similar to these boreal/northern peatlands are common in the Rocky Mountains (including the Uinta Mountains of Utah) and Sierra Nevada Mountains of the western U.S.—more than 600 miles south of the main area of boreal peatlands in Canada (Cooper and Andrus, 1994; Cooper and Wolf, 2006). Typically, these mountain peatlands occur as small, disconnected complexes in alluvial valleys and bedrock basins, many of which were glaciated during the Last Glacial Maximum. Climate is key, in both the boreal and mountain settings. Cool, humid, subpolar or montane climates, where precipitation exceeds evapotranspiration, create conditions such that soils are waterlogged and the rate of plant production exceeds the rate of decomposition, allowing organic material to accumulate as peat (Moore and Bellamy, 1974; Mitsch and Gosselink, 2007). All of the peatlands in the southern Rocky Mountains are classified as fens (peat-forming wetlands supported by groundwater), as opposed to bogs (peat-forming wetlands supported by direct precipitation [Cooper and Andrus, 1994; Chimner and others, 2010]). Mountain fens provide important ecosystem services, including water, carbon cycling, and habitat for wildlife. An increased knowledge of mountain fen systems will be needed to manage and/or mitigate landscape and ecosystem changes due to climate change over the next century.

[1] *Weber State University*
Department of Geosciences
1415 Edvalson St. DEPT 2507
Ogden, UT 84408-2507
mmatyjasik@weber.edu

[2] *Weber State University*
Department of Botany
1415 Edvalson St. DEPT 2504
Ogden, UT 84408-2504

[3] *Los Alamos National Laboratory*
DSA-4
P.O. Box 1663
Los Alamos, NM 87545

Matyjasik, M., Hernandez, M.W., Welsh, S., Ford, R.L., and Arnold, J., 2015, Classification of Wetlands in the Reader Creek Basin Using Remote Sensing and Water Chemistry, Uinta Mountains, USA, *in* Vanden Berg, M.D., Ressetar, R., and Birgenheier, L.P., editors, Geology of Utah's Uinta Basin and Uinta Mountains: Utah Geological Association Publication 44, p. 119–138.

Despite their ecological and hydrological importance, relatively few studies have been conducted in the mountain fens of the Rocky Mountains, unlike their high-latitude boreal counterparts (Cooper and Andrus, 1994; Cooper and others, 2012). Matyjasik and others (2003) were the first to broadly characterize the mountain wetlands of the Uinta Mountains and gather baseline data related to the hydrogeologic processes operating in these environments. The goal of the present study is to couple a remote-sensing based landcover classification with field-based data to develop a more complete understanding of the complex relationships between water chemistry, plant communities, and wetland distribution in the Reader Creek drainage basin of the Ashley National Forest, as an example of relatively pristine mountain wetlands of the Uinta Mountains in Utah. In the following sections we briefly present our study area, its hydromorphic characteristics, and Holocene wetland development. Understanding the geologic history and geomorphic characteristics of the study area are then used to develop correlation between multispectral classes of wetland plant communities and water chemical parameters.

STUDY AREA

Cooper and others (2012) noted that the occurrence of mountain wetlands in the western U.S. is dependent upon two crucial factors: (1) an appropriate hydrologic regime largely controlled by elevation and climate, and (2) the presence of appropriate landforms. They specifically noted the importance of glacial landforms, such as lateral and end moraines, and their constituent porous and permeable till in promoting wetland formation. These two factors are obviously in play with respect to the formation of wetlands in the Uinta Mountains.

Geologic and Geomorphic Setting

The Uinta Mountains underwent multiple and extensive glaciations during the Quaternary Period (past 2.6 million years). This is significant to this study because these glacial episodes produced the topography on which the modern ecosystems, including the mountain fens, of the Uintas developed during post-glacial/Holocene time. Atwood (1909) was the first to map and describe the glacial deposits over the entire range and identified two distinct episodes of late Pleistocene glaciation; he also speculated on the existence of an earlier third stage. More recent studies (see Munroe [2005] and Laabs and Carson [2005] for summaries) of the glacial geology of the Uinta Mountains have confirmed this general three-stage model (table 1).

Table1. *Pleistocene glaciations of the Uinta Mountains.*

Uinta Mountains Glaciation	Rocky Mountains Correlative	Marine Oxygen-Isotope Stage (MIS)	Approximate Age (ka)
Smiths Fork	Pinedale	2	32-14
Blacks Fork	Bull lake	6	160-130
Pre-Blacks Fork	Sacagawea Ridge	16	>660

*Table modified from Laabs and Carson (2005) and Munroe and Laabs (2009).

Till deposited during the Smiths Fork glaciation is of particular importance to this study as the subject mountain fens are developed on this substrate. Smiths Fork glaciers began to advance about 32,000 years ago, reached their maximum extent 25,000 years ago, and began retreating from their terminal moraines by 16,000 years ago (Munroe and Laabs, 2009). The Uinta Mountains were largely ice free by 14 to 13 thousand years ago (Munroe, 2002; Laabs and Carson, 2005).

Reader Creek Drainage Basin

Reader Creek is the informal name given to the unnamed stream that drains the valley containing the Reader Lakes in the Ashley National Forest, just south of the crest of the Uinta Mountains in northeastern Duchesne County, Utah. Reader Creek flows southeastward from its headwaters near the crest of the range to its confluence with the Middle Fork of the Whiterocks River. The drainage basin is approximately 32,800 ft long and 6560–9840 ft wide, with a total basin relief of 2625 ft.

The Reader Creek drainage basin (figure 1) occupies a glacial trough that trends northwest-southeast and lies between two ridges that extend above treeline. Quartz and arkosic sandstones of the informal formation of Hades Pass (middle Neoproterozoic, approximately 750 Ma), part of the Uinta Mountain Group, are exposed in the upper portions of the ridges (Bryant, 1992). This is the only bedrock unit exposed within the drainage basin, thus the subject wetlands have developed in a very quartz-rich environment. The bedrock ridges containing the drainage basin are good examples of the broad unglaciated divides in this part of the Uintas that are locally called “bollies” (Laabs and Carson, 2005).

The lower slopes of the confining bollies and the valley floor (figure 1) are covered by Smiths Fork till (late Pleistocene, Marine Isotope Stage [MIS] 2) (Bryant, 1992; Munroe and Laabs, 2009). The till is an unconsolidated, matrix-supported, poorly sorted deposit of pink sand and gravel. The larger clasts are angular to subrounded pebbles, cobbles, and boulders of Hades Pass sandstone. This material is typically less than 33 ft thick and was deposited by a variety of ice-ablation processes, including basal meltout, englacial meltout, and supraglacial meltout (Munroe and Laabs, 2009). According to Bryant’s (1992) and Munroe and Laab’s (2009) mapping, there is no till from the two earlier glaciations preserved within the Reader Creek drainage basin. The divides of the lower, eastern half of the drainage basin lie on low ridges covered in Smiths Fork till, whereas the drainage divides in the higher, western portion of the basin occupy bedrock ridges/bollies of Hades Pass sandstone. Both

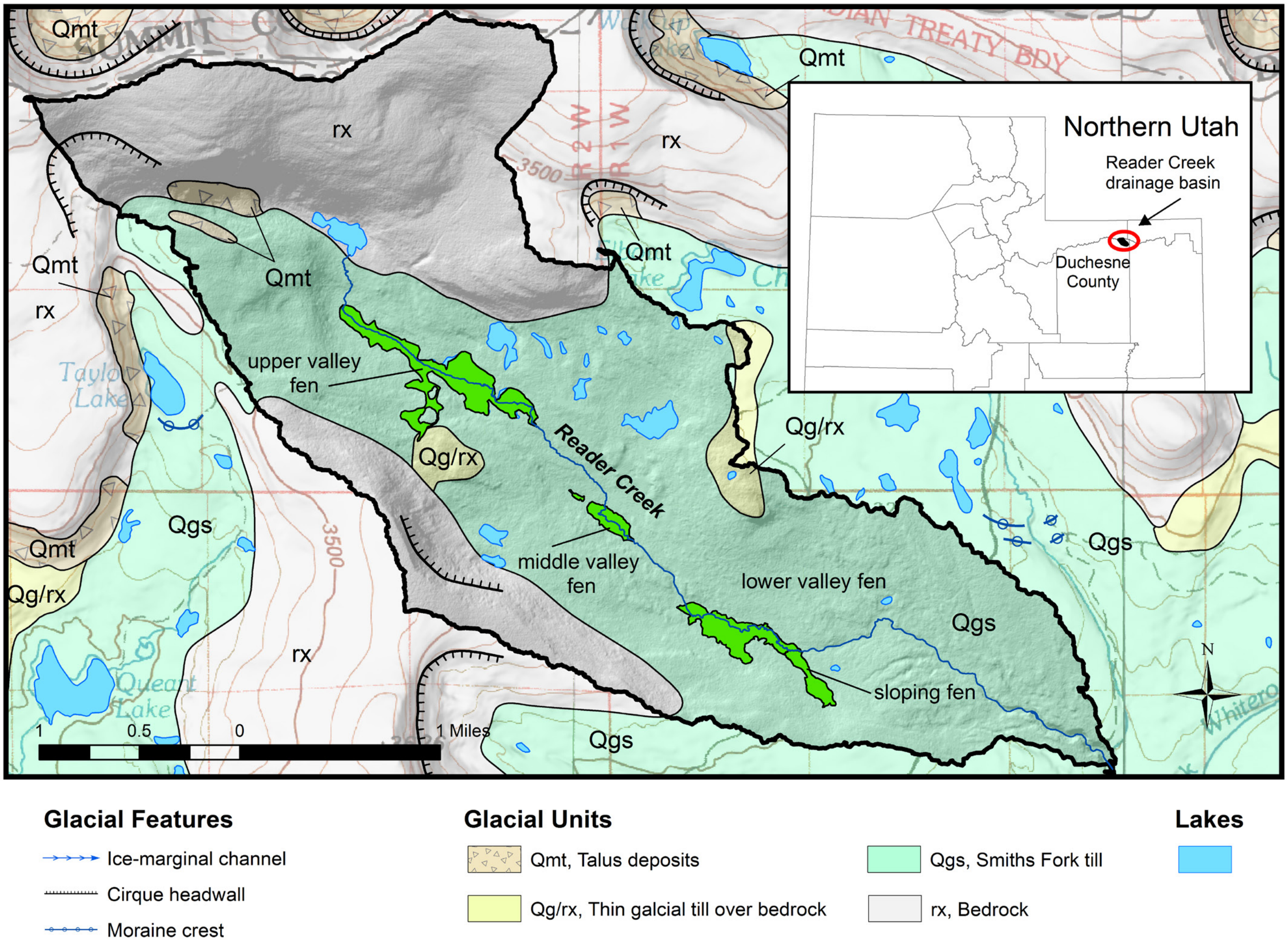

Figure 1. *Reader Creek basin (shaded area) overlain on the glacial geologic map published by Munroe and Laabs (2009). Contour interval: 50 m (164 ft). Index map shown in upper right corner of figure*

the bedrock ridges and exposed Smiths Fork till likely function as recharge areas for the groundwater within the drainage basin.

Overview of the Plant Communities

During the growing season of 2008 (July-September) the conspicuous valley vegetation was identified in the field using taxonomic keys in *A Utah Flora* (Welsh and others, 1993) and the *Uinta Basin Flora* (Goodrich and Neese, 1986). During the initial field investigation of the Reader Creek study area we identified 69 prominent plant species from 24 families. Vegetation monocultures and community types were defined through field identification and mapping. Throughout the basin, visually distinctive areas, minimum size of approximately 39 by 39 ft, were identified and inspected for dominant species, composing >15% of the plot, and associated eye-catching forbs. We placed 20 by 20 ft quadrats within the center of each area to insure adequate size for remote sensing procedures and used the Daubenmire cover classes to substantiate dominance (Daubenmire, 1959) at 22 locations. The location of each quadrat was recorded via a GPS.

We identified 14 distinct plant communities/monocultures: (1) *Picea engelmannii/Pinus contorta,* (2) *Salix planifolia,* (3) *Salix planifolia/Caltha leptosepala/Juncus drummondii/Solidago multiradiata,* (4) *Salix planifolia/Carex aquatilis,* (5) *Salix glauca/Dasiphora fruticosa,* (6) *Danthonia intermedia/Vaccinium ulignosum/Salix planifolia/Betula glandulosa,* (7) *Danthonia intermedia,* (8) *Eriophorum polystachion/Carex aquatilis/Eleocharis quinqueflora/Pedicularis groenlandica,* (9) *Carex aquatilis/Eleocharis quinqueflora,* (10) *Carex aquatilis/Carex limosa/Eleocharis quinqueflora,* **(**11) *Carex aquatilis,;* (12) *Carex limosa/Eriophorum polystachion,* **(13)** *Carex limosa,* and (14) Carex saxitilis. Seven of these plant communities/monocultures are wetland obligates dominated by members of the Cyperaceae family and another four communities contain species from other families also recognized at wetland obligates. The wetland obligate communities are composed of one or more of the following wetland indicator species recognized by the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (2014) based on the work by the Lichvar (2013): *Carex aquatilis, Carex limosa, Carex saxatlis, Eriophorum polystachion (***syn***. E. angustafolium),* and *Eleocharis quinqueflora.*

Climate

Modern climate data from 16 snowpack telemetry (SNOTEL) stations operated by the NRCS in the high Uinta Mountains 7854–10856 ft indicate mean annual temperatures at these elevations are below 32°F (29 to 31°F) and that the mean annual precipitation at these stations ranges from 21.5 to 42 in (mean = 30.2 in) (Munroe, 2003). With relief in excess of 6600 ft, the microclimates and associated vegetation of the Uinta Mountains are highly variable, ranging from cool, arid sagebrush steppes around the periphery of the range, to cool, moist subalpine forests at higher elevations (9840+ ft), to areas of alpine tundra above tree line (> 10991 ft) (Goodrich, 2005; Shaw and Long, 2007). Shaw and Long's (2007) regional analysis of the biogeography of the Uintas demonstrated that the various forest types within the range are strongly zoned by elevation. However, Goodrich (2005) showed that rock type and landforms strongly influence the occurrence of plant communities at smaller spatial scales.

According to data from the Chepeta (396) SNOTEL station, located near the eastern boundary of the Reader Creek drainage basin at an elevation of 10,240 ft, the average annual temperature at this station is 31.5°F (1990-2010), with an average summer temperature of 49.1°F; and an average winter temperature of 16°F. This station receives an average of 30.6 in of precipitation a year (1981–2010). The monthly values indicate that this area receives roughly equal amounts of precipitation in the summer (7 in, or 23% of the annual total) and in the winter (6.9 in, or 23% of the annual total).

Using the Köppen system, the climate of the Uinta Mountains area would be classified as a highland (H) climate, because of the substantial elevation-controlled variation in temperature and precipitation. However, average temperature conditions in the Reader Lakes area are very similar to a subpolar/boreal climate (Köppen: Dfc). This climate type is characterized by severe winters and cool, short summers, with only one to three months having a mean temperature exceeding 50°F. The Chepeta SNOTEL record has only one month, July, with an average temperature above 50°F. In North America, a subpolar/boreal climate occurs in a broad belt extending from northeastern Canada to Alaska. As previously mentioned, there is a strong correlation between the occurrence of the world's peatlands and subpolar climates.

WETLAND HYDROGEOMORPHIC TYPES

Hydrogeomorphic classifications of wetlands, which consider geomorphic setting, dominant water sources, and flow characteristics, are widely used in wetland studies. For our investigations, we chose to use a peatland classification developed by Charman (2002) that uses this hydrogeomorphic approach. Charman's classification places bogs and fens into six (6) geomorphic types: (1) raised bog, (2) blanket bog, (3) basin/depression fen, (4) sloping fen, (5) valley fen, and (6) floodplain fen.

The core of the wetland areas present in the Reader Creek drainage basin has peat thicknesses (>12 in) that qualify them as peatlands. These peatlands are fed by groundwater that either upwells directly under the peatland or flows from springs near the margins into the peatland, or both. Therefore, by definition, these peatlands are fens and the plant communities found there are groundwater-dependent ecosystems. Three of the four fen types recognized by Charman's (2002) hydrogeomorphic classification are present in the study areas: (1) sloping fens, (2) valley fens, and (3) depression fens. The pH of the subject fens ranges from 5.5 to 6.8, making them primarily intermediate fens (5.0<pH<6.5) using Chimner and other's (2010) geochemical classification. Our investigations focused on the sloping and valley fens located in the Reader Creek drainage basin. Four major fen complexes are located in the Reader Creek drainage basin, which we call (1) sloping fen, (2) lower valley fen, (3) middle valley fen, and (4) upper valley fen (figure 1).

The basic stratigraphic relationship observed in soil borings in the Reader Creek area is the presence of a peat layer/organic mat at the surface, of variable thickness, overlying a sandy gravel or gravelly sand (Matyjasik and Ford, 2000). The basal sand is generally pinkish gray, moderately to poorly sorted, and medium to coarse grained with some small angular pebbles. This basal sand and gravel is interpreted to be the top of the Smiths Fork till (MIS 2) of the Last Glacial Maximum, as mapped by Munroe and Labbs (2009). This deposit probably represents ground moraine, till deposited as the valley glacier was receding, subsequently reworked by outwash, fluvial, and/or colluvial processes during the Holocene. This deposit overlies, and is derived from the quartz sandstones of the formation of Hades Pass (Uinta Mountain Group), and functions as an unconfined aquifer. This reworked glacial till is the substrate on which all of the mountain fens within the Reader Creek area formed during post-glacial time.

Sloping Fen

The wetland area that begins near the northwest corner of section 8 T4N R1W, Uinta Base Line and Meridian, and grades to the southern floodplain of Reader Creek in the southeast portion of section 6 T4N R1W, is a sloping fen with distinctive ridge-and-pool morphology, making it a patterned fen (figure 1). The fen is oriented roughly perpendicular to Reader Creek and its head lies approximately 60 ft above the creek. Five distinct ridges, oriented roughly perpendicular to the overall slope, are present, spaced 200 to 490 ft apart. The overall longitudinal slope within the fen is approximately 0.03 to the northwest. However, the ridges act as steps between the longer treads of the nearly level pools. The overall effect is reminiscent of Mitsch and Gosselink's (2007) description of patterned fens resembling terraced rice fields. A steep slope or scarp-like feature is present on the downslope side of the peaty ridges. Ridge or scarp height varies between roughly 0.7 and 2.6 ft.

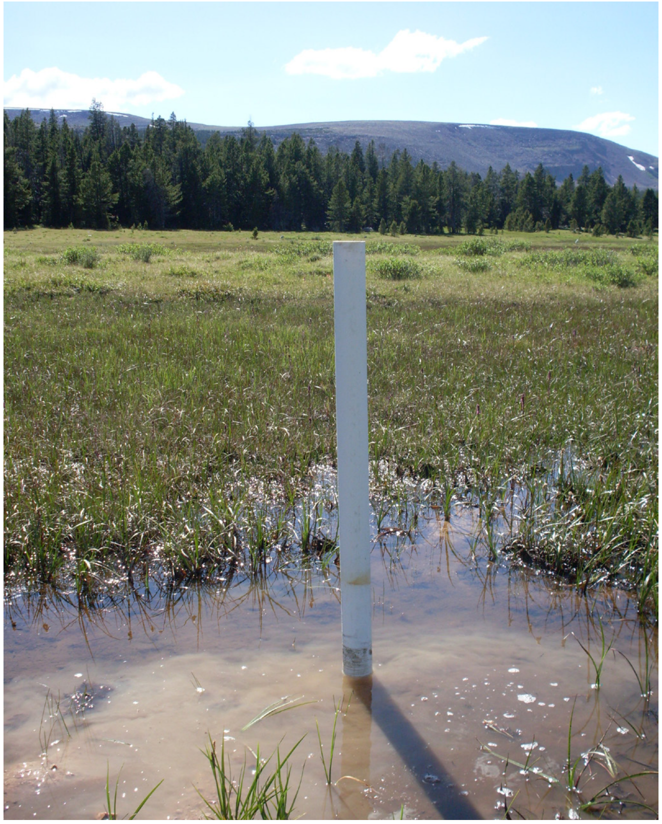

Figure 2. Eriophorum polystachion/Carex aquatilis/ Eleocharis quinqueflora/Pedicularis groenlandica *community on a sloping fen.*

Figure 3. Salix planifolia *community on channel levees.*

Table 2. *Valley fens in the Reader Creek drainage basin.*

Fen name	Elevation range (ft)	Length (ft)	Avg. Gradient (ft/ft)
Lower valley fen	10,483-10,535	3232	0.016
Middle valley fen	10,594-10,660	1969	0.033
Upper valley fen	10,781-10,929	6168	0.024

Measurements taken from Google Earth 2011 imagery.

This sloping fen is fed by numerous springs along its southern and western margin. During every field visit, standing water, up to 3–4 in depth was observed within the pools (figure 2). In addition, surface water was routinely observed flowing over the crest of the ridges.

The vegetation in the pools is dominated by *Carex aquatalis.* The low, wet portions of the ridges are distinguished by the plant community *Eriophorum polystachion/Carex aquatilis/Eleocharis quinqueflora/Pedicularis groenlandica.* The highest, driest ridge within the fen supports woody vegetation, particularly the scrub willow *Salix planifolia*. A peatland-margin wetland (described below) lies between the sloping fen and the non-wetland forested areas upslope

Valley Fens

The largest peatland areas within the Reader Creek drainage basin lie on the valley floor adjacent to Reader Creek. Unlike the sloping patterned fen, the gentle slope of these fens is roughly parallel to the channel of Reader Creek. The water table is at the surface in these areas and numerous small springs are located near their upslope margins. The channel of Reader Creek is incised into these peatlands and water is commonly seen draining from the peatland into the channel. Therefore, we classify these peatlands as valley fens. The water table under the levees was typically observed at 0.6 to 1.6 ft below the ground surface. The vegetation of the levees is dominated by willow (*Salix* spp.) thickets (figure 3). Areas of open water, without emergent vegetation, are common on the fen surface; we call these features fen ponds.

Three distinct valley fens occur within the Reader Creek drainage basin (table 2) that we refer to as the lower valley fen, middle valley fen, and upper valley fen. These fen areas stair-step in elevation and are bounded on their lower end by a transverse slope/ridge of sand and gravel (Smiths Fork till). These transverse features, associated with recessional moraines, could have acted to pond the local drainage and induce wetland formation.

Patterning (ridge-and-pool morphology) within the valley fens is also evident within the study area. Several large ridges, oriented roughly perpendicular to the overall valley slope are present in the lower valley fen, south of Reader Creek. These ridge-and-pool features are much larger than the subtle ridges of the sloping fen. Scarp heights, between adjacent sedge expanses, reach 3.6 ft. These ridges support a well-developed willow (*Salix* spp.) community similar to that on the fluvial levees. Several of the sedge expanses are classic quaking fens; a monocultural carpet or mat of Carex limosa, floating on, and covering, a body of water (figure 4).

Figure 4. Carex limosa *monoculture, quaking fen.*

Peatland-Margin Wetlands

In addition to the true peatlands in the area, the slightly steeper side slopes adjacent to the sloping and valley fens comprise a distinct landscape unit that we term peatland-margin wetlands. The morphology of this unit is dominated by small hummocks and hollows. The water table within this unit was typically observed to lie 0.6 to 1 ft below the ground surface. The peatland-margin wetlands appear to be correlative to Cooper and Andrus' (1994) peatland margin heath, which forms a distinctive belt along the margin of many sedge peatlands in the Wind River Range, Wyoming.

POST-GLACIAL WETLAND DEVELOPMENT

In the fall of 2009 we collaborated with Mitchell Power and Rebecca Koll (University of Utah) to obtain continuous cores, using a Livingston coring apparatus, from the fens of Reader Creek basin. A two-meter core from the upper portion of the lower valley fen of the Reader Creek basin (40.7704° N, 110.0409° W, 10,526 ft elev.) was taken near the transition between the levee of Reader Creek and the adjacent valley fen. The oldest sample, taken from the basal peat layer (80.7-81.1 in depth), has a conventional radiocarbon age of 8810 ± 50 ^{14}C yr B.P., and a calibrated date range of 9670-9818 cal yr B.P. (Koll, 2012). Thus, the stratigraphic record preserved in the lower valley fen spans more than half of post-glacial time (past 14-13 thousand years) and most of the Holocene Epoch (past 11,700 years). We also obtained a 12-foot core from a sloping fen in the neighboring Dry Fork drainage basin (40.7330° N, 109.9217° W, 10,395 ft elev.) in August 2010. A sample (97.6-98.0 in) from an organic-rich, silty sand in this core produced a radiocarbon age of 13,620 ± 60 ^{14}C yr B.P. (16,360-16,050 cal yr B.P.). Dry Fork's geologic and geomorphic setting is very similar to that of the Reader Creek basin. This radiometric age is one of the older post-glacial dates obtained from the Uinta Mountains and suggests that this portion of the southern slope was ice-free by roughly 16,000 years B.P. This result is consistent with Munroe and Laabs (2009) conclusion that the Smiths Fork glaciers began retreating from their terminal moraines by 16,000 years ago, but does argue for rapid retreat in this area.

Pollen and charcoal from the Reader Creek core was used by Koll (2012) to produce a local fire and vegetation history. Koll (2012) documented an early Holocene period (~10,300-8500 cal yr BP) of initial fen development on a post-glacial landscape best characterized as an open, spruce steppe. The general climate was probably both cooler- and wetter-than-present conditions. The peat observed in the base of the core, lying directly on the Smiths Fork Till, accumulated during this time. The middle Holocene (~8500-3200 cal yr BP) in the Reader fen core indicates a period of warmer- and wetter-than-present conditions. During this interval of time the spruce steppe was replaced by subalpine forest (*Pinus* and *Picea*). Koll (2012) noted that pollen from wetland plants (Family *Cyperaceae*) is present in this portion of the core, but peat accumulation has shifted to clastic deposition. Apparently, wetlands were still present in the basin, but the warmer temperature created conditions that were not conducive to peat production. The late Holocene (~3200 cal yr BP to present) interval in the Reader fen core is marked by increases in sandy flood-related layers and in the proportion of pollen from wetland species. Conditions are wet, but cooler than during the middle Holocene, and the modern groundwater and hydrologic regime was becoming established. Koll (2012) notes that the modern vegetation community was established by 900 cal yr BP, coinciding with the peat layer at the top of the core. Therefore, the modern fens systems within the Reader Creek drainage basin may only date to the last millennium. This is an important finding, though admittedly based on only one core/data point. It is also unclear if the establishment of the fens is driven by regional climate change, or by infilling of lakes on the valley floor (aka terrestrialization), or both. Koll's (2012) results for the Reader Fen, on the southern flank of the range, are very similar to those of an early study of the Leidy Peak area, on the northern flank, by Carrara and others (1985).

Table 3. *Uinta Mountain Alpine Plant Community Classification Scheme*

Class #	Setting	Land Cover Class	Symbol
1	Slopes, ground moraine, trail roads	Sandstone	ROCKS
3	Sloping fen	*Eriophorum palystachion/Carex aquatilis/ Eleocharis quinqueflora/Pedicularis groenlandica*	ERP06/CAAQ/ELQU2/PEGR2
4	Valley fen transitions	*Salix planifolia/Carex aquatilis*	SAPL2/CAAQ
5	Dry meadow, thin soils	*Danthonia intermedia*	DAIN
7	Dry transitional slope	*Danthonia intermedia/Vaccinium ulignosum/ Salix planifolia/Betula glandulosa*	DAIN/VAULO/SAPL2/BEGL
8	Valley fen	*Carex aquatilis*	CAAQ
10	Floating fen transition	*Carex limosa/Eriophorum polystachion*	CALI7/ERPO6
11	Sloping fen	*Carex aquatilis/Eleocharis quinqueflora*	CAAQ/ELQU2
12	Rocky slopes	*Salix glauca/Dasiphora fruticosa*	SAGLV/DAFRF
13	Wet meadow	*Salix planifolia/Caltha leptosepala/Juncus drummondii/Soliago multiradiata*	SAPL2/CALE4/JUDR/SOMU
14	Sloping fen	*Carex aquatilis/Carex limosa/Eleocharis quinqueflora*	CAAQ/CALI7/ ELQU2
16	Water	Water	n/a
19	Conifer	*Picea engelmannii/Pinus contorta*	PIEN/PICO

Note: Numerical inconsistency in class numbers is due to the aggregation of certain classes after initial classification showed certain classes as too spectrally similar to distinguish between each other.

MULTISPECTRAL CLASSIFICATION OF GROUNDWATER-DEPENDENT ECOSYSTEMS

Remote Sensing Methods

Development of Classification Scheme for Reader Creek Basin

The initial classification scheme was developed during field work in the Reader Creek drainage basin in the field season, summer 2008.

After analysis of the 22 quadrat sites representative of the prominent plant communities, preliminary image analyses resulted in identifying 13 distinct land cover classes suitable for image classification (table 3). The *Uinta Mountain Alpine Plant Community Classification Scheme* consists of 11 unique high-elevation vegetation classes and 2 other land cover classes (Class 1 – rock [bare slopes, ground moraine, trails/roads]; Class 16 – water). The final classification scheme represents the dominant land cover classes in the Reader Creek basin, which are abundant enough to be reasonably classified using airborne imagery.

Image Classification

Airborne multispectral imagery acquired September 1, 2009, as part of the National Agricultural Imagery Program (NAIP) were used in the supervised land-cover classification. The data were collected using a Leica Geosystems ADS80 Airborne Digital Sensor and orthorectified to produce 3.3 feet ground sample distance images. The files contain four bands (Near Infrared [NIR]: 833–887 nm, visible red: 608–662 nm, visible green: 533–587 nm and visible blue: 428–492 nm) (Leica Geosystems, 2010).

The remote sensing classification process consisted of seven major steps. The first step was to mosaic the downloaded 2009 NAIP image tiles using geospatial software (i.e., ENVI). The image tiles were mosaicked with a 20 pixel deep feather between the images. The images were than subsetted (step 2) to the drainage basin boundaries delineated from elevation rasters that were created from 5-meter auto-correlated DEMs acquired during the 2009 NAIP acquisition.

The third step in the classification process addressed low accuracies for the conifer class (Class 19) and spectrally overlapping classes (e.g., water overlapping with shadowed conifer areas). The areas of conifer and bare ground/exposed rock (Class 1), which occurred mostly in the upper, less vegetated slopes of the basin and intermingled with conifer, were masked out from the plant community classes. Two separate classifications were conducted and later combined in the final composite classification raster. Improvements in the classification resulted from minimizing the wide range of reflectivity produced by the shadows cast by conifers and elevated rock cliffs / rubble and corresponding high returns from

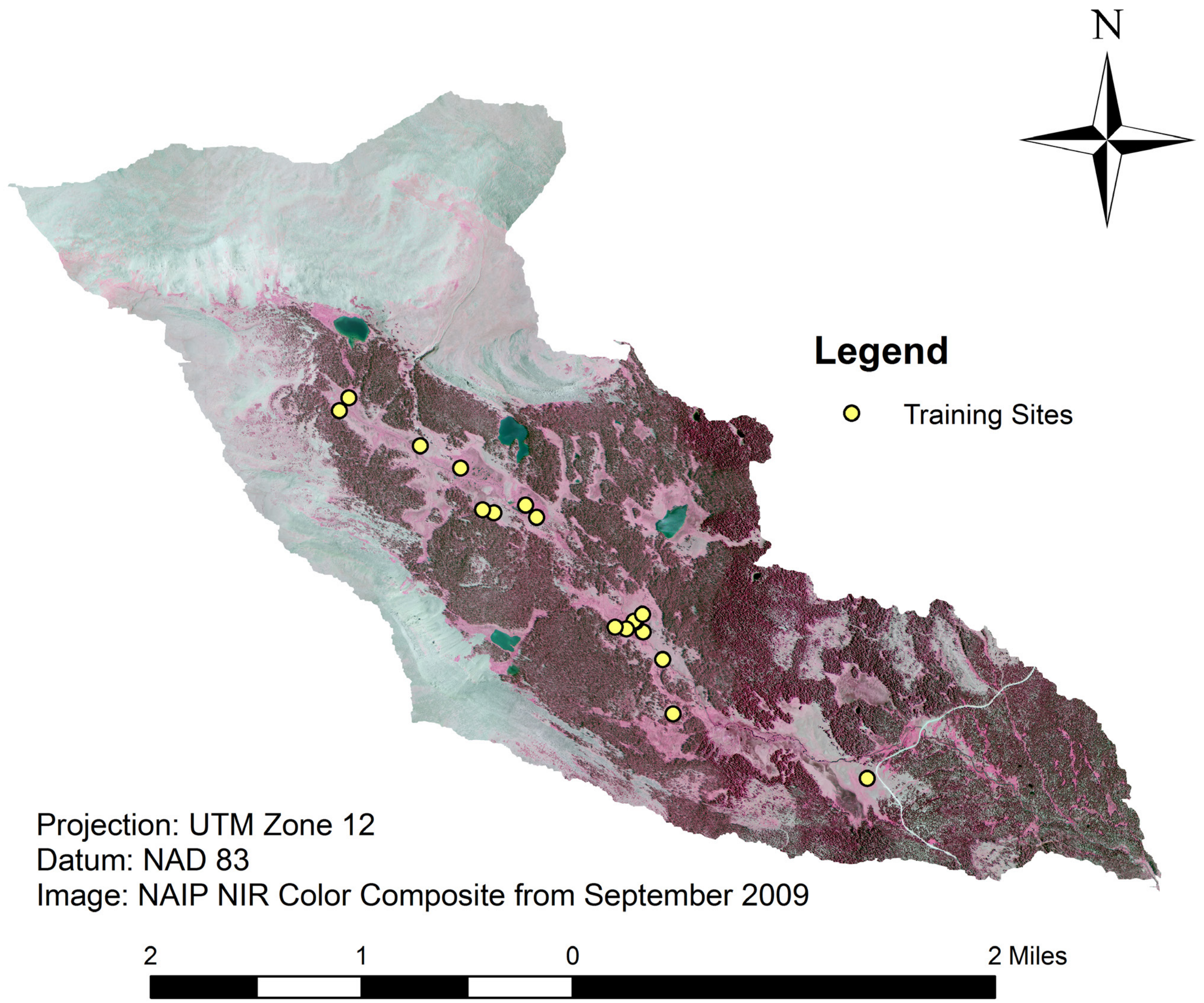

Figure 5. *Training sites used in the maximum likelihood classifier for the Reader Creek drainage basin. Imagery downloaded from the Utah AGRC data portal at http://gis.utah.gov.*

directly illuminated vegetation and bare surfaces.

Step 4, field collection of the image classification training sites, were identified and located using Trimble Juno SB GPS receivers (horizontal accuracy ≤ 9.8 ft) during September 2008 in Reader Creek basin (16 points) (figure 5). The training sites also represented quadrat sampling locations used for the description of vegetation communities.

The fifth step consisted of applying the supervised maximum-likelihood image classification algorithm to assign pixels to the land cover classes. The supervised classification scheme was chosen based on the field-identified plant community classes (i.e., training sites) determined in the drainage basin. This classification algorithm was chosen because it calculates the probabilities of all available classes and assigns each pixel to the class with the highest probability (Jensen, 2005).

The classification results were further processed (i.e., sieve and clump operations) to remove speckling from the classes by defining a minimum area (number of contiguous pixels) that represented a specific class to make the classification easier to interpret. Upon post-classification analysis, several classes that represented slight differences in ground / ambient light conditions were aggregated into composite classes representing variations in ground conditions. The resulting combined classification contained the 13 land cover classes presented earlier (figure 6).

Upon completion of the image classifications the classified rasters were merged together, and masked to the drainage basin boundary in step 6. The final mask defined the area of interest used for the final step, accuracy assessment.

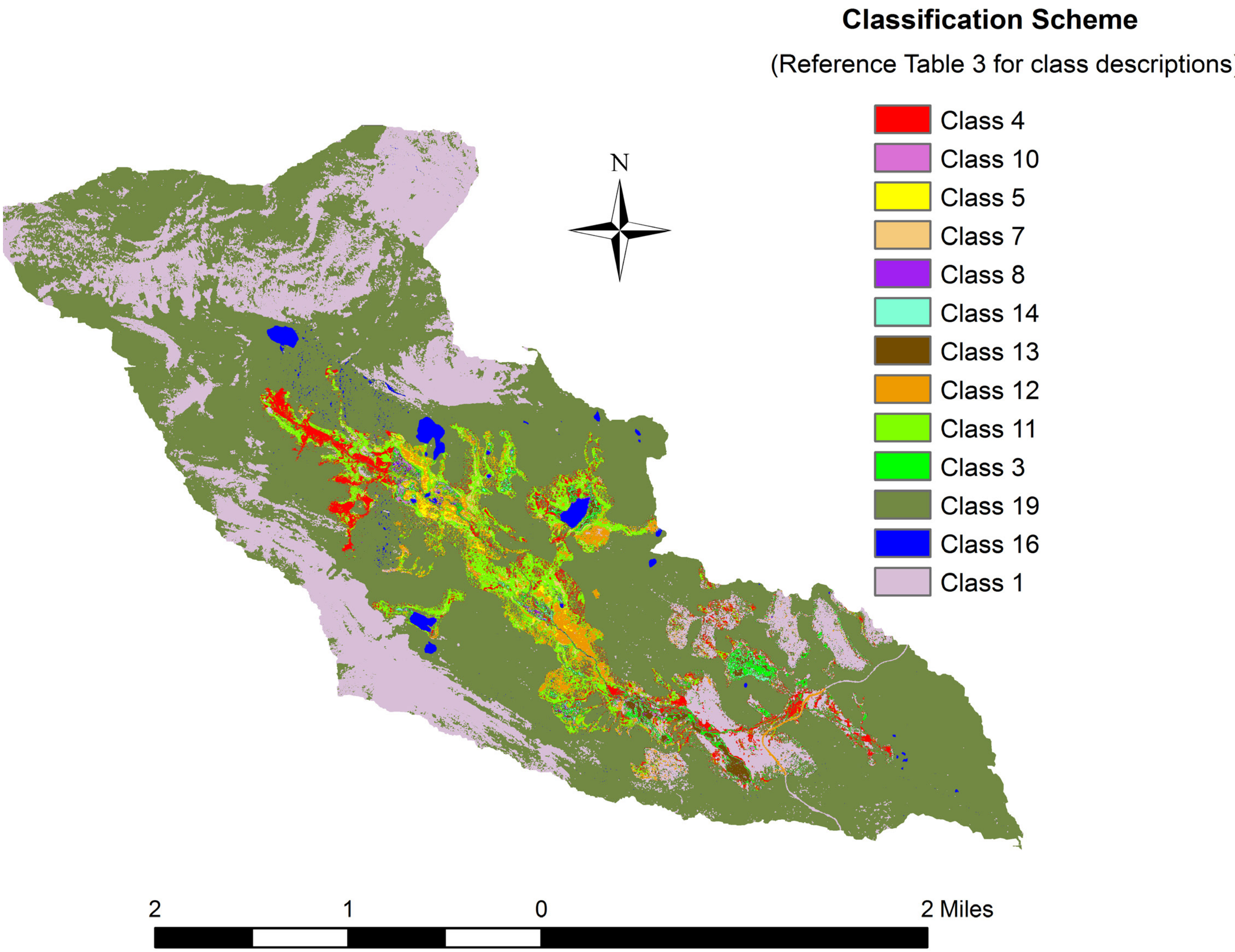

Figure 6. *Land cover classification of the Reader Creek drainage basin. Classification performed using a maximum likelihood classifier on the 4-band NAIP image shown in figure 5.*

Accuracy Assessment

Step 7, the accuracy assessment was accomplished using the method presented by Congalton and Green (2009). The assessment generates statistics from the error (confusion) matrix calculated using ground reference points spread across the classified raster (Jenson, 2005). Calculations included overall classification accuracy, kappa statistics, users' and producer's accuracies, and errors of commission and omission. A stratified random sample of reference points (1242 points) used in the accuracy assessment were generated in ENVI and assigned reference classes both in the post-classification field verified locations (119 points) and in the remaining locations (1123 points) verified using reference NAIP imagery.

Analysis/Results

The overall classification accuracy was 73%, the kappa coefficient 0.70 (out of 1.0). The producer's accuracies for the majority of high elevation wetland vegetation classes were greater than 75% (4, 5, 10, 11, 12, 13) (table 4). Class 7 (dry transitional slope) and Class 8 (valley fen) had accuracies of 73% and 70% respectively. Class 7 had overlap with Class 13 (wet meadow) due to the presence of *Salix planifolia* in both communities. Class 8 had overlap with Class 10 (floating fen transition) due to the intermingling of plant species across a broad transition between the two classes. The producer's accuracies for Class 3 (sloping fen), Class 16 (water) and Class 19 (conifer) were less than 70% (62%, 61%, and 36% respectively). Class 3 had overlap with Class 13 (wet meadow), which is expected due to both classes containing *Salix planifolia* (as mentioned above). Class 16 (water) had overlap with Class 8 (valley fen), which is also expected since standing water exists within Class 8. Class 19 (conifer) also has significant overlap with

Table 4. *Error matrix and associated accuracy statistics for the Reader Creek drainage basin supervised classification (NOTE: Values in the table are reported in percentages and not the number of cells).*

Reader Creek Drainage Basin Accuracy Assessment
Overall Accuracy = 72.71%
Kappa Coefficient = 0.7003

	Ground Reference (Percent)												
Class	Class_16	Class_4	Class_5	Class_7	Claass_8	Class_10	Class_11	Class_12	Class_13	Class_14	Class_3	Class_19	Class_1
Unclassified	1.61	0	0.96	0	6.98	0	0.68	0	0	5.38	1.88	1.32	0
Class_16	61.29	0	0	0	3.49	0	0	0	0	0	0	0	0
Class_4	0	84.09	0	1.92	0	0	0	0	2.78	0	1.88	21.05	10
Class_5	0	0	82.69	2.88	0	0	0	5.08	2.78	0	0	1.32	0
Class_7	0	4.55	0	73.08	0	0	0	5.08	2.78	0	2.35	1.32	0
Class_8	17.74	0	0	0	69.77	1.65	1.37	0	0	2.15	0	3.95	0
Class_10	3.23	0	0	0	9.3	77.69	4.79	0	0	2.15	3.29	0	0
Class_11	3.23	0	0	0	0	4.13	86.99	0	0	3.23	0.94	1.32	0
Class_12	0	0	2.88	6.73	0	0	0	79.66	0	1.08	0.94	7.89	0
Class_13	0	6.06	0	8.65	0	0	0	5.08	88.89	0	14.55	19.74	0
Class_14	4.84	0	0	0	2.33	3.31	3.42	0	0	68.82	4.69	3.95	0
Class_3	3.23	0	1.92	1.92	2.33	9.09	2.05	0	0	11.83	62.44	1.32	0
Class_19	4.84	0.76	0	0	4.65	4.13	0.68	1.69	2.78	3.23	5.63	35.53	10
Class_1	0	4.55	11.54	4.81	1.16	0	0	3.39	0	2.15	1.41	1.32	80
Total	100	100	100	100	100	100	100	100	100	100	100	100	100

Class	Commission (%)	Omission (%)
Class_16	7.32	38.71
Class_4	17.78	15.91
Class_5	8.51	17.31
Class_7	17.39	26.92
Class_8	25	30.23
Class_10	21.67	22.31
Class_11	9.29	13.01
Class_12	28.79	20.34
Class_13	67.35	11.11
Class_14	29.67	31.18
Class_3	20.36	37.56
Class_19	54.24	64.47
Class_1	80	20

Class	Prod. Acc. (%)	User Acc. (%)
Class_16	61.29	92.68
Class_4	84.09	82.22
Class_5	82.69	91.49
Class_7	73.08	82.61
Class_8	69.77	75
Class_10	77.69	78.33
Class_11	86.99	90.71
Class_12	79.66	71.21
Class_13	88.89	32.65
Class_14	68.82	70.33
Class_3	62.44	79.64
Class_19	35.53	45.76
Class_1	80	20

Class 13 (wet meadow) as well as Class 4 (valley fen transitions). Misclassification appears to be due to the variability of the conifer spectral signature, containing both lower values associated with shadows (and similar to water-saturated classes like Classes 4 and 13) and higher values seen in illuminated healthy vegetation. However, since neither Class 16 nor Class 19 is one of the critical wetlands classes (and the fact that all the wetland vegetation classes have a 62% or greater accuracy), we determined the wetlands classes are spectrally separable and suitable for classification in this and other Uinta Mountain drainage basins.

WATER CHEMISTRY

During our investigation, basic physiochemical water measurements were collected at 92 documentation sites (figure 7). Basic monitored physiochemical water parameters included temperature, pH, oxidizing reducing potential (ORP), dissolved oxygen, and specific conductivity. Example figures illustrating basic chemical properties of water represent July 2008 (figures 8–12). Ionic composition of water was analyzed in 87 locations including 18 piezometers (some of which were nested and screened to different depth intervals). Wetland hydrochemistry is influenced by three components: chemistry of recharging water, hydrochemical processes between water and sediments, and hydrochemical processes within the peatland sediments.

Chemical baseline for water chemistry is defined by the snowfield melt water. Its temperature measured in July 2008 and 2009 was between 36 and 41°F, pH between 6.75 and 7.64, ORP 192–265 mV, dissolved oxygen 6650–9002 µg/L, electric conductivity 1–8 µS/cm, and major ions present in the following ranges: Ca: 0.472–1.680 mg/L, Mg: 0.036–0.30 mg/L, Na: 0.475–2.00 mg/L, K: 0.27–0.60 mg/L, HCO_3-: 0.75–6.00 mg/L, SO_4^{2}-: 0.67–1.90 mg/L, Cl-: 0.59–1.01 mg/L, and NO_3-: 0.034–0.32 mg/L, PO_4^{3}-: 0.009–0.046 mg/L, SiO2: 0.066 mg/L.

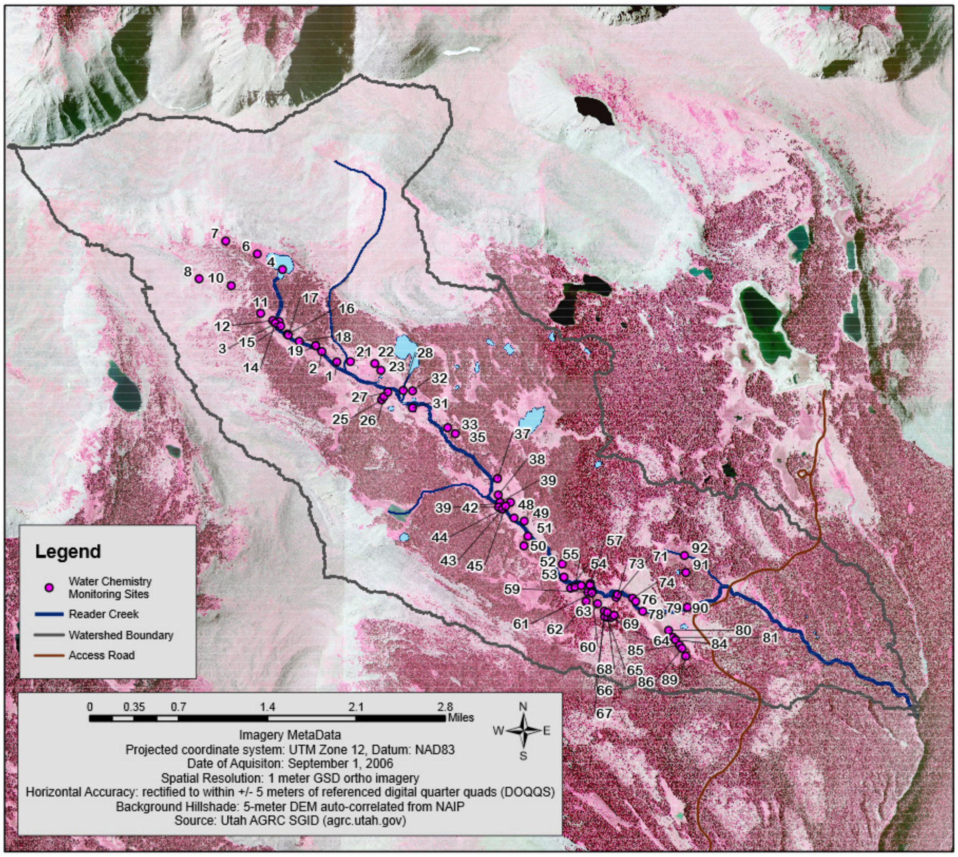

Figure 7. *Water chemistry and vegetation monitoring locations in Reader Creek drainage basin.*

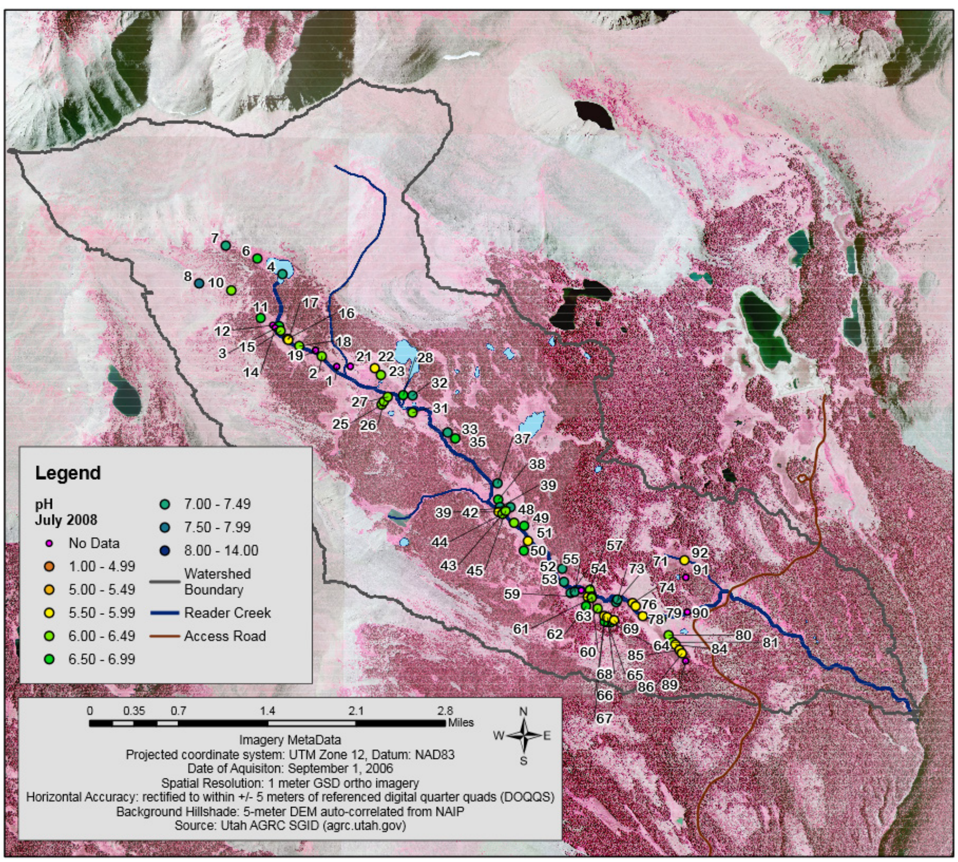

Figure 8. *Distribution of water pH in Reader Creek drainage basin, July 2008.*

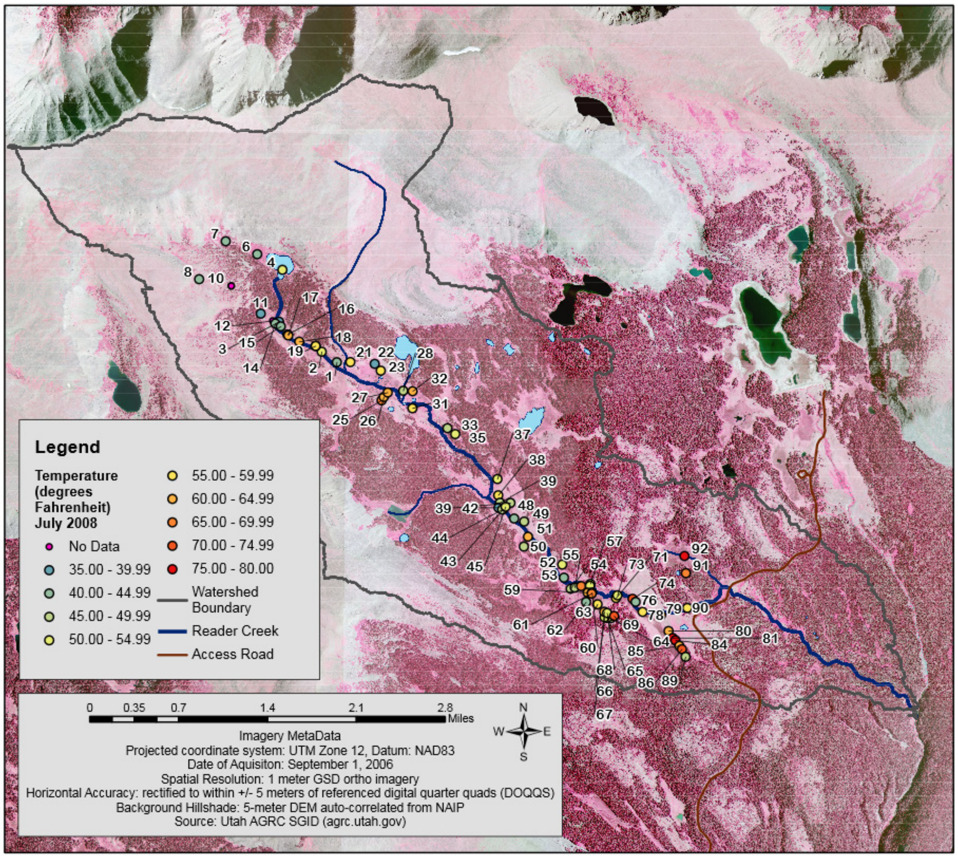

Figure 9. *Distribution of water temperature in Reader Creek drainage basin, July 2008.*

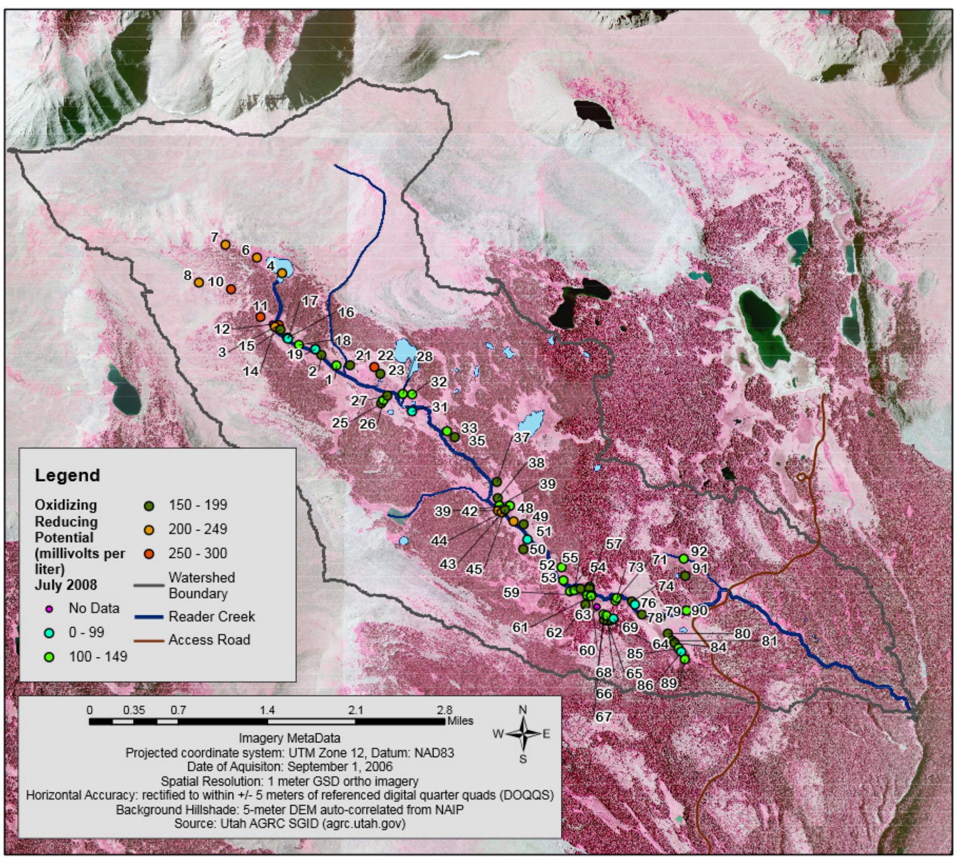

Figure 10. *Oxidizing-reducing potential in mvol/L in Reader Creek drainage basin, July 2008.*

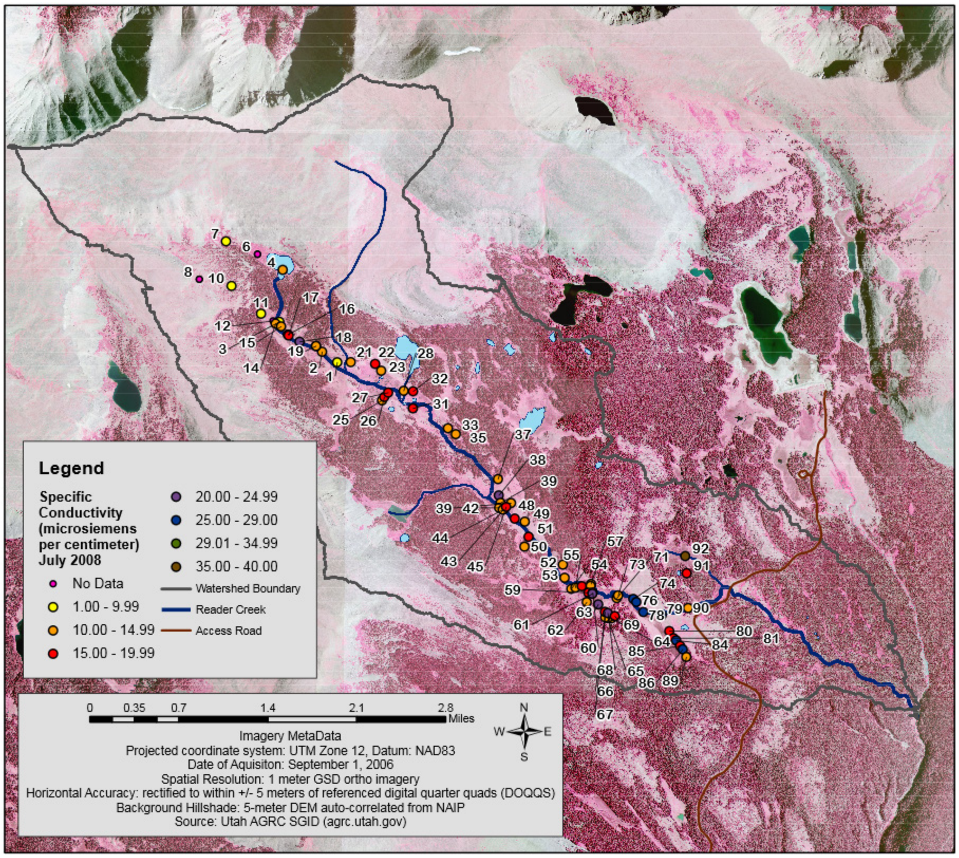

Figure 11. *Distribution of water specific conductivity in microSiemens/sec in Reader Creek drainage basin, July 2008.*

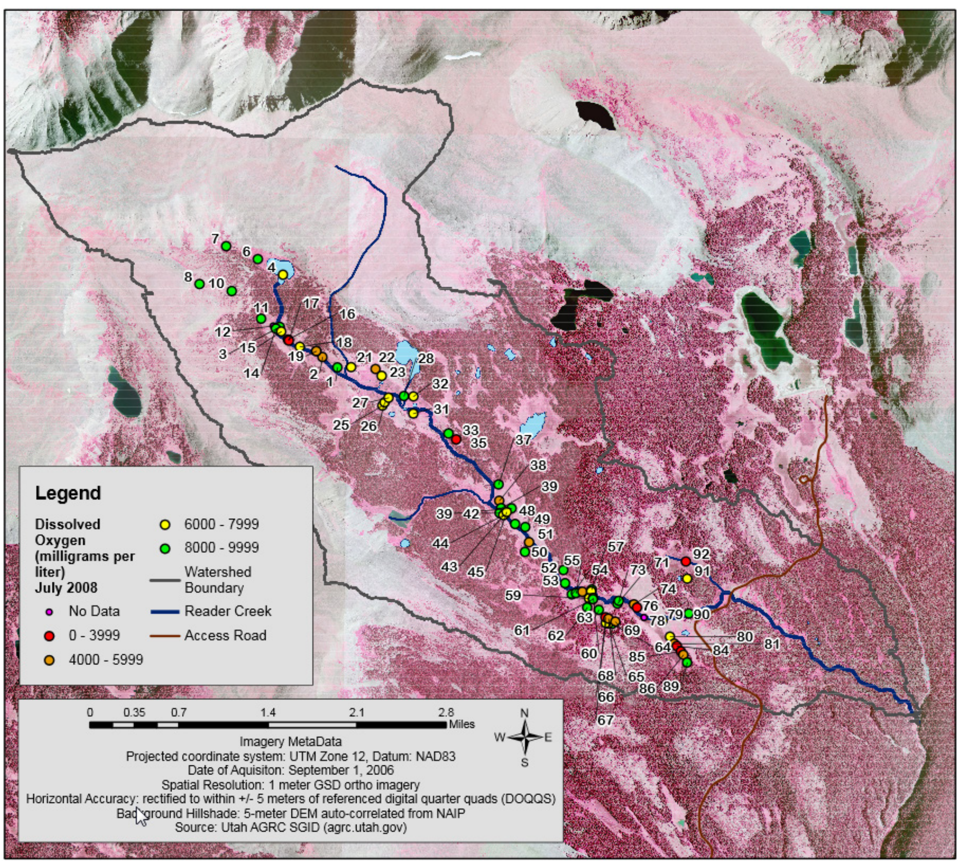

Figure 12. *Distribution of water dissolved oxygen (DO) in mg/L in Reader Creek drainage basin, July 2008.*

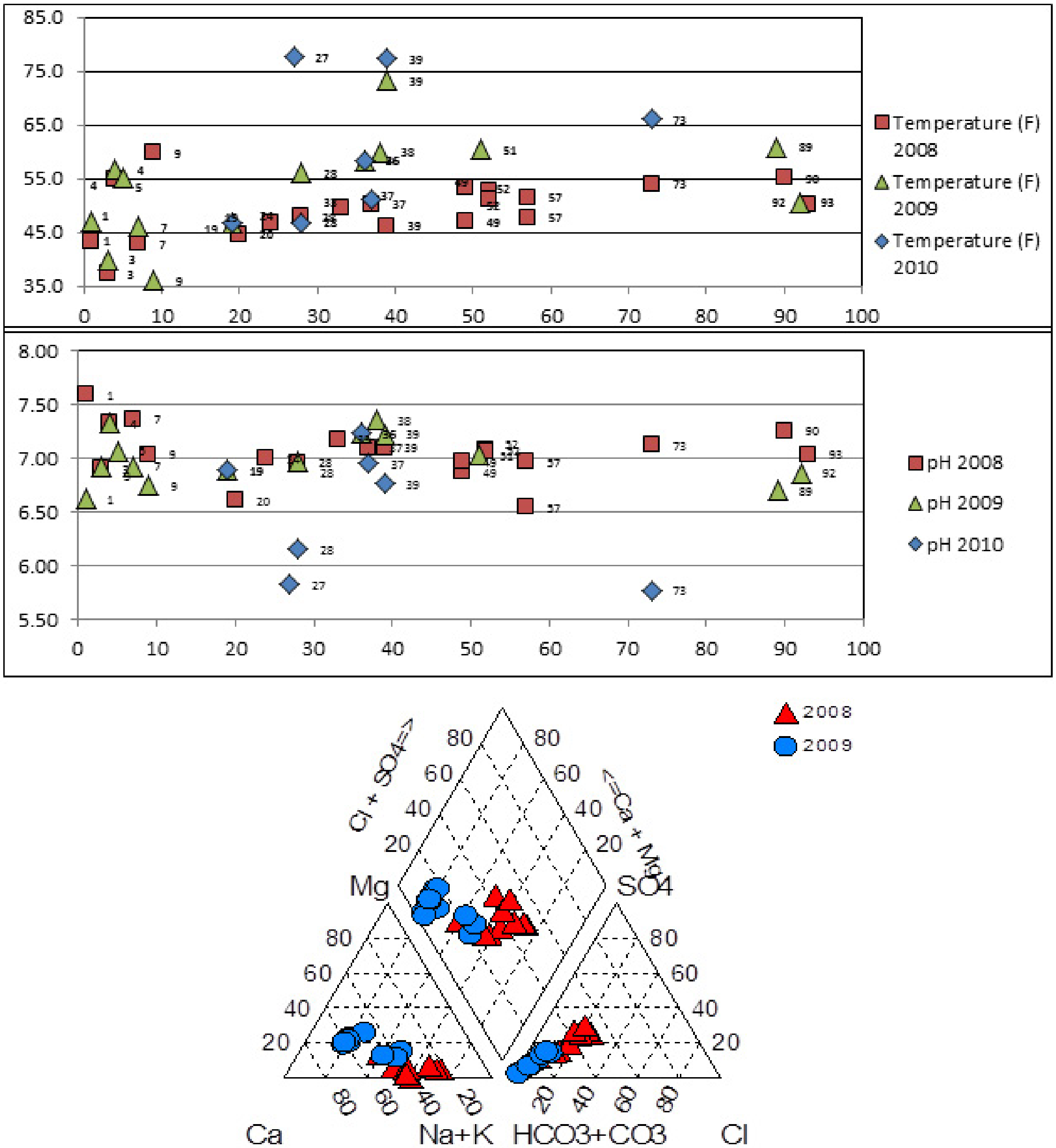

Figure 13. *Temperature, pH, and Piper diagram showing ionic composition in Reader Creek. Numbers on the upper graphs (X axis) refer to points presented in figure 7.*

Hydrochemical processes within wetland peats and sediments are best characterized by down-gradient evolution of water chemistry within Reader Creek, in meadow standing waters and tributaries, and within fens (as observed in piezometers).

All water samples were collected in the summer months (July–September) in 2008, 2009, and 2010. Overall water pH in the study ranges from 5.5 to 7.5 with most of samples with pH between 5.7 and 7.0 (figure 8). Temperature ranges widely from 36 to 80°F (figure 9). Water classes include relatively dominant Ca-HCO_3-type and Na-Cl-SO_4^{2-} type, which produce a spectrum of mixed variants of different proportions of the two main types. Oxidizing reducing potential is affected strongly by chemical processes between organic matter and mineral surfaces. ORP values range from 0 mvolts to 250 mvolts, with most values between 50 mvolts and 150 mvolts, indicating a broad zone of weakly reducing to weakly oxidizing conditions (Figure 10). Specific conductivity, which corresponds to total dissolved solids, indicates very low values (<20 μS/cm) that start from extremely low values for spring waters and surface waters to increasing values in the lower part of the drainage basin (figure 11). Dissolved oxygen content corresponds closely to turbulent flow conditions, which results in higher values (>7000 mg/L) in stream waters and some spring waters, and lower values (<6000 mg/L) in more stagnant waters characterized by slow, laminar flow (figure 12).

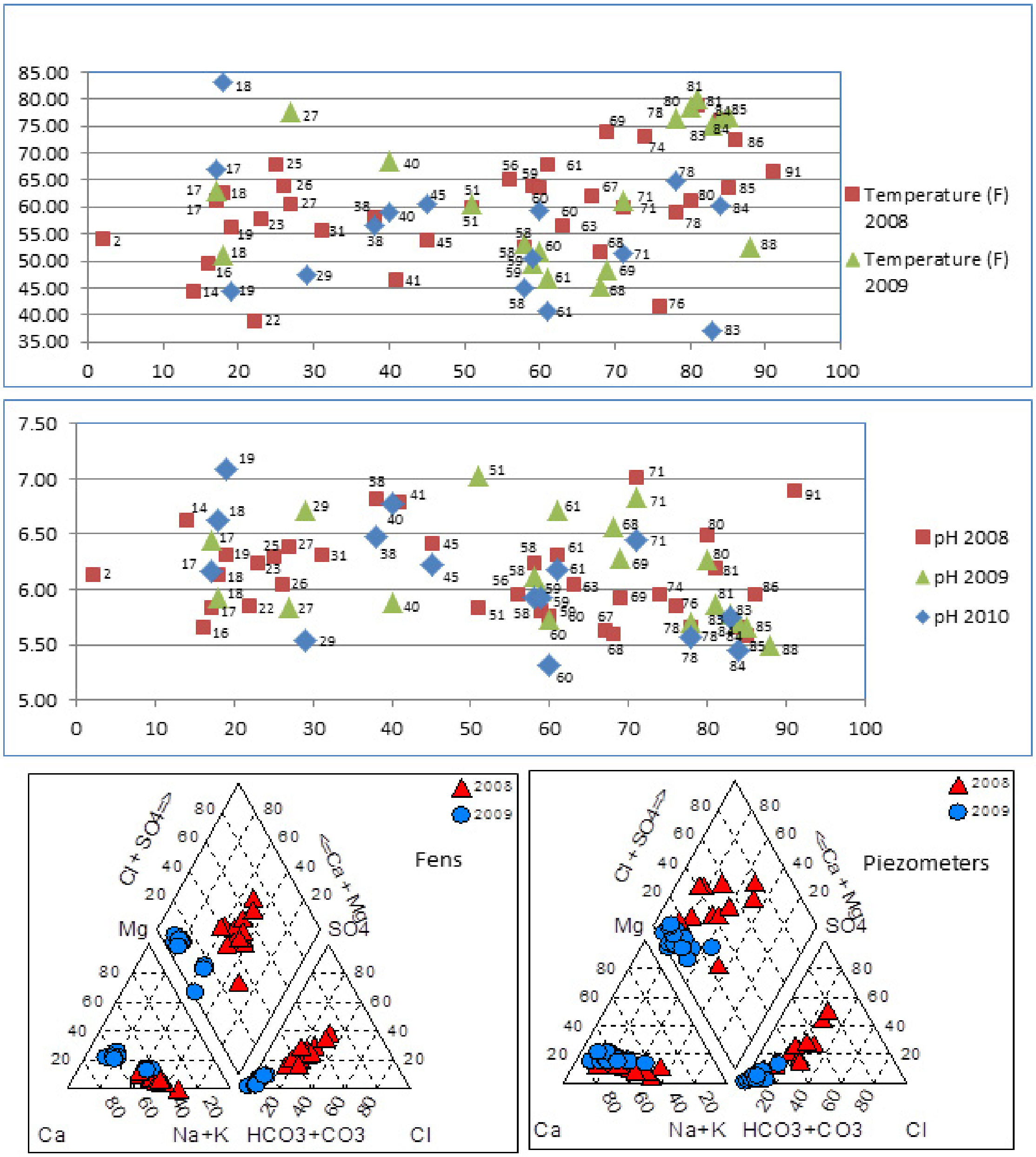

Figure 14. *Temperature, pH, and Piper diagram showing ionic composition in fens and piezometers. Numbers on the upper graphs (X axis) refer to points presented in figure 7.*

The Reader Creek temperatures mostly stay within the range from 42.8 to 51.8°F in fast flowing stretches of the stream (figure 13). Most pH values range from 6.6 to 7.1 (figure 13). Shift between Ca- HCO3- waters to Na-Cl waters is most likely caused by seasonal variations of recharging atmospheric precipitation (figure 13). The average ionic concentrations for all samples collected from Reader Creek are: Ca: 2.14 mg/L with standard deviation 0.83 mg/l, Mg: 0.392 mg/L (SD 0.24 mg/L), Na: 1.59 mg/L (SD 0.86 mg/L), K: 0.46 mg/L (SD 0.20 mg/L), HCO_3^-: 9.31 mg/L (SD 8.57 mg/L), SO_4^{2-}: 1.81 mg/L (SD 0.69 mg/L), Cl: 1.02 mg/L (SD 0.40 mg/L), NO_3^-: 0.26 mg/L (SD 0.20 mg/L), PO_4^{3-}: 0.035 mg/L (SD 0.046 mg/L).

Water samples collected in fens are characterized by overall higher ionic concentrations than in the Reader Creek samples. The average ionic concentrations for all samples collected from fens are: Ca: 2.74 mg/L with standard deviation 1.08 mg/l, Mg: 0.49 mg/L (SD 0.32 mg/L), Na: 1.79 mg/L (SD 0.86 mg/L), K: 0.50 mg/L (SD 0.25 mg/L), HCO_3^-: 6.26 mg/L (SD 5.09 mg/L), SO_4^{2-}: 1.88 mg/L (SD 0.82 mg/L), Cl: 1.27 mg/L (SD 0.58 mg/L), NO_3^-: 0.21 mg/L (SD 0.16 mg/L), PO_4^{3-}: 0.041 mg/L (SD 0.068 mg/L) (figure 14).

Water samples collected in piezometers are characterized by the overall highest ionic concentrations. The average ionic concentrations for all samples collected from piezometers are: Ca: 7.49 mg/L with standard deviation 4.41 mg/l, Mg: 1.16 mg/L (SD 0.58 mg/L), Na: 2.66 mg/L (SD 1.25 mg/L), K: 0.56 mg/L (SD 0.27 mg/L),

HCO_3^-: 17.82 mg/L (SD 12.01 mg/L), SO_4^{2-}: 2.22 mg/L (SD 1.06 mg/L), Cl: 1.72 mg/L (SD 0.78 mg/L), NO_3^-: 0.22 mg/L (SD 0.13 mg/L), PO_4^{3-} : 0.088 mg/L (SD 0.087 mg/L) (figure 14).

Observations of hydraulic head in nested piezometers indicate that there is at least locally upward recharge of groundwater to the wetland fens. Saturated peat can be described as a low-permeability unit, with a highly compartmented nature, which is illustrated by locally steep chemical gradients occurring over short distances. The fen water is weakly acidic to weakly basic (pH 5.2–8.1) and in most places the redox potential has positive values (110 to 175 mV), indicating moderate-rich to extreme-rich fen conditions. However, the fen water contains very low total dissolved solids (avg. 20 mg/L) typical of poor-fen or even bog conditions. Similar mineral-poor water has been observed in montane peatlands of Wyoming, and has been designated transitional rich fen conditions (Cooper and Andrus, 1994). Water chemistry and water-table measurements suggest a shallow-circulating groundwater system strongly affected by snow-melt recharge. Overall hydrochemically, these peatlands are transitional rich fens, having circum-neutral pH (more typical of moderate- to extreme-rich fen conditions) and very low total dissolved solids (typical of poor-fen or even bog conditions).

Temperature Profile of the Reader Creek Wetland

The hydrological rhythm of the Reader Creek wetlands is characterized by snow accumulation over 8 winter months, which is released during a melt period from June to July. Summer is normally characterized by atmospheric convection storms with recharge comparable to the summer months. In 2009, we placed 15 temperature probes in the lower meadow and the sloping fen in an attempt to better understand conditions in various hydrologic compartments (figure 15). Average annual temperatures in all probes range between 36.3 and 39.6°F. In all observation points, temperature was approaching freezing point in late September or early October (figures 15 and 16). In all observation points (2009 and 2010), temperature increases above freezing in early February when developed snow cover provides sufficient thermal blanket to melt the ice below the snow cover. Shallow standing fen water freezes as early as late July or early August (Probe 2, figure 15).

Water in a piezometer located in a willow berm near a tributary had temperature near freezing, but never froze the entire winter (Probe 1, figure 15). This suggests that a higher flow velocity, thus, higher kinetic energy of flowing water, might stabilize temperature of water in winter, and prevents water from freezing. Another tributary in the lower meadow (Probe 3, figure 15) and a shallow piezometer in the quaking fen (Probe 4, figure 16) appear to support this observation. Temperature of water also decreased below freezing in a deeper quaking fen and in the highest flark of the sloping meadow (Probe 5 and Probe 6, figure 16).

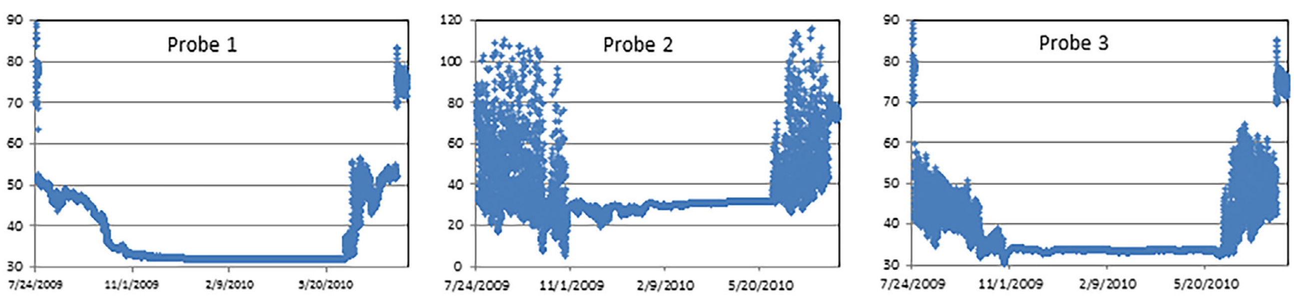

Figure 15. *Temperature profiles: Probe 5: a deeper piezometer in quaking fen (Lower Valley Fen); Probe 6: in the highest flark (sloping fen); Probe 7: in the highest string (sloping fen).*

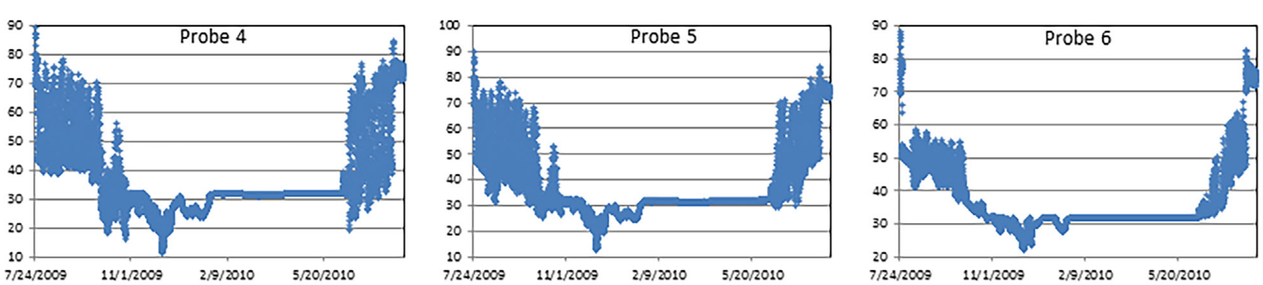

Figure 16. *Temperature profiles: Probe11: placed above Probe 10 above Reader Creek to illustrate air and snow temperature; Probe 12: in a creek at the south end of the sloping fen; in a small meander in a creek above Probe 11; Probe 14: in a soil pit along the edge of the sloping fen.*

Model: Correlations between Groundwater Geochemical Parameters, Flora Soil Requirements, and Remote-Sensing-Based Vegetation Classes

Water samples from 13 plant community/classes identified based on classification of NAIP CIR orthoimagery were examined to identify any correlative trends between these classes and various water chemical parameters. A distinct geomorphic feature of these wetlands is their significant compartmentalization. Basic water parameters including pH, dissolved oxygen, oxidizing reducing potential, and concentration of phosphates and nitrates were divided into classes ranging from low to high values (table 5). Preliminary observations indicate that each plant community class displays a unique combination of these parameters with very little overlap between respective plant communities (figure 17). Other researchers attempted to analyze similar relationships between water chemistry and wetland plant communities using similar chemical and physical properties (Johnston and Brown, 2013). Temperature was not used in our classification system because of very high short term variation of this parameter caused by weather conditions.

The following plant species have been identified and used in the subsequent correlation:

Water sedge (*Carex aquatilis*): does not adapt to coarse, textured soils, adapts well to fine textured soils, high tolerance to anaerobic conditions which translates to tolerance to low dissolved oxygen, medium fertility requirements, minimum 120 frost free days, pH 4–7.5, minimum temperature 38°F.

Mud sedge (*Carex limosa*): adapted to coarse textured soils, not adapted to fine textured soils, high tolerance for anaerobic conditions, low fertility requirements, minimum 85 frost free days, pH 4.8–7.5, minimum temperature 33°F.

Rock sedge (*Carex saxatilis*): adapted to both

Table 5. *Controlling plant species in plant communities/cover classes and water properties corresponding to their environmental requirements.*

Plant Class/Designation	Controlling Species	pH	Dissolved Oxygen	Redox Potential
Dry				
Class 5/Dry A	Danthonia intermedia	6-7.8	High	Intermediate-High
Class 7/Dry B	Vaccinium uliginosum	4.5-6	Intermediate-High	Low-High
Transition				
Class 4/Transition A	Salix planifolia	4.5-7	Low-Intermediate	Low-High
Class 13/Transition B	Caltha leptosepala	6.6-8.2	Intermediate-High	Intermediate-High
Wet				
Class 3/Wet A	Pedicularis groenlandica	5.8-7.2	Low-High	Intermediate
Class 8/Wet B	Carex aquatilis	4-7.5	Low-Intermediate	Low-Intermediate
Class 10/Wet C	Carex limosa	4.8-7.5	Low-High	Intermediate-High

pH	very low <5.65	low 5.65-5.90	intermediate 5.90-6.75	high 6.75-7.00	very high > 7.00
Dissolved Oxygen		Very low <2400 ug/L	low 2400-6000 ug/L	intermediate 5000-7000 ug/L	high > 7000 ug/L
ORP			low<70 mV	intermediate 70-150 mV	high > 150 mV
pH/DO			low < 2	intermediate 2-3	high >3
DO/ORP	very low <21	low 21-55	intermediate 55-80	high 80-100	very high >100
PO4/NO3	very low <1	low 1-1.8	intermediate 1.8-2	high 2-3.5	very high > 3.5

	pH	DO	ORP	pH/DO	DO/ORP	PO4/NO3
class 2	5.59 very low	2340 very low	92 intermediate	2.39 intermediate	25.43 low	0.43 very low
class 3	5.7-6.74 low - intermediate	2870-7200 low - high	18-203 low-high	0.94-1.94 low	22-46 low	0.33-1.78 very low to low
class 4	5.64 very low	1860 low	92 itermediate	3.3 high	20 very low	2.68 high
class 7	5.3-5.56 very low	2400-4640 low	89-176 intermediate-high	1.2-2.21 low-itermediate	13-52 very low to low	0.5-2 very low -intermediate
class 8	5.92-7.23 intermediate-very high	3380-6290 intermediate	27-125 low-intermediate	1.15-1.75 low-intermediate	50-125 low to very high	2-48 high to very high
class 10	5.7-6.7 low-intermediate	3090-7150 low-high	85-127 intermediate	0.87-1.69 low	27-67 low-intermediate	4 very high
class 11	5.65-6.44 low-intermediate	2650-5090 low-intermediate	23-58 low	1.27-2.13 low-intermediate	87-115 high to very high	
class 13	6.7-7.24 intermediate to very high	6080-6940 intermediate	94-235 intermediate-high	0.97-1.06 low	29-66 low-intermediate	0.1-0.77 very low
class 14	5.37-6.27 low - intermediate	1440-4530 low	below 0-210 low-high	1.12-2.13 low-intermediate	22-59 low-intermediate	0.06-3.19 very low-high

Figure 17. *Proposed procedure that correlates plant communities/cover classes with water pH, DO, ORP, NO_{3-}, and PO_4^{3-} as observed in the Reader Creek study area in 2008. This procedure allows prediction of water chemistry based on the plant communities/cover classes.*

coarse and fine textured soils, high tolerance to anaerobic conditions, frost free days 95, pH 6.1–8.0, minimum temperature 28°F. Note: This plant community is not listed in table 5 as it has a small spatial distribution.

Shrubby cinquefoil (*Dasiphoa fruticosa*): adapted to coarse and fine textured soils, anaerobic tolerance none, fertility requirement medium, frost free days minimum 180, pH 5.0–8.0, minimum temperature 28°F.

Elephanthead lousewort (*Pedicularis groenlandica*): adapted to medium textured soils but not to coarse or fine textured soils, fertility requirements low, pH 5.8–7.2 (in our classification class 3), frost free days 90.

White marsh marigold (Caltha leptosepala): adapted to coarse and medium soils, but not fine soils, anaerobic tolerance medium, frost free days 80, pH 6.6–8.2, minimum temperature 33°F.

Diamond leaf willow (*Salix planifolia*): adapted to coarse and medium soils but not to fine soils, anaerobic tolerance medium, fertility requirement low, frost free days minimum 80 days, pH 4.5–7.

Bog blueberry *(Vaccinium uliginosum*): adapted only to medium textured soils, fertility requirement low, frost free days 90, pH 4.5–6.

Timber Oatgrass (*Danthonia intermedia*): adapted to coarse textured soils, no anaerobic tolerance, medium $CaCO_3$ tolerance, pH 6–7.8, salinity tolerance – medium, frost free days 80, minimum temp 33°F.

Three chemical water parameters were found particularly useful to correlate with plant growth requirements: pH, dissolved oxygen, and reducing-oxidizing potential. Measured values of water pH were compared directly with minimum and maximum pH growth requirements. Dissolved oxygen in water was compared to anaerobic tolerance of the dominant plant in a vegetation class. Low to intermediate values of dissolved oxygen correlated very well with high anaerobic tolerance, while intermediate to high values correlated very well with low anaerobic tolerance. Ability to adapt to coarse, medium, or fine textured soils correspond to soil draining ability. Well-draining coarse soils allow more vigorous water flow and promote more oxidizing conditions in near-surface soil layers. Poorly draining fine soils promote more stagnant water conditions and, therefore, more reducing conditions. Ability to adapt to different types of soils correlated well with redox potential (ORP). Low values of redox potential were associated with fine textured soils (reducing to transitional environments), while high values were associated with coarse textured soils (oxidizing conditions). Each of the plant communities was characterized by unique ranges of pH, dissolved oxygen, and redox potential. Based on the correlation between observed water properties in 2008 and established vegetation classes, a new proposed hydrochemical-vegetation classification system was developed using a decision tree-like approach. It employs the six following parameters and their relationships: pH, DO, ORP, pH/DO, DO/ORP, and NO_3- / PO_4^{3}- (figure 17) This figure allows for the characterization of a broad range of chemical parameters associated with nine of the identified vegetation classes (classes 1, 12, 16, 19 are not wetland class types. See table 3). The same concept can be used to identify vegetation classes through a simple elimination process that is presented in figure 18. This decision tree-like process uses pH as a starting point, and four other parameters to generate decision points along the procedure. This approach provides more accurate class identification (table 5, figures 17 and 18).

The relationship between measured chemical parameters and the image-classified plant communities will not always produce equally satisfying correlation because pH and ORP are bedrock material dependent, and parameters such as dissolved oxygen and ORP are time dependent as water samples are exposed to reaction with atmospheric gases during measurement. We anticipate that this proposed classification system will require subsequent modification for unique local conditions, but, overall, the concept of using a combined set of vegetation environmental requirements and water parameters that correspond to these requirements appears sound.

CONCLUSIONS

We characterized the development and hydromorphic characteristics of the Reader Creek basin wetlands in the Uinta Mountains and developed a vegetation-hydrochemical classification of this alpine wetland system. This classification combined dominant land cover communities into thirteen distinct remote-sensing multispectral

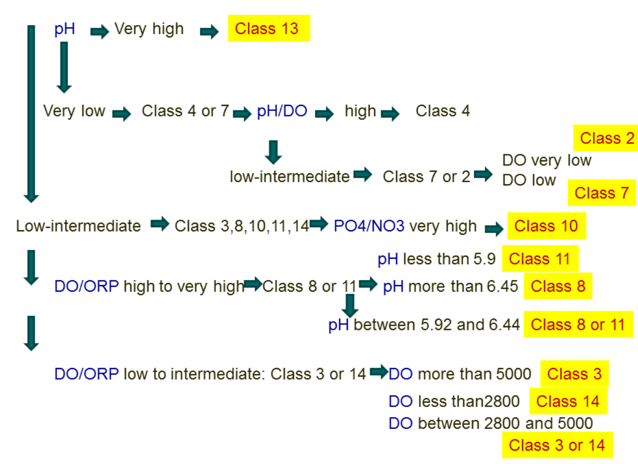

***Figure 18.** Proposed decision-tree-like approach that defines procedures to correlate water pH, DO, ORP, NO_3-, and PO_4^{3}- with vegetation classes as observed in the Reader Creek study area in 2008. This procedure allows anticipating plant communities/cover classes based on water properties. *For classification purposes Class 2 was aggregated with Class 4 because they could not be separated at the given spectral and spatial resolution. However, the field properties are described in the model.*

classes with overall classification accuracy of 73% and a kappa coefficient of 0.70. These multispectral classes were correlated with water chemistry parameters: pH, DO, ORP, pH/DO, DO/ORP, and NO_3- / PO_4^{3}-. These parameters were selected and tested based on preferred soil conditions for dominant plant species in each characterized plant community. We have also determined that these high altitude alpine meadows have developed for at least 9670 years in the post-glacial environments and are presently characterized by average annual water temperatures between 36.3 and 39.6°F, and long-lasting temperatures near freezing point. These conditions are similar to high north latitude boreal wetlands of North America and Europe, and, similarly, are very sensitive to climate change and associated temperature increases.

ACKNOWLEDGMENTS

We are very grateful to the Forest Service scientists working on the Ashley National Forest, especially Darlene Koerner, Sherel Goodrich, Mark Muir, and Chris Plunket, for encouraging and facilitating this research. We would also like to thank the Weber Basin Water Conservancy for assistance with the water analyses.

Funding was provided by Weber State University Office of Undergraduate Research and a cost-share agreement between WSU and the USDA Forest Service, Ashley National Forest.

REFERENCES

Atwood, W.W., 1909, Glaciation of the Uinta and Wasatch Mountains: U.S. Geological Survey Professional Paper 61, 96 p.

Bryant, B., 1992, Geologic and structure maps of the Salt Lake City 1° x 2° quadrangle, Utah and Wyoming: U.S. Geological Survey Miscellaneous Publication Series, map I-1997, scale 1:125,000.

Carrara, P.E., Short, S.K., and Shroba, R.R., 1985, A pollen study of Holocene peat and lake sediments, Leidy Peak area, Uinta Mountains, Utah: BYU Geology Studies, v. 32 (Pt. 1), p. 1–7.

Charman, D., 2002, Peatlands and environmental change: New York, Wiley, 301 p.

Chimner, R.A., Lemly, J.M., and Cooper, D.J., 2010, Mountain fen distribution, types, and restoration priorities, San Juan Mountains, Colorado, USA: Wetlands, v. 30, p. 763–771.

Congalton, R.G., and Green, K., 2009, Assessing the accuracy of remotely sensed data—principles and practices: Boca Raton, Florida, CRC Press, 183 p.

Cooper, D,J., and Andrus, R.E., 1994, Patterns of vegetation and water chemistry in peatlands of the west-central Wind River range, Wyoming, U.S.A.: Canadian Journal of Botany, v. 72,p. 1586–1597.

Cooper D.J., and Wolf, E., 2006, Fens of the California Sierra Nevada—landforms, geochemistry, vegetation, and influences of livestock grazing: USDA Forest Service report, Vallejo, CA.

Cooper, D.J., Chimner, R.A., and Merritt, D.M., 2012, Western mountain wetlands, *in* Batzer, D.P., and Baldwin, A.H., editors, Wetland habitats of North America—Ecology and conservation concerns: Berkeley, University of California Press, p. 313–328.

Daubenmire, R.F., 1959, Canopy coverage method of vegetation analysis: Northwest Science, v. 33, p. 43–64.

Goodrich, S., 2005, Vegetation of the Uinta Mountains and its relationship with geology and geomorphology, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain Geology: Utah Geological Association Publication 33, p. 263-282.

Goodrich, S., and Neese, E., 1986, Uinta Basin flora: USDA Forest Service-Intermountain Region, in cooperation with USDA Forest Service-Ashley National Forest and USDI Bureau of Land Management-Vernal District.

Jensen, J.R., 2005, Introductory d image processing (3rd ed.): New York, Prentice-Hall, 544 p.

Johnston, C. A., and Brown, T.N., 2013,Water chemistry distinguishes wetland plant communities of the Great Lakes coast: Aquatic Botany, v. 104, p. 111–120.

Koll, R.A., 2012, Long-term vegetation, climate, and fire history in the eastern Uinta Mountains, Utah, U.S.A.: Salt Lake City, University of Utah, M.S. thesis, 90 p.

Laabs, B.J.C., and Carson, E.C., 2005, Glacial geology of the southern Uinta Mountains, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain Geology: Utah Geological Association Publication 33, p. 235–253.

Leica Geosystems, 2010, Leica ADS80—Airborne Digital Sensor, Digital Airborne Imaging Solutions brochure/product specification sheet: Online, http://www.leica-geosystems.com.

Lichvar, R.W., 2013, The National Wetland Plant List—2013 wetland ratings: Online, Phytoneuron 2013-49: 1-241. (See also the official website of the National Wetland Plant List.)

Matyjasik, M., and Ford, R.L., 2000, Geomorphology and hydrology of selected wetlands of the Uinta Mountains, Utah, report submitted to Utah Wetland Coordinator, Governor's Office of Planning and Budget (State Contract #986266), 64 p.

Matyjasik, M., Ford, R.L., and Keate, N., 2003, Montane wetland hydrochemistry, Uinta Mountains, Utah: Hydrological Science and Technology, v. 19, p. 251–266.

Mitsch, W.J., and Gosselink, J.G., 2007, Wetlands (3rd ed.): New York, John Wiley and Sons, 722 p.

Moore, P.D., and Bellamy, D.J., 1974, Peatlands: New York, Springer-Verlag, 221 p.

Munroe, J.S., 2002, Timing of postglacial cirque reoccupation in the northern Uinta Mountains, northwestern Utah, U.S.A.: Arctic, Antarctic, and Alpine Research, v. 34, p. 38–48.

Munroe, J.S., 2003, Holocene timberline and paleoclimate of the northern Uinta Mountains, northeastern Utah, USA: The Holocene, v. 13, p. 175–185.

Munroe, J.S., 2005, Glacial geology of the northern Uinta Mountains, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain Geology: Utah Geological Association Publication 33, p. 215–234.

Munroe, J.S, and Laabs, B.J.C., 2009, Glacial geologic map of the Uinta Mountains area, Utah and Wyoming: Utah Geological Survey Miscellaneous Publication 09-4DM, scale 1:100,000.

Shaw, J.D., and Long, J.N., 2007, Forest ecology and biogeography of the Uinta Mountains, U.S.A.: Arctic, Antarctic, and Alpine Research, v. 39, p. 614–628.

USDA NRCS, 2014, The PLANTS Database (http://plants.usda.gov, 22 May 2014): National Plant Data Team, Greensboro, NC 27401-4901 USA. National Plant Data Center, Baton Rouge, LA 70874-4490 USA.

Welsh, S.L., Atwood, N.D., Higgins, L.C., and Goodrich, S., 1993, A Utah Flora (2nd ed., revised): Provo, Utah, Brigham Young University Print Services, 986 p.