SNOW MANAGEMENT AND MELTWATER ENHANCEMENT

by

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INTRODUCTION

This report summarizes the results of studies conducted under the project during the 1988 calendar year. For the most part, these activities centered on: (a) measurement of soil moisture changes, atmospheric variables, snowcover properties and crop yields at field sites established at Kerrobert and Richlea in the fall of 1987 (see progress report of February, 12, 1987); (b) analyses of these data and integration of the results with the information collected during the past five years which are archived in the data base of the Division of Hydrology. (c) the development of a "first - generation" model describing the interaction of between snowmelt infiltration, snowcover water equivalent and line spacing of a subsoiling treatment. (d) application of a Prairie Blowing Snow Model to data collected at various climatological stations in the Prairie Provinces to determine the relative amounts of snow that move in saltation and suspension and the amount lost to sublimation during wind transport - hence, the "potential amounts of snow available to be trapped and (e) derivation of a procedure for estimating soil water losses by evaporation during "Postmelt", the period following the disappearance of the seasonal snowcover up to the time of seeding of annual cereal grains.

SNOWMELT INFILTRATION

The 1987-88 winter season was characterized by very low snowfall at all study sites. Snowcover water equivalents (SWE) on many of the "unmanaged" plots at the time of melt were less than 50 mm. Only at Kerrobert (Reynold's farm) and Saskatoon where snow fences had been erected were there appreciable accumulations (Table 1). On the subsoiled field on the Wright farm the average SWE was approximately 47 mm; on the Reynolds farm the depth of snowcover was
highly variable ranging from large, snow-free patches to a maximum accumulation with a SWE of 188 mm on one of the fenced areas; and at Saskatoon the water equivalent of the snowcover ranged from 48 to 140 mm. The wide spatial variability in snowcover negated the possibility of obtaining representative "areal" data of the SWE-fertilizer-yield interaction on the different subsoiling treatments.

At Richlea, the total snowcover water equivalent available for infiltration resulted from snowfall which occurred just prior to the melt; hence the deflector strips showed little effect in increasing accumulation.

**Infiltration Into Cracked and Subsoiled Soils**

Table 1 gives the snowcover water equivalent (SWE), the snowmelt infiltration (INF), and the depth meltwater penetrated the frozen soil (d) monitored at the different sites in 1988. The relative locations of the measurement sites are shown in the schematic diagrams (Figs. 1, 2, 3 and 4). The data in Table 1 are consistent with the findings of snowmelt infiltration to undisturbed, cracked and subsoiled soils reported by Gray and Granger (1985). Namely, they show:

1. On Undisturbed Stubble:
   
   (a) For shallow snowcovers, infiltration amounts approximately equal to the SWE; for deep snowcovers, INF << SWE.
   
   (b) Meltwater penetrates a frozen soil only to shallow depths (range 160 to 560 mm, average = 356 mm).

2. In Cracks and Rips
   
   (a) Large amounts of infiltration. In several cases INF exceeds SWE and this is attributed to the flow of meltwater along the line and to direct entry of runoff into the surface opening, the undisturbed soil between the openings acting as a contributing area of infiltrating water. The effect is most evident at the Wright and Reynolds' farms on plots which were subsoiled on a line spacing of 1.4 m with a Kelco-bilt in the fall of 1986. At Wright's snowcover water equivalents of 45 and 49 mm resulted in 137 and 105 mm of infiltration into the rips.
Figure 1. Soil moisture monitoring sites - Reynold's Farm (west), Kerrobert, 1987/88.
Figure 2. Soil moisture monitoring sites - Reynolds Farm (east), Kerrobert, 1987/88.
Figure 3. Soil moisture monitoring sites - Wright's Farm, Kerrobert, 1987/88.
Figure 4. Soil moisture monitoring sites - Kernan Farm, Saskatoon, 1987/88.
Table 1. Snowmelt infiltration to cracked and subsoiled soils, Kerrobert, Richlea, Saskatoon, 1988.

<table>
<thead>
<tr>
<th>Site</th>
<th>No.</th>
<th>Description</th>
<th>SWE (mm)</th>
<th>INF (mm)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerrobert</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reynolds (W)</td>
<td>1</td>
<td>Ebson .7 (85)</td>
<td>63</td>
<td>55.2</td>
<td>680</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Killefer (83)</td>
<td>63</td>
<td>150.8</td>
<td>680</td>
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<tr>
<td></td>
<td>8</td>
<td>Adjacent #7</td>
<td>63</td>
<td>72.6</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Stubble</td>
<td>60</td>
<td>68.3</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Kello .7 (86)</td>
<td>43</td>
<td>28.4</td>
<td>280</td>
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<tr>
<td></td>
<td>13</td>
<td>Kello 1.4 (86)</td>
<td>60</td>
<td>100.7</td>
<td>780</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Adjacent #13</td>
<td>60</td>
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<td>280</td>
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<tr>
<td></td>
<td>15</td>
<td>Kello .7 (86)</td>
<td>57</td>
<td>121.2</td>
<td>760</td>
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<td></td>
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<td></td>
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<td>140</td>
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<td>400</td>
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<td>Adjacent #2</td>
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<td>105.1</td>
<td>800</td>
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<td>2F</td>
<td>Hubee .9 (87)</td>
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<td>218.8</td>
<td>1240</td>
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<td></td>
<td>3F</td>
<td>Hubee .9 (87)</td>
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<td>59.4</td>
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<td>4F</td>
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<td>194.2</td>
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<td>9.5</td>
<td>160</td>
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<td>10</td>
<td>Stubble</td>
<td>13</td>
<td>10.8</td>
<td>300</td>
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<td>Hubee .7 (87)</td>
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<td>Richlea</td>
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<td>600</td>
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<td>26.3</td>
<td>140</td>
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<tr>
<td></td>
<td>7</td>
<td>Stubble</td>
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<td>154.7</td>
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... continued
Table 1. continued

<table>
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<td>Adjacent #12</td>
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<td>Killefer .9 (87)</td>
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<tr>
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<td>Killefer .9 (87)</td>
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<td>14</td>
<td>Fallow</td>
</tr>
<tr>
<td>15</td>
<td>Hubee .9 (87)</td>
</tr>
<tr>
<td>18</td>
<td>Adjacent #15</td>
</tr>
</tbody>
</table>

---

a F = site was ringed by a snow fence
b Ebson .7 (85) = lines installed with Ebson plow in fall, 1985; depth = 400 mm, spacing = 0.75 m
c Killefer (83), Killefer (84) = lines constructed with Killefer plow in 1983 and 1984, respectively; depth = 600 mm; spacing 1.9 m
d Adjacent #7 = measurement of moisture change made in a soil column located 150 450 mm immediately adjacent to rip in which site No.7 is located
e Stubble = undisturbed stubble
f Kello .7 (86) and Kello 1.4 (86) = lines constructed with Kello-bilt plow in 1986 to a depth of ~600 mm on line spacings of 0.7 and 1.4 m, respectively
g Hubee 0.7 (87) and Hubee 0.9 (87) = lines installed with Hubee subsoiler to a depth of 500 mm in 1987 on spacings of 0.70 and 1.4 m respectively
h soil crack.

(b) Infiltrating meltwater penetrates to depths below the bottom of the rip and in cases where large amounts of infiltration occur, the depth may exceed a rootzone depth of 1 m. A strong relationship exists between INF and d with INF increasing almost linearly with d, or vice versa. However, unless a snowcover is unusually deep (SWE > 150 mm; depth ≈ >60 cm), d is less than 1 m (average = 630 mm). This finding supports a recommended depth for lines of the order of 500 mm.

3. Adjacent to a Crack or Rip

Infiltration into the soil column immediately adjacent to a rip or crack is less than that into the aperture, but greater
in amount to that into undisturbed stubble. This can be attributed to the increased hydraulic conductivity of the soil mass caused by lateral rupture and fracture of the soil during installation of the lines and to the rip or crack acting as a source of water for lateral movement. Note the data demonstrate a close relationship between the amounts of meltwater entering a rip and adjacent soil.

The findings (Table 1) are combined with information collected in previous years and summarized as average amounts of snowmelt infiltration to cracks, rips and undisturbed sites for different ranges of snowcover water equivalent in Table 2. The data show INFR increasing with SWE in both cracks and the rips with a trend for the rips to infiltrate more water than the "cracks". However, the ratio of the amount of infiltration into an opening to the amount infiltrating the same soil in undisturbed condition varies only slightly with SWE, on cracked soils the range in ratio - values varied between 3.4 and 4.3 with a mean of 3.8 and on "ripped soil between 5.4 and 6.5 with a mean of 5.8.

Figure 5 shows grouped mean values of soil water changes due to snowmelt infiltration which have been monitored in rips, cracks, adjacent to rips and undisturbed stubble plotted against snowcover water equivalent. Expressing these relationships in equational form gives:

Rips

\[ \text{INFR} = 16.86 \text{ SWE}^{0.432}. \]  \[1\]

Cracks

\[ \text{INFC} = 8.48 \text{ SWE}^{0.553}. \]  \[2\]


Table 2. Average amounts of snowmelt infiltration to cracks, rips and to uncracked/undisturbed soils for different ranges of snowcover water equivalent (INF).

<table>
<thead>
<tr>
<th>SWE</th>
<th>INFILTRATION&lt;sup&gt;a&lt;/sup&gt;</th>
<th>INFILTRATION&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncracked</td>
<td>Crack</td>
</tr>
<tr>
<td>&lt;30</td>
<td>12.4 (5)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>49.7 (2)</td>
</tr>
<tr>
<td>30-50</td>
<td>18.6 (7)</td>
<td>70.7 (2)</td>
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<td>50-70</td>
<td>23.7 (11)</td>
<td>84.1 (9)</td>
</tr>
<tr>
<td>70-100</td>
<td>28.0 (23)</td>
<td>95.7 (5)</td>
</tr>
<tr>
<td>100-150</td>
<td>30.5 (17)</td>
<td>116.6 (9)</td>
</tr>
<tr>
<td>&gt;150</td>
<td>34.5 (9)</td>
<td>147.0 (4)</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Values given for cracked and uncracked soils are from all regions in Brown and Dark Brown soil zones of the Province in which soil cracking was observed. The major soil types are heavy clay and clay loam.

<sup>b</sup> Values for subsoiled and undisturbed soil are for Kerrobert where the principal soil texture is a glacial clay loam. The subsoiling treatments included: (a) Killefer plow - depth = 600 mm, spacing = 1.9 m; (b) Ebson plow - depth = 400 mm, spacing = 0.75 m; (c) Kello-bilt plow - depth = 600 mm, spacings = 0.70 and 1.4 m; (d) Hubee subsoiler - depth = 500 mm, spacings = 0.70 and 0.90 m.

<sup>c</sup> Values in parentheses refer to the number of samples.

<sup>d</sup> Estimated values. The soil in the Kerrobert region exhibits some solonetzi characteristics, with infiltration to undisturbed stubble being consistently lower than at other locations in the Province by an approximate factor of 0.75.
Figure 5. Average amounts of snowmelt infiltration (mm) into cracks, rips, adjacent to rips and undisturbed stubble as a function of average depth of snowcover equivalent (mm).
Adjacent to Rips

For SWE \(< 80\) mm

\[\text{INFA} = 1.65 \text{ SWE}, \quad \text{and} \quad [3a]\]

For SWE \(> 100\) mm

\[\text{INFA} = -27.5 + 0.89 \text{ SWE}. \quad \text{[3b]}\]

Undisturbed Soils

\[\text{INF} = 5.0(1 - \theta_p)\text{SWE}^{0.584}, \quad \text{and} \quad [4]\]

where: INFR = infiltration into a rip (mm), INFC = infiltration into a crack (mm), INFA = infiltration into the soil column lying 150 to 450 mm adjacent to a rip (mm), INF = infiltration into undisturbed soil (mm), and SWE = snowcover water equivalent (mm). \(\theta_p\) = average premelt soil water (ice) content of the 0 - 300 mm soil layer expressed as a degree of saturation (mm\(^3\)/mm\(^3\)).

Spacing of Rips

Equations 1 to 4 are used for the development of a simple, conceptual model describing the average depth of snowmelt infiltration over a subsoiled field (INF(areaal)) as a function of SWE and line spacing(s). Consider a soil which has been subsoiled with only minor disturbance to the structure of the mass confined between the rips. The system can be represented by three individual soil blocks (rip, adjacent to rip, and undisturbed (see insert in Fig. 6)), each having its own infiltration characteristics. Taking the widths of the "rip" and "adjacent" blocks equal to the width of measurement of soil moisture changes, \(\approx 300\) mm, the water balance equation can be written as:

\[\text{INF(areaal)} * s = \text{INFR} * 0.3 + \text{INFA} * 0.6 + \text{INF} * (s - 0.9), \quad [5]\]
in which $s$ is in metres. Substituting the expressions for INFR, INFA and INF given by Eqs. 1 - 4 into Eq. 5 and solving gives:

For $s \geq 0.9$ and $\text{SWE} \leq 70$ mm

$$\text{INF(areal)} = (5.06 \text{SWE}^{0.542} + 0.99 \text{SWE} + (s - 0.9)[5(1 - \theta_p)\text{SWE}^{0.685}])/s \quad [6a]$$

and for $s \geq 0.9$ and $\text{SWE} \geq 100$ mm

$$\text{INF(areal)} = (5.06 \text{SWE}^{0.542} - 16.5 + 0.534 \text{SWE} + (s - 0.9)[5(1 - \theta_p)\text{SWE}^{0.685}])/s \quad [6b]$$

For snowcovers with $70$ mm $\leq$ SWE $\leq 100$ mm, the lesser amount of INF(areal) given by Eqs. 6a or 6b is used.

Equations 6a and 6b are plotted for a range of SWE-values and two levels of "Premelt" soil moisture ($\theta_p = 0.4$ and $\theta_p = 0.6$) in Figs. 6 and 7. Also plotted in the figures is INF(areal) for rips spaced at 0.7 m and for undisturbed soil. To demonstrate the application of the curves assume average annual snowfall water equivalents of 90 to 125 mm, respectively and snow management trapping efficiencies in the range of 60 to 75% of annual snowfall. Table 3 shows that in soils which are normally dry in the fall, lines should be spaced between 0.7 and 1.3 m, depending on SWE and in soils which are usually wet in the fall, lines should be spaced at 0.9 m or less. The depth of a "normal" snowcover with a water equivalent of 54 mm, (0.60 * 90 mm), is of the order of 22 cm. For shallower depths of snowcover, the line spacing can be increased. For example, lines spaced between 1.3 or 2.2 m would infiltrate 15 cm of snow, depending on soil wetness.

The model can be expected to give reasonable predictions of areal infiltration in the first year of subsoiling for cases where the subsoiling operation has not produced substantial lateral fracturing of the mass of soil confined between the "rips". It is limited to these cases because the expression for infiltration to "undisturbed" soil (Eq. 4) does not describe the process for disturbed soils. Comparisons between measured and calculated areal infiltration amounts are given in Fig. 8. "It is suspected that with line spacings less than
Figure 6. Relation between "areal" infiltration, line spacing and snow water equivalent for "dry" (premelt soil moisture = 0.40 mm³/mm³), subsoiled soils.

Figure 7. Relation between "areal" infiltration, line spacing and snow water equivalent for "wet" (premelt soil moisture = 0.60 mm³/mm³), subsoiled soils.
Figure 8. Comparison between "measured" and "modelled" amounts of "areal" infiltration.
Table 3. Spacings of rips in (m) for annual snowfall water equivalents of 90 and 125 mm, trapping efficiencies of 60 and 75% and two levels of "Fremelt" soil moisture. $\theta_p = 0.4$ and $\theta_p = 0.6$.

<table>
<thead>
<tr>
<th>Snowfall Water Equivalent (mm)</th>
<th>Trapping Efficiency (%)</th>
<th>Rip Spacing ($\theta_p = 0.4$)</th>
<th>Rip Spacing ($\theta_p = 0.6$)</th>
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</thead>
<tbody>
<tr>
<td>90</td>
<td>60</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>90</td>
<td>75</td>
<td>1.05</td>
<td>0.7</td>
</tr>
<tr>
<td>125</td>
<td>60</td>
<td>0.95</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>125</td>
<td>75</td>
<td>&lt;0.7</td>
<td>&lt;0.7</td>
</tr>
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</table>

0.7 m, most commercial subsoilers will cause sufficient disturbance and fracture to the soil mass between the rips that, at least in the first year, a soil will have the capacity to infiltrate all water from snow accumulations which are likely to be trapped by a stubble management practice <36 cm), independent of the soil moisture content. It can be expected that the infiltration characteristics of a subsoiled soil will decrease naturally in time due to settlement and packing. However, field observations suggest that the beneficial effects of subsoiling on meltwater enhancement may be "longer lasting" in rips placed at wide spacings (to some maximum) due to natural cracks which develop between the lines in response to strong gradients in soil moisture caused by differential withdrawal patterns.

Based on the evidence collected to date it is suggested that subsoiling to a depth between 400 – 500 mm on a line spacing between 0.9 and 1.2 m will allow efficient meltwater augmentation from a snow (stubble) management practice in most glacial till soils in the Province and normal snowfall and soil moisture conditions. For slightly solenetic soils the spacings should be decreased slightly. These criteria are supported by visual observations of crop growth. With lines spaced at 1.4 m or wider crop growth and maturity is nonuniform, the plants directly over the lines are taller and mature more slowly.
EFFECTS OF SNOW MANAGEMENT AND SUBSOILING ON CROP YIELD

An important goal of the study is to obtain information on the effects of snow management and subsoiling practices on crop yield. Yield data are also used to index the longevity of the treatment effects.

For the 1987-88 season at the Kerrobert sites, the subsoiled plots were in 2nd-year stubble and, because of the patchy snowcover, no supplemental fertilizer was added. Also the patchy growth and poor stand negated meaningful yield data from the entire area of a plot. As a consequence, samples were taken with a small-plot combine (Wintersteiger) at selected locations within the fields so as to provide yield information over the range of observed snowcover water equivalents. Figure 9 shows the increase in yield with increased snowmelt infiltration relative to the yield from undisturbed stubble plots showing the lowest yield. The soil water increases for the subsoiled areas were estimated by the model for areal infiltration to subsoiled sites using the observed snowcover water equivalents, or from infiltration amounts observed at soil moisture monitoring sites located at or near to the sites where the combine samples were taken. The best-fit line through the data (taken through the origin) indicates that each additional 25 mm of water produces a yield increase of about 190 kg/ha of spring wheat. There was no discernable difference in yields from areas subsoiled on .7 m and .9 m spacings.

The data in Table 4 show the effects on yield of subsoiling treatments without snow management. They show a decrease in treatment effect on yield with time. In the first two years following installation the change is small; in the first year there is an average difference of 435 kg/ha compared to the yield from undisturbed stubble (34% increase), while in the second year a difference of 377 kg/ha (30% increase) is observed. In the fourth year the difference has reduced to 20 kg/ha (only 1% increase). It is mentioned however, that this small residual effect in the fourth year is likely due, at least in part, to the low amount of precipitation (snow and rain) received in 1987, the only year with fourth year data. Over the life of the trials the average annual precipitation has been less than normal.
Figure 9. 1988 yield - soil moisture interaction on undisturbed and subsoiled soils at Kerrobert expressed as increases above the lowest amounts observed on undisturbed stubble.
Table 4. Effect of subsoiling on the yield of spring wheat without snow management and supplemental additions of fertilizer.

<table>
<thead>
<tr>
<th>Landuse and Age of Rips</th>
<th>SWE(^a) mm</th>
<th>Rain(^b) mm</th>
<th>Yield (kg/ha)</th>
<th>Range in Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fallow(^e)</td>
<td>110</td>
<td>610</td>
<td>1.44</td>
<td>1.05 - 1.71</td>
</tr>
<tr>
<td>Stubble Rips</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st year</td>
<td>52</td>
<td>110</td>
<td>435</td>
<td>1.18 - 1.60</td>
</tr>
<tr>
<td>2nd year</td>
<td>50</td>
<td>122</td>
<td>377</td>
<td>1.18 - 1.52</td>
</tr>
<tr>
<td>3rd year</td>
<td>42</td>
<td>122</td>
<td>132</td>
<td>1.06 - 1.15</td>
</tr>
<tr>
<td>4th year</td>
<td>26</td>
<td>100</td>
<td>20</td>
<td>1.01</td>
</tr>
</tbody>
</table>

\(a\) Mean snowcover water equivalent.
\(b\) Average growing season rainfall.
\(c\) Difference in yield from that on stubble (1-year rotation).
\(d\) Ratio of mean yield on treatment to that on stubble.
\(e\) 4-year average yield from crop on fallow without snow management was 1896 kg/ha.

**SNOW TRANSPORT**

Snow management for agriculture involves the modification of land surface roughness to achieve the desired spatial distribution in snowcover. This is accomplished by increasing the roughness height in target areas and may include height reductions in source areas.

In order to develop a rational snow management strategy it is necessary to know how much snow is available for distribution as a result of climate and landuse. Regional climate determines not only the quantity of snowfall, but also the amount of snow lost to sublimation and mid-season melt events. The effects of regional climate on snow water availability can be modified at a local scale by landuse practices to create a micro-climate more conducive to snow conservation. There are numerous ways to trap snow, ranging from the use of
simple, inexpensive vegetative barriers (tall stubble and trap strips) to the more expensive, mechanical barriers (Wyoming Snow Fence). Knowledge of snow transport phenomena is required in order to establish design criteria in respect to the preferred location, orientation, height and porosity of snow trapping devices, and to evaluate the economic feasibility of a management procedure.

The primary objective of this segment of the study has been the development and application of a computer model for predicting the snow transport fluxes, namely saltation, suspension and sublimation, and the directional re-distribution of the seasonal snowfall at different locations in the Prairie and Parkland regions of Saskatchewan. Development of the system is based on the simulation program for snow transport described by Pomeroy (1988), the Prairie Blowing Snow Model (PBSM). This model calculates the mass transport of snow as saltating and suspended flow and the sublimation rate of snow in transport. Input to the model consists of hourly meteorological measurements, namely: windspeed, air temperature and relative humidity. The model also requires a surface roughness parameter in the form of stubble height and a fetch distance over which the wind is allowed to act. Further information regarding the theory, development, calibration and testing of the PBSM is described by Pomeroy (1988).

Implementation of PBSM

A number of simplifying assumptions were necessary in order to apply the model for its intended purpose. The most important of these are summarized below.

1. The model consists of a uniform, flat plane of land (linear catchment) of unit width and variable length with its major axis parallel to the prevailing wind direction. The length of the plane is divided into elements, each 100-m in length, so that roughness heights can be specified by the user at various points in the flow. Within each element it is assumed that landuse and surface conditions are constant.

2. It is assumed: (a) the snow flux at the most upper–wind boundary of the plane is zero (a barrier prevents any horizontal flux from upwind areas), (b) water enters only in the vertical direction as
precipitation and (c) new snowfall has a density of 100 kg/m$^3$ and is uniformly-distributed over the duration of an event.

(3) A fetch of 300 m is required for the development of steady-state flow. If there is insufficient snow on the first three elements to allow fully-developed flow, elements are added until the flow condition is established.

(4) If during a simulation the model encounters an element whose surface roughness features prevent snow transport, a downwind erosional fetch of 300 m (3 elements) is required for re-development of steady-state flow.

(5) Sublimation losses are assumed zero until steady-state flow conditions are established.

(6) The "effective" aerodynamic roughness height on an element is the "input" stubble height less the snow depth.

(7) The model maintains a water balance within it's boundaries. Snow can be relocated downwind, transported out at the downwind end, sublimate and melt.

(a) Snow transport occurs during any hour the meteorological records indicate blowing or drifting snow provided; (1) an element is snow-covered, (2) the hourly windspeed overcomes the aerodynamic roughness and (3) the fetch distance is ≥300 metres.

(b) Snow is re-deposited on a downwind element whose roughness height prevents erosion. The density of wind-deposited snow is assumed to be 250 kg/m$^3$.

(c) Snow transported and not re-deposited within the plane is available for trapping.

(d) Melt is the observed decrease in snow depth as retrieved from the AES data set. Meltwater is maintained on the element and snow that has been converted to meltwater is removed from the snow inventory.
Results

The blowing-snow saltation-, suspension- and sublimation fluxes to a height of 5-m over stubble and fallow surfaces of various lengths are simulated using climatological data collected during the winter months at Prince Albert (1971-76), Regina (1970-76), Swift Current (1971-76) and Yorkton (1970-76).

Snow Transport Fluxes - Fetch Distance = 1000m

The simulations for Regina for stubble (height = 25 cm) and fallow land and 1000 m fetch are shown in Figs. 10 and 11. These "pie" charts pictorially depict the disposition of the mean annual snowfall with the sectors giving the percentages of the annual snowfall that on average; remain as snowcover, are transported by saltation, and suspension, or are lost by sublimation due to wind transport from a fetch of 1000 m. The reader is reminded that the model assumes snowfall is the only source for eroded snow. For a stubble surface (Fig. 10), on average 53% of the snowfall is removed of which 35% (44 mm water) is lost to sublimation and the remaining 18% is transported from the land unit by saltation and suspension. If the blowing-snow (saltation and suspension) is trapped, it would amount to approximately 23,000 kg or $23m^3$ (23 mm) of water per unit width. In comparison, the simulations for fallow (Fig. 11) show a decrease of 24% in the amount of snowfall retained as snowcover, an increase in sublimation loss of 7% and an increase in total transport in suspension and saltation of 17%. These findings "quantify" elements of the "blowing snow" phenomena important to the application of snow management practices for water conservation, namely:

1. Significant amounts of water are lost to sublimation during wind transport. These losses are less on stubble than on fallow.
2. A fetch of fallow offers greater potential for accumulating snow at the downwind end than an equal fetch of stubble.

Table 5 summarizes the "simulated" snow transport fluxes and the amounts of snowfall retained as snowcover at the four stations. These findings show:
Figure 10. Average percent of mean annual snowfall transported in saltation and suspension, sublimated and remaining as snowcover on a 1000-m fetch of stubble at Regina (period of record 1970-76).

Figure 11. Average percent of mean annual snowfall transported in saltation and suspension, sublimated and remaining as snowcover on a 1000-m fetch of fallow at Regina (period of record 1970-76).
Table 5. Modelled average annual saltation, suspension, and sublimation fluxes and remaining snowcover on a 1000-m plane of unit width in stubble and fallow at Prince Albert, Regina, Swift Current, and Yorkton, SK., as a percent of mean annual snowfall (1970-76).

<table>
<thead>
<tr>
<th>Location</th>
<th>Landuse</th>
<th>Snowfall mm</th>
<th>Saltation %</th>
<th>Suspension %</th>
<th>Sublimation %</th>
<th>Snowcover %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prince Albert</td>
<td>Stubble</td>
<td>110</td>
<td>3</td>
<td>6</td>
<td>23</td>
<td>68</td>
</tr>
<tr>
<td>Fallow</td>
<td>4</td>
<td>9</td>
<td>27</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regina</td>
<td>Stubble</td>
<td>115</td>
<td>6</td>
<td>13</td>
<td>34</td>
<td>47</td>
</tr>
<tr>
<td>Fallow</td>
<td>10</td>
<td>26</td>
<td>41</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swift Current</td>
<td>Stubble</td>
<td>126</td>
<td>4</td>
<td>7</td>
<td>22</td>
<td>67</td>
</tr>
<tr>
<td>Fallow</td>
<td>8</td>
<td>21</td>
<td>29</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yorkton</td>
<td>Stubble</td>
<td>124</td>
<td>3</td>
<td>5</td>
<td>15</td>
<td>77</td>
</tr>
<tr>
<td>Fallow</td>
<td>4</td>
<td>9</td>
<td>23</td>
<td>64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) On stubble land at Prince Albert, Swift Current and Yorkton on average approximately 10% (range of 8-11%) of the annual snowfall is relocated by saltation and suspension; at Regina about double this percentage (19%). Also, the sublimation loss is substantially higher at Regina, at 34% of annual snowfall over a 1000-m fetch.

(2) The snow transport fluxes are greater on fallow than stubble. The most significant increases occurring at Regina and Swift Current where the saltating and suspended fluxes doubled and the sublimation loss increased by 7% with change in land use.

(3) Independent of landuse and the percent of annual snowfall lost to sublimation over a 1000-m fetch is equal to or greater than the amount of snow transported in saltation and suspension with factors ranging from 1 to 2.6.

Direct application of these "quantitative" results to the design of snow management practices is limited by the "constraints" of the simulation routine. However, they "clearly" demonstrate the "higher" potential of snow management practices better snow water conservation at Regina and Swift Current, especially
on fallow land, and the need for minimizing fetch distance to reduce sublimation losses.

Orientation of Barriers

Roses of the blowing/drifting (suspension and saltation) snow flux and the wind directional frequency in eight principal directions (N, NE, E, SE, S, SW, W, NW) for Regina are given as Figs. 12 and 13. Comparing these data it is evident that at Regina the principal directions of transport correspond closely with the directional frequency-of-occurrence of prevailing winds. 88.5% of the annual blowing snow flux originates from NW, W, SE and E directions and 77.5% of the wind events occur from these same directions. However, the roses are not identical. Only 22.5% of the total flux is produced from the SE. the direction in which winds are most frequent (23.3%) and have the highest mean velocity (6.5 m/s), whereas 27.5% of the annual flux is transported by NW-winds with approximately the same mean windspeed (6.4 m/s) but comprise only 18.1% of the wind events. These results are not unexpected as snow transport is not only a function of windspeed frequency; one major wind event in a specific direction could significantly alter the flux-distribution. Likewise, winds in a specific direction may be generally of low velocity so as to not cause transport. This is evident in the data for Prince Albert (Figs. 14 and 15) which show that winds from the S and SW, while representing 20.4% of events, transport only 1% of the drifting snow.

The analysis demonstrates the preferred orientation for a snow trapping barrier at Regina is NE to SW (ie. perpendicular to NE and SE winds), with 50% of the annual wind-transported flux available for trapping. Also, some portion of the annual flux transported by winds orientated at an acute angle to the barrier will also be trapped. It is possible that some of the "trapped" snow may be eroded by winds moving parallel to the obstruction. This would not appear to be a serious problem at Regina because NE-SW winds occur infrequently (4.5% of the total) and the adjacent flux is large (38.4% of the total).

Similar analyses of wind data for the other stations suggest orientations for a management practice of N-S at Prince Albert and Swift Current and SW-NE at Yorkton.
Figure 12. Percent of annual blowing/drifting snow (suspension and saltating) flux as a function of direction at Regina (average from 1000-m fetches of stubble and fallow) 1970-76.

Figure 13. Wind rose showing directional frequency of hourly winds at Regina (period of record November to April, 1970-76).
Figure 14. Percent of annual blowing/drifting snow (suspension and saltating) flux as a function of direction at Prince Albert (average from 1000-m fetches of stubble and fallow, 1971-76).

Figure 15. Wind rose showing directional distribution of hourly winds at Prince Albert (period of record November to April, 1971-76).
Influence of Fetch Distance

Figure 16 (a,b,c) shows the disposition of annual fluxes and snowcover on stubble (height = 25 cm) at the four locations plotted with fetch distance. At Prince Albert and Yorkton the mass flux in saltation and suspension remains relatively constant at 9,000 to 10,000 kg/m independent of fetch distance (Fig. 16a). Thus the quantity of snow available for trapping by a downwind barrier will not be increased by increasing the fetch distance at these stations. In contrast, at Regina and Swift Current, the mass flux transported in saltation and suspension decreases with increasing fetch at distances greater than ≈ 1 km. This is attributed to the fact that at distances greater than 1000 m sublimation becomes the dominant flux for most combinations of windspeed, temperature, relative humidity and roughness height. Figure 16b shows sublimation increasing rapidly with increasing fetch, and for a distance of 4000 m the annual flux at Regina is 254,000 kg/m (64 mm water equivalent), contrasted to a loss at Yorkton over the same distance of only 112,000 kg/m (28 mm water equivalent). In order to balance high sublimation rates snow is eroded from the snowcover, thereby decreasing its' depth. This decrease affects the transport process in two ways: (a) it reduces the amount of snowcover available for transport and (b) it increases the roughness height of the surface by exposing a larger area of stalks of stubble to the wind. In respect to the latter, subsequent wind-speed events, which would ordinarily cause saltation with complete snowcover, will not cause transport due to the increased roughness height. Regina and Swift Current fall in climatic zones with winds which favour high transport rates and scouring, Yorkton and Prince Albert are in zones of lower transport rates.

The percentage of the mean annual snowfall remaining as snowcover on fetches of stubble greater than 300-m is shown in Fig. 16c. At Yorkton approximately 78 percent of the annual snowfall remains as snowcover, independent of distance; at both Prince Albert and Swift Current the amount of snowcover declines from 70 percent of snowfall with a 300-m fetch to 60 percent on a 4000-m fetch; and at Regina the percentage of snowfall remaining as snowcover increases slightly as the fetch distance increases from 300 to 500 metres, and then declines to 40 percent of annual snowfall at 4000 m.
Figure 16. Mean annual mass flux of snow in saltation/suspension, sublimation and percent of snowfall remaining as snowcover over a stubble surface versus fetch distance at four locations in Saskatchewan.
The disposition of fluxes and snowcover with fetch distance on fallow land is illustrated in Figure 17 (a,b,c). At both Regina and Swift Current the blowing snow flux increases appreciably with fetch for distances between 300 and 1000 m. At Regina the maximum flux occurs at 1000 m, whereas at Swift Current the maximum has not been reached in a distance of 4000 m. The increase in flux between 300 and 1000 m at these two stations is attributed to the combined effects on the transport of snow of the frequency-of-occurrence of high windspeeds and insufficient snow to satisfy fully-developed, steady-state flow conditions. Because the requirements for fully-developed flow in saltation and suspension are given priority by the model, if there is not an adequate supply of snowcover in the first three elements, elements are added to satisfy the requirement. For a 300-m fetch there are no additional elements available for this purpose; for a 500 m fetch there are 2 elements and in a 1000 m fetch there are 7 elements. Thus, the probability of achieving steady-state conditions increases with fetch.

Comparing Figs. 16b and 17b it can be observed that at Regina the sublimation mass flux over a 4000-m surface of fallow is 40 % higher than the flux on stubble and at Yorkton the flux is about 60 % higher. Similarly, Figs. 16c and 17c show a smaller percentage of annual snowfall remaining as snowcover on fallow than on stubble at each of the four stations. The amount that remains at any given location is relatively independent of fetch distance.

Also, the findings in Figs. 16 and 17 show greater amounts of snow transport and sublimation at Regina than at Swift Current. This result was not expected given that Swift Current normally experiences higher windspeeds. For example, during the study period (1970 - 1976) the mean monthly for November through April at Swift Current was 6.86 m/s, while at Regina it was 6.03 m/s. The thirty-year (1951 - 1980) mean windspeeds at Swift Current and Regina are 6.71 and 6.05 m/s, respectively (Atmospheric Environment Service, 1981).

It was anticipated that the difference in transport rates may be explained by differences in the number of occurrences of blowing/drifting events at the two locations. A comparison of the mean annual number of hourly events at Regina (678) and Swift Current (628) showed a difference of 50. In the winters of 1970-71 and 1973-74, the number of transport events at Swift Current was slightly higher than at Regina (2 to 3 percent); for the remaining three seasons
Figure 17. Mean annual mass flux of snow in saltation/suspension, sublimation and percent of snowfall remaining as snowcover over a fallow versus fetch distance at four locations in Saskatchewan.
Regina experienced from 18 to 34 percent more events. The primary reason for the difference in number of blowing snow events at the two locations is that during a winter a snowcover at Swift Current is usually subjected to several thaw events. When melt occurs the model converts the water equivalent of a depth of snowcover "immobile" ice (or liquid water) thereby reducing the quantity of snow available for transport. For accounting purposes the ice/water equivalent is included in the total snowcover water equivalent reported by the model and this has the effect of making it appear as if the snowcover is deeper than it really is. It should also be remembered that the mechanism in the model for melting snow is crude and the calculation of melt may be inaccurate.

In summary, the findings demonstrate:

(1) The effect of fetch distance on wind transport fluxes depends on surface roughness conditions.

(2) The shorter the fetch distance, to a site-specific minimum, the larger the amount of "upwind" snowcover available for management.

(3) The amount of snowfall retained as snowcover depends largely on the regional climate and surface roughness conditions and to a lesser extent on fetch distance.

It is worth noting that typical fetch distances on cultivated land surrounding Regina and Swift Current areas are much longer than those in the Prince Albert and Yorkton areas. Therefore it is likely that sublimation losses due to wind transport may be several times higher in southern regions of the Province than on areas to the North and East.

**EVAPORATION DURING POSTMELT PERIOD**

During "Postmelt", the six-to-nine week period following the disappearance of the seasonal snowcover up to the time of seeding of annual crops, a soil moisture profile can undergo significant changes due to: the withdrawal of water from the surface layer by evaporation, vertical and lateral drainage, and the infiltration of precipitation. An analysis of soil moisture changes monitored during Postmelt at approximately 160 dryland sites in the Brown and Dark Brown...
soil zones of Saskatchewan between 1978 and 1985 revealed that evaporation is the dominant process affecting these changes. All sites (100%) showed evaporation losses during the Postmelt period; whereas at only 54% of the sites was the soil thaw sufficiently rapid to allow measurable amounts of infiltrated meltwater to move deeper into the root zone. In undisturbed and uncracked soils, evaporation losses are significant when compared to the gains from meltwater infiltration and precipitation. For fallow lands the average ratio of snowmelt infiltration (INF) to evaporation (EVAP) was 0.4, and for stubble it was 0.6. Cracked soils and subsoiled, on the other hand, not only allow for significantly greater infiltration, but also allow meltwater to penetrate deep into a soil profile, thus protecting it from being lost to evaporation. The average ratio INF/EVAP for cracked soils was 2.4. In undisturbed soils daily evaporation rates in the first days following the disappearance of snowcover were as high as 9 mm/d from fallow and 7 mm/d from stubble and on average, evaporation losses in the first 7-day and 16-day periods following complete ablation of a snowcover are equal to the average amounts of snowmelt infiltration received by fallow and stubble, respectively.

Any model whose purpose is to estimate the effects of meltwater enhancement procedures on crop yields must have the capability of predicting the available soil water reserve at the time of seeding. Clearly, the system must not only correctly simulate the infiltration process for frozen soils, but must also consider evaporation losses during Postmelt. Several models are available for estimating soil moisture changes during the crop growing season, however the application of these systems to the Postmelt period is limited. For example, the Versatile Soil Moisture Budget (VSMB), which is commonly used to predict soil moisture reserves, treats infiltration to frozen soils in an unrealistic manner. As well, the VSMB calculates evaporation, or rather evapotranspiration, using root extraction relationships; however on farmed land, throughout most of Postmelt there is there is little vegetative growth and evaporation, rather than evapotranspiration, dominates. In addition, most evaporation models in use, including the Complementary Relationship Areal Evapotranspiration (CRAE) model, assume that the soil heat flux and storage terms are negligible. However, during Postmelt when a soil is still frozen, this assumption is not valid. While the soil is thawing, a significant fraction of the available energy (net radiation)
is apportioned to soil heat flux and goes to supplying the energy required for
the solid-to-liquid phase change. In such a situation these models tend to
significantly overestimate the actual evaporation. For example, calculations
made by Dyck and Granger (1979, 1980) showed that the CRAE model overestimated
the actual evaporation on average by an amount of 28 mm in the first 30 days of
the post-melt period.

A model for evaporation losses during "Postmelt" has been developed and
undergone preliminary evaluation and verification tests (Granger and Gray, 1989).
Development of the model follows the procedure Penman used in deriving the
veloping the combination equation for a saturated surface. The general
expression for evaporation from a non-saturated surface is:

\[
E = Q + \frac{\gamma}{\Delta} [f(u)(e^*_a - e_a) - f(u)(e^*_S - e_a)].
\]  

[7]

in which Q is the "net" energy available for evaporation (the sum of net
radiation, ground heat flux and internal energy changes). The first term in the
brackets is the drying power, the second term represents the potential
evaporation, \(E_p\) as accepted by van Bavel (1966), Priestley and Taylor (1972) and
others. The application of the formulation is limited because it requires a a
measurement of the surface temperature, a parameter which is rarely monitored.

Consider the usual situation encountered in the field where evaporation
occurs from a non-saturated surface at a rate less than the potential, that is
\(0 < E < E_p\). The relative evaporation (\(G\)), the ratio of actual to potential
evaporation (\(G = E/E_p\)), that is,

\[
G = \frac{E}{E_p} = \frac{f(u)(e - e_a)}{f(u)(e^*_S - e_a)}.
\]

[8]

should be unique for each set of atmospheric and surface conditions. Equation
[8] shows that G is governed by the vapor deficit at the evaporating surface (\(e^*_S - e_S\)), or the availability of water. For a wet surface, where \(e_S\) approaches \(e^*_S\),
G approaches unity; for a very dry surface, G approaches zero. Substituting,
the equality, \(E = GE_p = Gf(u)(e^*_S - e_a)\) into Eq. [7] and simplifying leads to
the general expression for evaporation from non-saturated surfaces as:

\[
E = \frac{\Delta Q}{(\Delta G + \gamma)} + \frac{\gamma G_{E_a}}{(\Delta G + \gamma)}, \text{ or }
\]

\[
G = \frac{\gamma E}{\Delta Q + \gamma E_a - \Delta E}.
\]

[9]  

[10]  

Priestley and Taylor (1972), Black (1979), Federer (1979) and others have related parameters similar to G to soil water deficits or to available water supply. These relationships have the disadvantages that they are empirical, site specific and neither single-valued nor unique. The practical application of the model (Eq. 9) would be enhanced if G could be related to readily-measured or calculated parameters. These would exclude the surface parameters of vapor pressure and temperature.

Morton (1983) suggests that the effects of changes in availability of soil water on \( E_p \) can be assessed by their effects on temperature and humidity gradients. Since an increase in E causes the vapor pressure of the overlying air to increase, the drying power reflects to some extent the dryness of a surface. Further, the sum of \( E_a \) plus the available energy supply, Q, should index the "potential" for evaporation. Following this logic, it is assumed that G could be related to the relative "drying" power (D), the ratio of \( E_a/E_a + Q \). The relationship is dimensionless and inverse, for a dry surface, \( G = 0 \), \( E_a \) is large and D approaches unity; for a wet surface, \( G = 1 \), and \( E_a \) and D approach zero. A study of the G – D relationship was conducted using atmospheric and soil moisture measurements made at Saskatoon and Bad Lake, Saskatchewan on native grass, wheat and non-cropped (fallow and wheat stubble) land during the spring period of soil thaw and crop growing season. The findings are reported in Fig. 18. They show a trend, which is independent of landuse and soil condition, for G to decrease non-linearly with increasing D. Unfortunately the lack of measurements from wet environments (D < 0.3) do not allow complete description of the relationship over the full range of G. An exponential function fitted to the data, which include measurements for 158 periods varying in length from 2 to 30 days, gave the equation:
Figure 18. Relationship between relative evaporation (G) and relative drying power (D) for stubble, wheat grass and fallow surfaces.
G = \frac{1}{1 + 0.028 e^{0.045D}} \quad [11]

with a standard error of estimate of \( G \) of 0.051. Equation 11 can be used with Eq. 9 to calculate evaporation. Note, the expressions are independent of surface parameters (surface temperature and vapor pressure) and they do not require an estimate of potential evaporation.

**LITERATURE CITED**


