Modelling the Transport and Sublimation of Blowing Snow on the Prairies

J.W. POMEROY
National Hydrology Research Institute
Environment Canada
11 Innovation Boulevard
Saskatoon, Saskatchewan S7N 3H5, Canada

D.M. GRAY AND P.G. LANDINE
Divison of Hydrology / Department of Civil Engineering
University of Saskatchewan
Saskatoon, Saskatchewan S7N 0W0, Canada

ABSTRACT

A physically-based model of blowing snow transport and sublimation processes over level terrain, the Prairie Blowing Snow Model (PBSM), calculates annual quantities of a) snow transported to the edge of and b) snow sublimated whilst blowing off agricultural fields, using measurements of land use and snowfall, wind speed, temperature and humidity for hours in which blowing snow occurs. A simulation of snow losses for Saskatchewan summer-fallow and grain-stubble fields having various uniform fetch distances suggests that appreciable amounts of snow are lost to transport and sublimation. After full development of transport, the average depth of snow water removed from a uniform fetch does not increase notably with increasing fetch length, however the amount sublimated compared to the amount transported off the fetch increases dramatically with increasing fetch length, dominating snow losses for fetches greater than one km.

INTRODUCTION

In open environments, blowing snow controls the evolution and distribution of snowcover quite markedly. Most hydrological studies of the wind redistribution of snow have focused on the areal distribution of snow water equivalent and its measurement (Kuz'min, 1960; Steppuhn and Dyck, 1974; Granberg, 1978; Schroeter, 1988, Tesche, 1988). However, a growing recognition has been given to the loss of water due to sublimation during wind transport (Dyunin, 1961; Schmidt, 1972; Tabler, 1975; Pomeroy, 1988; Pomeroy, 1991) and the effect of this loss on the resulting snowcover. An ensemble of physically-based blowing snow transport and sublimation algorithms termed the Prairie Blowing Snow Model or PBSM (Pomeroy, 1988; 1989) has been recently applied by Landine and Gray (1989) to calculate seasonal snow accumulation for agricultural environments. They report annual sublimation losses from blowing snow on 1-km fetches of summerfallowed prairie ranging from 23% to 41% of annual snowfall. These losses increase by 1.4 fold for a fetch of 2 km and 1.75 fold for a fetch of 4 km, indicating that consideration of blowing-snow sublimation losses may be critical in assessing the water budget of Prairie environments. This paper briefly describes pertinent elements of the PBSM and demonstrates its application in elucidating the disposition of snow in a prairie environment.

THE PRAIRIE BLOWING SNOW MODEL

The PBSM algorithms calculate rates of steady-state blowing snow transport and sublimation assuming unlimited upwind snow supply, known surface roughness and known upwind fetch (hence boundary-layer height) on relatively level terrain. The model is process-based; hence is derived from theory and the results of extensive measurements in Saskatchewan (Pomeroy, 1988; 1989). Data from field studies in Saskatchewan (Landine and Gray, 1989), in Alaska (Tabler *et al.*, 1990) and in Scotland (Pomeroy, 1991) have shown acceptable agreement between measured parameters (eg. mass flux and mass of snowcover accumulation) and those simulated by PBSM, or its algorithms, in cases where natural conditions are near to the assumptions employed by system. Additional studies specifically directed toward model validation are encouraged. The PBSM divides snow transport into saltation, the movement of particles in a "skipping" action just above the snow surface, and suspension, the movement of particles suspended by turbulence and extending to the top of the surface boundary-layer. Sublimation rates are calculated for a column of saltating and suspended blowing snow extending to the top of the boundary layer.

Saltation

The saltation transport rate may be derived by partitioning atmospheric shear stress into that required to free particles from the snow surface, that applied to non-erodible surface elements and that available to transport particles. Pomeroy and Gray (1990) found the following expression valid over the snow-covered prairies,

$$Q_{salt} = \frac{0.68\ \rho\ u_t^*}{u^*\ g}\ [u^{*2} - u_n^{*2} - u_t^{*2}]\ , \qquad [1]$$

where Q_{salt} is the saltation transport rate (kg m^{-1} s^{-1}), ρ is the air density (kg m^{-3}), g is the gravitational acceleration coefficient (m s^{-2}), u* is the atmospheric friction velocity (m s^{-1}) and the subscripts n and t refer to the shear stress (hence friction velocity) applied to the non-erodible surface elements and to the snow surface at the transport threshold respectively.

The atmospheric friction velocity is associated with the wind speed profile and the saltation rate, its value being influenced by a feed-back mechanism from the additional surface roughness created by saltating snow. Hence for blowing snow conditions over complete snowcovers Pomeroy and Gray (1990) found:

$$u^* = \frac{u_z\ k}{\ln[\frac{163.3\ z}{u^{*2}}]}\ , \qquad [2]$$

where k is von Kàrmàn's constant (0.4). u* is in ms^{-1} when the wind speed, u_z, at height z (m) is in ms^{-1}.

The threshold friction velocity, u^*_t, is that friction velocity found at the termination/initiation of transport, typical values are 0.15 to 0.25 m s^{-1} for fresh, loose, dry snow and during snowfall and 0.25 to 1.0 m s^{-1} for older, wind-hardened, dense or wet snow. The non-erodible friction velocity, u^*_n is found as a function of the friction velocity and the arrangement of surface roughness elements that protrude above the snow surface. Hence,

$$u_n^* = u^*(1 - \frac{1}{c_r})\ , \qquad [3]$$

where c_r is a roughness coefficient. For agricultural land uses Lyles and Allison (1976) suggest an equation to estimate c_r from stubble geometry as:

$$c_r = 1.638 + 17.04\, N_{st}\, A_{st} - 0.117\, \frac{L_y}{L_x}, \qquad [4]$$

where N_{st} is the number of stubble stalks per unit area (m^{-2}), A_{st} is the exposed silhouette area of a single typical stalk (m^2), L_y is the distance between stalks parallel to the wind vector and L_x is the distance perpendicular to the wind vector. For wheat fields in Saskatchewan typical values for N_{st} are 320 stalks m^{-2} and A_{st} is calculated using a stalk diameter of 3 mm and a height equal to 250 mm minus the depth of snowcover and the ratio L_y/L_x is equal to one.

Suspension

Suspended snow diffuses upwards from the saltation layer and its transport rate is found by integrating the mass flux over its region of predominance, i.e. over the depth of flow extending from the top of the saltation layer to the top of the surface boundary-layer. The mass flux is the mass concentration multiplied by the mean downwind particle velocity; this velocity is equal to that of a parcel of air (Schmidt, 1982). Hence, it follows from Eq. 2 that:

$$Q_{susp} = \frac{u^*}{k} \int_{h^*}^{z_b} \eta(z)\, \ln\left(\frac{163.3\, z}{u^{*2}}\right) dz, \qquad [5]$$

where Q_{susp} is the transport rate of suspended snow (kg m^{-1} s^{-1}), h^* is the lower boundary for suspension (approximate top of the saltation layer), z_b is the top of the surface boundary-layer for suspended snow and $\eta(z)$ is the mass concentration of suspended snow (kg m^{-3}) at height z (m).

Solving for a steady-state one-dimensional diffusion equation Pomeroy (1988, 1989) related the vertical profile of suspended mass concentration to particle fall velocity, turbulent diffusivity of snow, concentration of snow in the saltation layer and the balance between sublimation and vertical flux of snow. The resulting steady-state mass concentration of suspended snow may be approximated as,

$$\eta(z) = \eta(z_r)\, e^{-1.55\,(z_r^{-0.544} - z^{-0.544})}. \qquad [6]$$

Where $\eta(z_r)$ is the reference mass concentration for suspension; Pomeroy (1988) suggests this equals 0.8 kg m^{-3}, based on measured values in saltation and suspension. The height, $z_{r\,(m)}$, at which this concentration occurs was found to vary with friction velocity as:

$$z_r = 0.05628\ u^* . \qquad [7]$$

Whilst z_r approximates the saltation layer height, h^*, for much of its range, the saltation/suspension interface is more precisely calculated from particle trajectory analysis (Greeley and Iversen, 1985) as

$$h^* = \frac{u^{*2}}{12.25} . \qquad [8]$$

This interface height, h^* (m) is used by the PBSM as the lower boundary height for suspension of snow, and z_r is used in Eq. 6 to find suspended mass concentration at heights from h^* to z_b.

Sublimation

The theory of sublimation of snow during wind transport is described by Dyunin (1959) and Schmidt (1972). The rate of sublimation is controlled by a balance between convective heat transfer to a snow particle, turbulent transfer of water vapour from a snow particle and particle cooling due to the release of latent heat by sublimation. Sublimation causes a reduction in the mass of a blowing snow particle as it is blown downwind. The rate of sublimation from a particle increases with size, elevation, and wind speed; is directly proportional to the water vapour deficit between the particle and surrounding air; and doubles for each 10 ^{o}C rise in air temperature. For a column of blowing snow extending from the surface to the top of the boundary layer for suspended snow, the rate of sublimation loss per unit area of snowcover, q_{subl} (kg m^{-2} s^{-1}) is:

$$q_{subl} = \int_0^{z_b} c_{subl}(z)\ \eta(z)\ dz , \qquad [9]$$

where c_{subl} (s^{-1}) is the sublimation loss rate coefficient calculated at each height for the distribution of particle sizes. Pomeroy (1988) presents techniques to calculate this coefficient from standard meteorological observations. His procedures parameterize atmospheric feed-backs to sublimation by using water-vapour and temperature gradients from field observations during snow storms.

Snow Surface Erosion/Accumulation

Consider fluxes in the downwind and vertical directions (x,z) where the flux perpendicular (y -direction) to the flow is assumed negligible and the frame of reference for z is the top of the snow surface. The surface snow erosion rate at location x, $q_v(x,0)$ (kg m^{-2} s^{-1}) is set by a mass balance of snow entering and leaving an overlying control volume of the atmosphere in both horizontal and vertical directions and through sublimation occurring within the volume (see Fig. 1). The control volume is defined so that its top approximates the top of the surface boundary-layer for blowing snow, hence the upward diffusion flux at the top of the control volume equals zero. Therefore, $q_v(x,z_b)$, the vertical flux at the top of this layer equals the negative of the snowfall rate. The mass balance for the volume, over a unit surface area, gives the surface snow erosion rate as:

$$q_v(x,0) = \frac{dQ_{salt}}{dx}(x) + \frac{dQ_{susp}}{dx}(x) + q_{subl}(x) + q_v(x,z_b) \ . \qquad [10]$$

Fully-developed conditions occur when the surface erosion rate is equal to the sublimation rate less the snowfall rate, and can develop under invariant atmospheric and surface conditions and an adequate fetch of mobile snow. The fetch required for full development varies with snow supply and land use; non-vegetated ground, hard or incomplete snowcovers often deter fully-developed snow transport. Takeuchi (1980) reports distances of 150 to 300 m for transport rates to reach full development in the lowest 0.3 m of the atmosphere; Pomeroy (1988) suggests a distance of 500 m for full development to a height of 5 m.

Snow accumulation occurs where surface roughness elements or topographic depressions cause a decrease in wind speed and hence saltation and suspension transport rates, or when [$-q_v(x,z_b)$] (the snowfall rate) is greater than surface erosion caused by the downwind increase in the transport rate and the loss to sublimation.

Implementation

Implementing the PBSM involves adapting it for conditions of limited upwind snow supply and incomplete flow development over realistic snowcover configurations and depths. Once adapted, the PBSM can use meteorological and land use information to calculate blowing snow transport, sublimation and accumulation/erosion over a season.

Meterological data used by the PBSM are standard Atmospheric Environment Service, Environment Canada (AES) hourly observations of wind speed, direction, air temperature and relative humidity; daily observations of snow depth and snowfall amount; and hourly observed occurrences of snowfall, blowing snow and drifting snow.

The PBSM calculates blowing snow transport, sublimation and erosion/deposition on an hourly basis for Land Surface Elements (LSE) of 100 m in length. Calculations are run over a season using hourly meterological inputs and simulated surface conditions (from the previous hour) such as snowcover extent, snow depth, snow water equivalent, immobile ice content and aerodynamic surface roughness. As shown in Fig. 2, in this application, LSE(s) are assembled into a flat plane of land (fetch) having unit width and a variable length, with the major axis oriented parallel to the hourly wind direction. Vegetation roughness heights and fetch distance are specified for each LSE within the fetch. As shown in Fig. 2 for a hypothetical case, the fluxes of saltation, suspension and sublimation change with fetch distance as does the snow remaining on the ground.

Certain operating procedures are specified to calculate seasonal snow balances with the PBSM, these are:

1) EXTERNAL SNOW FLUXES. Snow enters the fetch only as precipitation in the vertical direction, $q_v(x,z_b)$. Therefore: at the upwind edge of the fetch, the downwind fluxes, $Q_{salt}(0) = 0$ and $Q_{susp}(0) = 0$, and at the cross-wind edge of the fetch, the cross-wind flux, $q_y(x,z) = 0$.

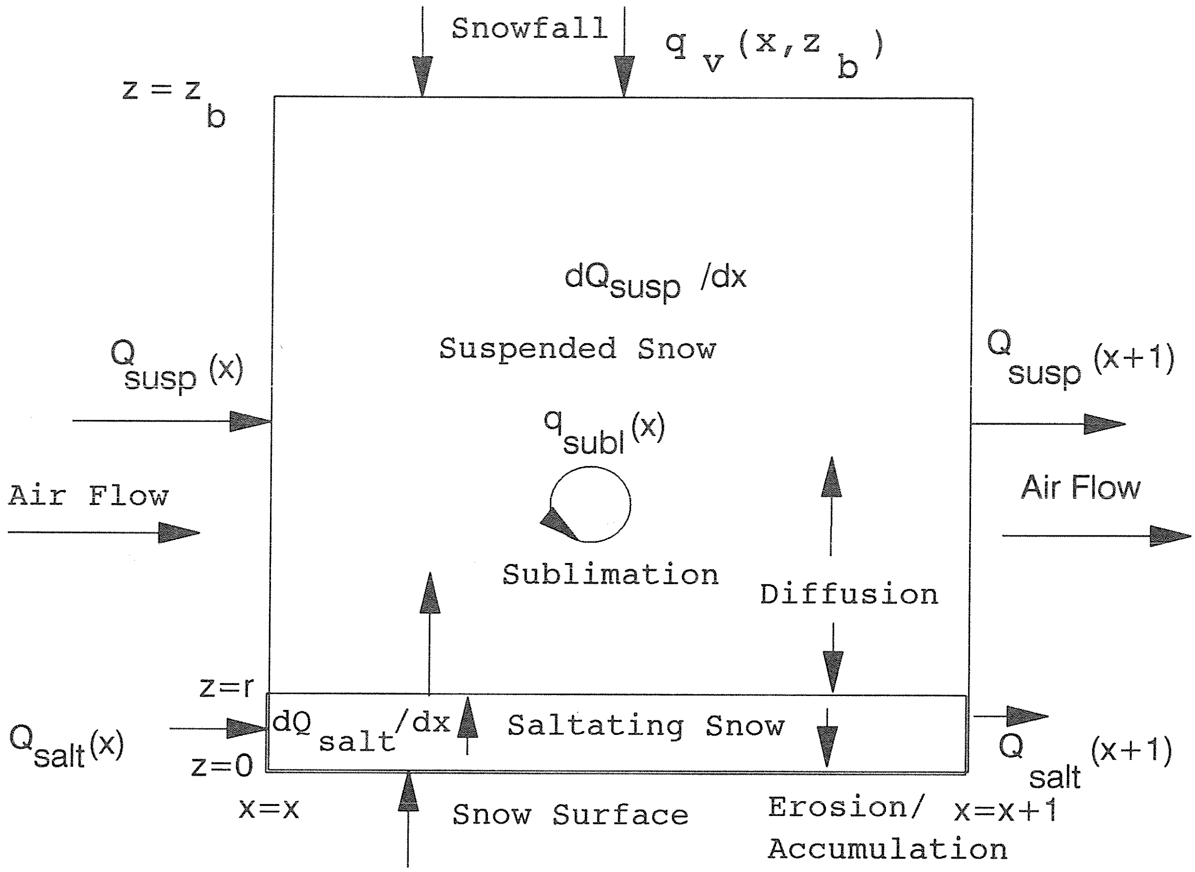


Figure 1. Control volume for blowing snow transport and sublimation. The blowing-snow process algorithms may be conceived in terms of internal components and boundary fluxes to a column of blowing snow extending upwards from the snow surface to the top of the boundary-layer.

2) INTERNAL SNOW FLUXES/TRANSFORMATIONS. Snow is relocated within the fetch, transported to the downwind edge of the fetch, sublimated over the fetch or melted on the fetch. Surface evaporation, infiltration and runoff are negligible over the winter. Therefore:

$$Q_{salt}(x+100) + Q_{susp}(x+100) =$$

$$\int_x^{x+100} [q_v(x,0) - q_v(x,z_b) - q_{subl}(x)]\,dx + Q_{salt}(x) + Q_{susp}(x)\,, \qquad [11]$$

where the snow surface erosion flux $q_v(x,0)$ is unknown and,

$$\int_t^{t+1} q_v(x,0)\,dt < -[\int_0^{t+1} q_v(x,0)\,dt + MELT]\,, \qquad [12]$$

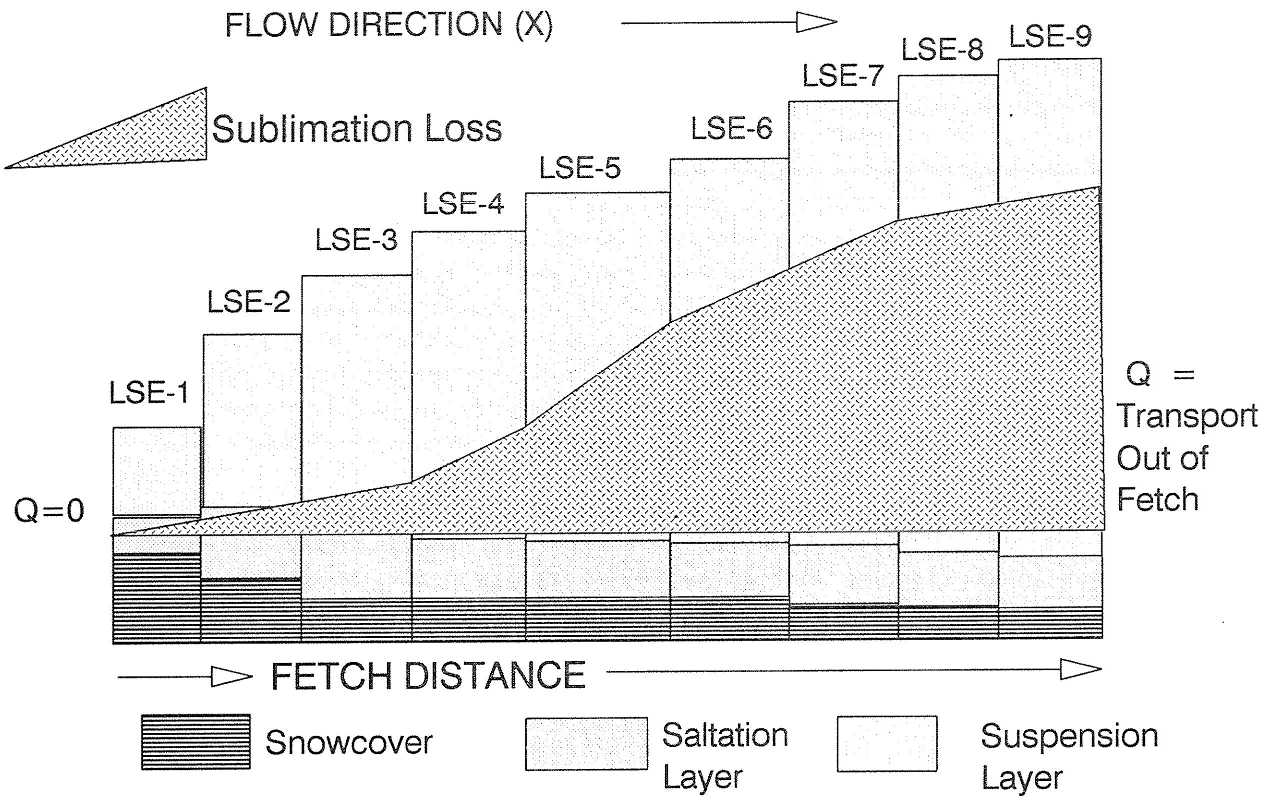


Figure 2. Prairie Blowing Snow Model applied to a fetch: cross-sectional view. Hypothetical arrangement of Land Surface Element control volumes over the corresponding snowcover. Note the growth of boundary layer extent and sublimation loss and the decline in snowcover over the fetch.

where t is time elapsed since the beginning of the snow season, MELT is the cumulative melted snow-water and Eq. 12 limits the snow that may be eroded over a unit time interval to the seasonal snow accumulation less the seasonal snowmelt.

3) FLOW DEVELOPMENT. Fully-developed flow requires 300 m of fetch (3 LSE). If insufficient snow is eroded from the first three LSE to support fully-developed flow, sequential LSE (within the specified fetch) are added until the condition is supported. Sublimation losses are negligible until full-development occurs.

4) SNOW EROSION/ACCUMULATION. Blowing snow is deposited on any LSE whose surface roughness prevents erosion. 300 m of fetch is required to re-establish fully-developed flow when accumulation is induced by a surface roughness change. The density of accumulated wind-blown snow is 250 kg m^{-3}.

5) UPPER & LOWER BOUNDARY CONDITIONS. The "exposed" roughness height on an LSE is the stubble height less the depth of snowcover. Blowing snow transport is integrated to a height of 5-m (snow above this height is not normally redeposited) whilst sublimation is integrated to the top of the boundary-layer.

6) SNOW TRANSPORT OCCURRENCE. Snow transport occurs during any hour the meteorological observations indicate blowing or drifting snow, provided an LSE is snow-covered and the wind-speed high enough to overcome effects due to exposed surface roughness. This indexes snow availability for transport.

7) SNOWFALL. Snowfall occurs at a uniform rate over the duration of a storm. Newly-fallen snow (without immediate redistribution) has a density of 100 kg m^{-3}.

8) SNOWMELT. When the maximum daily air temperature exceeds 0 °C, any decrease in the depth of snowcover observed by AES is converted to snowmelt water and retained on the LSE as "immobile ice", unavailable for further redistribution and non-contributing to the snow depth.

PRAIRIE BLOWING SNOW: SIMULATIONS AND IMPLICATIONS

Simulations were run for sixteen stations in Alberta, Saskatchewan and Manitoba, over the years 1970 to 1976; a span of low and high snow years. A selection of averaged seasonal results from these simulations is shown to demonstrate the differences in the disposition of snow between the open, chinook-prone southern Prairies and the more northerly and forested Parklands. Whilst standard fetch distances are used for comparisons in this example, the reader should note that long fetches are the most common in southern Saskatchewan whilst fetches of one or two kilometre and less are predominant in the parklands.

The average disposition of snow as a percentage of annual snowfall over a 1000-m fetch of stubble (grain stalk height = 250 mm) and fallow (surface roughness equivalent to grain stalk height = 10 mm) land use is shown for Regina, Prince Albert, Swift Current and Yorkton, Saskatchewan in Figs. 3a and b. Relative quantities of snow, expressed as a percentage of annual snowfall, that on average are transported to the edge of the fetch (saltation, suspension) and sublimated during transport (sublimation) are compared to the Residual. The Residual is the unaccounted snow water that is lost to surface evaporation, interception, infiltration, runoff plus that remaining as snowcover. In Parkland regions, where more consistently cold weather suppresses mid-winter melts and evaporation, the Residual is primarily composed of the remaining late-winter snowcover. However in the southern Prairies, chinooks cause rapid mid-winter melts and concomitant evaporation, runoff and infiltration; without further evaluation of these processes it is difficult to relate the Residual to remaining snowcover or over-winter soil moisture gains.

Examining the case for Regina; over a 1000-m fetch of stubble 53% of the annual snowfall is removed; of that removed, two-thirds is lost to sublimation and the remaining one-third is transported off the fetch. In comparison, on fallow land 77% of annual snowfall is removed, of that removed 55% is lost to sublimation and 45% is transported off the fetch. The simulations for the four stations indicate that on average:

1) At Prince Albert, Swift Current and Yorkton at least 8% (range 8-11%) of annual snowfall is transported to the edge of a 1000-m fetch of stubble (saltation + suspension); at Regina about double this percentage.

2) Blowing snow transport is greater on fallow than on stubble. The largest increase with a change in land use from stubble to fallow occurs at Swift Current where snow transported off the fetch nearly triples and the sublimation loss increases by a factor of 1.3.

3) The percentage of annual snowfall lost to sublimation from a 1000-m fetch ranges from 1 to 2.6 times the amount of snow transported off the fetch, the ratio is somewhat higher for stubble land use.

4) The Residual at the Parkland stations (Prince Albert, Yorkton) is larger than at Regina and Swift Current. The difference can be largely attributed to climatic differences: lower wind speeds, air temperatures and vapour pressure deficits at the northerly sites; and to vegetation differences: mixed grassland, deciduous/boreal forest versus open grassland. The substantially higher Residual value for stubble at Swift Current versus

Regina is likely due to the increased influence of chinooks in "immobilising" or ablating snowpacks at Swift Current.

The simulations for the other 12 stations tend to confirm the trends in snow disposition with land cover, land use and climate.

Variation in the mean annual blowing snow transport with fetch length is demonstrated for Prince Albert, Regina, Swift Current and Yorkton in Fig. 4 for fallow (4a) and stubble (4b) land uses. The value plotted is the summation of seasonal saltation and suspension transport; i.e. the snow transported off the fetch. Its units are mass of snow per unit width perpendicular to the flow, this value should be resolved into directional components before comparing to actual accumulations in shelterbelts, etc. Of note at all stations is the rapid increase in transport in the first 300 m of fetch distance; with adequate snow supply this is the distance over which fully-developed flow is established. Once established, the annual snow transport at Prince Albert and Yorkton remains reasonably constant with distance at between 9,000 and 10,000 kg m^{-1} for stubble and between 13,000 and 15,000 kg m^{-1} for fallow.

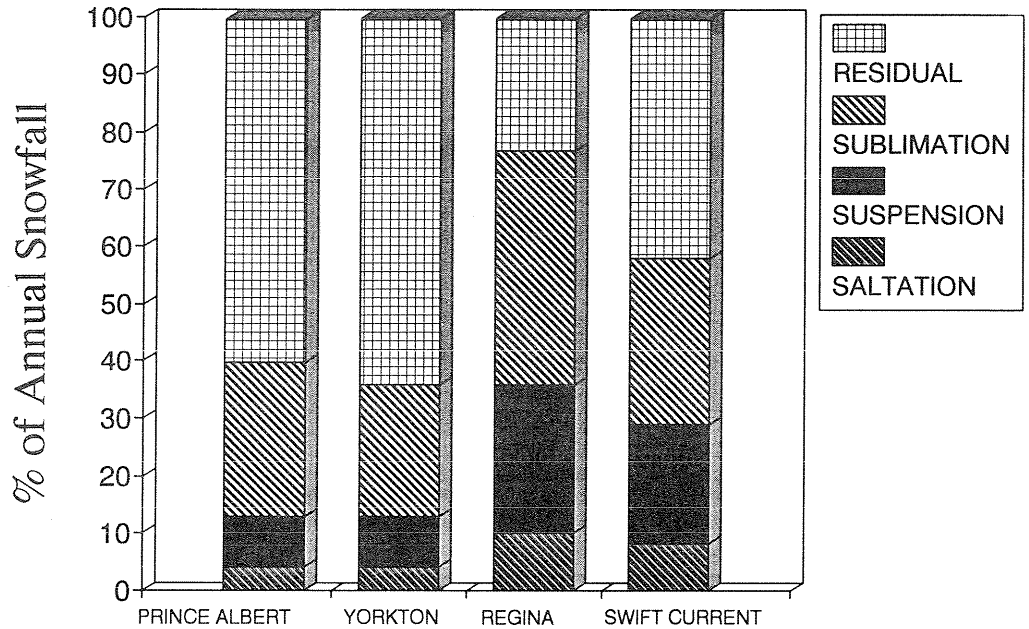
In contrast to the Parkland sites, snow transport on the open prairie changes notably with fetch. For fallow fetches up to 1000 m, snow transport increases with distance, the maximum occurring off fetches of 1000 m for Regina and 4000 m for Swift Current. The rapid increase in transport with fetch distance up to 1000 m is attributed to the effects of high winds and insufficient snowcover to sustain fully-developed flow. Because requirements for fully-developed flow are given priority by the implementation of PBSM, if there is not sufficient snow on the first three LSE to satisfy saltation and suspension transport then subsequent LSE are added until full-development is achieved. This modelling feature simulates the snow-depleted wind-scoured areas that can cover large areas of the southern Prairies in winter and are often the limiting factor to snow transport. For stubble, snow transport decreases slowly with increasing fetch for distances greater than 1000 m. This decrease is attributed to:

1) The requirement to reduce aerodynamic roughness by filling in stubble before snow transport can easily proceed beyond an element, and
2) Cumulative depletion of available snow by sublimation during transport over the fetch, for most combinations of wind speed, temperature and relative humidity.

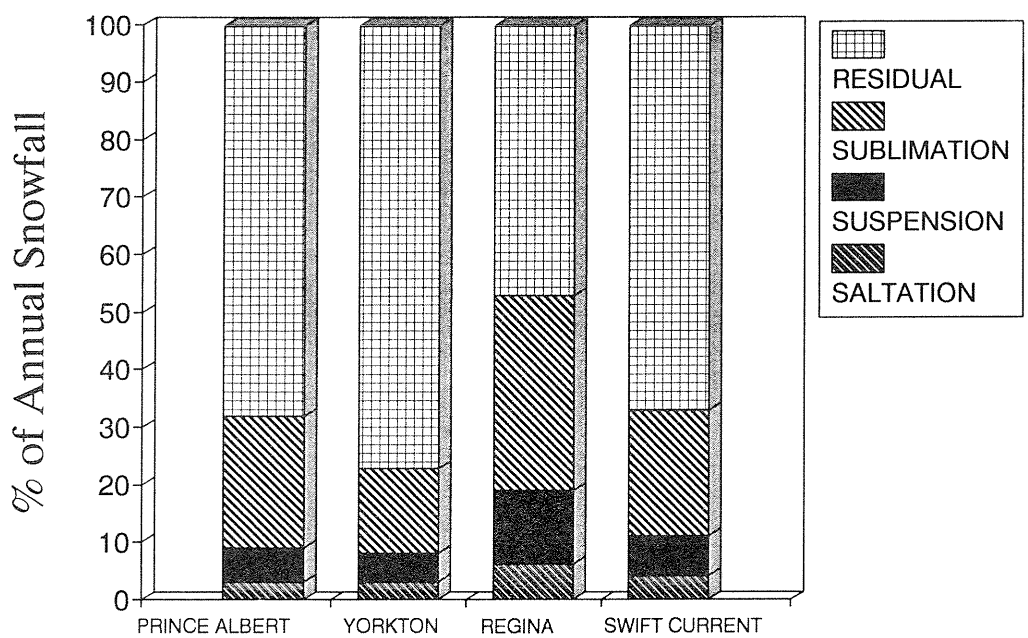
The probability that the snow supply available for transport can overcome losses due to snow accumulation in exposed stubble and sublimation decreases with increasing distance.

The effect of snow transport and sublimation on the average water balance over a fetch is shown in Fig. 5 for the four stations. The values plotted are losses to blowing snow transport and sublimation respectively in terms of snow water equivalent per unit area averaged over the fetch distance. Snowcover loss due to snow transported off the fetch (saltation + suspension) dominates for fetches up to between 500 and 1000 m in length. This is especially prominent for the first 300 m of fetch distance because of the increase in transport from the leading edge. Quantities of snow transport loss are notable but variable, for example 94 mm water equivalent on 300 m of fallow at Regina and 42 mm on the same fetch at Prince Albert. Stubble causes a greater relative reduction in transport in the southern Prairie, where transport from fallow is twice that from a 250-mm height cover of stubble. In comparison, transport at fallow Parkland sites is about one-quarter to one-fifth more than that over stubble.

As fetch distance increases beyond 1000 m, blowing snow sublimation increases to dominate the depletion of snowcover. Sublimation losses are 85 mm water equivalent over a

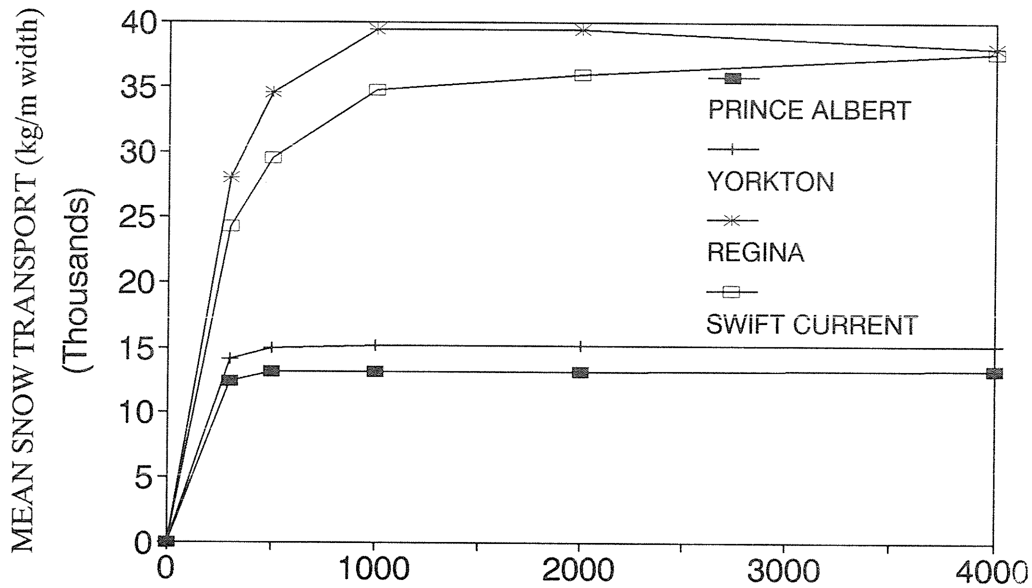


(a) Fallow



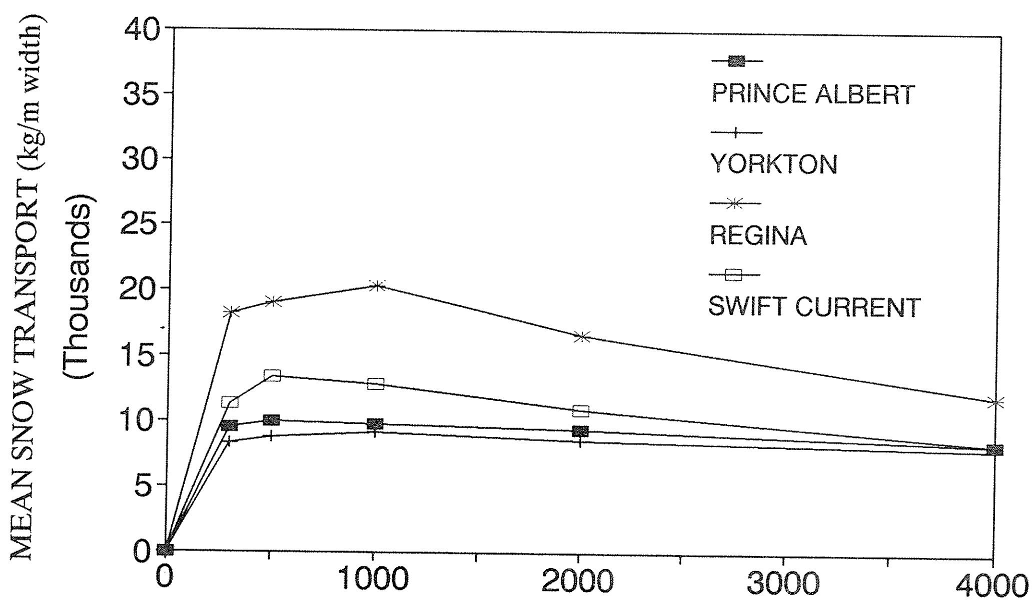
(b) Stubble

Figure 3. Disposition of annual snowfall over a 1000-m fetch: a) fallow, b) Stubble (250 mm height). Average over 1970-76 for two Parkland stations: Prince Albert and Yorkton, Saskatchewan and two southern Prairie stations: Regina and Swift Current, Saskatchewan. Mean annual snowfall is 110, 124, 115 and 126 mm respectively; percentages shown are proportions of this snow disposed on average over the fetch.



Fetch Distance (m)

(a) Fallow



Fetch Distance (m)

(b) Stubble

Figure 4. Mean annual blowing snow transported off a fetch: a) fallow, b) stubble (250 mm height). Average over 1970-76 for two Parkland stations: Prince Albert and Yorkton, Saskatchewan and two southern Prairie stations: Regina and Swift Current, Saskatchewan. The transport value is mass per unit width perpendicular to the flow direction, this value should be distributed according to actual transport vectors before comparing to snow drift accumulations at the edge of fields.

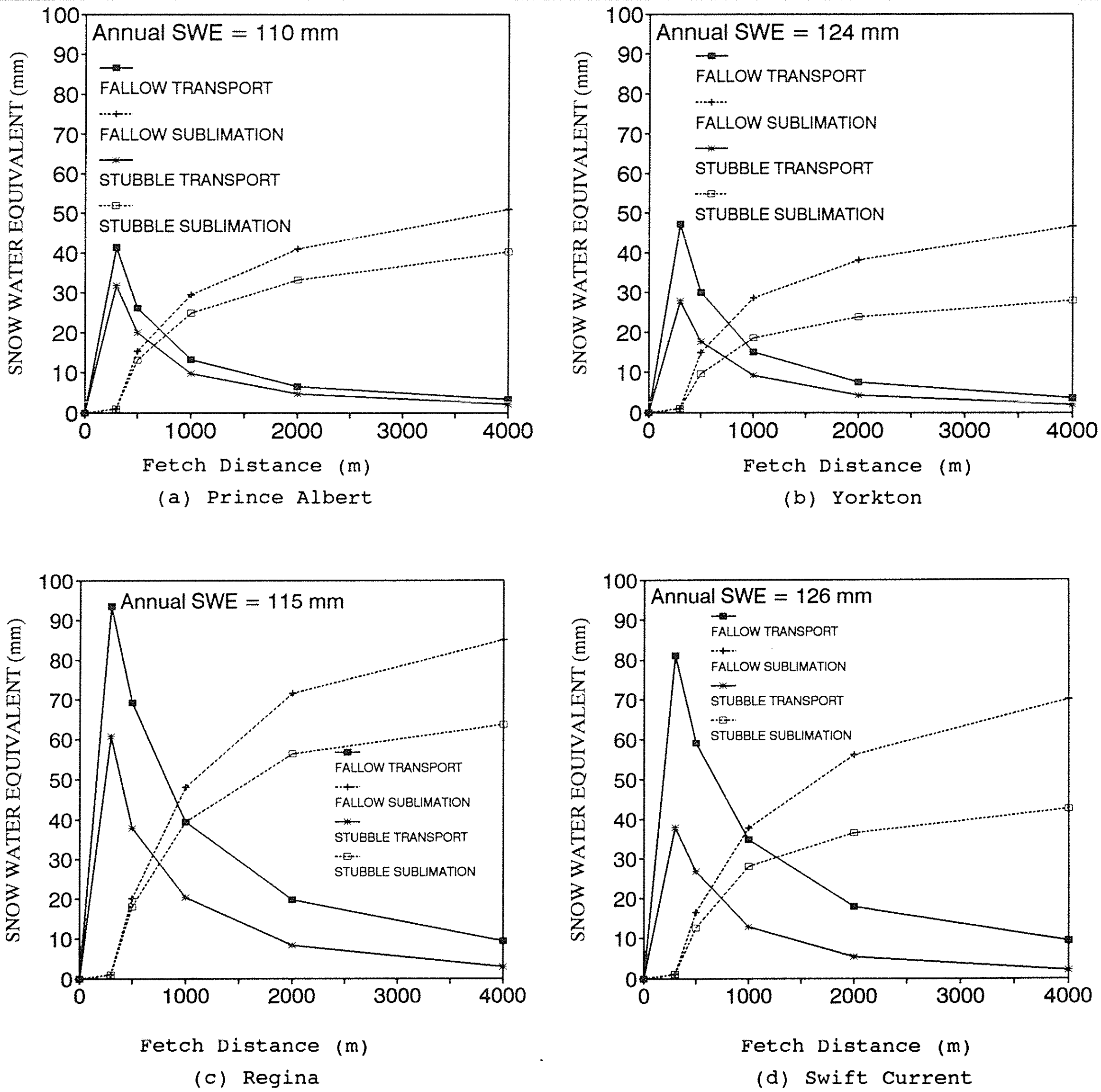


Figure 5. Mean annual snow disposition as a function of fetch distance and land-cover: a) Prince Albert, b) Yorkton, c) Regina and d) Swift Current. Values shown are average annual blowing snow transport and sublimation in mm of snow water equivalent averaged over the fetch for fallow and stubble (250 mm height) land-covers.

4000-m fallow fetch at Regina and 47 mm for the same fetch at Yorkton. The effect of land use on snowcover loss due to sublimation is more consistent among sites than the effect on transport. For fetches of identical length on the southern Prairie, sublimation losses over fallow are 1.5 to double those for stubble, while in the Parklands losses on fallow are 1.2 to 1.5 times the loss for stubble.

At all locations, the sum of transport and sublimation does not change appreciably from its 1000-m-value (Fig. 3) for fetches from 300 to 4000 m. The implication of the change from primarily transport loss for fetches less than 1000 m to primarily sublimation loss for longer fetches, is most striking for the regional water balance rather than that of the fetch itself. Snow transported off the fetch is available for trapping by shelterbelts, woodlands, sloughs and snow fences, providing a critical input to water supplies in these locations. However "consumption" of blowing snow by sublimation over long transport distances removes this water from surficial supplies and potential management.

CONCLUSIONS

Modelling the winter snow regimes for several sites in the grain-growing region of western Canada using the Prairie Blowing Snow Model indicates:

1) On the open southern Canadian Prairies, blowing snow transport and sublimation may consume from two-thirds to four-fifths of the annual snowfall and in the more forested northern Parklands, over one-third of annual snowfall may be removed from open sites.
2) In the Parklands, the quantity of snow transported off a fetch typically increases with fetch length for distances up to 300 m, then remains relatively constant with fetch length. On the open Prairies snow transported off the fetch increases with fetch distance up to about 1000 m then slowly declines with further increases in distance.
3) The snow per unit of land surface removed by transport and sublimation on a seasonal basis does not change appreciably with increasing fetch at distances greater than 300 m.
4) Sublimation losses of blowing snow increase with fetch length, consuming appreciable portions of annual snowfall when fetches exceed about 500 m in length and dominating snow losses for fetches exceeding 1000 m in length. Modelling results for southern Saskatchewan indicate the sublimation loss approaches three-fourths of annual snowfall on fallow land.

These snow redistribution processes have important consequences for measures that would control snow accumulation; for runoff generation, soil moisture status and groundwater recharge on adjoining land surfaces that trap snow; and for water budgets on local, basin or regional scales.

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