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GEOMORPHIC CHARACTERISTICS OF FENS IN THE SAN JUAN MOUNTAINS, COLORADO

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Abstract—Fens are abundant in the formerly glaciated valleys of the San Juan Mountains, Colorado. Fens function as critical sedimentary sinks in alpine regions and record anthropogenic and natural phenomena that occurred in vicinity of the fens. For example, increased rates of sedimentation resulting from mining activity or forest fires can be identified. Whereas ecologists have contributed much in the study of fens, unfortunately, geomorphologists have almost ignored their study. Thus, no consistent classification systems of alpine fens based on geomorphology exists. We investigated geomorphic and sedimentary properties of alpine fens in the San Juan Mountains. Based on this, we developed a geomorphic classification scheme for fens, which consists of three classes: 1) valley-bottom, 2) valley-side, and 3) terrace. Morphometric measures of fen circularity and elongation were obtained for seventy fens. Valley-side fens are more elongated than either valley-bottom or terrace fens of similar elongation. Overall, the elongated fens have less circularity. Sediments were also sampled at the field sites. The sieved sediments yielded distinct mean phi values that conformed to the three categories. Coarse-grained particles were associated with valley-side fens, and medium-grained particles with valley-bottom and terrace fens, respectively. Thus, from a geomorphic perspective, our criteria of locational, morphometric, and grain-size analysis provide a consistent classification for alpine fens.

INTRODUCTION

Understanding the geomorphic aspects of fens is necessary to appreciate the roles fens play in the alpine environments. Figure 1 shows a cross section of a typical fen that is observed throughout the study region. Serving as sources and sinks for material, fens are regulators of material and energy flow. For example, rainwater can enter a fen and either be retained, be incorporated into the groundwater, or be taken up by plants; or it can evaporate or exit the fen. Unfortunately, despite such important roles fens play in alpine regions, few studies have focused on the geomorphology of fens (Rocchio, 2005; Watters and Stanley, 2006; Warburton and Evans, 2010; De Mars and Garritsen, 1997; Devito et al., 1997; Vitek and Rose, 1980). Because the San Juan Mountains contains a significant number of fens, this research seeks to answer the question: What are the geomorphic characteristics of alpine fens and what variables are common amongst those observed throughout the region? The following steps were employed to create a geomorphic classification of alpine fens: 1) geomorphic maps were created to determine hydrologic relation of fens to surrounding landscapes, 2) morphological characteristics of each fen were measured, and 3) soil grain-size analyses to determine sedimentary characteristics was undertaken.

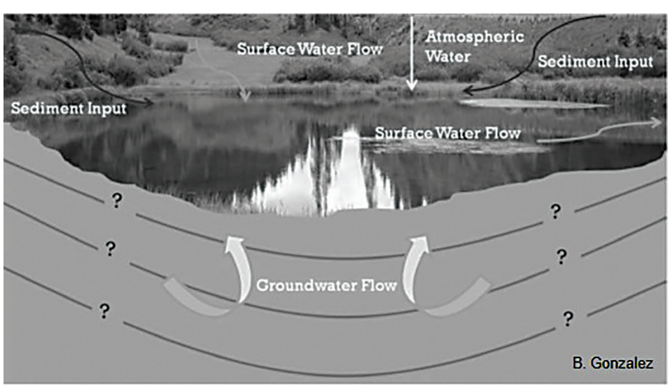

FIGURE 1. Fens as sources and sinks, featuring atmospheric water, surface water, and groundwater inputs and outputs.

Fens are a dynamic type of wetlands, sustained primarily by groundwater and surface water (Bedford and Godwin, 2003). Also, fens contain at least 40 cm of peat within a soil profile (Rocchio, 2005), and should contain 95% water (Charman, 2002). Like other wetland types, fens are a storehouse of information about organismal activities and physical events of the past and present environments (Charman, 2002). Multiple factors, such as animal grazing and burrowing, mining, construction of major roads, fires, and altering of the landscapes, have an impact on the functions of a fen. Thus, the geomorphic processes associated with fen systems are essential to understanding the roles that fens play in the environment.

A survey of the literature illustrates that most of the research on fens has focus on ecology, restoration, and hydrology (Euliss et al., 2004; Cowardin et al., 1979; Austin, 2008; Johnson and Valppu, 2003; Cooper and MacDonald, 2000; Almendinger and Leete, 1998; Hauer and Smith, 1998; Faber-Langendoen, 2005; Chimner et al., 2008; Cooper et al., 2006), and six studies have focused on geomorphology (Rocchio, 2005; Watters and Stanley, 2006; Warburton and Evans, 2010; De Mars and Garritsen, 1997; Devito et al., 1997; Vitek and Rose, 1980). As certain types of organisms belong exclusively to fens, much research has been devoted to evaluating the types of vegetation present in the fens (Euliss et al., 2004; and Cowardin et al., 1979). Austin (2008) surveyed 88 fens and found that nearly half of them were affected primarily by human activities. Such features as ditches and drainage lines, and damage from vehicle use were found to influence the fens. Johnson and Valppu (2003) studied soil and crop cover within small-scale plots, plant transplants, monitoring of large-scale soil applications, and suggested ways to restore peatlands. Cooper and MacDonald (2000), after examining what plant species naturally colonize fens on mined surfaces, developed restoration methods to address extensively mined peatlands. They evaluated the techniques for the restoration of dominant plant species in mined areas.

Almendinger and Leete (1998) studied rare vegetation in fens by incorporating the role of hydrology in six calcareous fens in the Minnesota River Basin. Their study suggested that hydrogeology, landforms, and geology are significant factors in fen development. Taking a hydrogeomorphic approach that encompasses hydrological sources and regime, and geomorphic settings, Hauer and Smith (1998) investigated a riverine wetlands environment, and concluded that fens foster: 1) surface-, subsurface water storage, 2) nutrient cycling, removal and retention of sediments, and 3) maintenance of plant and wildlife habitat, and detrital biomass. Faber-Langendoen (2005) discovered that fens in depressions were fed water from adjacent rivers and lakes. In addition, he also found that water-table fluctuation affects groundwater flow to the fen system. Likewise, Chimner et al. (2008) and Cooper et al. (2006) suggested that development of a fen is linked to natural and anthropogenic changes in hydrology, glacial history, and landforms.

Rocchio (2005) examined fens in glacial topography and found that the impacts of water diversions, ditches, peat mining, and livestock management were significant on the hydrology of the fens. Such hydrologic changes could lead to peat oxidation and decomposition, changes in subsurface water storage capacity, fen shapes, and vegetation.

Watters and Stanley (2006) studied water flows through fens and, in particular, peatland surface-drainage networks. Peat deposits were found to alter stream path, velocity, and flow stability.

The rate of peat erosion and the impact of peat block transport on fluvial systems were studied by Warburton and Evans (2010); the authors illustrated that peat deposits could act as obstacles in channel flow, bed topography, bank stability, and physical habitat (cf. Evans and Warburton, 2007). De Mars and Garritsen (1997) suggested that groundwater flow and water quality influence the various components of fens located in a meadow environment. Studying the simulation of groundwater and analyses of water samples, they demonstrated that changes in water management and groundwater pollution are critical for the vegetation types present in a fen meadow environment.

Devito et al. (1997) showed that the ecological function of fens depends much on local hydrology. More specifically, when a water deficit occurs, the direction of subsurface water flow may be reversed.

Vitek and Rose (1980) investigated a patterned fen in the Sangre de Cristo Mountains in Colorado. They pointed out the significance of morphology, hydrology, solifluction, peat thickness, and rates of erosion and deposition on a patterned fen system.

STUDY AREA

The majority of wetlands in the San Juan Mountains are fens, not bogs, because fens do not necessarily retain surface water year-round. The fens occur on or near breaks in slopes, or in low-lying areas where water is discharged and often remains on the surface (Rocchio, 2005).

The majority of the fens we focus on in this paper are located throughout the San Juan Mountain Caldera, except California Gulch that is west of the caldera rim. The fen sites are all within the Animas and Uncompahgre watersheds, and range in elevation from 3000-3600 m (Fig. 2). The fens we focus on in this paper are situated in five locations: California Gulch, Glacial Lake Ironton, Howardsville, and the North and South sites of the Red Mountain Pass (Fig. 3).

REGIONAL GEOLOGY, HYDROLOGY, AND PEDOLOGY

The San Juan Mountains consist of Precambrian crystalline basement rocks, and Paleozoic, Mesozoic, and Eocene-aged sedimentary rocks along with a Tertiary-aged volcanic cover-

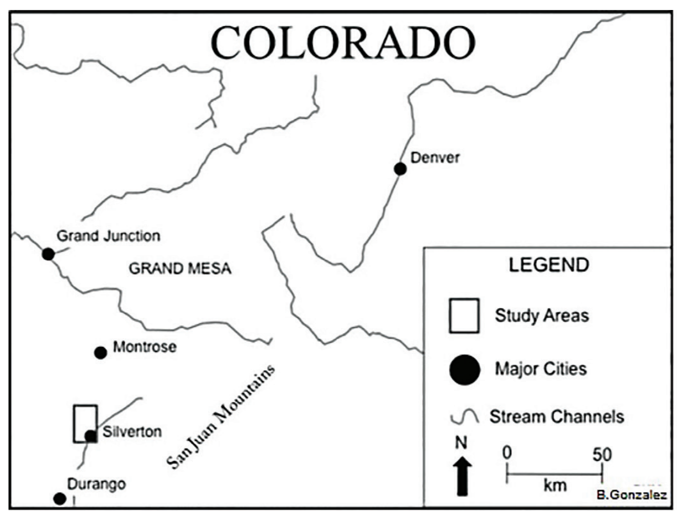

FIGURE 2. Location map of research area with the study sites outlined with a box.

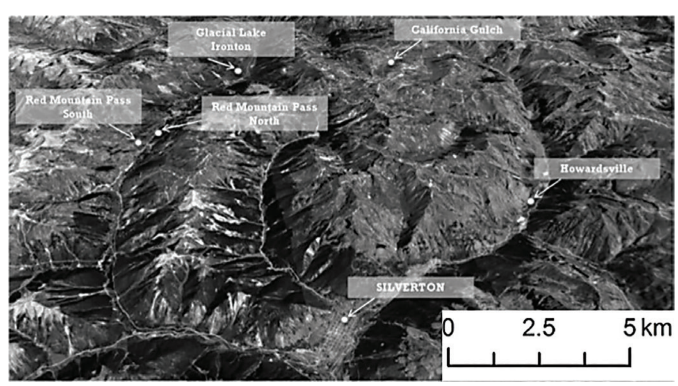

FIGURE 3. Study sites about Silverton, Colorado and the Silverton Caldera (Google Maps, 2017).

ing (Church et al., 2007). The San Juan and Silverton Calderas produced a 1-km-thick Oligocene-aged volcanic layer. The volcanic layer is heavily faulted, hydrothermally altered, and mineralized during the Oligocene and Miocene (Church et al., 2007). The faults and fractures are essential to the water flow (Blair et al., 1996).

Pleistocene glaciers subsequently carved numerous valleys in the area (Vincent et al., 2007). Based on ^{14}C analyses of bog and lake sediments, glaciers retreated 15-18,000 years BP (Maher, 1972; Carrara et al., 1984). After deglaciation in the late Quaternary, streams continued to cut the valleys (Moore, 2004). With continued erosion, alluvium filled the valley floors on which wetlands formed.

Hydrology has been a major factor in the creation and the preservation of fens in the valleys, because usually thick alluvium allowed for surface water collection in aquifers to support fens (Rocchio, 2005). Streams such as Mineral Creek, Red Mountain Creek, and the Animas River now exist contiguously to the Silverton Caldera, and provide an adequate water supply for the sustenance of fens around the margins (Stanton et al., 2007). Groundwater is also critical in sustaining fens, because it provides meteoric water to replenish the fen (Rocchio, 2005).

Soils in the study sites are characterized by parent-material type, slope, drainage, and depth to water table. Soil composition varies from a combination of peat, loam, sand, clay, gravel, and cobble (NRCS, 2011). Drainage is poor to very poor, and depth to bedrock is usually >203 cm except in Glacial Lake Ironton, whose depth is 102-203 cm. Depth to water table is roughly 15-51 cm, excluding the Red Mountain Pass North area, which can be up to 203 cm. Each fen site is part of a larger fen complex, with each site extending over a 0.0003-0.18 km^2 and 3000-3600 m in elevation. Of the five selected study sites, the Glacial Lake Ironton fen does not exhibit the properties of a true fen, because the top 40 cm of its soil lacks peat.

METHODS

Geomorphic mapping

The study areas were mapped at a scale of 1:3000, following standard geomorphic mapping procedure (de Graaff et al. 1987; Demek, 1972; FGDC, 2006; Gardiner and Dackombe, 1983). Topographic and geologic maps at 1:24,000 were used to supplement geomorphic mapping in the field. Digital topographic maps and orthorectified aerial photographs were used in ArcGIS®, and printed for a reference in the field.

Morphometry

The morphometry of the fens was calculated using ArcGIS® and orthorectified photographs from the NRCS (2011). Length, width, perimeter, and area were measured in the field and calculated using ArcGIS®. The circularity and elongation were measured for seventy fens, in addition to the five fens from the study sites. Circularity is based on the area of each fen divided by the area of a circle, replacing the circumference with the perimeter of each fen as:

$$F_c = \frac{A_f}{A_c}$$

where: A_f is the area of the fen, and A_c is the circularity of the fen based on the perimeter of the fen. Though perimeter was incorporated into the circularity, it was not used in the elongation because the fen perimeter is not a perfect circle. Elongation was calculated as the length of fen divided by the width as:

$$F_e = \frac{F}{W}$$

where: L is the length of the fen based on the long axis, and W is the width of the fen, perpendicular to the long axis. The larger the value of elongation, the more elliptical the fen. In theory, when the length of the fen equals the width, the fen would be circular.

Sampling sediment

Sampling sediment was conducted following Goudie et al. (1981) and SSDS (1993). At each sample site, a pit of 40 cm in diameter was excavated to a depth of 100 cm. Sediment was then removed. After extraction, sediment was sealed, and further subsampled to avoid compression and expansion in 2 cm increments with about 15-18 subsamples per sediment sample (Fig. 4). To prevent contamination, tools were cleansed thoroughly with distilled water three times between sampling. Subsamples were weighed and sieved with U.S.A. Standard Testing Sieve screens with mesh sizes of 1.19 mm, 0.59 mm, 0.42 mm, 0.25 mm, and 0.07 mm (i.e., #16, #30, #40, #60, and #200). Cumulative frequency diagrams were created for each subsample following Balsillie et al. (2002) to determine the distributions of grain-sizes, the mean phi, and standard deviation.

FIGURE 4. A sediment sample from the California Gulch fen with the top of the unit on the left side of the photograph.

RESULTS

Morphology from maps and field

California Gulch

The California Gulch (CG) is situated at an elevation of ~3600 m and has a surface area of 0.002 km^2. The CG fen complex (37º55'47"N, 107º36'16"W) is located northwest of Animas Forks and north of Silverton. The western slopes are characterized by exposed extrusive rocks. The eastern edge exhibits areas of rockfalls, which serve as water and debris flow paths (White, 1981), of which steep sides incline at 5-8°. The West Fork of the Animas River is eroding the bedrock, which consists of the Eureka and Burns Members (Luedke and Burbank, 1987). The Gulch also has dikes and sills of porphyritic quartz latite, and mineralized faults (Luedke and Burbank, 1987). The CG fen (Fig. 5) slopes to the east-southeast at 2-4°, draining into the West Fork Animas River that flows along the narrow valley bottom. The fen is situated on sloping ground next to a large igneous rock outcrop to the southwest, a smaller one in the center portion of the fen, and a third one on the northeast lower side of the fen.

Glacial Lake Ironton

Glacial Lake Ironton (GLI) is at ~3000 m in elevation and is 0.0003 km^2 in area (Fig. 6). The fen site is surrounded by lush vegetation (Fig. 6). Overall, the fen complex slopes to the north-northeast at ~2° with valley slopes ranging 4-8°. Though the slopes are relatively gentler in the west portion, they are relatively steeper in the east. The Henson, Burns, Eureka, and San Juan members are present along with mineralized veins, faults, and hydrothermally altered rocks (Burbank and Luedke, 1964). Talus and glacial drift occur along the slope bases in the fen complex, as well as sedimentary rocks consisting of the Molas Formation, Ouray Formation, and Leadville Limestones (Burbank and Luedke, 1964). Numerous fens occur within the GLI fen complex, but the chosen sample site is located at 37º56'22"N, 107º40'19"W, west of Mineral Creek.

Howardsville

The Howardsville (H) fen complex is situated on a river terrace east of the Animas River at an elevation of ~3000 m (37º50'39"N, 107º35'6"W) and has an area of 0.005 km^2; it is north of Silverton (Fig. 7). The valley slopes range from 4-8°. In the southeast, extrusive outcrop of the Burns and Eureka Members dominate (Luedke and Burbank, 2000). The lower valley slope portion and the river terrace are dominated by talus, alluvial cones, fans, and glacial drift, with the eastern slope cut by hydrothermally altered dikes, faults, and veins. The western section shows cliffs covered in taluses of various compositions, presumably mobilized by water flow along valley floors (White, 1981). The eastern portion has two major debris flow paths; both extend onto the valley floor into the fen. The fen is adjacent to steep bluffs and forested areas. Multiple water-flow paths start from the fen and extend to the river. A beaver dam is present in the fen and is surrounded by fine-grained sediment, gravel, and cobbles.

Red Mountain Pass North

The Red Mountain Pass North (RMPN) fen complex is 0.018 km^2 in area and located at 37º54'10"N, 107º42'31"W at ~3400 m elevation (Fig. 8). Its slopes range from 1 to 4° to the south-southwest and contains three small fens that drain to a tributary of Red Mountain Creek. The site is surrounded by extrusive igneous rocks and roche moutonnée. Numerous roche moutonnée are west of the fen and impede water flow. The surrounding slopes consist of the Burns Formation, which is composed of colluvium of breccias, tuffs, and rhyo-dacitic bedrock, and their associated flow paths. At the base bedrock slopes, unconsolidated debris is exposed, creating concave and convex shapes, and slopes >40°. To the east, slopes are gentler. Mineral Creek flows alongside the largest pond in the fen

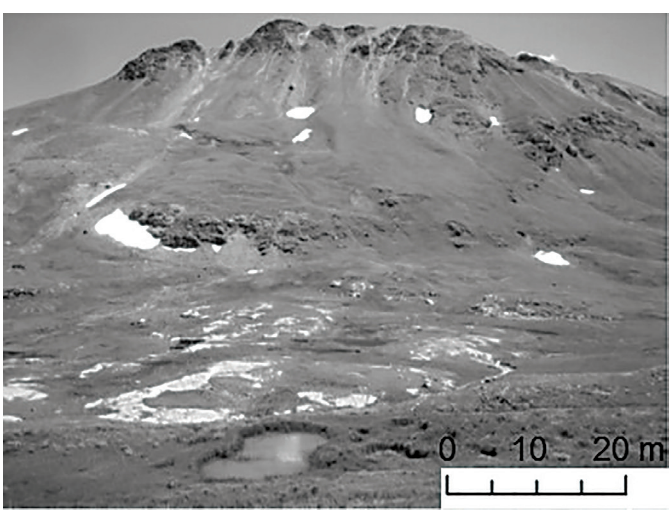

FIGURE 5. The upper portion of the California Gulch fen, including the uppermost pond. The photograph was taken looking to the east-southeast.

FIGURE 6. Glacial Lake Ironton fen, surrounded by willow shrubs and covered in grasses and exposed soil. The photograph was taken looking to the north-northwest.

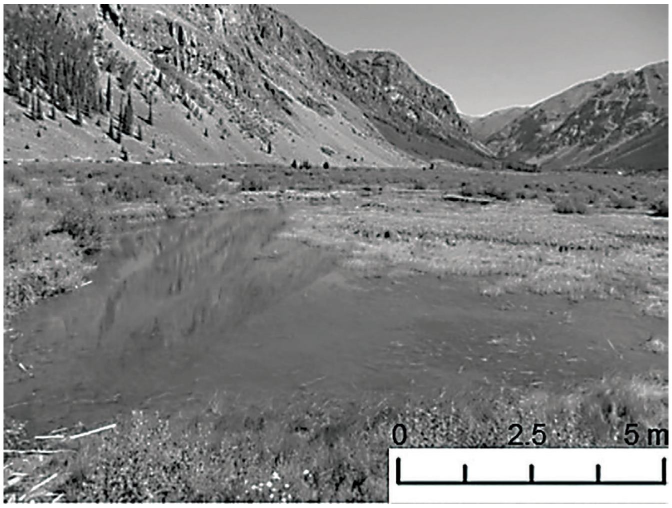

FIGURE 7. The Howardsville terrace fen, with a beaver dam visible in the center of the photograph. The photograph was taken looking upstream of the Animas River valley.

Figure 8. Looking to the north at Red Mountain Pass North fen.

complex. Altered igneous rock associated with ore deposits is present east of the RMPN fen.

Red Mountain Pass South

Located <700 m from the North site, the Red Mountain Pass South (RMPS) fen complex slopes 1-3° to the south-southeast at an elevation of ~3400 m (Fig. 9). The complex is 0.014 km2 in area, located at 37º53’44”N, 107º42’50”W. The RMPS flows into the Animas Watershed whereas the RMPN flows into the Uncompahgre Watershed. Igneous rocks and roche moutonnée are located to the west. Above the edge of the fen are areas of exposed igneous rock and depressions between the roche moutonnée. Along the eastern portion of the fen is an abrupt break in slope of >40°. Northeast of the fen is a gravel surface, and to the east are steep slopes covered with boulders, cobbles, and gravels trending down slope from exposed quartz-latite bedrock.

GRAIN-SIZE ANALYSIS

Soil samples and the subsamples were analyzed for grain-size distribution throughout the soil column. Mean grain-sizes (ϕ) with standard deviations (σ) varying at each study site were determined (Table 1). Sample means ranged from 0.0178 to 1.6028ϕ, and σ ranged from 1.0182 to 1.8092. Grain-sizes ranged from medium- to coarse-grained sand. Subsample means ranged from -0.2277ϕ to 1.5100ϕ with σ range from 0.6657 to 1.8060. Sand sizes ranged from very coarse to fine-grained.

At the CG fen site, the soil profile (0-65.5 cm) consists entirely of coarse-grained sand with a mean of 0.2112ϕ ±1.1985. Subsamples, with increasing depth, has means of 0.4560 f, 0.3952ϕ, 0.0951ϕ, 0.1572ϕ, 0.1353ϕ, and 0.1351ϕ, respectively. It is coarse-grained and consistent with the 65.5 cm profile. The GLI soil profile (0-16 cm) has medium-grained sand, with a mean of 0.9045ϕ ±1.4853. The H fen soil profile (0-36 cm) contains medium-grained sand with a mean of 1.6028ϕ ±1.8092, with its subsamples ranging between 0.6466ϕ ±1.5466 and 2.4122ϕ ±1.6233. This profile has the greatest grain-size range, from coarse to fine. At the RMPN, the soil profile (0-70 cm) is coarse-grained sand with a mean of 0.0178ϕ ±1.0182. The subsample means ranged between 0.1351ϕ ±1.1345 and -0.0881ϕ ±0.8868, with grain sizes ranging from very coarse to coarse. The soil profile at RMPS is medium-grained sand and has a mean of 1.0516ϕ ±1.7385. The means of its subsamples ranges from 0.0852ϕ ±1.6891 to 1.5343ϕ ±1.7035. The mean 1.5343ϕ ±1.7035 was derived from the visible grain-size change at depths of 26-28 cm.

Location and morphometry

Based on our mapping and morphometric analyses, three types of fens emerged: 1) valley-bottom, 2) valley-side, and 3) terrace (Fig. 10). The GLI and RMPS fen complexes were categorized as valley-bottom fens because both complexes formed in alluvial valleys and are surrounded by moderately steep valley sides. The CG and the RMPN fen complexes, were considered valley-side fens as they slope towards the valley floor. Lastly, the H fen is classified as a terrace fen because it resides on a terrace adjacent to the Animas River.

FIGURE 9. Red Mountain Pass South fen, with roche moutonnée in the background. The photograph was taken looking to the west.

TABLE 1. Sieve data for all sites and sections. Bold indicates data for entire profile over the shown depth range.

Sample	Depth (cm)	Mean (ϕ ±σ)	Grain-size
CG	**0-65.5**	**0.2112±0.1985**	**Coarse**
CG	0-25	0.4560±1.2822	Coarse
CG	25-36	0.3952±1.3326	Coarse
CG	36-43	0.0951±1.1236	Coarse
CG	43-50	0.1572±1.1781	Coarse
CG	50-55	0.1353±1.1645	Coarse
CG	55-65.5	0.1351±1.1576	Coarse
GLI	**0-16**	**0.9045±1.4853**	**Coarse**
HV	**0-36**	**1.6028±1.8092**	**Medium**
HV	0-9	0.6466±1.5466	Coarse
HV	9-31	1.5100±1.8060	Medium
HV	31-36	2.4122±1.6233	Fine
RMPN	**0-70**	**0.0178±1.0182**	**Coarse**
RMPN	0-15	0.1351±1.1345	Coarse
RMPN	15-60	-0.2277±0.6657	Very coarse
RMPN	60-70	-0.0881±0.8868	Very coarse
RMPS	**0-68**	**1.0516±1.7385**	**Medium**
RMPS	0-38	0.0852±1.6891	Coarse
RMPS	26-28	1.5343±1.7035	Medium
RMPS	38-68	1.3245±1.7706	Medium

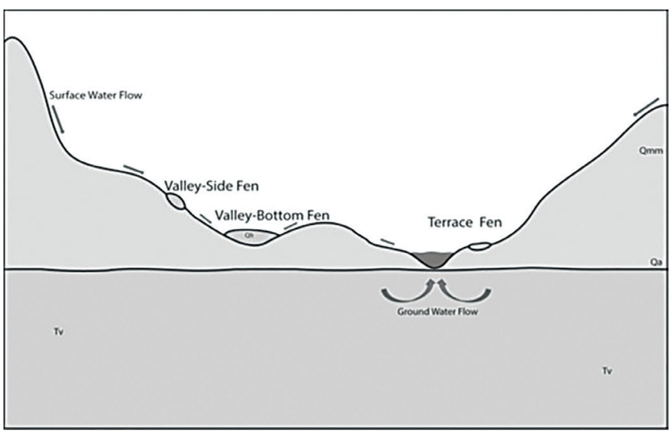

FIGURE 10. Classification of fens based on geomorphic location. (Qa=Quaternary alluvium, Qh=Quaternary Holocene sediment, Qmm=Quaternary mass movement, Tv=Tertiary volcanic bedrock).

Aside from classifying fens based on location, the five fens illustrate location-type (Table 2), and morphometric analyses were used to categorize the additional seventy fens; they were delineated using orthorectified photographs and ArcGIS®. The morphometric properties were calculated for all seventy fens (Table 3).

The mean circularity and elongation for valley-bottom fens are 0.7, with valley-side and terrace fens showing little variation as their mean and median values; they are all 0.6.

TABLE 2. Site, classification, fen elongation, and area associated with each of the five main fens.

Site	Classification	Elongation	Area (km^2)
CG	Valley-side	2.6	0.002
RMPS	Valley-bottom	2.1	0.014
GLI	Valley-bottom	1.2	0.0003
RMPN	Valley-side	2.6	0.018
HV	Terrace	1.9	0.005
Mean		*2.1*	*0.008*

TABLE 3. Fen Morphometry: mean and median values of area, circularity, and elongation values of seventy fens.

Fens	Area, km^2 (mean, median)	Circularity (mean, median)	Elongation (mean, median)
Valley-bottom	0.004, 0.003	0.7, 0.7	1.7, 1.9
Valley-side	0.004, 0.004	0.6, 0.6	2.4, 2.4
Terrace	0.004, 0.003	0.6, 0.6	1.9, 1.9

Valley-bottom fens exhibit the greatest circularity. Regarding elongation, valley-bottom fens have a mean of 1.7 and a median of 1.9 (ranging from 1.2 to 2.2), whereas terrace fens have a mean and median of 1.9 (ranging from 1.6 to 2.2). In contrast, valley-side fens have a mean and median elongation of 2.4 (ranging from 2.2 to 2.8). Valley-side fens are more elongated than either valley-bottom or terrace fens, which tend to be more circular. Notably, valley-side fens are the only type whose elongation values exceeded 2.2. Also, valley-bottom fens have the largest range of values among the three types. Overall, valley-side fens are more elongated than either valley-bottom or terrace fens. In conclusion, morphometry is consistent with the amount of slope observed at each location.

DISCUSSION

Water flux of fens

Field observations of the topography clearly demonstrate that the five fens receive materials primarily from the sides. Steep slopes appear to funnel materials of various grain-sizes carried by water to lower-lying areas. The process is evident in the valley-bottom fens, both the GLI and the RMPS. They are both surrounded by steep slopes and have water flowing into and out of them. Valley-side fens, such as the CG and the RMPN, sit at the base of valley slopes and are prone to the influence of stream water and groundwater. At the terrace fen H, the Animas River dictates times and amount of sedimentation.

Geology and groundwater also influence the material fluxes of fens, coupled with the level of the water table. The surrounding rocks, presence of fractures, and alluvium thickness can facilitate or impede surface- and groundwater flows. In the CG, surface water is channeled from the igneous rock to the west, whereas the RMPN receives water from flows that are diverted around roche moutonnée and bedrock outcrops. The GLI and the RMPS receive additional water from streams that cut through the alluvium and flow downslope of bedrock slopes. The H fen receives additional water that flows over Quaternary deposits and to the terrace. The depth to the water table for the CG fen is over 200 cm and at the RMPN fen, up to 203 cm (NRCS, 2011). These valley-side fens appear to be sustained by water seeping from bedrock at the base of slopes. Alternatively, the GLI has an estimated depth to bedrock of 15-90 cm and the water table at the RMPS is >91 cm (NRCS, 2011). Both these valley-bottom fens are replenished by groundwater. Lastly, the terrace fen H has an estimated depth to groundwater ranging 15-50 cm (NRCS, 2011).

Morphometry and grain-size

Because no geomorphological classifications for wetlands have been suggested in the past we created a geomorphic classification based on morphometric and grain-size analyses. Soil profile analyses and comparisons of overall grain-size to types of fens suggest a pattern. Valley-bottom and terrace fens contain medium- to coarse-grained sand, and valley-side fens contain coarse- to very coarse-grained sands. The soil profiles from valley-side fens, the CG and the RMPN, contain coarse to very-coarse sand grains. The soils from the valley-bottom fen, RMPS (68 cm depth), and the terrace fen H (36 cm depth) contain medium-grained sands. Overall, excluding the GLI site for lacking peat, valley-side fens have coarse-grained sand, and valley-bottom and terrace fens have medium-grained sediments. Presumably larger grain-sizes would be found in valley-bottom fens as larger grains are funneled to the flatter surface as the result of mass; however, the results suggest the opposite, where larger-grained sands tend to remain on valley slopes and are not transported to the valley-bottom.

The slopes of the valley sides may also influence the deposition of larger grain sizes in these valley-side fens. As for valley-side fens, CG slopes ~2º, at the sample site, which is within 50-m distance from a major break in slope. The RMPN slopes range from 1 to 4º. The flow velocity would decrease as it reaches a break in slope and deposits coarse grains on the sloping fens. In contrast, the valley-bottom and terrace fens have slopes roughly 1-2º. The sample sites were more distant from the valley sides, and, thus, more fine- to medium-grained sediment is deposited at the terrace fen, H, and overall medium-sized grains at the valley-bottom fens GLI and RMPS. The abrupt slope changes control water flow velocity and reach, and, hence, the depositional pattern.

Regional flooding appears to be closely linked to sedimentation. The H fen formed on a terrace that is surrounded by steep valley walls is prone to inundation during Spring floods. The soil profile at H has an overall medium-grain texture, whereas the texture varied from coarse-, medium-, to fine-grained sand, which may be attributed to the flooding of the Animas River during a dam break as a result of snowmelt between 1973 and 1974 (USGS, 2012). Other floods and mass movement such as mudslides may also be responsible for such grain-size alterations. The RMPN is a valley-side fen where materials are often transported downslope through the fen, which is consistent with variable sedimentation rate. This is demonstrated by its subsamples being coarse-grained at the surface to very-coarse grained at depth.

CONCLUSIONS

Our study of alpine fen complexes in the San Juan Mountains of Colorado resulted in a classification scheme based on morphology. The morphometric analyses and geomorphic mapping helped delineate the boundaries for material fluxes into the fens, and grain-size analyses defined the fen sedimentary characteristics. First, based on location, elongation, and circularity, seventy fens were classified as either valley-bottom, valley-side, or terrace fens. Valley-side fens were more elongated than valley-bottom and terrace fens, which exhibit similar elongation to each other. The variable grain sizes of sediments also conform to the three categories. Corresponding to the locations, larger grain sizes occur at valley-side fens that are closer to the sources, rather than in valley-bottom or terrace fens. Thus, at the San Juan Mountains, locational, morphometric and sedimentary analyses resulted in three distinct types of alpine fens, valley-bottom, valley-side, and terrace. We expect that this pattern has universal application.

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