SPATIALLY DISTRIBUTED SNOWMELT INPUTS TO A SEMI-ARID MOUNTAIN WATERSHED

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ABSTRACT

Spatial variability in snow accumulation and melt due to topographic effects on solar radiation, drifting, air temperature, and precipitation is important in determining the timing of snowmelt releases. Precipitation and temperature effects related to topography tend to affect snowpack variability at large scales and are generally included in models of hydrology in mountainous terrain. The effects of spatial variability in drifting and solar input are generally only included in distributed models at small scales. Previous research has demonstrated that snowpack patterns are not well reproduced when topography and drifting are ignored. These observations imply that larger scale representations that ignore drifting could be greatly in error. Detailed measurements of the spatial distribution of snow water equivalence within a small, intensively studied, 26-ha watershed were used to validate a spatially distributed snowmelt model. This model was then compared to basin-averaged snowmelt rates for a fully distributed model, a single point representation of the basin, a two point representation that captures some of the variability in drifting and aspect, and a model with distributed terrain and uniform drift. The model comparisons demonstrate that the lumped, single point representation and distributed terrain with uniform drift both yielded very poor simulations of the basin-averaged surface water input rate. The two-point representation was an improvement but the late season melt required for the observed streamflow was still not simulated because the deepest drifts were not represented. These results imply that representing the effects of subgrid variability of snow drifting is equally or more important than representing subgrid variability in solar radiation.

INTRODUCTION

The spatial variability of snowmelt processes has received increasing attention in recent years (Blöschl et al. 1991, Kirnbauer et al. 1994). Varying precipitation input, drifting, and solar radiation intensity on sloping surfaces, all related to topography contribute to the heterogeneity of surface water input from snowmelt (Seyfried and Wilcox 1995, Tarboton et al. 1995). One of the more marked effects of spatially variable accumulation and melt is the effect on the timing of snowpack releases.

While the importance of topography in determining snow accumulation and melt has been well established, potential methods to represent the effects of topography on drifting have not been well explored. Several researchers have examined the detailed physics of snow transport under known wind fields (Tabler 1975, Tabler and Schmidt 1986, Pomeroy and Gray 1995). Others have approached the problem through empirical means (Elder et al. 1989, 1991, Blöschl and Kirnbauer 1992). Tarboton et al. (1995) estimated drifting for a small watershed by calibrating a drifting parameter in an energy and mass balance snowmelt model at each grid cell (Tarboton and Luce, 1997). While this calibration appears to be stable for the years at the site for which it was done, the relationships between topography and drifting do not appear to be easily generalized. If the distributed drifting cannot be calculated based on readily obtained spatial data, it becomes another of the unknown or unknowable parameters in distributed models to which Beven's (1996) discussion on distributed modeling speaks.

Because precise mapping of a drifting parameter may be difficult, a general characterization of the effect through a subgrid parameterization for a larger scale model may be more manageable. At 30-m grid resolution, drifting can be explicitly represented, while for larger model elements, only the net effect of drifting needs to be described. This study addresses the question of what level of detail is necessary in representing topography and spatial variability of drifting in distributed snowmelt modeling.

METHODS

We used distributed and lumped snowpack models to examine the ability of simplified representations of spatial variability in topography and drifting to estimate surface water input. Each of four simulations was considered as a

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hypothesis to be compared with distributed snow water equivalent measurements such as those described by Cooley (1988) and the timing of basin outflow through a weir. First, the fully distributed snowmelt model was run with the distributed topography and distributed drift factors reported in Tarboton et al. (1995). This simulation was used to check the validity of the snowmelt model and calculate the basin-averaged snowmelt flux for conditions approximating the actual conditions. The next two simulations were dramatic simplifications of the representation. From aerial photography and field observations, it is clear that drifting occurs primarily on northeast facing slopes, while southwest facing slopes are scoured. This strong covariance in processes, yielding a shallow snowpack over time on southwest facing slopes versus a deep snowpack over time on northwest facing slopes, suggested that a simplification of the basin into a north basin and a south basin may still yield some of the observed basin-wide behavior in snowpack distribution. The second simplification was to treat the basin as a single unit with a single aspect, slope, and drift factor. This simulation was to confirm it as a relatively poor approximation and see where the two-basin simplification fell between the fully-lumped and fully-distributed representations. A final simulation examined the importance of the drift factor. In this simulation, the spatial variation in topography was preserved, but the drift factor was set to unity everywhere, removing the spatial variability due to drifting, but modeling the control that topography has over incident radiation.

The study was carried out using data from the Upper Sheep Creek subbasin of the Agricultural Research Service's Reynolds Creek Experimental Watershed in southwestern Idaho. The Upper Sheep Creek watershed has an area of 26-ha, with elevations ranging between 1840 and 2040 m (Figure 1). Most of the basin is covered by low sagebrush and mountain big sagebrush communities. Aspen grow in a strip along the northeast facing slope where the drifts form. Severe winter weather and winds keep the aspen dwarfed to a height of about 4 m. Average annual precipitation is 508 mm, and the first-order stream exiting the basin is ephemeral.

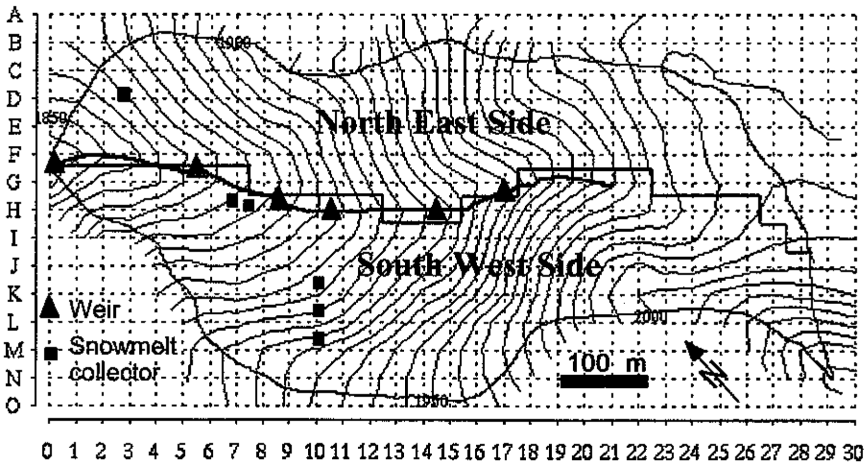


Figure 1: Map of Upper Sheep Creek with snow survey grid. Contour interval is 5 m.

A grid was surveyed over the watershed to facilitate distributed data gathering in the basin (Figure 1). The spacing on the grid was 30.48 m (100 ft), and the long axis is oriented roughly 48 degrees west of north. Measurements of snow water equivalent were taken on portions of the grid within the watershed on 9 dates in 1993 with a snow tube and scale. Precipitation, temperature, relative humidity, and incoming solar radiation were measured for water year 1993 at a weather station near location J 10. Wind speed was measured at D 3.

Distributed solar radiation was calculated in two steps. Pyranometer data at the weather station was used to calculate an effective atmospheric transmission factor. Local horizons, slope, and azimuth were used to find local sunrise and sunset times and integrate solar radiation received on the slope for each time step. The calculated atmospheric transmission factor characterized cloudiness for incoming longwave radiation calculations.

The snowmelt model is an energy and mass balance model with a vertically lumped representation of the snowpack. It is more completely described in Tarboton and Luce (1997). Two primary state variables are maintained in the model, snow water equivalent, W [m], and internal energy of the snowpack and top 40 cm of soil, U [kJ m^{-2}]. U is zero when the snowpack is at 0°C and contains no liquid water. These two state variables are updated according to

$$dU/dt = Qsn+Qli-Qle+Qp+Qg+Qh+Qe-Qm$$

$$dW/dt = Pr+Ps-Mr-E$$

where Qsn is net solar radiation; Qli is incoming longwave radiation; Qle is outgoing longwave radiation; Qp is advected heat from precipitation; Qg is ground heat flux; Qh is the sensible heat flux; Qe is the latent heat flux; Qm is heat advected with melt water; Pr is the rate of precipitation as rain; Ps is the rate of precipitation as snow; Mr is the melt rate; and E is the sublimation rate. The model is driven by inputs of precipitation, air temperature, humidity, wind speed and incoming solar radiation. Snow surface temperature, a key variable in calculating latent and sensible heat fluxes and outgoing longwave radiation is calculated from the energy balance at the surface of the snowpack where incoming and outgoing fluxes must match. These simulations were run on a 6-hr time step.

The model is distributed by running at each grid cell within the watershed using the 30.48 m grid shown in Figure 1. The model uses a drift multiplier to estimate enhancement of local incoming snow through wind transport. The fraction of precipitation falling as rain or snow is a function of temperature. The fraction falling as snow is assumed to be susceptible drifting, i.e. redistribution by wind. Snow accumulates in some areas (mainly in the lee of ridges) and is scoured from other areas (mainly ridges and windward slopes). In the model this redistribution process, which really occurs after snowfall, is lumped together in time with the occurrence of snowfall. Grid snow accumulation is modeled as snowfall times a drift multiplier, which is a spatial field of distinct factors for each grid location. The drift multiplier is greater than 1 where accumulation is enhanced by drifting and less than 1 where scour occurs. The drift multiplier field was calibrated from 1986 snow survey data from Upper Sheep Creek. Drift multipliers were adjusted at each grid cell to match the snow water equivalent on February 25 and March 26, 1986 (Tarboton et al., 1995). Values of the multiplier over the basin ranged from 0.2 to 6.8, with an average of 0.975.

Site characteristics used for the single point and two point representations of the basin are summarized in Table 1. For the single point, the average basin elevation and drift factor were used. Slope and aspect were calculated along the long axis of the basin to estimate the lumped basin behavior. For the two point model, representative cells were picked for the North East Side and South West Side of the basin to set slope, aspect, and elevation. Each point was assigned an average drift factor for the region it represented.

Table 1: Effective site characteristics used for the single point and two point representations of the basin.

	Single Point Representation	North East Side	South West Side
Slope:	0.159	0.286	0.345
Aspect:	312 °	299 °	357 °
Drift Factor:	0.975	0.62	1.29
Elevation:	1925 m	1912 m	1939 m
Relative Area:	100 %	47%	53 %

RESULTS AND DISCUSSION

Maps of observed snow water equivalent over Upper Sheep Creek watershed are shown in Figure 2. The effect of drifting in concentrating snow accumulation, and consequently late season snow water equivalent along the southwest side of the basin is evident. Maps of modeled snow water equivalent with the fully distributed snowmelt model (Figure 2) show a generally similar pattern, but are difficult to compare quantitatively. Table 2 lists the basin-averaged snow water equivalent from the observations and the model, showing that the fully distributed model tends to overestimate snow water equivalent in the early melt season and slightly underestimate snow water equivalent in the late melt. Plotting observed against modeled data for each date (Figure 3) shows that the model

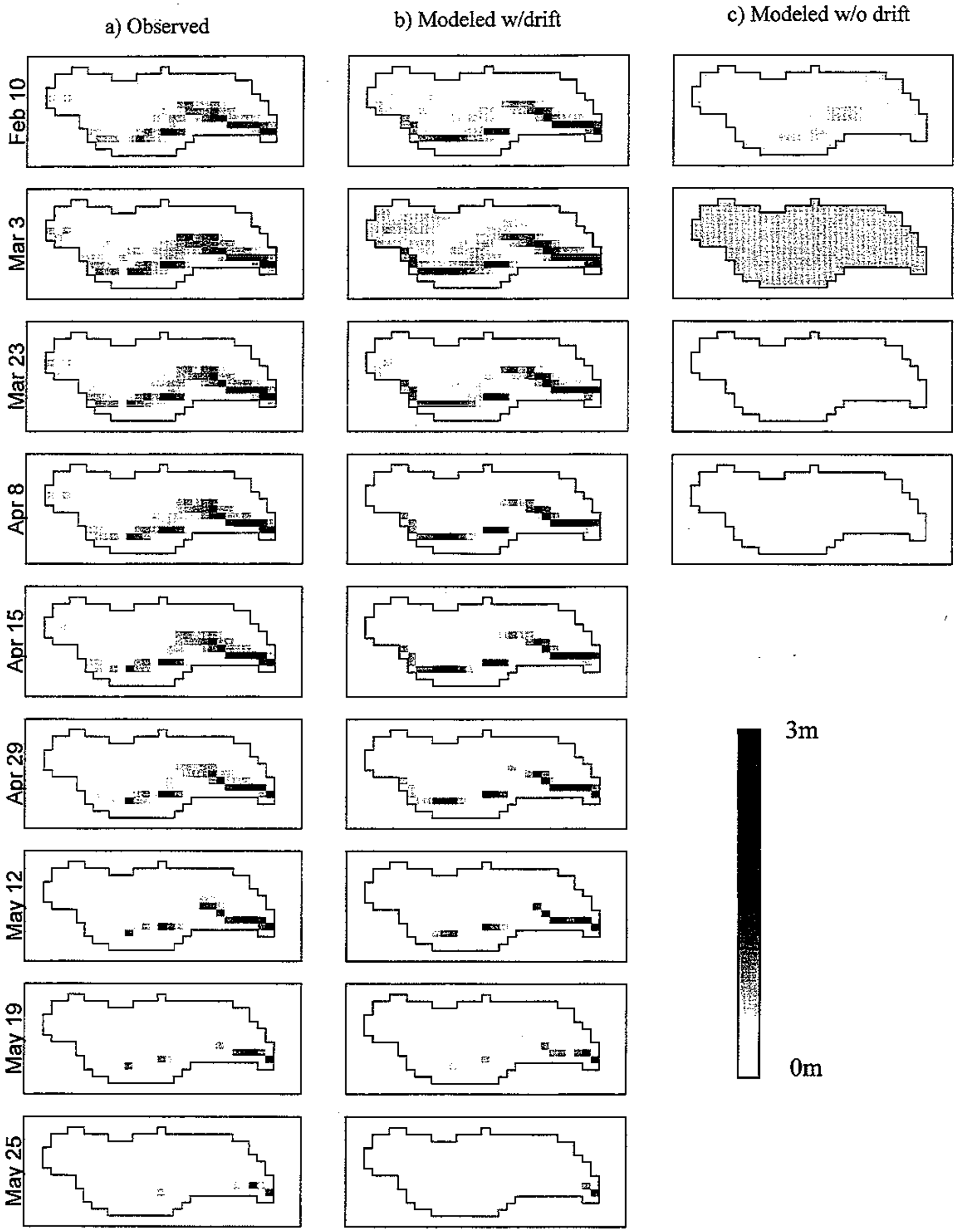


Figure 2: Snow water equivalent mapped over basin on 9 dates of snow survey in 1993 for a) observed, b) modeled with spatially varying drift factor, and c) modeled with uniform drift factor. No snow modeled after April 8 with uniform drift factor.

generally overestimates snow water equivalent for locations with moderate to high snow water equivalents, but underestimates snow water equivalent where there is little snow, with systematic overestimation most apparent in the early melt season. The correlation coefficient (Pearson's r) and a measure of fit to the 1:1 line (Wilmott 1981,Wilmott et al. 1985) are given in Table 3. All Pearson r's are significant at the $p < 0.00001$ level. These results obtained with multipliers calibrated in 1996 show drifting patterns that compare favorably with 1993 observations, suggesting consistency in drifting from year to year.

Table 2: Basin-averaged snow water equivalent (m) from observations and models.

Date	Observed	Model w/drift	Model no drift
Feb 10	0.22	0.28	0.28
Mar 3	0.28	0.38	0.39
Mar 23	0.23	0.23	0.10
Apr 8	0.18	0.16	0.00
Apr 15	0.17	0.16	0.00
Apr 29	0.13	0.13	0.00
May 12	0.09	0.07	0.00
May 19	0.04	0.03	0.00
May 25	0.02	0.01	0.00

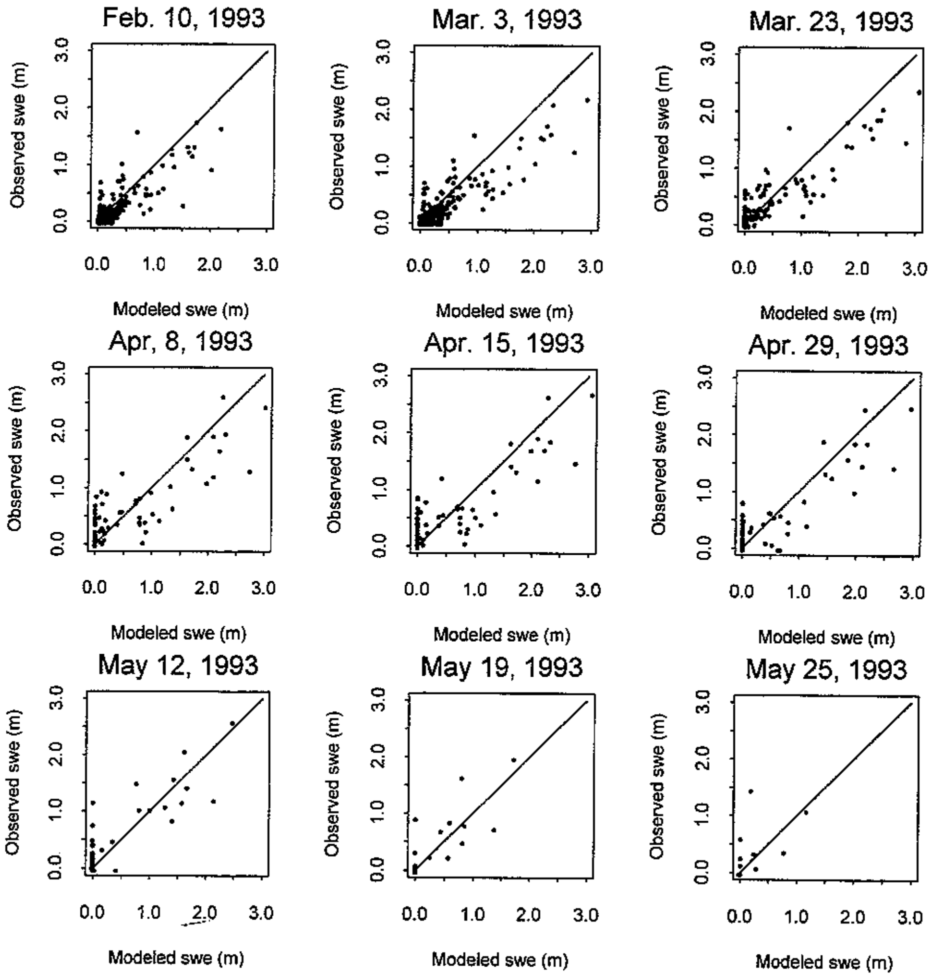


Figure 3: Comparison of observed and modeled snow water equivalent for each snow survey date. The line through each plot is the 1:1 line.

Table 3 Correlation between modeled and measured images.

Date	Pearson's r	Willmott's d
Feb 10	0.83	0.90
Mar 3	0.84	0.90
Mar 23	0.90	0.94
Apr 8	0.88	0.93
Apr 15	0.89	0.94
Apr 29	0.89	0.94
May 12	0.90	0.94
May 19	0.87	0.92
May 25	0.65	0.76

We also compared modeled and measured surface water inputs (snowmelt plus rain) averaged over the period between snow water equivalent measurements. Cumulative surface water input and sublimation from the snowpack (loss) can be calculated as the measured cumulative precipitation less the measured snow water equivalent on a particular date. The average loss rate for the periods between measurements was then calculated from the cumulative values. Figure 4 shows the average snow loss rate based on the measurements and based on the distributed model with drifting plotted over time. Before the melt season begins, the measured rates are slightly greater. During the second measurement interval (Feb 10 to Mar 3), the model lost less snow, yielding the increased error in snow water equivalent seen on March 3 in Table 2. During the next measurement interval the model dramatically overpredicted losses, mostly as melt. From Figure 2, it appears that much of the difference is in the south facing part of the basin with low snow water equivalents. The model shows buildup and loss of snow in this area, while the measurements indicate that perhaps none was there. Figure 5 shows the calculated basin-average surface water input rate versus modeled basin-average surface water input rate for the four models (distributed with drifting, single point, two regions, distributed no drifting). To prepare Figure 5, we subtracted the modeled sublimation from the measured loss rate to estimate the "measured" surface water input rate. Because sublimation is small relative to melt during the melt season, this is a very small correction but makes the comparisons more exact. The most striking feature of Figure 5 is how well the distributed model with drifting performs excepting for one measurement period (March 3 to 23) where surface water input is substantially overpredicted . The other models show a poor comparison between measured and modeled surface water input rate. These results suggest that the basin-averaged surface water input rates from the distributed model with drifting are reasonably representative of the actual surface water input rates experienced by the basin during the late melt season.

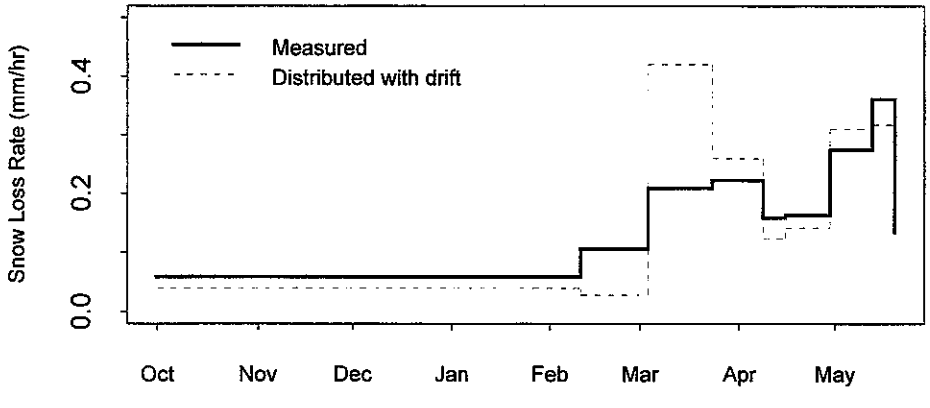


Figure 4: Measured average loss rate and modeled loss rate over time for the period October 1992 to May 1993. Losses are the sum of melt and sublimation.

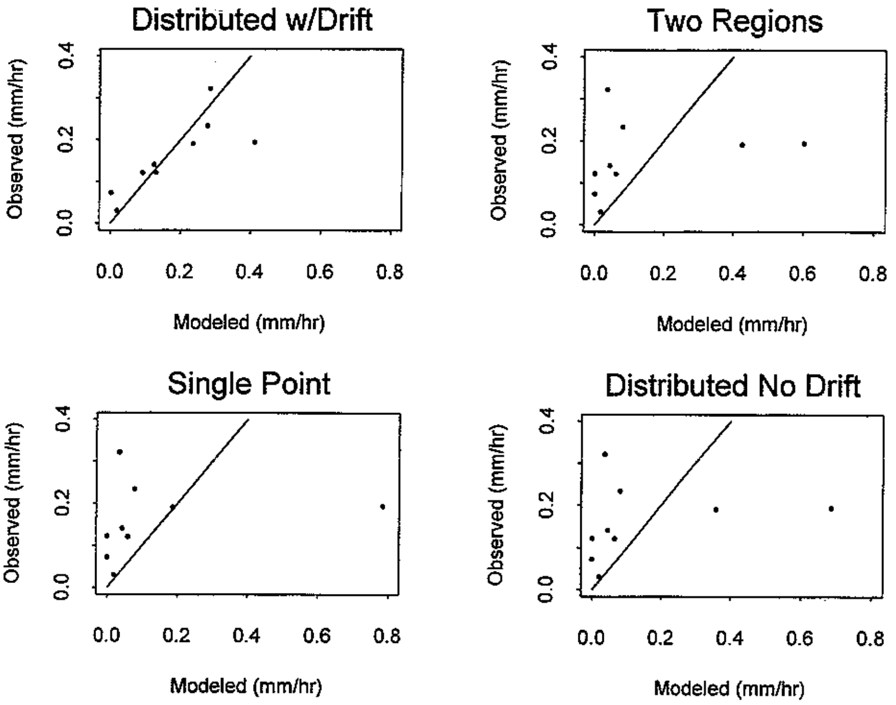


Figure 5: Observed and modeled average surface water input rate for the 9 periods defined by the 9 snow water equivalent measurements and the beginning of the water year (no snow). Line is 1:1 line.

Cumulative modeled surface water inputs over water year 1993 and the cumulative streamflow are shown in Figure 6. Figure 7 shows the observed streamflow from the basin at the outlet (cell F0) compared to the basin-averaged surface water input rate from each of the model runs. From this series of graphs, the effect of the fully distributed model with a distributed drift factor becomes evident. While one would generally want to model runoff generation for comparison to flow through a weir, the timing of surface water input relative to the runoff rate is extreme enough in these cases that detailed modeling is not justified. Almost universally, a rising hydrograph requires

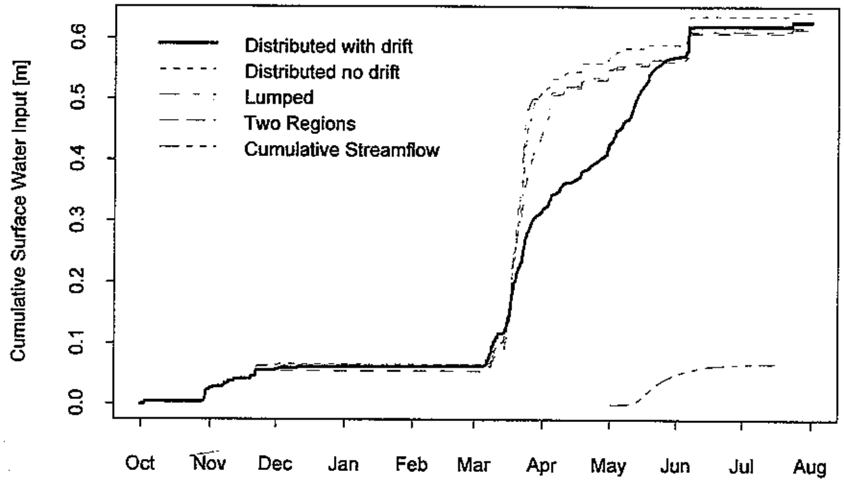
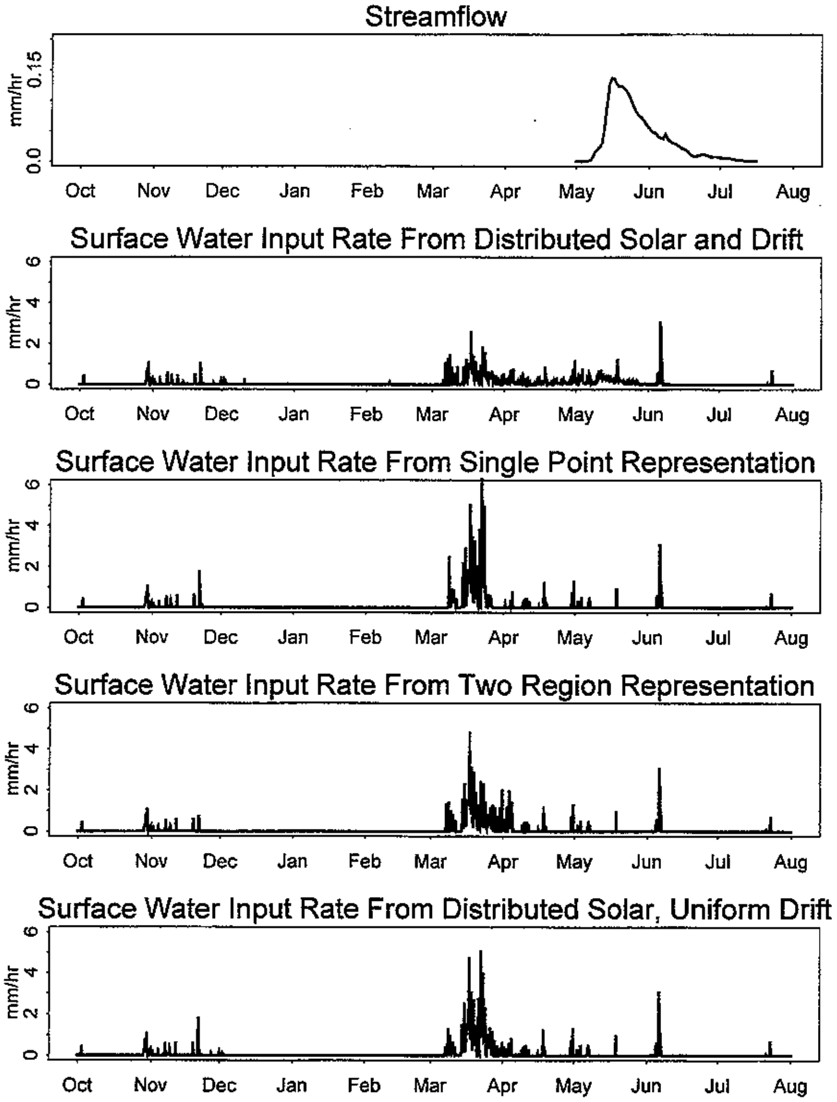


Figure 6: Cumulative surface water input for each of the four models and cumulative streamflow for the period October 1992 to July 1993.

Significant rain or snowmelt. The fully distributed model with distributed drift multiplier is the only model that predicts significant melt late in the season coinciding in timing with the observed rise of the streamflow hydrograph. The other models show surface water inputs concentrated almost entirely in the month of March, which is an unlikely source of water for peak streamflow in May. The lumped model representing the basin as a single point process shows this characteristic strongly. By splitting the model into two regions, some improvement in timing is realized, but still not enough to reasonably describe the timing of basin outflows. Running the model with distributed elevation and solar inputs but without distributed drift multipliers yielded basin-average melt rates most similar in timing to those from the single point representation of the basin. The snow water equivalent modeled in this manner shows considerably less variability than the measured or modeled with spatially varying drift factor (Figure 2). The consequence is that the basin behaves more in unison. These results imply that spatial variability in the drift multiplier has a greater effect on the behavior of Upper Sheep Creek than spatial variability in solar radiation and temperature.


Streamflow

Surface Water Input Rate From Distributed Solar and Drift

Surface Water Input Rate From Single Point Representation

Surface Water Input Rate From Two Region Representation

Surface Water Input Rate From Distributed Solar, Uniform Drift

Figure 7: Surface water inputs from snowmelt and basin outflow for the period October 1992 to July 1993. a) Observed streamflow. b) Distributed model run with drift. c) Lumped run. d) Two region run. e) Distributed with no drift multipliers.

Comparing the observed streamflow hydrograph in Figure 7 with measured surface water inputs in Figure 4 it is interesting to note that basin-wide surface water inputs in March and April do not result in streamflow whereas only slightly higher basin averaged surface water inputs in May seem to drive the runoff hydrograph. Figure 2 shows that May's basin-averaged surface water input occurs over a much smaller area, and therefore represents a much higher input rate per unit area. This supports the assertion of Stephenson and Freeze (1974) that runoff in this basin occurs from sustained input to the small portion of the basin under the largest drifts.

CONCLUSIONS

In obtaining these results, we compared one model to another. It is necessary in such a case to ascertain which model, if any, best describes the observed conditions. We validated a distributed snowmelt model with spatially varying drift factor against detailed snow water equivalent measurements. Comparisons of patterns of snow water equivalent on each measurement date showed reasonable correlation but a bias towards overestimation by the model, particularly in the early melt season. This corresponds with an underestimation of surface water input throughout the accumulation season followed by an overestimation of surface water input during March. By the mid to late melt season, there is generally better agreement. From the maps in Figure 2, it appears that much of the discrepancy centers around the south west facing slope. It is likely that because of the generally low snow water equivalents on these slopes that the drift factor here was poorly estimated through the 1986 calibration. Differences of snowpack distribution from one year to another may be a common problem and accurate estimates of drifting may be difficult to obtain, even with detailed snow survey information from prior years. From the results of the distributed simulation, it can be seen that the timing of basin snowmelt is sensitive to this type of error. Between the time the snow on the south west facing slope melted and the end of May, distributed model results compared favorably to measurements. During this time period, melt from the much deeper drifts on the north east facing slopes contributed most of the surface water inputs. These deeper drifts caused by prevailing winds are more consistent from year to year as indicated by the noted correlation between vegetation patterns and drift patterns in Upper Sheep Creek (Flerchinger et al. 1994).

In semi-arid mountainous watersheds such as Upper Sheep Creek, wind plays a large role in redistributing snow, and the spatial variability and pattern of snow water equivalent is highly dependent upon wind induced drifting. Drifting results in delayed surface water inputs and sustains melt into late spring. Using detailed snow water equivalent measurements and distributed snowpack modeling, we considered the level of detail necessary to represent effects of spatial variability of snowmelt processes at the scale of a small watershed (~ 400 m across). We found that representing basin snowmelt as a single point yields incorrect results. Using two regions with contrasting drifting and solar input to represent the basin, we found some improvement. We also examined the relative contribution of solar input and drifting to the observed spatial patterns of snow water equivalent and the temporal patterns of surface water input. Our results highlight the point that incorporating detailed drifting information, which may be difficult to obtain, is perhaps of greater or equal importance than modeling the effects of local topography on radiation.

ACKNOWLEDGMENTS

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