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Designing a Living Snow Fence for Snow Drift Control

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Abstract

Blowing and drifting snow continues to be a transportation and safety hazard with significant economic costs. Critical design criteria for the construction of a living (vegetated) snow fence are reviewed and presented using the most currently available design equations. Coupled with an analysis of climate and topographical data, the design criteria are applied to an area in Rocky Mountain National Park historically prone to snow drifting. The long-term average snow accumulation season (period beginning with the first blowing snow and ending with maximum drift density) was calculated from air temperature as between 4 November and 10 April, and these dates compared well with those based on nearby snow observations. Over the snow accumulation season, the potential for snow transport based on wind characteristics was 21.4 tonnes m^{-1} (all wind directions), of which 21.0 tonnes m^{-1} occurred along a mean drifting direction of 259° (nearly perpendicular to the road at the study site). The potential for snow transport based on snow characteristics (754 tonnes m^{-1}) exceeded the potential for snow transport based on wind characteristics, thus indicating that wind was the primary factor controlling drift formation. Using a snow transport of 23.9 tonnes m^{-1}, determined using the long-term average snow water equivalent plus one standard deviation (occurred in three out of 25 years of observations), the required snow fence height needs to be 1.61 m tall, set back 56.4 m from the road. The fence will have a trapping efficiency of 79% when an effective porosity of 50% is achieved. Comparisons of these design parameters to snow drift conditions created behind a structural fence indicated that living snow fence design parameters are likely appropriate and realistic.

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Introduction

The costs associated with reduced visibility due to blowing snow and the accumulation of snowdrifts on roads are substantial (e.g. Seppala, 1999; Decker et al., 2003). Snowdrifts jeopardize public safety, emergency service accessibility, interrupt business, and increase wildlife mortality. Controlling the duration and extent of snow drifts helps reduce snow removal costs. The quantity of drifted snow can be hundreds of times greater than direct precipitation, and therefore most time and costs are associated with removing wind-blown snow. Expensive road damage may occur due to the infiltration of water under pavement, blockage of ditches and culverts, and the use of snow removal equipment. Moreover, blowing and drifting snow are a transportation safety hazard (including air travel), as drifts can cause a sudden loss of vehicle control, reduce visibility, obscure signs, promote ice formation, and reduce road width. Economic impacts can be substantial. For example, a 45-hr airport closure in December 2006 due to blowing snow accumulation on runways at Denver International Airport resulted in an estimated loss of $43 million, and an estimated $31 million budget for an improved snow removal equipment/plan (Leib, 2007).

Snow fences trap snow by decreasing the wind velocity, hence transport capacity, of snow in the lee of the barrier or fence. Snow is then accumulated behind the barrier, some distance away from the area being protected. The usual design is a slatted (or porous) structural fence, but solid barriers (rock walls) have been proven effective in mountain areas (Baker and Dutch, 1992). Structural snow fences (usually a slatted fence) have effectively been used to reduce drifting on roads (e.g. Martinelli et al., 1982), but they have a short service life, are costly to erect and remove, disrupt wildlife movement, and are not aesthetic. In contrast, ''living'' (vegetated) snow fences offer several advantages over structural fences, including lower costs and aesthetic value when properly designed (Greb, 1980; Shaw, 1991).

Improperly designed or maintain snow fences, whether structural or living, may actually increase drifts across roads and decrease visibility, thereby compounding the problem for various reasons. For example, fences that are too low may quickly reach capacity in major storms, resulting in drift extension across the protection area (Shaw, 1991); fences that are of insufficient length may result in long, curl drifts due to vortices that develop at the ends of the fence (Tabler, 1980); and fences that are too close to the protection area or that fall into disrepair may result in drift extension across the protection area (Shaw, 1991).

Proper design of snow fences at the specific location of the protection area, and subsequent maintenance, can mediate all of these issues; however, living snow fences are especially sensitive to certain design and maintenance issues compared to structural fences. Whereas structural fences, when designed properly, can provide immediate protection from blowing and drifting snow, the design of living snow fences needs to account for changes in vegetation height and density over time, thus potential changes in snow trapping properties over time. For example, roughly 10 years

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were required after planting until the vegetation in a living snow fence program in North Dakota reached sufficient height and density to effectively trap snow (NDDOT, 2009). As described here, special design considerations, such as multiple rows of different vegetation types and drifting provided by upwind shrubs to enhance moisture to downwind vegetation should be considered in living snow fence design.

There are several reports available (e.g. Shaw, 1991) focusing on the novel considerations of living snow fence installation, efficiency, maintenance, and ecological impacts. Shaw (1991) reported that for similar snow storage capacities, installation costs for living snow fences are less than that for a structural snow fences, and that living snow fences have a much longer service life (50–75 years for a living fence versus 5–7 years for a typical slatted snow fence). Although living snow fence installation costs tend to be lower compared to structural snow fences, maintenance costs for any type of snow fence vary considerably with location. When considering all costs (installation, maintenance, and the time required for a living snow fence to become fully effective) over the service life of a snow fence, the costs for a living and structural snow fence can be similar (Tabler, 2003). Living snow fences can be aesthetic and provide habit for wildlife, the latter often being undesirable near a road. Additional potential effects associated with living snow fences include changes in the nitrogen content of vegetation with changes in snow depth (Walsh et al., 1997), vegetation species composition (Stanley et al, 1998), and increases in soil moisture and temperature (Holt, 1995; Hinkel and Hurd, 2006); such changes may or may not be desirable at a given location.

The design parameters provided through detailed analysis of site climatology and conditions are critical for effective snow drift control, and this analysis is often overlooked, resulting in snow fence failure (no drift control, or even exacerbation of drifting). Provided effective snow drift control is achieved through proper design considerations, these advantages of living over structural snow fences potentially means that living snow fences may be a cost-effective, environmentally conscious alternative to structural snow fences. Given the importance of these critical snow fence design concerns (including height, density, length, and setback distance: Tabler, 1980; Norem, 1985; Takeuchi et al., 2001), and the fact that both living and structural snow fences often fail due to improper pre-construction design, the objective of this paper is to review and describe the design characteristics of a living snow fence that achieves maximum effectiveness and minimum aesthetic and ecological disturbance for snow drift control at a site prone to snow drifting in Rocky Mountain National Park, Colorado, U.S.A.

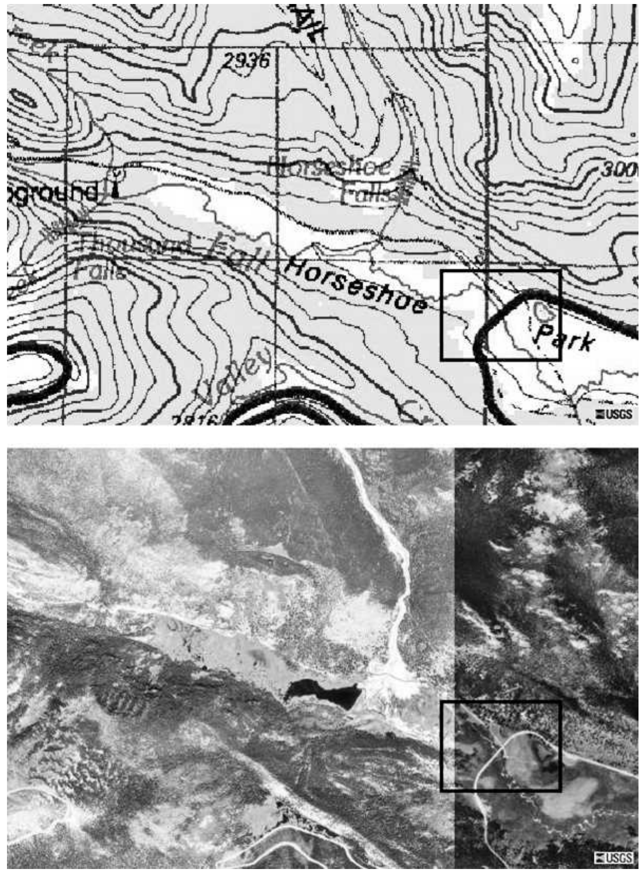

FIGURE 1. Topographic map and corresponding aerial photograph showing the problem area for protection consideration by the living snow fence (black square). Source: http://terraserver-usa.com. The study area is along U.S. Highway 34 (Fall River Road; see box), 40°24′N, 105°38′W in Rocky Mountain National Park, Colorado. The top figure shows the topography (50-foot contour intervals); the bottom figure is an aerial photograph of the same area. Topographic map and image courtesy of the U.S. Geological Survey.

CONTROLS ON SNOW DRIFT FORMATION BEHIND A SNOW FENCE

Snow is relocated on the ground by wind through creep (large crystals), saltation (medium crystals), and turbulent diffusion (small crystals; Nixon et al., 2006). Therefore, any obstacle that results in a decrease in wind speed will result in a decrease in snow transportation, especially snow relocated through the process of turbulent diffusion (Pomeroy, 1989). An effective snow fence must not only decrease snow transport through a decrease in wind speed, but must also provide a suitable downwind area for the snow to accumulate, thus the requirement for the fence to have some porosity. The snow drift that forms in the lee of the snow fence is thus determined by decrease in wind speed achieved through both fence height and porosity, over the length of the fence. These snow fence characteristics, in turn, determine the maximum snow drift capacity of the snow fence, referred to as the equilibrium drift. Once this equilibrium drift, representing the drift capacity of the fence, is reached, the fence can no longer trap snow. Where the drift ends, there is no accumulation of snow, and a switch back to a scour zone and transport area.

Study Site

Established in 1915 in recognition of the high-altitude mountain environment, Rocky Mountain National Park's high elevation, complex terrain, and windy, wintertime conditions make public road access to many areas of the park difficult if not impossible. The location of the problem area to be protected by the living snow fence is U.S. Highway 34 (Fall River Road), 40°24′N, 105°38′W, at an elevation of 2597 m a.s.l. (Fig. 1). At this location, the highway traverses an extensive, nearly straight east-west–orientated valley extending all the way up to the Continental Divide. The approximately 12-km-long valley contains a small river (Fall River) that serves as a prefect funnel for katabatic cold-air drainage flows. Thus, high, persistent wind speeds coupled with an ample snow supply, commonly result in blowing and drifting snow at this location. The problem area is located in Horseshoe Park, a 0.8-km-wide by 4.8-km-long relatively flat (0.7% slope) valley once occupied by a glacial lake formed behind terminal moraines that dammed Fall River (Jarrett and Costa, 1993). Vegetation in the valley consists of willows (*Salix* spp.) along the margins of the river, meadow grasses along the valley floor, and ponderosa (*Pinus ponderosa*) and lodgepole (*Pinus contorta*) pine and aspen (*Populus tremuloides*).

At the study site, a structural snow fence was installed in the fall and removed in the spring to address the snow drifting problem. The snow fence was a standard commercially available wooden vertical slat-and-wire fence with 3.8-cm-wide slats spaced roughly 6.5 cm apart. The structural snow fence was 1.22 m tall, 90 m long, and was set back 24 m from and parallel to Highway 34 (see Fig. 10 for the observed snow drift created by the constructed snow fence). The high maintenance costs, labor, lack of effective drift control and unappealing aesthetics for a national park setting were the motivation behind the consideration of replacing the constructed structural snow fence with a living snow fence.

Climatological data pertaining to wind and snow data that are required to properly calculate the snow fence design parameters as described below (as is usually the case) were not available at the exact location of the problem area on Fall River Road. Fortunately, however, the Estes Park meteorological station located near the park's main east entrance was available to provide climatological data. Although at a lower elevation than the study site (2384 m a.s.l.), and at a distance of approximately 7.5 km, wind velocity measurements recorded likely underestimated the wind velocity at the study site since the meteorological station was not situated in a relatively narrow valley. Meteorological measurements at that location, however, were the nearest available source for long-term meteorological data, and corrections were made when applicable to account for differences in elevations (see Methods).

Long-term (1971–2000) snow water equivalent data were available from direct measurements made at the Bear Lake SNOTEL site (SNOwpack TELemetry site operated by the Natural Resources Conservation Service), located roughly 10.5 km south of the study site at an elevation of 2897 m a.s.l. Similar to the study site on Fall River Road, the Bear Lake SNOTEL site is also located at the terminus of a prominent east-west–oriented valley extending up to the continental divide.

Methods

The procedures used to calculate the snow fence design parameters are described by Tabler (2003). Based on decades of research, Tabler (2003) synthesized and summarized the procedures and calculations that should be used in snow fence design, and those recommended procedures and calculations have been used here (summarized in Fig. 2). The snow accumulation period, amount of snow, wind climatology, and site characteristics were used to determine whether drift formation was limited by wind or the availability of snow. Then, design parameters (species, required height, setback and set-in distances, and orientation) were calculated for a year with average snow conditions, and with the average snow conditions exceeded.

SNOW ACCUMULATION SEASON

The snow accumulation season is defined as the period of drift growth, not necessarily coinciding with the period when snow actually falls since a late-season snowfall may occur after significant melting has already taken place. The snow accumulation season begins with the first blowing snow event that results in drifts persisting through the winter, and ends when the drifts reach their maximum volume (Tabler, 1988). The season was determined based on the dates when the mean monthly air temperature, T_a, decreased below 0 °C in the fall, and increased above 0 °C in the spring. Over the period from 1 August 1948 through 31 December 2001, the mean monthly T_a data based on hourly averages from the Estes Park meteorological station are given in Table 1. Assuming that the mean monthly T_a applied to the middle of the month, dates were interpolated using

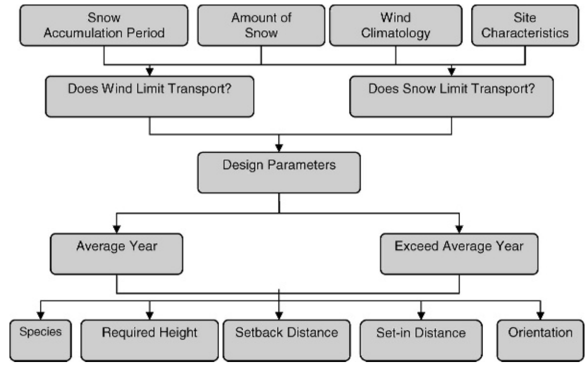

FIGURE 2. Design procedure summary flowchart used to design the living snow fence in Rocky Mountain National Park.

$$n = 30(T_{a+})/(T_{a+}T_{a-}) \quad (1)$$

where n is the number of days from the middle of the warmer month to the 0 °C date added to the mid-date of the warmer month in the fall (subtracted in the spring) and T_{a+} and T_{a-} are the mean air temperatures (°C) of the warmer and colder months, respectively.

Since the study area is located in mountainous terrain at a higher altitude (2597 m a.s.l.) than the Estes Park Station (2384 m a.s.l.), 0 °C dates were estimated as a statistical function of elevation (in m a.s.l.), latitude, and longitude:

$$\text{Date} = \text{A} + \text{B}(\text{elevation}) + \text{C}(\text{latitude}) + \text{D}(\text{longitude}) \quad (2)$$

where A, B, C and D are 713, −0.0236, −5.05, −1.32 ($r^2 = 0.70$); and −270, 0.0389, 7.54, −0.34 ($r^2 = 0.85$) Fall Date and Spring Date, respectively, as determined from regression analyses of 10- to 30-year means of monthly T_a from 80 meteorological stations in Colorado (Tabler, 1988).

POTENTIAL SNOW TRANSPORT BY WIND DIRECTION

Using wind direction and wind speed data based on the monthly frequency distribution of hourly wind observations during the snow accumulation season, the potential snow transport as a function of wind direction for each month of the snow accumulation season was calculated. First, a power-law relation was used to correct the anemometer height at Estes Park (6.096 m) to the standard height of 10 m above ground level (Z):

$$C_u = U_{10}/U_z = (10/Z)^{1/7} = (10/6.096)^{1/7} = 1.073 \quad (3)$$

where C_u is the correction factor for the wind speed, U.

The erosion, transport, and deposition of snow all depend on the wind speed and turbulence in the surface layer of the atmosphere (the lowest 10–100 m). The primary transport mechanisms are saltation and suspension. Transport due to saltation usually begins at a threshold U_{10} of 5–8 m s^{-1} (18–

TABLE 1

Mean monthly maximum, minimum, and average air temperatures (T_a; °C), and mean total snowfall (h_s; cm) over the period 1 August 1948 through 31 December 2001, measured at Estes Park, Colorado. Source: Western Regional Climate Center (http://www/wrcc.dri.edu).

		J	F	M	A	M	J	J	A	S	O	N	D
T_a (°C)	Max.	3.56	4.78	7.17	11.9	16.9	22.6	25.7	24.7	21.1	15.6	7.94	4.28
	Min.	−8.72	−8.17	−6.28	−2.78	1.39	5.06	7.83	7.00	3.17	−1.06	−5.11	−8.00
	Mean	−2.58	−1.70	0.44	4.56	9.15	13.83	16.77	15.85	12.14	7.27	1.42	−1.86
h_s (cm)	Mean	9.7	16	22	10	1.3	0.25	0	0	1.3	2.5	9.4	14

29 km h^{-1}) (Schmidt, 1980; Gauer, 2001), with the transition from saltation to suspension occurring at U_{10} = 7–11 m s^{-1} (25–40 km h^{-1}). Field measurements report that snow transport and drift formation can occur at U_1 = 4–6 m s^{-1} (Z = 1 m) which converts to U_{10} = 5.6–8.3 m s^{-1} (20–30 km h^{-1}), using Equation 3 (Kobayashi, 1972; Gauer, 2001). Li and Pomeroy (1997), however, found that based on observations, the threshold U_{10} for dry snow varied from 4 to 11 m s^{-1} (14 to 39 km h^{-1}) with an average of 7.7 m s^{-1} (28 km h^{-1}).

Therefore, using 5.6 m s^{-1} (20 km h^{-1}) as the threshold for U_{10}, the estimated potential snow transport (q, kg m^{-1}) for each U class i equal to or greater than the threshold for each direction class j was calculated as:

$$q_{i,j} = f_{i,j} D 86400 \left(Cu U_{i,j}\right)^{3.8} / 233847 \qquad (4)$$

where $f_{i,j}$ is the frequency of observations in the i^{th} wind speed class and the j^{th} direction class, D is the number of days in the month within the snow accumulation season, and $U_{i,j}$, is the mid-class U in m s^{-1} (Tabler, 2003). For the total monthly potential snow transport for each wind direction class, Q_{upot}, j is the sum of q_i for each wind direction class.

POTENTIAL SNOW TRANSPORT BASED ON SNOWFALL

In addition to calculating the potential snow transport from wind data, it was also calculated based on snowfall (Q_{spot}). Comparing the Q_{upot} to Q_{spot} indicates if snow transport is limited by wind or snowfall (Tabler, 2003). The potential snow transport based on snowfall was calculated as:

$$Q_{spot} = 0.5 T S_{we} \qquad (5)$$

where T is the maximum transport distance, set equal to 3000 m, and S_{we} is the total snow water equivalent in mm over the snow accumulation period based on the long-term (1971–2000) bi-monthly averages directly measured at the Bear Lake SNOTEL site.

OBSERVATIONS OF EXISTING DRIFTS

Near the end of the snow accumulation season (14 March 2004), measurements were made of the snow drift created by a structural snow fence at the study site. Along seven transects along the length of the drift spaced roughly 10 m apart, the distance from the back of the fence to the start of the drift was measured. Then, snow depth was measured 0.50 m past the start of the drift, and every 1.0 m until the end of the drift was reached. At a distance of 1.50 m from the edge of the drift closest to the fence, snow temperature and density were measured at a depth of 0.10 m from the surface and at the base of the snowpack. Snow density was measured with a 100-cc sampler (Taylor-LaChapelle Snow Density Kit, Model ST-1, Taylor Scientific Engineering, Seattle, Washington, U.S.A.) and a 100-g HOMS tubular spring scale. Snow temperature was measured with a dial stem thermometer (model PT-50R, Taylor Scientific Engineering, Seattle, Washington), and snow depth with a folding, 1-m-long ruler.

Results and Discussion

SNOWFALL CHARACTERISTICS

The snow accumulation season, defined as the period starting with the first blowing snow event that results in drifts and ends when the drifts reach their maximum density, was estimated as a function of mean monthly air temperature with a statistical adjustment to account for the difference in elevation between the meteorological station and the study site. Using Equation 1, and the data provided in Table 1, the fall (start) and spring (end) dates for the snow accumulation season were 28 November and 10 March, respectively, at the Estes Park meteorological station. With the adjustment to account for the increase in elevation at the study site (i.e. Equation 2), however, the snow accumulation season extended to 4 November through 10 April.

The calculated dates of the snow accumulation season compare well to those measured at the nearest SNOTEL site, Bear Lake (2896 m a.s.l.). The observed beginning of the season (date when snow water equivalent (SWE) > 1 mm for at least three consecutive days) and end of the season (date of maximum SWE) at Bear Lake was 27 October and 28 April, respectively, based on 25 years of observations (Fig. 3). Theses dates were comparable to those calculated using Equation 2 (4 November–10 April; Fig. 3), and were even closer when Equation 2 was used with the actual Bear Lake elevation and location (29 October–21 April). Based on the comparison of the long-term observation of the SWE, the calculations of the snow accumulation season based on long-term air temperature records appear to provide realistic estimates when adjusted for site elevation.

The potential for snow transport for all wind directions during the snow accumulation season (Q_{upot}) was 21.4 tonnes m^{-1}, and was greatest with west-southwest to westerly winds

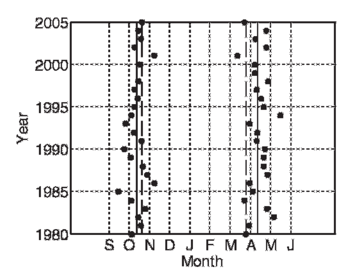

FIGURE 3. Snow accumulation season based on SNOTEL observations made at Bear Lake, Colorado (2896 m a.s.l.). The 25-yr mean start (circles on left side) and end dates (circles on right side) were 27 October and 28 April, respectively (solid lines). Dates calculated using Equations 1 and 2 were 4 November and 10 April (dashed lines).

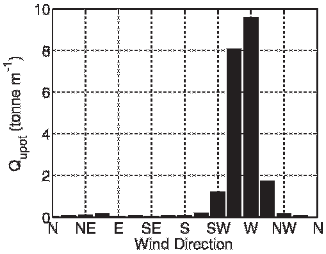

FIGURE 4. The potential transport of snow by wind (Q_{upot}) as a function of wind direction over the 4 November–10 April snow accumulation period.

(Fig. 4). Since averaging the wind speed over a given time interval can mask wind gusts, and because it is these wind gusts that have the potential to drift snow, the maximum wind speeds over the snow accumulation season need to be considered when calculating snow drift properties. Wind gusts above the threshold 5.6 m s^{-1} occurred throughout the snow accumulations season (Fig. 5), and these gusts were primarily from the west parallel to the Fall River valley and perpendicular to the highway (Fig. 6). When integrated over the entire snow accumulation season, this resulted in a large potential for snow transport in the prevailing wind direction (Fig. 4). Although the valley in which the site was located is oriented along a WNW-ESE axis (Fig. 1), ample fetch for snow transport was still present with westerly winds. This, coupled with perpendicular orientation of the road at the study site to the prevailing wind direction, presented a high potential for wind-blown snow transport. For example, the relevant wind directions for drift formation across the road were SSW through NNE (210° through 30°). The total Q_{upot} for these wind directions over the snow accumulation season was 21.0 tonnes m^{-1} along a mean drifting direction of 259°.

Drift formation is a function of both snow characteristics (e.g. depth and density), and wind characteristics (e.g. direction and velocity). The potential for snow transport based on snowfall depends mainly on the snow water equivalent, which is a function of both snow depth and density. Since the design of the living snow fence is based on long-term snow characteristics at the study site rather than those in any given year, the total (maximum) snow water equivalent during the snow accumulation season determined from bi-monthly measurements made at the Bear Lake SNOTEL site was used (503 mm; Fig. 7). The maximum SWE and Q_{spot} was reached in late April (Fig. 7), and the total potential for snow

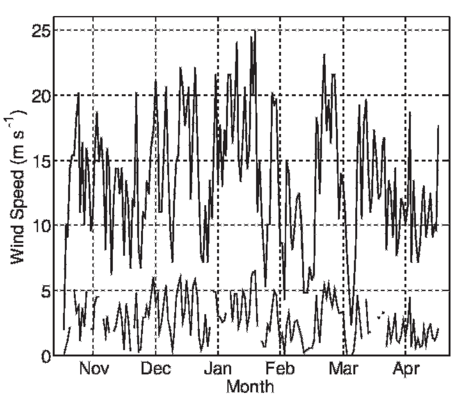

FIGURE 5. Daily average (thin line) and maximum (thick line) 10-m wind speed measured at the Estes Park meteorological station over the snow accumulation season (4 November 2002–10 April 2003).

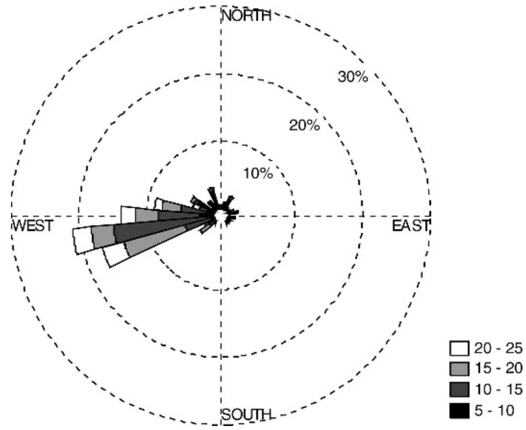

FIGURE 6. Wind rose based on the maximum 10-m wind speed (m s^{-1}) measured at the Estes Park meteorological station over the snow accumulation season (4 November 2002–10 April 2003).

transport based on the total SWE during the snow accumulation season was 754 tonnes m^{-1} (Equation 5).

Given the large amount of snow in the Rocky Mountain region, snow drift formation is likely limited by wind, not the amount of snow. This was confirmed by the calculations of potential snow transport. Since Q_{spot} was much greater than Q_{upot}, wind was the primary factor limiting snow transport and resulting drift formation. For an infinite fetch, the potential snow transport (Q_{inf}) equals Q_{upot} (21.0 tonnes m^{-1} for the relevant wind directions) (Tabler, 2003). At the study site, the actual fetch (F), the upwind distance contributing to the potential snow transport, was estimated from Figure 1 together with site visits. The prevailing wind direction at the site was likely influenced by the steep-sided valley (Horseshoe Park) with its orientation roughly along 100–280°. Therefore, the fetch running west from the site to the end of Horseshoe Park was approximately 2800 m. The mean annual snow transport, $Q_{t,ave}$, was then calculated as:

$$Q_{t,ave} = Q_{inf}\left(10.14^{F/T}\right) \quad (6)$$

(Tabler, 2003), slightly reducing Q_{inf} to $Q_{t,ave}$ = 17.6 tonnes m^{-1}.

The living snow fence design parameters are based largely on the annual snow transport calculation, and in order for the design parameters to be robust, $Q_{t,ave}$ was calculated using multi-year air temperature, snow, and wind data. Determining the design parameters for a particular year, however, allows the snow fence to be designed to accommodate years when the snow transport exceeds the average amount. The ratio of the design year (based on

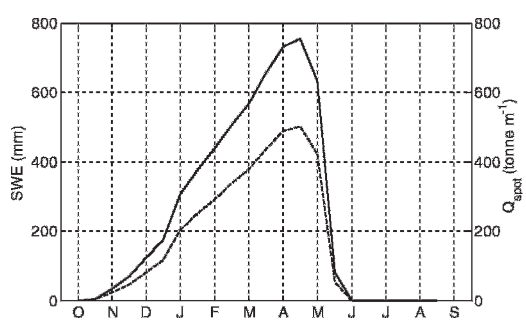

FIGURE 7. Snow water equivalent (SWE: dashed line) and the potential for snow transport based on SWE (Q_{spot}: solid line) based on the long-term (1971–2000) bi-monthly SWE measurements made at the Bear Lake SNOTEL site.

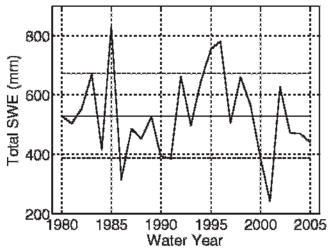

FIGURE 8. Total snow water equivalent (SWE) for each water year (1 October–30 September) measured at Bear Lake SNOTEL site. Horizontal lines are the mean (solid line; 529 mm) ± one standard deviation (dashed lines; 143 mm).

a probability of occurrence) to the average snow transport is known as the design modulus, K, and when multiplied by $Q_{t,ave}$ gives the design transport, $Q_{des} = KQ_{t,ave}$. Thus, the probability of exceeding the long-term average snow transport in an average year is 0.5 (50 years out of 100 years; K =1), which gives a design transport of 17.6 tonnes m^{-1}.

Figure 8 shows that the average SWE of 530 mm (water years 1980–2005) plus one standard deviation (143 mm) was achieved in three out of 25 years (12%). To account for this probability of exceeding the average SWE by one standard deviation, Q_{des} was calculated using a corresponding K of 1.36 (Tabler, 1997, 1982). When multiplied by $Q_{t,ave}$, this gives a Q_{des} value of 23.9 tonnes m^{-1}. Therefore, based on the long-term observations of snow and wind characteristics near the study site, the design characteristics of the living snow fence were calculated using Q_{des} = 23.9 tonnes m^{-1}, representing a realistic upper limit to blowing and drifting snow at the study site.

LIVING SNOW FENCE CHARACTERISTICS

The required height for the snow fence above the snow surface, H_{req} (m), was calculated using the equation:

$$H_{req} = \left[Q_{des}/\left(3+4P+44P^2 60P^3\right)\right]^{0.455} \quad (7)$$

where Q_{des} is in tonnes per m^{-1}, and P is the porosity ratio (Tabler, 2003). The solution to Equation 7 with P = 0.5 (usual case) for Q_{des} = 23.9 tonnes m^{-1} is 1.39 m. The required snow fence height, when added to the maximum long-term (1948–2001) snow depth of 0.22 m measured at Estes Park, results in a required snow fence height of 1.61 m.

To avoid any snow deposition on the road, the minimum distance between the fence and the road (the setback distance, D_{min}) for a fence with a porosity of 50% is $35H_{req}$, equal to 56.4 m for conditions at the study site. Snow will also be trapped on the upwind side of the fence, and size of the drift (both upwind and downwind) of the fence will change as the vegetation grows. The maximum drift length in the upwind direction ($15H_{req}$) corresponds to set-in distance of 24.2 m upwind of the fence. In addition, the fence should be aligned parallel to the roadway (Figs. 1 and 2), which in this case, is nearly perpendicular to the prevailing wind direction (i.e. prevailing wind direction is 259°N, and the road orientation is 30–210°N with a perpendicular angle of 255°N).

A snow fence is deemed "fully effective" when it reaches a trapping efficiency of 75%. This corresponds to a porosity of 50%, the porosity when snow fences are most effective (i.e. form the largest drifts). To determine the trapping efficiency, first the snow storage capacity, Q_c, must be determined. Using a P = 0.50 and a vegetation height, $H_{veg} = H_{req}$ = 1.61 m, Q_c can be calculated as:

$$Q_c = \left(3+4P+44P^2 60P^3\right) H_{req}{}^{2.2} \quad (8)$$

giving Q_c = 24.2 tonnes m^{-1}. Since $Q_{t,ave}$ (17.6 tonnes m^{-1}) was less than Q_c, the average snow trapping efficiency (E_{ave}) was calculated as:

$$E_{ave} = [1/(A_f/A_e)] \\ E_o\left\{0.5(A_f/A_e)\left[1(A_f/A_e)^2\right]^{0.5} + 0.5\sin^1(A_f/A_e)\right\} \quad (9)$$

where A_f and A_e are the cross-sectional areas of the drift at the end of the season and the equilibrium drift when the fence is filled to capacity, respectively, and E_o is the initial trapping efficiency when the fence is empty (Tabler, 2003). Using Equation 9 with $A_f = A_e$ assuming E_o = 95% gives:

$$E_{ave} = 0.95\left\{0.5\sin^1(1)\right\} = 0.79 \quad (10)$$

To achieve this average trapping efficiency of 79%, the living snow fence needs to achieve a porosity of 50% (difficult to maintain since vegetation changes with time). To accomplish this, a minimum of two staggered rows, are usually required. To reduce the likelihood of openings developing in the fence, three staggered rows are preferable. The placement of a row of shrubs upwind of the actual fence (typically 1.5 m upwind) will protect the newly planted conifers and supplement soil water recharge from the drift they create. This positive feedback between several rows of vegetation acting to create drifts, thus supplying downwind vegetation with moisture and insulation, is often observed in treeline vegetation (e.g. krummholz) and can help the living snow fence maintain itself. As the vegetation grows, however, it is important to manage not only the fence's porosity, but also the vegetation height since the drift created will become even larger as the H_{veg} exceeds H_{req}.

OBSERVATIONS OF DRIFT BEHIND A STRUCTURAL SNOW FENCE

Near the end of the snow accumulation period (14 March 2004), measurements of the snow drift created by the existing constructed structural vertical slat-and-wire snow fence at the proposed location of the living snow fence were made. The constructed snow fence was installed and the measurements were made to simulate the drift created by the living snow fence (in order to assess if the living snow fence design parameters were reasonable). Based on the March 2004 snow course data, the SWE for the Big Thompson Basin was 74% of the 1971–2000 mean, and was 77% of the 1971–2000 mean for the Hidden Valley snow course. Therefore, the properties measured should be increased by roughly 25% to better approximate long-term conditions.

Except near the edges of the drift, the snow density did not vary much between near the surface and at the base of the snowpack (Fig. 9a; mean 452 kg m^{-3}, s.d. 28.1). The high snow density, lack of spatial variability, and isothermal snow temperatures (0 °C at 0.10 m from the snow surface and at the base of the snowpack, at all transects), indicated that the drift was in the ripening phase or possibly the output phase of the melt period (Dingman, 2002). The snow water equivalent, expressed as a height of water calculated using the mean density (i.e. the mean of the 0.10 m and base densities) at each location was fairly constant across the length of the drift (Fig. 9b) with a mean value of 0.15 m

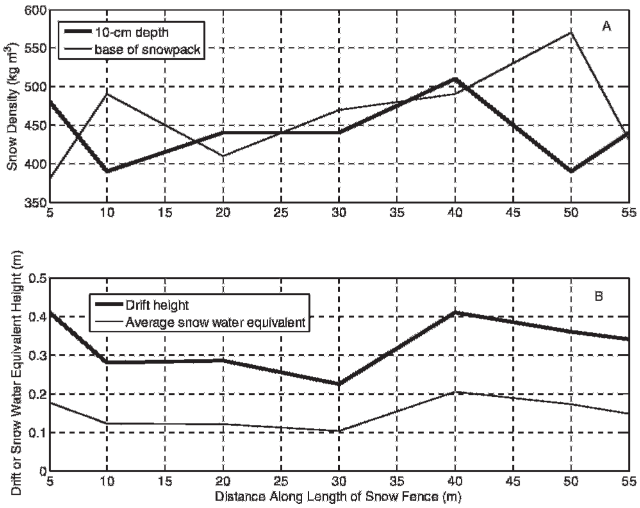

FIGURE 9. (A) Snow density measured near the surface (10-cm depth) and base of the snowdrift 0.50 m from the start of the drift downwind of the structural fence. (B) Mean drift height and snow water equivalent (expressed as a height) using the mean density at each location as shown in panel (A).

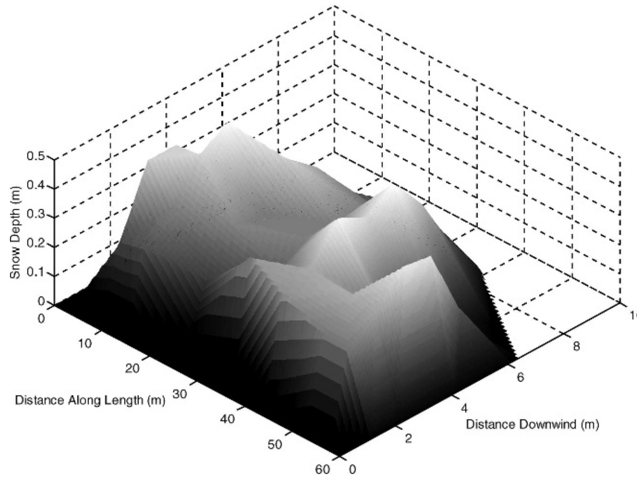

FIGURE 10. Visualization of snowdrift behind structural fence based on measurement along seven transects at 10-m intervals.

(s.d. 0.04). The mean ratio of h_m/h_s was 0.15/0.27 = 0.56 (the mean ratio of ρ_s/ρ_w).

The 1.2-m-tall constructed fence created a drift nearly 0.50 m deep extending nearly 9 m downwind of the fence (Fig. 10) with a mean depth of 0.27 m (s.d. 0.13). If these values were increased by 25% to account for the 25% below-average snow conditions in 2004, the mature drift would have a maximum depth of roughly 0.63 m and a maximum length of 11.25 m. For a vertical slat-and-wire fence less than 2 m tall, however, the expected equilibrium drift would have a length of about $34H$ (41.48 m), and a maximum depth of about $1.03H$ (1.26 m) Tabler (2003). Given the 0 °C isothermal snow conditions at the time of the drift measurements, it is likely that the snowdrift had undergone at least some melt. Both the expected and observed drift length and depth resulting from the constructed fence, however, are less than the calculated living snow fence maximum required height of 1.61 m and a setback distance of 56.4 m, therefore these design parameters should be more than adequate to provide efficient drift control at this location.

Summary and Conclusions

This paper reviews and summarizes the required climatological data and design parameter calculations for the practical design of a living snow fence in Rocky Mountain National Park. Blowing and drifting snow represents a safety hazard and often results in significant economic losses. Vegetated or living snow fences can be more cost effective, efficient, and aesthetic than structural snow fences; however, a rigorous analysis of design parameters based on sound climatological data is required to ensure the effectiveness of the fence. In fact, many living snow fences have failed due to improper (or the absence of proper) design calculations. The advantage of the living snow fence's long life span makes proper design even more critical.

Using Fall River Road in Rocky Mountain National Park in Colorado, an area chronically affected by blowing and drifting snow, as a case study, the collection of fairly easily accessible climatological data (e.g. air temperature, wind speed and direction) were used to determine that the potential for snow drift formation was limited by wind speed and direction, not snowfall amount. Observations of snow characteristics from both long-term records available at a nearby location and measured at the study site confirmed both the potential for snow transport and the design characteristics of a living snow fence. The calculations showed that a living snow fence with a height of 1.61 m with a porosity of 50% set back 56.4 m from the road would be sufficient to trap blowing snow at an efficiency of 79% with above-average snowfall conditions (mean snowfall exceeded by one standard deviation).

Given that the advantages of a living over a structural snow fence, especially in a park setting, can be substantial, this paper has outlined a systematic, practical procedure to produce the required design parameters for a living snow fence. Hopefully these procedures and recommendations will be followed here and in other locations so that blowing and drifting snow can be effectively controlled when required.

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