EVAPORATION LOSSES OF WINDBLOWN SNOW, AND THE POTENTIAL FOR RECOVERY 1/

By

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Introduction

A recent mathematical model (Schmidt, 1972) demonstrates a previously unrecognized potential for significant evaporation (sublimation) from snow particles during their transport by wind. Our studies with snow fences in Wyoming also have indicated large sublimation losses from wind-blown snow (Tabler and Schmidt, 1972; Tabler, 1971). This paper provides evidence supporting a method we have used to estimate annual sublimation amounts, and demonstrates the magnitude of these losses from extensive wind-swept areas.

Transport Distance Concept

In an earlier paper (Tabler, 1971), I proposed a method for estimating sublimation loss from wind-blown snow as a step in determining the storage capacity required in snow-fence systems. The basic concept is the "transport distance," R_m, defined as the average distance a snow particle must travel before completely evaporating (Fig. 1). The "contributing distance" (or "fetch"), R_c, upwind of a snow fence or natural barrier may be much less than R_m. If we assume steady, uniform flow across a smooth, horizontal surface of infinite extent (implying the absence of spatial and temporal gradients for factors affecting sublimation), then the rate of sublimation should be constant with respect to time and travel distance. Thus the amount of sublimation would be directly proportional to travel distance (R_c) so that for a single event, as shown in the previously cited paper,

$$Q_\ell = \theta\ P\ R_c^2\ /\ 2R_m \quad , R_c \leq R_m \tag{1}$$

where Q_ℓ is sublimation loss over the distance R_c, and θ is the ratio of the amount of snow that is relocated by the wind to that which falls as precipitation, P. For P, R_c, and R_m in feet, Q_ℓ is in units of ft^3 water-equivalent per foot of width perpendicular to the wind. If we use bars above variables to indicate average values over a number of events (or an entire season),

$$\overline{Q}_\ell = \overline{\theta}\ \overline{P}\ R_c^2\ /\ 2\overline{R}_m \quad , R_c \leq \overline{R}_m \tag{2}$$

Of course, values for θ, P, and R_m will be different for each geographic location. At study sites in southeast Wyoming, with elevations between 7500 and 8500 ft, we have found $\overline{R}_m$ to range from 3300 to 4500 ft, and have observed values for $\overline{\theta}$ from 0.9 to 0.5, depending on vegetation, topography, and climate.

A Test of the Method

In cooperation with the Wyoming Highway Department, we recently used Eq. (2) in the design of an extensive snow control system for Interstate Highway 80 in southeast Wyoming. Average storage capacity, $\overline{Q}_c$, for each of 28 new fence systems along the highway was estimated by subtracting sublimation loss (Eq. 2) from the total amount of relocating snow at each site:

$$\overline{Q}_c = \overline{\theta}\ \overline{P}\ R_c\ (1 - R_c/2\overline{R}_m) \quad , R_c \leq \overline{R}_m \tag{3}$$

For this application, $\overline{R}_m$ was assumed to be 3300 ft, based on previous experience (Tabler and Schmidt, 1972). The snow transfer coefficient for each site was estimated from preliminary measurements of snow remaining on the contributing areas after drifting events. R_c was measured from aerial photographs, but for most sites was found equal to $\overline{R}_m$. Mean winter precip-

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itation was estimated at 9.6 inches from data published by the National Weather Service for nearby stations.

The first winter (1971-72) after the fences were built, two systems were studied to compare their performance with that predicted by Eq. (3). The two sites selected for this study are about 30 miles apart, and were chosen to represent climatic, as well as geographic, extremes along the highway. These two sites also typified local extremes of conditions affecting the snow transfer coefficient. Site A is characterized by short-grass vegetation so that $\theta = 1.0$, while sagebrush vegetation at Site B accounts for significant natural snow storage over the distance R_m.

The fence system at Site A is about 1600 ft long, and consists of an 8-ft-tall lead fence followed by two 12-ft fences spaced 200 and 500 ft behind the lead fence. At Site B, fences are about 1100 ft long. The 8-ft lead fence is followed by a 10-ft fence spaced at 220 ft, followed by a 12-ft fence spaced at 235 ft. These large-capacity systems are ideally suited to test the design equation (3) because they remain highly efficient in trapping blowing snow until they are about 80% full.

Snow depth and water-equivalent were sampled behind the two fence systems after each major drifting event, or at periods no greater than two weeks, during the accumulation season. Snow depths were probed at 10-ft intervals along four permanent transects at Site A, and three permanent transects at Site B. Water-equivalent was sampled with a Mount Rose sampler at 10-ft intervals along one randomly selected transect at each fence.

Precipitation was sampled with shielded recording gages located in small forest openings near both sites.

Measured snow water-equivalent storage was compared to that estimated by Eq. (3), from the cumulative measured precipitation values, and the original design estimates for $\overline{R}_m$ (3300 ft at both sites) and $\overline{\theta}$ (1.0 at Site A and 0.9 at Site B). Over the winter of study, precipitation was only about 75% of the anticipated long-term mean. The protected road cuts remained free of snow drifts, however, indicating the two fence systems were highly efficient in trapping incoming snow.

Discrepancies between observed and predicted values (Fig. 2) are to be expected, since both θ and R_m vary considerably from storm to storm. By using cumulative precipitation in Figure 2, storm-to-storm variation is increasingly dampened as the season progresses. Drift ablation between successive measurement dates contributed only slightly to the deviations in Figure 2; total net water-equivalent loss due to evaporation and melt over the accumulation season was about 10% of peak storage.

Because there is as yet no entirely satisfactory way to measure R_m independently of snow deposition behind the fences, Figure 2 serves only as an illustration of how the original estimates for θ and R_m, in combination with Eq. (3), were used to predict the amount of wind-blown snow arriving at the fence systems. Although the data cannot be considered as explicit verification of Eq. (3), these results demonstrate the utility of the transport distance concept, and encouraged us to apply the method to estimate sublimation losses from extensive areas.

Losses from Extensive Areas

Since snow particles cannot, on the average, travel farther than $\overline{R}_m$ without completely evaporating, sublimation loss over any distance R exceeding the transport distance will be given by

$$\overline{Q}_\ell = \overline{\theta}\ \overline{P}\ (R - \overline{R}_m/2) \quad , R \geq \overline{R}_m \qquad (4)$$

Losses given by Eqs. (2) and (4), expressed in percent of the total relocated precipitation (θPR), are plotted in Figure 3 as a function of the distance R between natural traps. For areas where major natural traps for blowing snow are spaced at distances of 0.5-, 1-, 2-, and $3R_m$, it is seen that 25, 50, 75, and 83% of the relocated snow is evaporated back to the atmosphere during transport. These figures are conservative because natural traps for snow on the plains are typically limited either in their capacity or efficiency, or both, allowing an even greater portion of the blowing snow to be lost to evaporation.

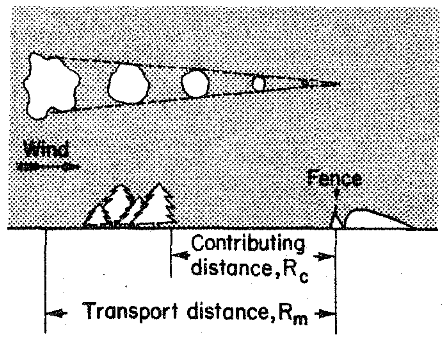

Figure 1

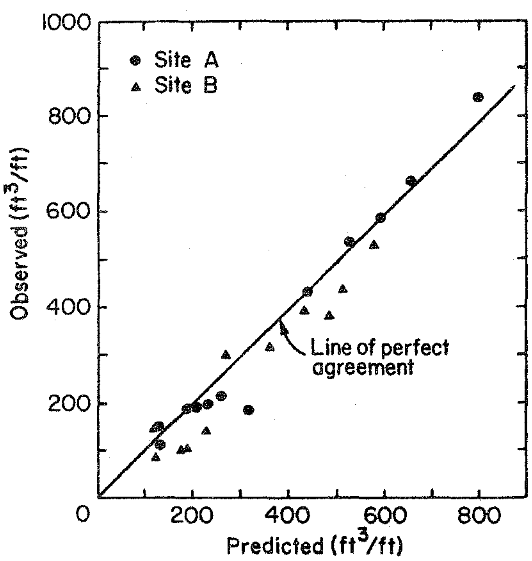

Figure 2

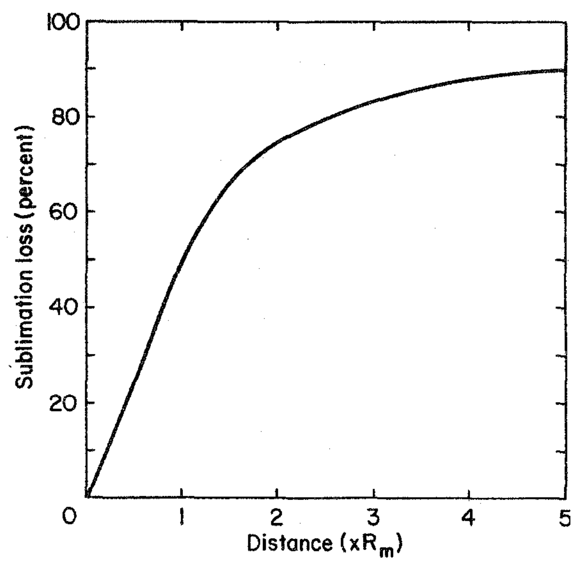

Figure 3

As an example of the magnitude of these losses, let us assume factors typical of the low-growing sagebrush lands at 8,000 ft elevation along the highway study area, with $\bar{\theta} = 0.7$, $\bar{R}_m = 4{,}000$ ft, $\bar{P} = 8$ inches (0.67 ft), and R = 8,000 ft. Then from Eq. (4), the average annual sublimation loss over the distance R would be about 2,800 ft^3 of water-equivalent per foot of width perpendicular to the wind, or about 224 ac-ft per mi^2 -- about 52% of the average winter's total precipitation. There can be little doubt that sublimation of blowing snow is a major component of the hydrologic cycle in such an area.

Potential for Recovery

To explore the potential for recovering these losses by means of snow fences, consider the economic constraint where fence spacing must be such as to minimize construction cost per unit volume of increased water-equivalent storage. If it is assumed that construction cost is linearly related to storage capacity, then it can be shown that for distances exceeding the transport distance, the criterion of minimum cost is met with a spacing between fence systems equal to R_m. Where major natural accumulation areas are spaced at 2-, 3-, and $4R_m$, fences spaced at ($1R_m$) would be expected to increase total snow accumulation by about 100, 200, and 300% respectively, for areas where all precipitation is relocated by wind (i.e., $\theta = 1.0$). Even larger increases would be possible if the value of water were great enough to offset the economic constraint assumed in this example. Theoretically, all of the transport sublimation loss on an area could be recovered if barriers were spaced sufficiently close to eliminate blowing snow completely.

APPENDIX -- NOTATION

P = Precipitation.

Q_ℓ = Transport sublimation loss over the distance R, expressed in volume of water-equivalent per unit width perpendicular to the wind.

Q_c = Storage capacity of a fence system, expressed in volume of water-equivalent per unit length perpendicular to the wind.

R = Distance between major natural accumulation areas.

R_c = Upwind distance contributing snow to a snow fence.

R_m = "Snow transport distance," defined as the average distance a snow particle must travel before it completely evaporates.

θ = Snow transfer coefficient, defined as the ratio of the amount of snow that is relocated to that which falls as precipitation.

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