Simulation of soil moisture and other components of the hydrological cycle using a water budget approach

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Akinremi, O. O., McGinn, S. M. and Barr, A. G. 1996. **Simulating soil moisture and other components of the hydrological cycle using a water budget approach**. Can. J. Soil Sci. **75**: 133–142. Accurate simulation of soil moisture content at any time of the year is important to agriculture in dry regions due to the vital role soil moisture plays in crop production. In certain applications, such as drought monitoring, other components of the hydrologic cycle such as runoff, snowmelt runoff, deep drainage and evaporative loss must also be accurately estimated. The goal of this study was to develop a model which accurately accounts for the major components of the hydrological cycle in order to simulate soil moisture content for drought monitoring and crop yield prediction. The **versatile soil moisture budget (VSMB)** was evaluated and modified to improve the prediction of soil moisture content, runoff from rainfall and snowmelt, drainage of moisture out of the root zone and soil surface temperature. The modified components of the model were independently tested and validated using field and published data. The soil moisture output from our modified model correlated well with observed changes in soil moisture during the growing season under wheat, fallow and over the winter. The moisture content of the surface layer was simulated with greater accuracy than that of deeper layers. The soil moisture simulated by the modified model compares better with measured values than that simulated using the original version of the VSMB. The simulation of snow dynamics at Lethbridge, a chinook-dominated region, gave credibility to the snowmelt runoff predicted by the model.

Key words: Soil moisture, modelling, runoff, evapotranspiration, snowmelt, Canadian prairies

Akinremi, O. O., McGinn, S. M. et Barr, A. G. 1996. **Étude en simulation de l'état hydrique du sol et des autres composantes du cycle hydrologique au moyen de la méthode du bilan hydrique**. Can. J. Soil Sci. **75**: 133–142. Il est important pour l'agriculture des régions sèches de pouvoir compter en tout temps de l'année sur une évaluation en simulation de la teneur en eau du sol, en raison du rôle primordial que joue ce facteur pour la production des cultures. Pour certains opérations, comme la surveillance continue du niveau d'aridité du sol, d'autres composantes du cycle de l'eau: ruissellement des eaux de surface, ruissellement de l'eau de fonte, drainage en profondeur et pertes par évaporation, doivent également être évaluées avec exactitude. L'objet et nos travaux étaient la construction d'un modèle qui prenne en compte avec précision les principales composantes du cycle hydrologique, afin de simuler la teneur en eau du sol pour la surveillance continue du niveau d'aridité et pour la prédiction des rendements des cultures. Nous avons modifié le bilan universel de l'eau du sol (BUES) pour améliorer les prédictions de la teneur en eau du sol, de l'écoulement des eaux de pluie et de fonte des neiges, du drainage de la rhizosphère et de la température à la surface du sol. Les composantes modifiées du modèle étaient testées individuellement et validées en regard des données sur le terrain et des données publiées. Les valeurs de teneur en eau du sol obtenues par le modèle modifié produisaient de bonnes corrélations avec les changements observés dans la teneur en eau du sol durant la saison de végétation sous blé ou sous jachère ainsi que durant l'hiver. La teneur en eau de la couche de surface était simulée avec plus d'exactitude que celle des couches profondes. Les valeurs de teneur en eau du sol produites par le modèle modifié correspondaient mieux aux valeurs mesurées que celles générées par la version originale du BUES. La simulation de la dynamique de la neige à Lethbridge, région soumise à des épisodes de chinook, confortait les valeurs prédites d'écoulement de l'eau de fonte obtenues par le modèle.

Mots clés: Eau du sol, modélisation, écoulement des eaux de surface, évapotranspiration, eaux de fonte des neiges, Prairies canadiennes

The seasonal moisture content in the rooting depth of prairie soils is rarely sufficient to meet the evapotranspiration demand, and therefore, limits biomass production and crop yield. In addition to its direct impact on yield, soil moisture affects processes that have a bearing on soil productivity and agricultural sustainability such as runoff, erosion, and leaching of nutrients (Hobbs and Krogman 1971; Campbell et al. 1984; Granger et al. 1984). The amount of spring stored soil moisture also influences producers' decisions to crop or fallow under flex-cropping (Brown et al. 1981). Accurate estimates of soil moisture at various times will be valuable to producers making crop-fallow decisions and groups interested in regional crop forecasts and drought monitoring.

Raddatz et al. (1994) derived a set of equations relating crop moisture use, obtained from a moisture budget, to crop district yield for various crops on the prairies. These authors demonstrated how these equations can be used for real time estimates of average prairie yield. The accuracy of such yield estimates will depend on how accurately soil moisture is accounted for during the growing season.

Many of the previous studies involving the VSMB (Baier et al. 1979) focused solely on testing the accuracy of the model with respect to one component, either soil moisture (De Jong 1988; Boisvert et al. 1992) or snowmelt runoff (Hayhoe et al. 1993). However, accurate simulation of one component should not be achieved at the expense of other model components if the hydrological cycle and the impact of its components is to be understood.

Some deficiencies which limit the use of the VSMB for generating drought indices were encountered during a preliminary evaluation of the model. These deficiencies were addressed by modifying, testing and validating several components of the VSMB. This paper reports the results obtained from the modified model for several components of the hydrological cycle.

METHODS

Model Evaluation

An evaluation of the VSMB model (Baier et al. 1979) was undertaken using measured soil moisture data from various crop rotations at the Semiarid Prairie Agricultural Research Centre, Swift Current, Saskatchewan (latitude 50.3°N, longitude 107.7°W and elevation 883 m) (Campbell et al. 1983). The soil moisture under wheat was measured eight times during the year and twice (spring and fall) for soil in fallow. The soil at Swift Current belongs to the Brown Chernozemic Swinton Loam series. Model simulation was carried out during each of the growing seasons from 1967 to 1978. Each year, the model was initialized with the measured spring soil moisture from the continuous wheat rotation as well as the fallow phase of a fallow-wheat rotation and simulation was terminated on a day corresponding to the fall sampling date.

Model Modifications

Following our initial evaluation, the VSMB model was modified to improve the simulation of **potential evapotranspiration (PE)**, soil moisture content, rainfall runoff, surface soil temperature, snowmelt infiltration and snowmelt runoff.

The original VSMB employs the equation of Baier and Robertson (1965) which uses temperature and latitude to estimate PE. As a result of our access to solar radiation data, the Baier-Robertson equation was replaced with the Priesly-Taylor equation (Priestly and Taylor 1972). In this approach, 1.28 was used for the Priestly-Taylor α value, while net radiation was obtained from observed solar radiation using a regression equation for a grass surface (Linacre 1993). It was assumed that the use of solar radiation to generate PE would produce a better estimate than one based solely on temperature.

For infiltration and moisture redistribution, we used a simple cascade algorithm adapted from the Ceres-Wheat model (Ritchie and Otter 1985). The new algorithm used field capacity to determine flow between zones, and was linked to an empirical subroutine that accounts for upward and downward redistribution of soil moisture by unsaturated flow. Precipitation, less runoff, was applied to the surface layer and the flux of moisture out of this layer became input into the layer below. Similar to the moisture redistribution between adjacent layers, moisture was allowed to move out of the bottom soil layer at moisture contents below field capacity. An empirical constant was defined to specify the fraction of the field capacity above which soil moisture is lost as drainage from the bottom layer. The value of this constant was 0.75, obtained by comparing the deep drainage from our model to that obtained from the mathematically more rigorous LEACHM model (Hutson and Wagenet 1991) using the same input data under fallow. The use of this empirical constant can be bypassed by setting its value to 1.

To simulate rainfall runoff, we employed the **Soil Conservation Service (SCS)** curve number technique (USDA, Soil Conservation Service 1972). The SCS technique relates rainfall runoff to the antecedent moisture in the surface soil layer. This modification required a soil curve number to be included in the input data. The value of 80 was used as the curve number for the soil at Swift Current and Lethbridge.

The section of the original VSMB which differentiated between snowfall and rainfall was considered obsolete and was eliminated since actual measurements of total precipitation and rainfall were available. The **water equivalent of snowfall (SWE)** was obtained as the difference between the daily total precipitation and rainfall.

An accurate determination of freeze-thaw cycles is critical to the estimation of snowmelt runoff. In the original VSMB, the freeze–thaw cycle was demarcated using a daily maximum air temperature of –6.7°C. This was modified by calculating the soil surface temperature directly using an algorithm adapted from the EPIC model (Williams et al. 1990) which considered the insulating effects of snow and residue cover on soil surface temperature. The soil was assumed frozen if the calculated soil surface temperature was below 0°C. This algorithm was tested with the observed soil temperature data from Lethbridge.

We retained the McKay (1964) equation used in the original VSMB for calculating snowmelt, but developed a new approach for calculating snowmelt runoff. Our approach was similar to that of Ash et al. (1992) in which snowmelt runoff was a product of the total snowmelt and the relative soil moisture content in the first layer at freezing:

$$RR = MLT\,(\theta_1/\theta_f) \qquad (1)$$

where RR is the snowmelt runoff, MLT is the snowmelt, θ_1 is the volumetric moisture content of the first layer at freezing and θ_f is its moisture content at field capacity. The advantage of Eq. 1 over the original VSMB is that snowmelt runoff is independent of the depth of the first layer and that the Hobbs and Krogman (1971) overwinter storage constants do not have to be specified. For frozen soil, runoff was calculated using the above approach, otherwise, it was calculated using the SCS curve number technique.

The snowmelt runoff algorithm was tested using the data of Nicholaichuk and Read (1978) collected between 1970 and 1976 on 4–5 ha plots at Swift Current. Because the runoff data were collected from experimental plots adjacent to the crop rotation plots, both soil characteristics and moisture contents corresponding to the runoff measurements were available.

Model Calibration and Validation

The modified model was tested using the same soil moisture data from Swift Current that were used for model evaluation. As a result of the various modifications made to the model, it was necessary to reduce the values of the input variable, *K*, a set of crop coefficients which is unique for each crop growth stage and soil layer during the testing stage. The original VSMB was run using drying curves *G* and *D* (Baier et al. 1979) for cropped and fallowed soils, respectively, while the modified VSMB used curves *E* and *D* for cropped and fallowed soils. The model was calibrated using soil moisture data in 1974 and 1977, wet years, and 1983, a dry year outside the 12-yr study period.

The modified model was validated using independent soil moisture data measured at Lethbridge under continuous wheat and the fallow phase of a fallow-wheat rotation (1977–1986). This second source of soil moisture data was obtained at the Research Centre, Lethbridge, Alberta (latitude 49.7°N longitude 112.8°W and elevation 899 m) from a crop rotation experiment initiated in 1911 (Dormaar 1983). The soil at Lethbridge is a Dark Brown Chernozemic Clay Loam, Lethbridge series. Soil characteristics and long-term soil moisture status were described by Chang et al. (1990). The soil moisture content was determined twice during the growing season, before seeding and after harvest. The phenological growth stages of wheat at Lethbridge (required by the VSMB) were estimated using the biometeorological time scale model of Robertson (1968).

Snow Dynamics and Over-winter Moisture Recharge

As the VSMB was designed for multi-year simulation, it was necessary to verify the snow dynamics and over-winter moisture recharge components of the modified model. The original and modified version of the model were initialized with observed fall soil moisture from Swift Current and Lethbridge for each of 6 yr (1970–1975). The simulated and observed soil moisture contents in the following spring were then compared at the two sites.

RESULTS AND DISCUSSION

Model Deficiencies

The measured fall soil moisture contents under fallow and those simulated using the original and modified VSMB are shown in Table 1. The original model did not simulate runoff or drainage during any of the 12 yr. The absence of simulated runoff at Swift Current was not considered to be a problem during most years because of the arid nature of this region. However, rainfall runoff has been previously reported from a watershed at Swift Current (Nicholaichuk 1967). The lack of drainage, even under fallow, during the 12 yr may be unrealistic as results from Campbell et al. (1984) showed that a significant amount of nitrate-nitrogen may be leached from the rooting zone in a wet year at the same experimental site.

The original VSMB model did not account for changes in soil moisture below 0.9-m depth even in a wet year like 1970 (Fig. 1). The absence of a mechanism to account for the redistribution of moisture below field capacity in the original VSMB may be responsible for the failure to account for soil moisture changes below 0.9 m. This could also explain the lack of drainage from the original VSMB. The model overestimated soil moisture in the top 0.6 m under wheat while the moisture in the 0.9–1.2 m depth was underestimated.

The total amounts of moisture within the rooting zone of soil under fallow were compared for the two models using regression analysis. The intercepts of the regression equations were not statistically different from zero and the slopes were not statistically different from 1 for the two models. The two models underestimated the fall soil moisture, however, the modified model was better than the original VSMB (R^2 of 0.82 vs. 0.75) in simulating the changes in soil moisture under fallow at Swift Current.

A comparison of the simulated evaporation shows that the values simulated by the modified model were lower than those simulated by the original VSMB (even in those years when both models predicted no runoff and no drainage). A possible reason for this is that the PE obtained using the Priestly-Taylor equation were lower than those estimated with the original VSMB (Table 1). De Jong and Tugwood (1987) obtained mean PE of 590 and 687 mm with the Priestly-Taylor and Baier-Robertson I equations, respectively, at Swift current for 1 May to 30 September periods. These are similar to the values shown in Table 1, which is expected since the same equations were utilized in both studies. Another possible reason for higher evaporation by the original VSMB is the tendency of the model to overestimate the soil moisture in the surface 0.6 m (Fig. 1). As evaporation is related to the relative soil moisture content of the surface layer under fallow, a wetter than expected surface layer will increase the amount of evaporation.

Model Testing and Validation

The crop coefficients that produced the best agreement between simulated and observed soil moisture during the testing stage (Table 2) are lower than those used in the evaluation of the original VSMB. In simulating the soil moisture regime under natural grassland, De Jong and MacDonald (1975) reported that it was necessary to vary the crop coefficients as the growing season progressed and obtained crop coefficients that were lower than those recommended for sod. The smaller crop coefficients obtained in this study could have resulted from the change of the equation for calculating PE, and/or the modification made to account for infiltration and moisture redistribution.

Moisture Content Under Wheat at Swift Current

The simulation at Swift Current cannot be considered a truly independent test, because soil moisture data for 2 of the 12 yr were used to calibrate the modified model. The results, however, demonstrate the performance of the modified model at various phenological stages during the growing season and form a baseline with which to compare the results obtained with an independent data set from Lethbridge. Figures 2 and 3 show the results obtained, by soil layer, at five crop stages during the 12 yr of simulation at Swift Current using the original and modified VSMB.

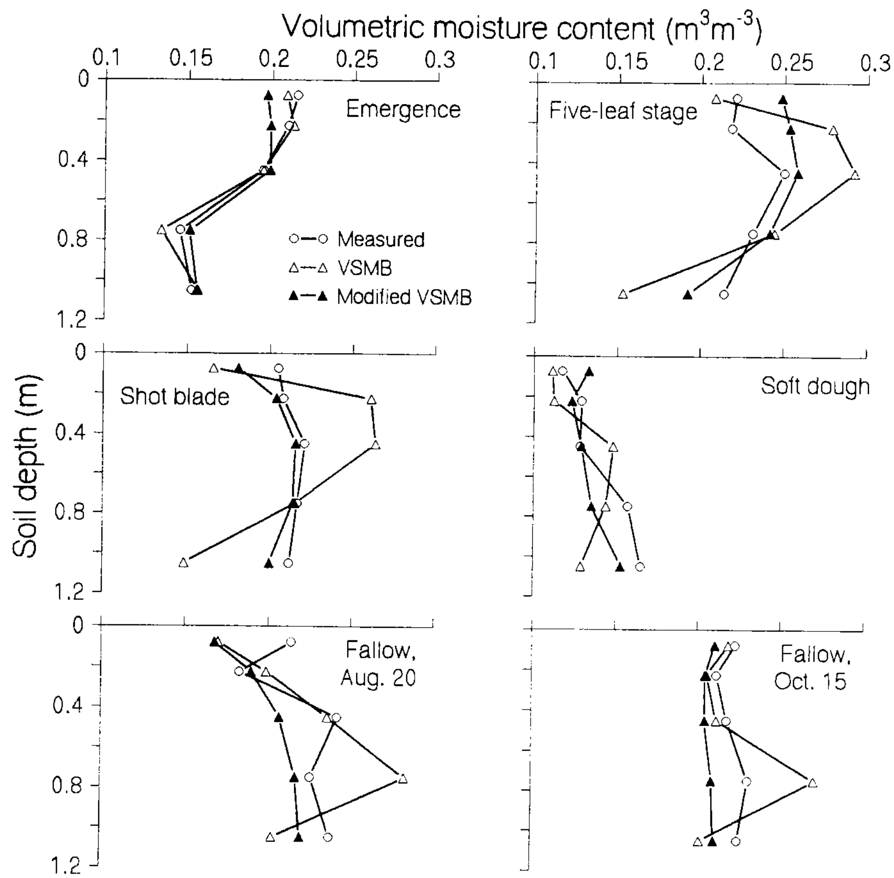

Fig. 1. Changes in soil moisture content in a wet year (1970) at Swift Current as simulated by the original and the modified VSMB.

Table 1. Components of the moisture balance to 1.2 m depth under fallow as measured and simulated by (a) original VSMB and (b) modified VSMB for Swift Current

Year	Precipitation measured	Spring moisture measured	Fall moisture measured	Fall moisture simulated	PE simulated	Evaporation simulated	Runoff simulated	Drainage simulated
				(mm)				
(a)								
1967	127	302	274	266	614	163	0	0
1968	176	189	220	205	635	161	0	0
1969	187	187	246	197	665	174	0	0
1970	280	223	266	269	652	235	0	0
1971	140	197	204	178	697	157	0	0
1972	164	192	213	193	597	164	0	0
1973	93	241	223	200	662	135	0	0
1974	269	245	267	272	600	226	0	0
1975	237	257	281	245	601	248	0	0
1976	234	221	241	229	639	226	0	0
1977	245	178	238	191	670	233	0	0
1978	192	227	236	215	651	207	0	0
(b)								
1967	–	–	–	262	528	157	2	8
1968	–	–	–	239	560	126	0	0
1969	–	–	–	230	585	144	0	0
1970	–	–	–	250	542	214	28	12
1971	–	–	–	195	581	143	0	0
1972	–	–	–	203	559	153	0	0
1973	–	–	–	200	593	135	0	0
1974	–	–	–	258	557	225	9	22
1975	–	–	–	280	535	212	0	2
1976	–	–	–	235	618	217	1	1
1977	–	–	–	219	584	203	1	0
1978	–	–	–	238	567	180	1	0

Table 2. The input parameters for the VSMB at Swift Current and Lethbridge

	Depth (m)				
Swift Current	0–0.15	0.15–0.3	0.3–0.6	0.6–0.9	0.9–1.2
	Moisture content (m^3 m^{-3})				
Saturation	0.55	0.55	0.51	0.45	0.45
Field capacity	0.30	0.31	0.31	0.30	0.30
Permanent wilting point	0.1	0.1	0.1	0.1	0.1
	Crop coefficients (dimensionless)				
Planting to emergence	0.40	0.10	0.05	0.01	0.01
Emergence to jointing	0.40	0.15	0.10	0.02	0.01
Jointing to heading	0.55	0.20	0.20	0.10	0.05
Heading to soft dough	0.55	0.25	0.25	0.15	0.05
Soft dough to ripening	0.55	0.25	0.25	0.15	0.05

	Depth (m)			
Lethbridge	0–0.3	0.3–0.6	0.6–0.9	0.9–1.2
	Moisture content (m^3 m^{-3})			
Saturation	0.50	0.47	0.47	0.47
Field capacity	0.31	0.33	0.38	0.38
Permanent wilting point	0.1	0.1	0.15	0.15
	Crop coefficients (dimensionless)			
Planting to emergence	0.50	0.05	0.01	0.01
Emergence to jointing	0.55	0.10	0.02	0.01
Jointing to heading	0.75	0.20	0.10	0.05
Heading to soft dough	0.80	0.25	0.15	0.05
Soft dough to ripening	0.80	0.25	0.15	0.05

The surface layer of the soil (0–0.15 m) was the most responsive layer to moisture inputs and outputs, showing a wide range in moisture contents as a result of precipitation events and daily evapotranspiration. It was also one of the layers that was best simulated by the modified model. The original model overestimated the moisture in this top layer while the soil moisture in the two lower layers were generally underestimated.

The range of soil moisture contents declined with depth and there was a general decrease in the coefficient of determination (R^2) between the simulated and the observed moisture contents. The exception was the 0.3–0.6 m layer where the R^2 was higher than that of the top layer (0.77 vs. 0.73). The variation in moisture content in the 0.9–1.2 m layer was less than that in the upper soil layers; the original VSMB simulated the soil moisture content in this lower layer poorly with an R^2 of 0.38. The poor simulation of soil moisture content in this layer by the original VSMB could be a result of the model's failure to transmit moisture to this layer during the growing season (Figs. 1 and 3). When all five soil layers were combined (Fig. 3), R^2 for the modified VSMB was higher than that obtained from the original model (0.69 vs. 0.60).

Moisture Content Under Wheat at Lethbridge

Differences between simulated and measured soil moisture contents from the 10-yr simulation (1977–1986) for contin-

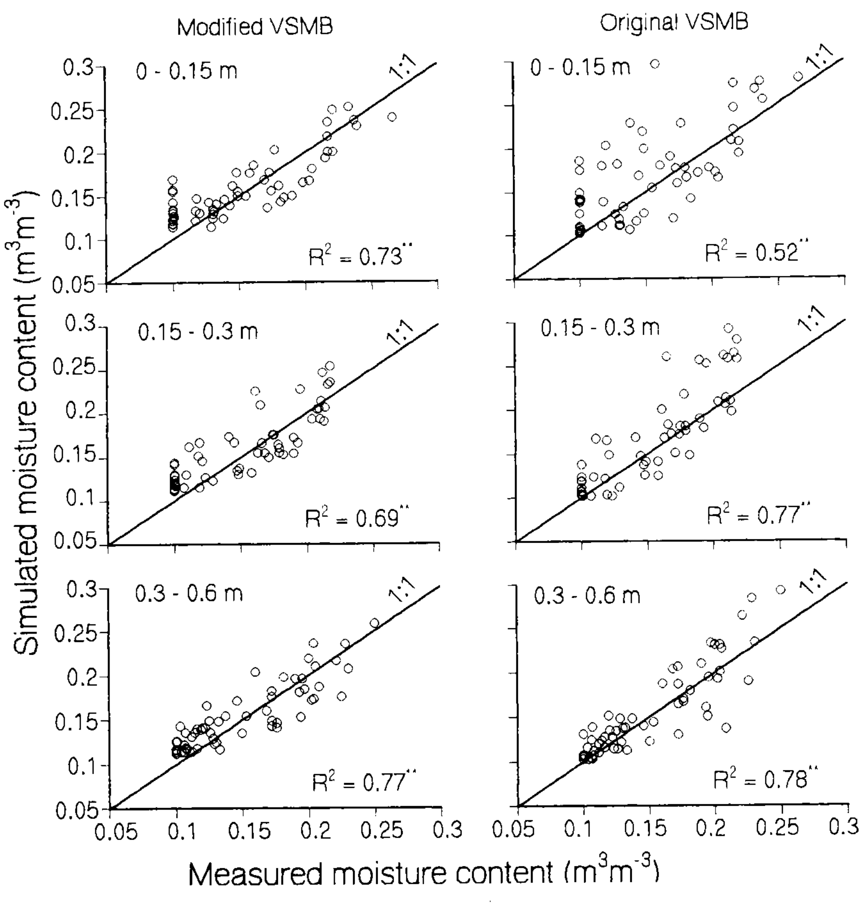

Fig. 2. Simulated and measured moisture content in the 0–0.6 m depth under wheat over five crop stages at Swift Current (1967– 1978) using the original and modified VSMB.

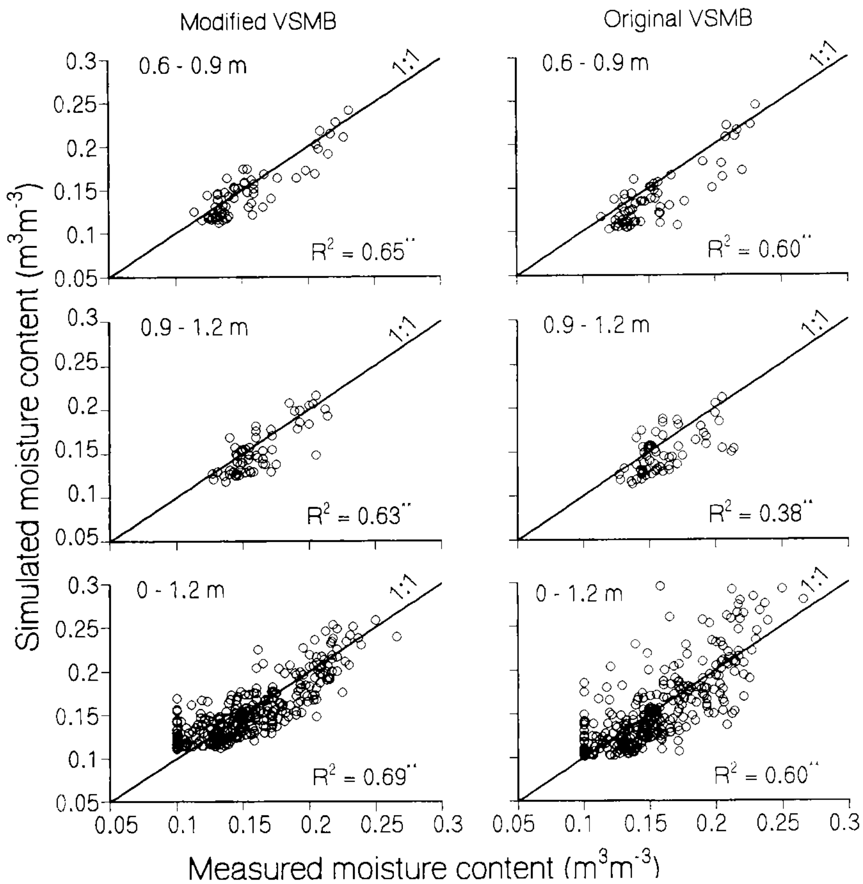

Fig. 3. Simulated and measured moisture content in the 0.6–1.2 m depth under wheat over five crop stages at Swift Current (1967– 1978) using the original and modified VSMB.

uous wheat at Lethbridge (Fig. 4) were similar to those for the 12-yr simulation at Swift Current (Figs. 2 and 3). The moisture content of the surface 0.3 m was well simulated with R^2 of 0.97. The model's accuracy declined with depth such that at the 0.9–1.2 cm depth the model did not account for variations in observed moisture ($R^2 = 0$). The fall moisture content in the 0.9–1.2 m depth changed very little between years, suggesting that it may be under the influence of a water table. The water table at Lethbridge varies between 2 and 5 m and rises as high as 1 m in wet years (G. J. Beke, Agriculture and Agri-Food Canada, Lethbridge, AB, personal communication). This was not a problem at Swift Current where the water table ranges from 10 to 15 m (H. H. Stepphun, Agriculture and Agri-Food Canada, Swift Current, SK, personal communication). When moisture levels predicted at Lethbridge for the 0-1.2 m layers were combined, the simulation of soil moisture content by the modified VSMB had a coefficient of determination of 0.67, considerably larger than a value of 0.49 for the original VSMB (Fig. 4).

Deep Drainage of Soil Moisture

No drainage of moisture below the rooting zone was simulated by either the modified or the original VSMB for soils cropped to wheat during the 12 growing seasons at Swift Current. The low annual precipitation, and the ability of wheat to use available soil moisture within the rooting zone probably accounts for the negligible amount of leaching. Under fallow, deep drainage was simulated by the modified VSMB at Swift Current in 5 of the 12 yr (Table 3), with appreciable amounts in wet years (1970 and 1974).

At Lethbridge, deep drainage was simulated in 3 of the 10 growing seasons under wheat and in 5 yr out of 10, under fallow. The amount of leaching simulated by the modified model was significant in several years at Lethbridge, however, there are no published data with which to compare the simulated values.

Snow Dynamics and Over-winter Moisture Recharge

During six winters (1970–1976), the modified model underestimated average spring soil moisture content by 10% (6% by original VSMB) at Swift Current and 5% (8% by original VSMB) at Lethbridge (Table 4). The simulated gain in moisture over winter ranged from 9 mm (3 mm observed) in the winter of 1975/1976 to 72 mm (125 mm observed) in the 1972/1973 winter at Swift Current. The moisture gains at Lethbridge were within a similar range except for the 1974/1975 winter when 102 mm was simulated (125 mm observed), reflecting higher precipitation. Soil moisture in the spring was underestimated mainly in the upper 0.3 m. It is unlikely that this underestimation is due to model over-

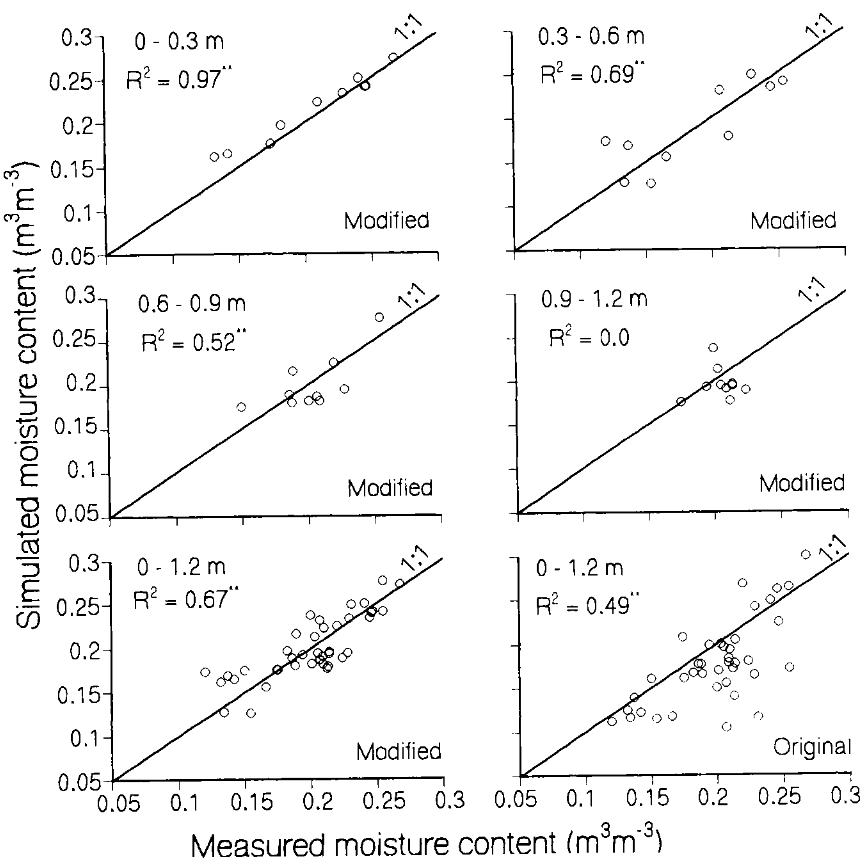

Fig. 4. The simulated and measured fall soil moisture content under wheat at Lethbridge (1977–1986).

Table 3. The deep drainage (from spring to fall) of moisture below the rooting depth as simulated by the modified VSMB at Swift Current and Lethbridge

Year	Total precipitation	Drainage from fallow	Drainage from wheat
	(mm)		
Swift Current			
1967	127	8	–
1970	280	12	–
1974	269	22	–
1975	237	2	–
1976	234	1	–
Lethbridge			
1978	453	90	–
1980	273	34	6
1981	256	64	20
1983	148	5	–
1985	246	14	5

estimation of evaporation and/or snowmelt runoff. The mean potential snow evaporative loss for the months of December to March ranges from 72 mm at Calgary to 116 mm at Lethbridge (Louie 1977). Simulated mean evaporation at Lethbridge, from fall to spring (Table 4), was 48 mm, which is less than one-half the values reported by Louie (1977). On the other hand, simulated snowmelt runoff at Swift Current was lower than measured amounts from adjacent plots in 3 of the 6 yr measured (Fig. 5). Therefore, factors other than the overestimation of winter evaporation or snowmelt runoff were responsible for the model's tendency to underestimate the spring soil moisture. It is suspected that in some years, the snow blow-off coefficient of 0.7 (30% snow loss) underestimates snow accumulation and consequently spring soil moisture. De Jong and MacDonald (1975), who based their assumption that no snow was lost from native prairie on the results of Ripley (1973), used a snow blow-off coefficient of 1. The 30% blow-off loss we assumed may have been too high in some years (e.g winters that are less windy than normal). Since supporting data are sparse, no attempt was made to adjust the snow blow-off coefficient in this study but further investigation is warranted.

The simulated accumulation of snow, expressed as the SWE was compared to the measured depths of snow-on-ground (Fig. 6). The SWE is not identical to snow depth since changes in snow density with time and snow ripening are not accounted for by the modified model. However, the modelled SWE followed the pattern of observed snow accumulation and disappearance during the winter. The McKay (1964) equation as used in the original snowmelt algorithm of Baier et al. (1979) appears to have simulated the timing and magnitude of snowmelt accurately. The modified model also simulated the disappearance of snow during multiple chinook events at Lethbridge (Fig. 6).

Soil Temperature and Snowmelt Runoff

The modified model simulated soil surface temperatures at Lethbridge accurately (R^2 = 0.79) especially for tempera-

Table 4. The simulated and measured (obs) components of the hydrological cycle (mm) during winter seasons using the original and modified VSMB

Year	Fall moisture obs	Spring moisture obs	Simulated spring moisture modified	Simulated spring moisture original	Total precipitation obs	Simulated evaporation modified	Simulated evaporation original
Swift Current							
70/71	183	214	205	221	110	38	31
71/72	139	185	160	162	83	23	20
72/73	149	274	221	243	171	54	50
73/74	136	238	197	202	191	41	28
74/75	183	235	224	230	144	46	26
75/76	191	194	199	204	118	43	31
Mean	163	223	201	210	136	41	31
Lethbridge							
70/71	187	226	211	198	146	51	51
71/72	182	254	230	223	195	55	48
72/73	190	207	204	202	77	32	39
73/74	183	267	258	258	188	46	47
74/75	187	314	289	279	241	60	47
75/76	190	225	224	218	125	41	45
Mean	187	249	236	230	162	48	46

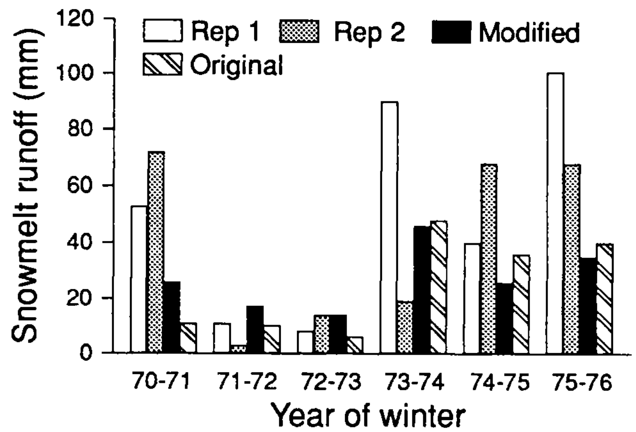

Fig. 5. Simulated and measured snowmelt runoff from stubble plots at Swift Current using the original and modified VSMB.

tures above 0°C (Fig. 7). For temperatures below 0°C, the model underestimated the soil temperature, perhaps as a result of not taking into consideration heat transfer from lower soil layers. As temperatures around 0°C have the greatest effect on freeze-thaw cycles, the model was considered sufficiently accurate to predict freezing and thawing.

The snowmelt runoff simulated by the original and modified VSMB was compared with measurements by Nicholaichuk and Read (1978) (Fig. 5). Runoff was underestimated in 3 of the 6 yr and within the range of observed values in the remaining winters. As a result of large experimental error associated with runoff measurements (Fig. 5), the discrepancies between simulated and observed values may not be solely due to the model. For example, during the 1970/1971 winter, total accumulated snow was 59 mm, which is lower than the mean measured snowmelt runoff of 60 mm (Fig. 5). As some portion of the snow was lost by ablation and sublimation and some infiltrated the soil (see

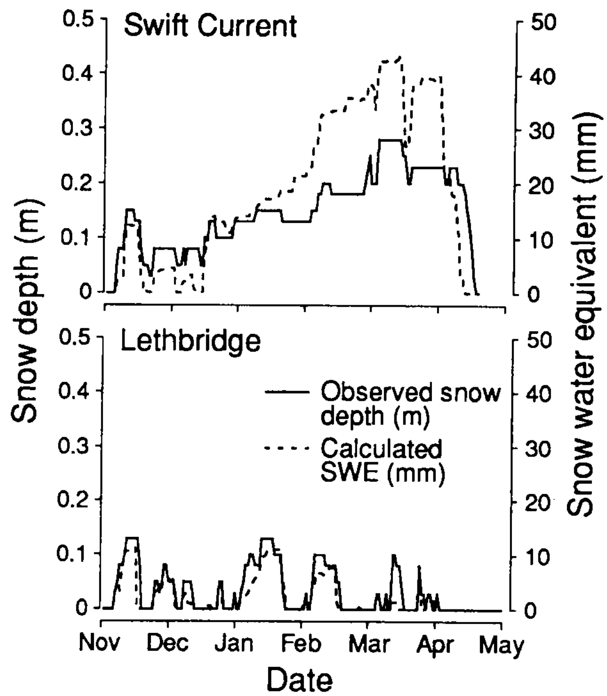

Fig. 6. Changes in snow accumulation during the 1973-74 winter at a) Swift Current, and b) Lethbridge.

fall versus spring measured soil moisture, Table 4), the simulated runoff of 26 mm appeared reasonable.

There was little difference between the runoff amounts simulated by the modified and the original VSMB except in the 1970/1971 winter when the original VSMB simulated a runoff of 11 mm compared to 26 mm (60 mm observed) by the modified model. The discrepancies in Figure 5 probably indicate spatial variability of snowfall, errors associated with snowmelt runoff measurement and the unrealistic use of a constant snow blow-off coefficient.

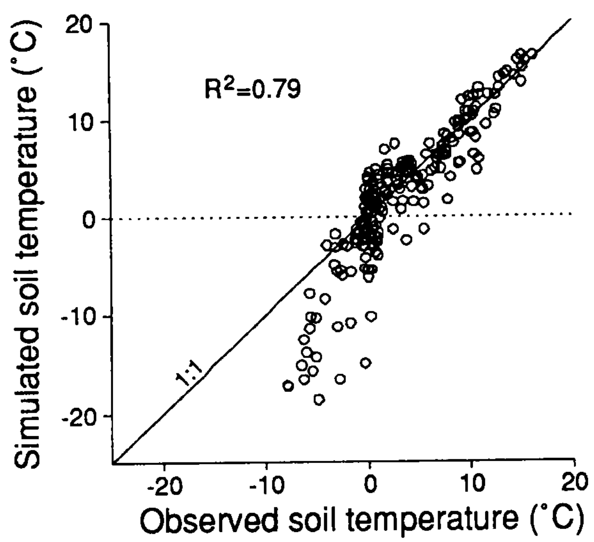

Fig. 7. Temperature simulated at soil surface and observed at 5 cm depth during the 1989/90 winter at Lethbridge.

SUMMARY

There was a need to modify the original VSMB to realistically simulate higher soil moisture contents at lower depths (0.6–1.2 m) under wheat and fallow. The VSMB model was modified to improve the simulation of potential evapotranspiration, soil moisture content, soil surface temperature, snowmelt infiltration and snowmelt runoff. The crop coefficients obtained by a 3-yr calibration were smaller than those previously recommended as input to the original model. The modified model reflected the changes occurring during the growing season under a wheat crop as well as under fallow. The moisture content in the surface layer was simulated with greater accuracy than at lower depths. The soil moisture contents simulated by the modified model compare better with measured values than those simulated using the original version. The simulation of snow dynamics at Lethbridge, a chinook-dominated region, provided a test of the snow subroutine and gave credibility to the snowmelt runoff predicted by the model.

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