Success of SPAW and WEPP in simulating accumulation and melt of snow

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1. Abstract

Lack of a method to properly account for snowmelt runoff and erosion in the Revised Universal Soil Loss Equation Version 2 (RUSLE2) hampers use of the model in areas where there is a period of melting of snow accumulated during the winter. Because RUSLE2 relies on input data sets to drive the erosion process, we sought models that could effectively estimate snow accumulation and melt and provide data from which snowmelt erosivity databases could be developed. The Soil-Plant-Air-Water (SPAW) and Water Erosion Prediction Project (WEPP) models were tested for ability to model snow accumulation and melt events from daily weather data collected from 12 selected weather stations in cold or high elevation cropland areas of the western US, the northern Great Plains, the upper Midwest and the north-eastern US.

Default SPAW snow accumulation and melt is based on average daily air temperature, with accumulation occurring at 0 and melt at 0.5 ^{0}C, respectively. Adjusting the default temperatures in SPAW allows for a much better match to the observed data. Snow accumulation is based on five-day running average temperatures, which tends to capture larger snow accumulation events while missing smaller ones. The WEPP winter routine assumes accumulation occurs when temperatures are 0 ^{0}C or below, and melt occurs when maximum temperatures are above -2.8 ^{0}C and other conditions are met. WEPP is responsive to climate data and therefore captures small snow events well and over predicts short duration events. WEPP also tends to break greater snow accumulation events into smaller ones due to considering melt at relatively low temperature as well as sublimation losses. The performance of both SPAW and WEPP is related to the total precipitation and ET of the stations simulated. Results of the tests did not favor either model. Each excelled and fared poorly under certain conditions.

2. Introduction

Winter hydrologic events are a dominant cause of erosion in some areas of the world and particularly in the northern United States and Canada. In some areas where mean winter temperatures are slightly less than 0 °C (32 °F), such as cropland in the higher precipitation zones of NE Oregon, SE Washington, and N Idaho, multiple snow melt and rain events normally occur each winter. In areas with colder temperatures, such as higher elevation cropland, snow accumulates through the winter and melts during a spring melt period.

Winter erosion in the Universal Soil Loss Equation (USLE) is estimated either by 1) using the EI of the winter precipitation, including snow, and increasing the K factor substantially to reflect the reduced strength of thawing soil and offset the low calculated erosivity of falling snow, or by 2) using an empirical relationship for an equivalent R value developed from erosion data collected in freeze/thaw dominated areas of the Pacific Northwest with assumption of a constant K factor. Neither approach is universally applicable to all areas where winter hydrology is important in generating runoff and erosion. The equivalent R factor approach is used in The Revised Universal Soil Loss Equation Version 2 (RUSLE2). However, more process-based techniques are needed for RUSLE2 to adequately estimate snow melt erosion on cropland across the western states as well as other areas of the US with significant winter hydrologic effects. To more accurately estimate winter runoff and erosion requires snow accumulation, time of melt, condition of soil at melt (frozen, thawing, or unfrozen), erodibility as a function of water content, and other factors. An important part of meeting this need is to adapt or develop models or techniques to estimate snow accumulation and melt. The objective of this study was to test selected available models for their ability to model snow accumulation and melt events. The models selected were the Soil-Plant-Air-Water (SPAW) and Water Erosion Prediction Project (WEPP) models. While both of these models also estimate soil freeze and thaw, this study did not include these factors. Data is readily available to test estimates of snow accumulation and melt, whereas there is little data to test soil freeze and thaw models. Tests were conducted with data from 12 weather stations, listed in Table 1. These were selected for their wide distribution, range in winter climate, availability of snow on ground data, and availability of WEPP data files.

3. Methods

SPAW The SPAW model simulates the daily hydrologic water budgets of agricultural landscapes by two connected routines, one for farm fields and a second for impoundments such as wetland ponds (Saxton and Willey, 2004). Field hydrology is represented by: 1) daily climatic descriptions of rainfall, temperature, and evaporation; 2) a soil profile of interacting layers each with unique water holding characteristics (Saxton and

Rawls, 2005); and 3) annual crop growth with management options for rotations, irrigation, and fertilization. The simulation estimates a daily vertical, one-dimensional water budget depth of all major hydrologic processes such as runoff, infiltration, evapotranspiration, soil water profiles, and percolation (Saxton and Willey, 2005). To provide realistic, year-around hydrologic representations of agricultural fields, a routine is included which accounts for snow accumulation, snow melt, and soil freezing. Default snow accumulation is assumed to occur any day in which the average daily air temperature is 0 °C (32 °F) or less and precipitation is recorded. Snow density is assumed as a constant of 0.10 g/cm^3, thus snow water equivalent is readily estimated from snow depths. A running average of snow water and snow depths is computed with no losses assumed. Snow melt is a function of daily maximum air temperature (Saxton, 2005). Cold weather constants for snow melt and soil freezing simulation routines can be adjusted, if necessary, to more appropriately represent snow depths and soil freezing patterns. Temperatures associated with the initiation of snow accumulation and melt are also adjustable. Increasing the snow melt rate factor (0.00 - 5.00, default 4.00 in metric units) will increase the melt rate but does not change the accumulated depths which are estimated from air temperature and precipitation data (Saxton, 2005). Melt caused by rainfall on snow is not considered by the model.

Field input data are in three general categories of climate, soils, and crops. The climate data are those from a climatic database and regional estimates. Soils data are interpretations from soil profile descriptions of those typical of the simulated field. Crop data are annual descriptions of locally observed crop growth parameters (Saxton and Willey, 2005). The specific field input data used in subsequent SPAW simulations for this study were: 1) a location climate data input consisting of the modified climate data record and a default evaporation file provided with the SPAW model; 2) a silty loam soil data input provided with the SPAW model; and 3) a pasture of warm season grass as the crop data input with no irrigation or fertilizer application, also provided with the SPAW model. Several simulations were run in SPAW for each of the 12 weather stations, each time changing the snow accumulation and melt temperatures or snow melt rate factor. For each simulation, a daily hydrological budget output file was created and graphical outputs generated. All simulations were run over a 41-year period, from January 1, 1960 to December 31, 2000. This time period was chosen based on completeness of the observed snow depth records in the historical climate data for each weather station.

WEPP (version 2004.7) The WEPP model is a continuous simulation computer program which predicts soil loss and sediment deposition from overland flow on hillslopes, soil loss and sediment deposition from concentrated flow in small channels, and sediment deposition in impoundments. WEPP includes components for weather generation, frozen soils, snow accumulation and melt, irrigation, infiltration, overland flow hydraulics, water balance, plant growth, residue decomposition, soil disturbance by tillage, consolidation, erosion, and deposition. The winter processes that WEPP simulates are frost and thaw development in the soil, snow accumulation, and snow melt. In order to make more accurate predictions, the average daily values for temperature, solar radiation, and precipitation are used to generate hourly temperature, radiation, and snowfall values. The snow accumulation subcomponent estimates the depth of the snow on the ground on a daily or hourly basis. Snowfall increases the snow pack, while warming temperatures and rainfall consolidate (increase the density of) the snow pack. The snow melt equation incorporates four major energy components of the snow melt process: air temperature, solar radiation, vapor transfer, and precipitation. The following assumptions are made for snow melt calculations: 1) any precipitation that occurs on a day when the maximum daily temperature is below 0 °C (32 °F) is assumed to be snowfall; 2) no snow melt occurs if the maximum daily temperature is below -2.8 °C (27 °F); 3) the snow pack does not melt until the density of the snow is greater than 0.35 g/cm^3; 4) the surface soil temperature is 0 °C (32 °F) during the melt period; and 5) the albedo of melting snow is approximately 0.5 (Flanagan and Nearing, 1995).

Four separate data inputs are required to run simulations in WEPP. Like SPAW, three of the inputs are climate, soil, and crop management files. The fourth input is a slope file that describes slope along the hill segment. The modified climate data were converted from daily values to hourly values using the WEPP weather generator CLIGEN. Missing components needed for running the winter simulations were also generated by CLIGEN in this step. The specific input data used in subsequent WEPP simulations for this study are as follows: 1) the location climate data input consisting of hourly data; 2) a short grass silt loam soil data input provided with the WEPP model; 3) a short grass prairie as the crop management data input, also provided with the WEPP model; and 4) the default slope file consisting of three slopes—two, nine, and three percent over a length of 125 feet. A simulation was run in WEPP for each of the 12 weather stations. Water and winter output files were created for each simulation. All simulations were run over a 41-year period, from January 1, 1960 to December 31, 2000.

4. Results

4.1 Results evaluation It was found difficult to evaluate a modeling scenario by looking at the model fit visually because 41 years of model runs include several thousands of days with snow on ground and thousands of snow fall days. We developed a series of parameters to evaluate the results, which include: (1) number of days models predict snow-on-ground versus observation (%); (2) correctly predicted snow-on-ground days (%)

(models predict snow on ground when there was observed snow); (3) days models exaggerated (%) (predicted snow-on-ground when none was observed); (4) days models missed (%) (predicted no snow-on-ground when snow was observed); and (5) total predicted events vs. observed events (%). A few other parameters can be used to evaluate model performance: (6) over prediction days (%) (days with predicted snow-on-ground are more than observation), (7) under prediction days (%)(days with predicted snow-on-ground are less than observation). (6) and (7) can be used for WEPP but may not be meaningful for SPAW because WEPP considers snow compaction and consolidation and thus snow density changes over time, whereas SPAW treats all new and old accumulated snow as constant density with a value of 0.1 g/cm^3. For the same reason, minimum square index was found not to be a good index for SPAW. (8) Snow water equivalent (SWE) would be a good indicator to compare how much snow water predicted in snow-on-ground if there were observed snow density data available yet such is not the case for historical climate data. To evaluate the overall performance of a model, the prediction should have highest number of days on which snow is predicted correctly, lowest number of days missed or exaggerated, and predicted snow depth as close as to 100% (for WEPP). Over and under predicted days should be low and relatively balanced.

4.2 Results of SPAW As previously discussed, we ran 5 scenarios of SPAW for each station. Results evaluated by the parameters suggested in section 3.1 indicate that the best scenario of each station was the scenario with a snow accumulation (daily average) temperature of 32 ^{0}F and snow melting temperature (daily maximum) of 37 ^{0} F, which gives highest correctly predicted snow-on-ground days and least exaggerated and missed days. Correctly predicted snow-on-ground days were 70% to 93% of the observation for all stations except for Mesa Verde, CO. (Table 1). The total predicted events were 44 to 89% of the observation. Inspecting the snow accumulation events of the model prediction indicated that SPAW missed many small events and only predicted longer period events (e.g., >5day snow-on-ground events) correctly. This is because the SPAW winter routine that computes snow contains a “cold phenomena code” which does not allow for snow accumulation if the five-day running average soil temperature for a given day (also based on air temperatures) is above 0 ^{0}C (32 ^{0}F). The hypothesis being that snow on warm soil will not accumulate (Saxton, 2005). For this reason, SPAW in fact only targets snow accumulations that last more than five days; any events shorter than 5 days may have been missed. Therefore, SPAW predicts >5-day events fairly close to the observation (Table 2), whereas SPAW missed most of the shorter events. However, it should be noted that historical snow-on-ground data were observed daily; a snow on ground may be observed at the same day the snow fall occurred, or it may be observed at the second day if it is an overnight event and is observed during both days. Therefore, the 1-2 days events predicted by SPAW were only 2 to 52% of the observation (Table 2).

The prediction of SPAW was greatly related to ET and annual average temperature. The higher the annual average Tmax, and the higher the ET, the less satisfactory the prediction. Clearly, the correctly predicted days has strong negative correlation with ET. ET on the other hand is related to Tmax and Tmin. As discussed previously, only melted snow is considered as snow loss and accounted in snow depth prediction. SPAW only considers melt in calculating loss of snow and does not consider snow loss with sublimation. Therefore, a better snow mass balance algorithm in SPAW is needed.

4.3 Results of WEPP WEPP correctly predicted snow-on-ground days were 51% to 89% of the observation for all stations except for Mesa Verde, CO. (Table 1). The overall correctly predicted snow days, missed days, and exaggerated days have no difference from SPAW although WEPP employed a much more sophisticated, process based model. Because WEPP is process based, any precipitation assumed to occur as snow according to air temperature, will be recorded, no matter how short it stayed on ground. As a result, WEPP predicted 1.5 to 3.4 times more 1-2 day events than observation; accordingly, total predicted events were 124% to 209% with an average of 178 % of the observation (Table 1, Table 2). WEPP also over predicted >5 day snow accumulation events (94% to 172%) (Table 2) yet under predicted long snow-on-ground events (e.g., events longer than 30 days). This may be because WEPP assumes no snow melt occurs if the maximum temperature is below -2.8 ^{0}C (27 ^{0}F), in other words, any maximum temperature higher than 27 ^{0}F will cause snow melt, which is 10 ^{0}F lower than the snow melting temperature of the best SPAW scenario. Therefore, more snow is lost through melt and sublimation and thus long accumulation events were broken into small ones. That is also the reason for WEPP to predict less SWE in snow pack than SPAW. The WEPP prediction is also closely related to precipitation, ET and annual average temperature. The higher the annual average Tmax, and the higher the ET, the less satisfactory the prediction. Clearly, the correctly predicted days has strong negative correlation with ET.

5. References

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Table 1 Summary of WEPP and SPAW Predictions of Snow Days vs. Observation (%)

Station	SPAW					WEPP				
	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
Bethany, MO	103	76	24	27	68	113	78	22	36	158
Lawrenceville, NY	103	89	11	14	47	106	89	11	17	124
Morris, MN	107	93	7	14	54	94	85	15	9	161
Monticello, UT	85	77	23	8	59	61	51	49	10	209
Jackson, MI	109	85	15	24	58	111	83	17	28	144
Hayden, CO	91	86	14	5	44	73	66	34	7	234
Mesa Verde, CO	49	47	53	2	54	46	41	59	5	174
Sioux Falls, SD	114	92	8	22	69	102	82	18	20	175
McHenry, ND	80	70	30	10	48	91	84	16	7	196
Savage, MT	90	83	17	8	89	80	70	30	10	191
Moscow, ID	93	79	21	14	53	105	72	28	33	190
Lafayette, IN	128	84	16	44	66	135	84	16	51	176

(1) Total predicted versus observed snow-on-ground days (%)
(2) Correctly predicted snow-on-ground days (%)
(3) Missed snow-on-ground days versus total observed snow-on-ground days (%)
(4) Exaggerated snow-on-ground days versus observed snow-on-ground days (%)
(5) Total predicted events versus observed events (%)

Table 2 Number of Events Observed and Predicted by WEPP and SPAW

Station	Total			1-2 days			>5 days			Aver. Length (days)		
	Obs.	WEPP	SPAW	Obs.	WEPP	SPAW	Obs.	WEPP	SPAW	Obs.	WEPP	SPAW
Bethany, MO	202	320	137	73	141	24	73	98	79	8.1	5.8	12.3
Lawrenceville, NY	317	394	150	116	174	25	119	128	90	13.1	11.1	28.5
Morris, MN	205	331	110	84	135	9	86	131	83	21.7	12.7	43.3
Monticello, UT	208	434	123	77	265	23	82	77	75	15.2	4.4	21.7
Jackson, MI	313	452	180	116	205	48	114	131	94	8.9	6.8	16.8
Hayden, CO	254	595	53	134	348	3	72	124	45	19.0	5.9	94.4
Mesa Verde, CO	285	497	155	134	296	28	88	83	85	13.4	3.5	12.0
Sioux Falls, SD	228	399	157	80	166	22	99	136	97	14.0	8.2	23.2
McHenry, ND	164	322	79	50	144	11	76	115	54	30.7	14.3	50.8
Savage, MT	194	370	172	66	155	34	83	120	99	16.3	6.8	16.6
Moscow, ID	226	429	119	104	256	26	73	83	65	8.7	4.8	15.4
Lafayette, IN	232	408	153	99	231	26	71	94	82	6.6	5.0	12.7