THE INFLUENCE OF THE SPATIAL DISTRIBUTION OF SNOW ON BASIN-AVERAGED SNOWMELT

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ABSTRACT

Spatial variability in snow accumulation and melt due to topographic effects on solar radiation, snow drifting, air temperature, and precipitation is important in determining the timing of snowmelt releases. Precipitation and temperature effects related to topography 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 included only in distributed models at small scales. Previous research has demonstrated that snowpack patterns are not well reproduced when topography and drifting are ignored, implying that larger scale representations that ignore drifting could be 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-region 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.

KEY WORDS: spatial variability; distributed catchment modeling; snow hydrology

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 relate to topography and 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 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). Jackson (1994) and 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. While this calibration appears to be stable for the years at the site for which it was done, the relationships between topography and drifting are not 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 discussed by Beven (1996).

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; 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 snow drifting in distributed snowmelt modeling.

METHODS

Study area

The study was carried out using data from the Upper Sheep Creek subbasin of the Reynolds Creek Experimental Watershed in southwestern Idaho, which enjoys a long and rich history of hydrologic research (Stephenson and Freeze, 1974; Cooley, 1988; Duffy et al, 1991; Flerchinger et al., 1992, Flerchinger et al. 1994, Jackson, 1994, Seyfried and Wilcox, 1995; Tarboton et al., 1995; among others). Much of the work has focussed on runoff generation mechanisms in the basin, concluding that groundwater flow through layered basalts is the primary source of streamflow. All of the above studies have noted the importance of the snowdrift that forms in the southwest portion of the basin in contributing water during the period of greatest runoff. This background of previous work measuring snow drifting (Cooley 1988), a previously developed and calibrated distributed hydrologic model (Jackson, 1994; Tarboton et al., 1995), and an understanding of the relationship to basin hydrology provide a good foundation from which to explore the effects of the spatial distribution of snow on basin averaged snowmelt.

The Upper Sheep Creek watershed has an area of 26 ha, with elevations between 1840 and 2040

m (Figure 1). Low sagebrush communities cover the northeast portion of the basin, and big

sagebrush communities cover most of the southwestern half of the basin. Aspen grow in a

narrow strip along the northeast-facing slope where the drifts form (Figure 2). Severe winter

weather and winds keep the aspen dwarfed to heights between 4 and 7 m. Average annual

precipitation is 508 mm, and the first-order stream exiting the basin is ephemeral.

Study outline

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 hypothesis and 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 Jackson (1994) and 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 simplifications of that representation. From aerial photography and field

observations, it is clear that drifting occurs primarily on shadowed, northeast-facing slopes, while

sunnier, southwest-facing slopes are scoured by prevailing winds.   This strong covariance in

processes yields a shallow snowpack over time on southwest-facing slopes versus a deep

snowpack over time on northeast-facing slopes and suggests that a division of the basin into a

north basin and a south basin may yield some of the observed basin-wide behavior in snowpack distribution. This single division into two regions is a substantial simplification compared to the 255 cells used in the fully distributed model.

The second simplification treated the basin as a single unit with a single aspect, slope, and drift factor. This simulation was run to confirm that it gave a poor approximation to the data and to see where the two-region simplification fit 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.

Data collection

Measurements of snow water equivalent were taken on nine dates in 1993 with a snow tube and scale. A grid guided distributed sampling over the watershed (Figure 1). The spacing on the grid is 30.48 m (100 ft), and the long axis is oriented 48 degrees west of north. 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. Flow is measured at a weir at location F 0.

Model description

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 effect of plant canopy on snowmelt is parameterized by decreasing the albedo of the snow surface as the snow depth decreases below the canopy height. This parameterization is most appropriate for short vegetation, such as sagebrush. Because the aspens are free of leaves until the soil warms slightly, the errors introduced by not considering the taller canopy are minimal.

The distributed model runs the point model (described in the preceding two paragraphs) at each cell in the grid (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 multiplied by the drift multiplier to estimate grid cell precipitation. The drift multiplier 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 (Jackson, 1994; Tarboton et al., 1995). Values of the multiplier over the basin are shown in Figure 2 (Jackson 1994) and ranged from 0.2 to 6.8, with an average of 0.975. A value less than one indicates that the basin loses more snow to neighboring basins than it gains.

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

Site characteristics used for the single-point and two-point representations of the basin are summarized in Table I. For the single-point model, 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 northeast and southwest sides of the basin to set slope, aspect, and elevation. Each point was assigned an average drift factor for the region it represented.

RESULTS

Maps of observed snow water equivalent over Upper Sheep Creek watershed are shown in Figure 3a. The effect of drifting in concentrating snow, 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 3b) show a generally similar pattern. Table II 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 4) shows that the fully distributed model overestimates snow water equivalent for locations with moderate to high snow water equivalents, but underestimates snow cover 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 III. It should be noted that

there is a degree of spatial autocorrelation, the structure of which is not exactly known. The

goodness of fit implied by the r values may therefore be somewhat overstated. These results,

obtained with multipliers calibrated using 1986 measurements (Jackson 1994), show drifting

patterns that compare favorably with 1993 observations, suggesting consistency in drifting from

year to year.

A comparison of the predictions of the distributed model using a uniform drift factor over the

basin (Figure 3c) to the observed data (Figure 3a), shows that drifting is an important process in

creating variability in snow water equivalence across the basin and in determining the timing of

melt outflows. Differences in melt caused by differences in solar radiation and temperature

across the basin are not great enough to explain the spatial patterns of snow water equivalent

values over the basin. The snow water equivalent modeled in this manner shows considerably

less variability than that measured or modeled with spatially varying drift factor. Consequently,

all cells in the basin become snow-free almost simultaneously, and the persistence of the

snowpack in the basin is dramatically reduced relative to observations. This result implies 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.

As an additional check on the behavior of the fully distributed model, 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 5 shows the average snow loss rate based on the measurements and 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 (February 10 to March 3), the fully distributed model lost less snow, which increased the error in snow water equivalent seen on March 3 in Table 2. During the next measurement interval, the model overpredicted losses, mostly as melt. From Figure 3, it appears that much of the difference is in the south facing part of the basin, which has low snow water equivalents. The model shows buildup and loss of snow in this area, while the measurements indicate that perhaps no accumulation occurred.

Figure 6 shows the calculated basin-averaged surface water input rate versus modeled basin-averaged surface water input rate for the four models (distributed with drifting, single point, two regions, distributed no drifting). To prepare Figure 6, 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. The most striking feature of Figure 6 is how well the distributed model with drifting performs except for one measurement period (March 3 to 23), where the surface water input is substantially overpredicted. The other models show poor comparisons between measured and modeled surface water input rates. These results suggest that the basin-averaged surface water input rates from the fully distributed model, which includes snow drifting, are reasonably representative of the actual surface water input rates experienced by the basin during the late melt season. They

also show that the alternative models considered in this study give poor predictions of melt outflow rates.

Streamflow is a second source of evidence that can be used qualitatively to come to the same conclusion that of the four models examined, only the fully distributed model gives reasonable estimates of snowpack outflow. Flerchinger et al. (1992) provide a conceptual model of runoff generation in the basin, suggesting that early melt primarily serves to recharge the groundwater while later melt generates streamflow through a groundwater response. During average snow years (such as 1993), they found response times through a confined aquifer on the order of 3-5 days. From the cumulative modeled surface water inputs over water year 1993 and the cumulative streamflow (Figure 7), it can be seen that the timing of basin-averaged surface water input rates for the three simplified models (one-point, two-point, and distributed without drifting) differs from that of the fully distributed model. It is also apparent that very little surface water input (flat line) is predicted by the simplified models during the period of greatest streamflow (steep line), while the fully distributed model is still predicting substantial outflow during that time period (steep line). Timing is a little easier to compare precisely in Figure 8, from which the same conclusion may be drawn. Comparison to Figure 7 shows that the brief spikes in surface water input predicted by the three simplified models after mid-April (rainfall) contain little water. 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.

DISCUSSION AND CONCLUSIONS

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 on wind-induced drifting. Snow drifting delays surface water inputs and provides

melt water into late spring. Using detailed snow water equivalent measurements and distributed

snowpack modeling, we examined the effects of spatial variability of snow accumulations on

snowmelt processes at the scale of a small watershed (~ 400 m across). We found that

representing basin snowmelt as a single point yields inaccurate results. Using two regions with

contrasting drifting and solar input to represent the basin improves the simulations little. 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 show that

detailed snow drifting information, which may be difficult to obtain, is equally or perhaps more

important than modeling the effects of local topography on radiation.

This examination relied heavily on a distributed snowpack model for reference, and some effort

has been made to test how appropriate the model is for this basin. Comparisons of measured and

modeled patterns of snow water equivalent on each measurement date showed reasonable

agreement. The model showed some bias towards overestimation of snow water equivalent in

the early melt season with better agreement in the middle and late melt season. Surface water

input was slightly underestimated throughout the accumulation season, and overestimated in the early melt season. By mid to late melt season, there is generally better agreement in surface water input rates. From the maps in Figure 3, it appears that much of the discrepancy centers on the southwest-facing slope. Because of the generally low snow water equivalents on these slopes, it is likely that the calibration using 1986 data resulted in poor estimates of the drift factor. Alternativel, the drifting here may have been inconsistent between the 1986 and 1993 snow seasons. This source of error demonstrates how sensitive timing of basin snowmelt is to estimates of distributed drifting and how difficult those estimates are to obtain. Between the time the snow on the southwest-facing slope melted and the end of May, distributed model snow water equivalent and melt rates compared favorably to measurements. During this time period, melt from the much deeper drifts on the northeast-facing slopes contributed most of the surface water inputs. These deeper drifts are caused by prevailing winds and are probably much 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)

Snowmelt modeling at the catchment scale is generally done as a part of water balance modeling. There is some question as to whether potential errors in drifting, such as those found in the distributed snowmelt model, would propagate through to runoff generation estimates. In Figure 8, the fully distributed model shows a peak basin-wide surface water input rate during March. From Figure 5, we know that the surface water input rates predicted by the fully distributed model in Figure 8 are about twice what they should be during March. Because runoff in this basin occurs from sustained input to the small portion of the basin under the largest drifts

(Stephenson and Freeze, 1974), it is unlikely that the relatively small depth of melt modeled on the southwest facing slope, where the errors appeared to be the greatest, would appear as runoff. Errors in this area of the basin would most likely be manifested as errors in evapotranspiration. The concentrated surface input under the drifts, up to 3 m over the melt season, yields most of the runoff through subsurface flow (Flerchinger et al., 1992) and saturation overland flow, suggesting that errors in the amount of snow drifting over the area of the deep drifts could be translated directly into errors in runoff.

Accurate estimates of snow drifting in a basin are difficult to obtain, but they are important to the prediction of basin snowmelt. Errors in estimates of both basin-wide evapotranspiration and basin runoff may occur from errors in estimates of snow drifting when using a distributed hydrology model. None of the lumped representations used in this study included a subgrid parameterization that represented the effects of drifting, and consequently none provided a reasonable simulation of melt water inputs to the basin. An important challenge lies in finding a subgrid parameterization that addresses this important source of spatial variability in snow water equivalent. A bigger challenge may lie in relating the basin-wide surface water input rate to runoff generation processes that are spatially dependent on drifting.

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Table I. Effective site characteristics for single-point and two-point representations of the basin

	Single-point representation	Northeast side	Southwest 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%

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

Date	Observed	Model with 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

Table III. Agreement between modeled and measured images

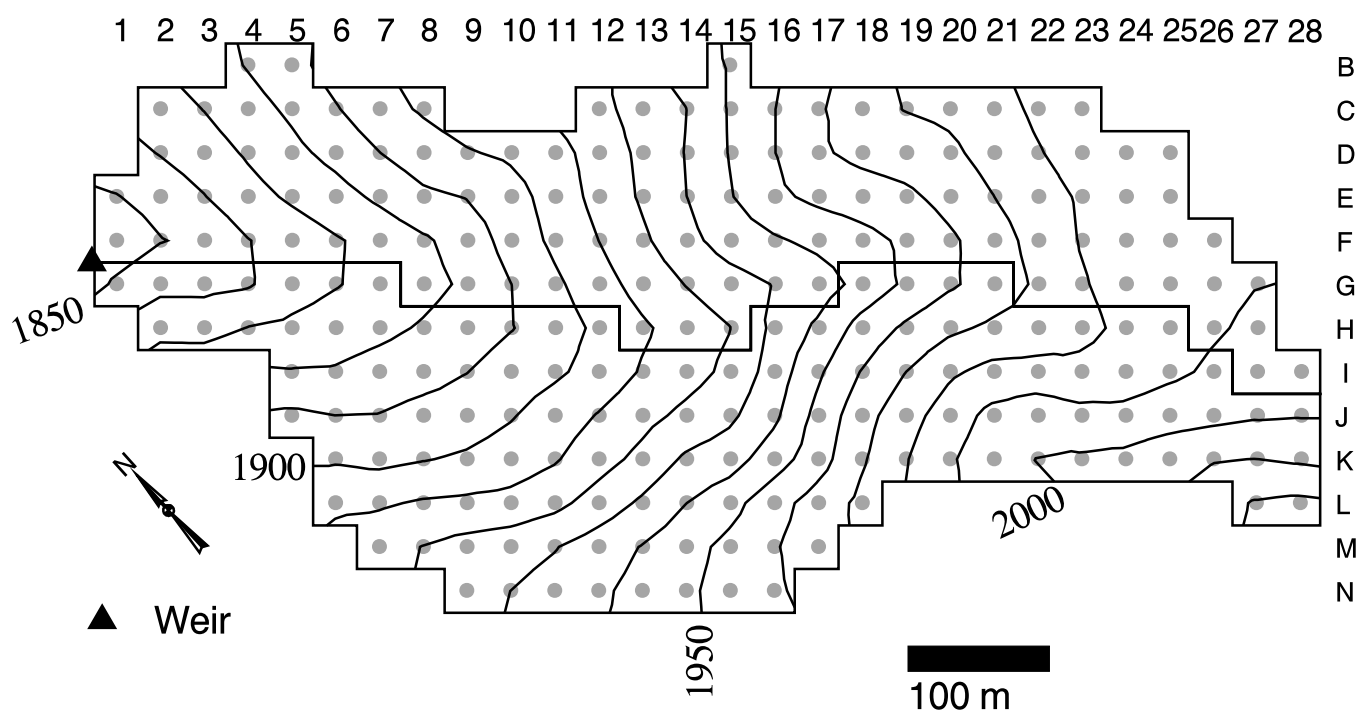| Date	Pearson's r	Willmott's d
Feb 10	0.83	0.90
Mar 3	0.84	0.90
Mar 23	0.90	0.94
Apr 8	0.88	0.93
Apr 15	0.89	0.94
Apr 29	0.89	0.94
May 12	0.90	0.94
May 19	0.87	0.92
May 25	0.65	0.76

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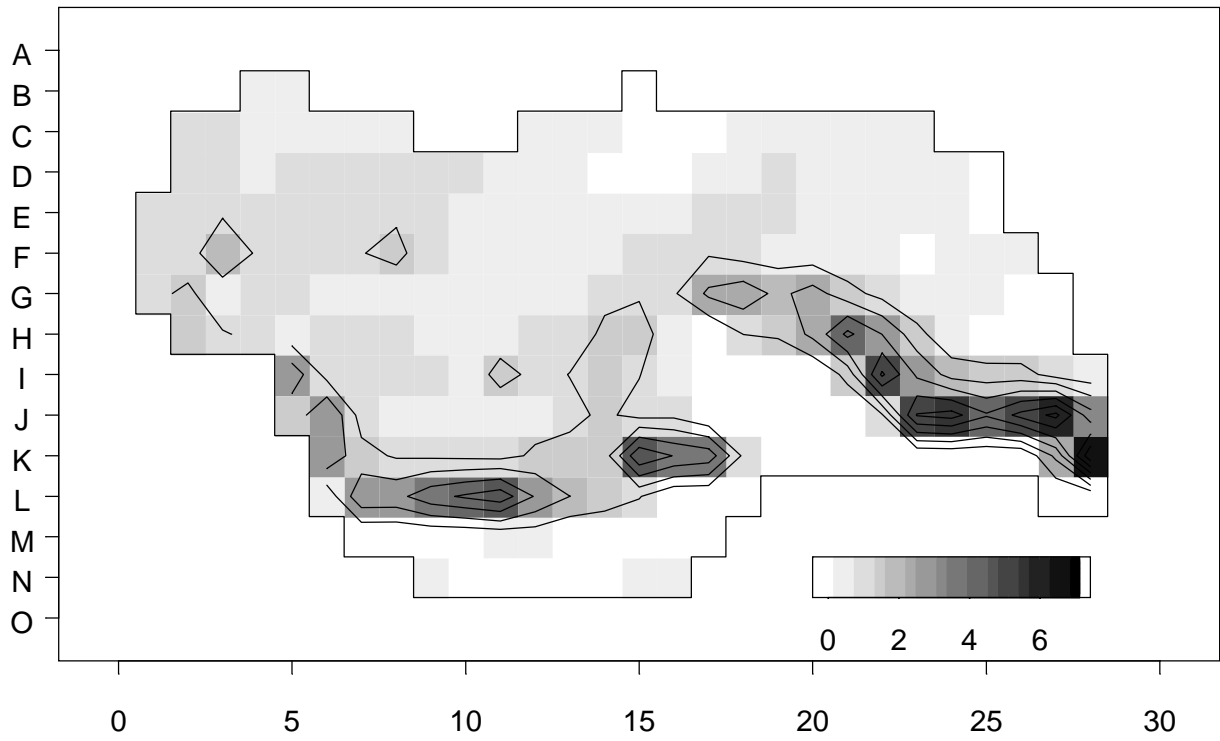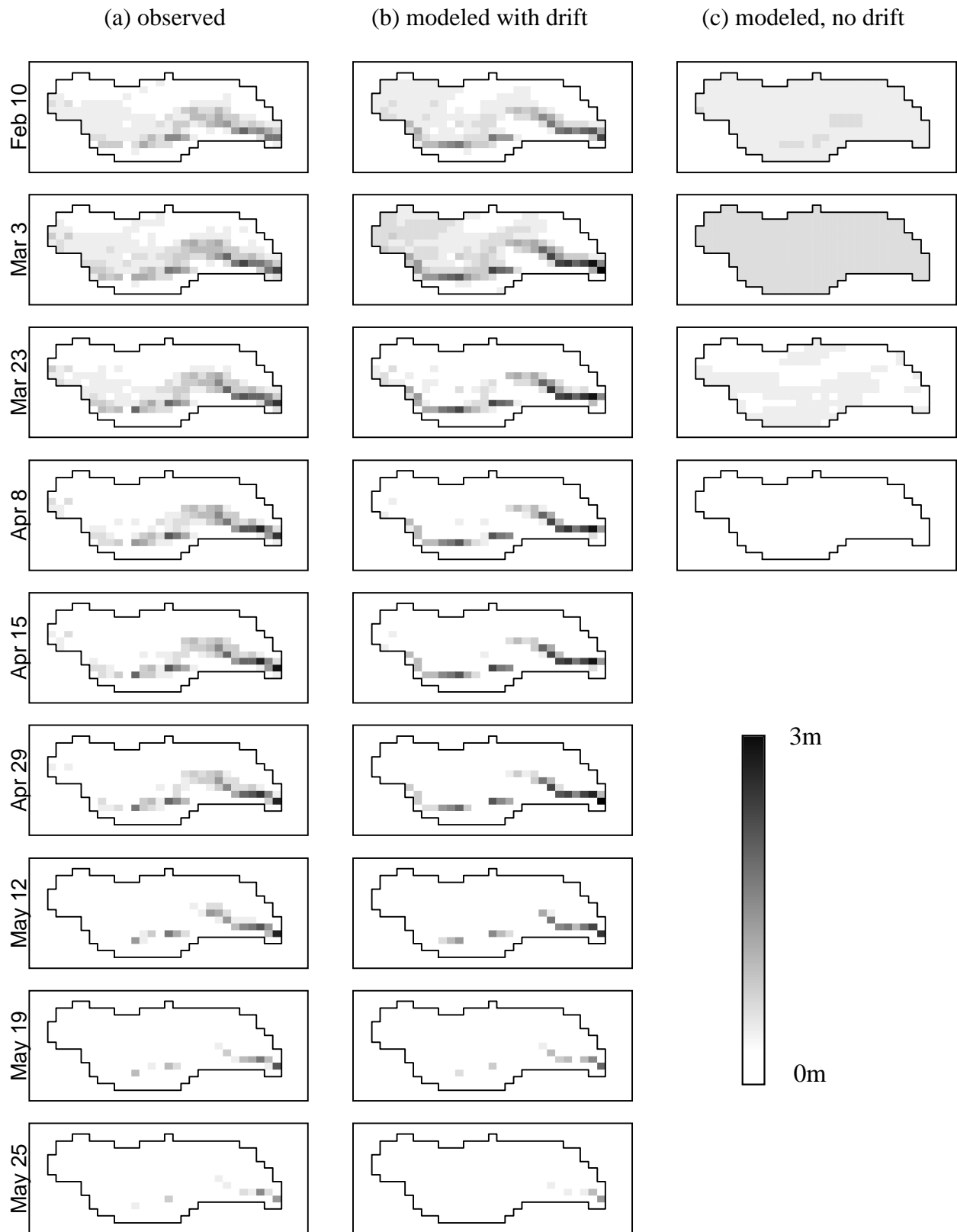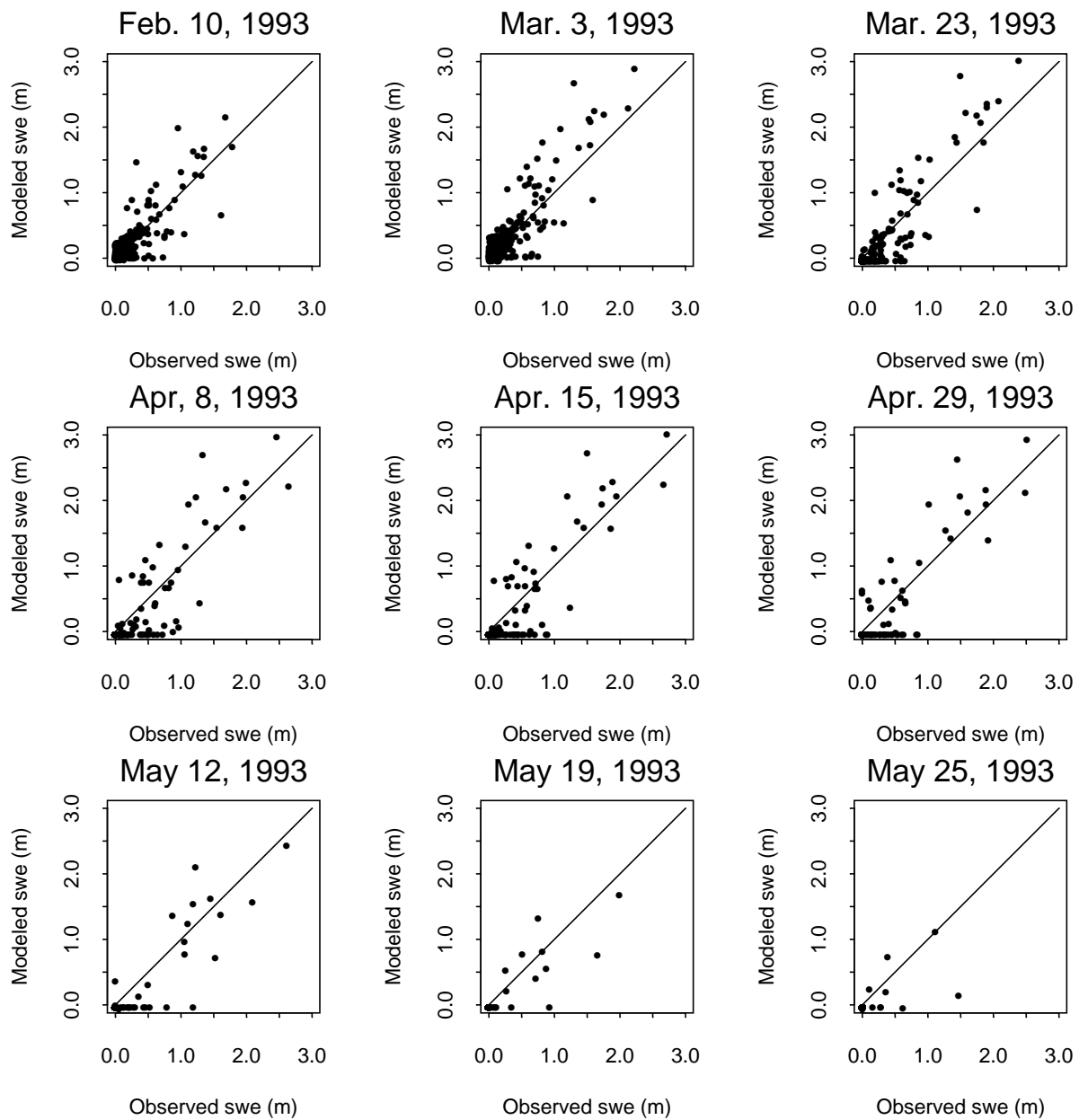
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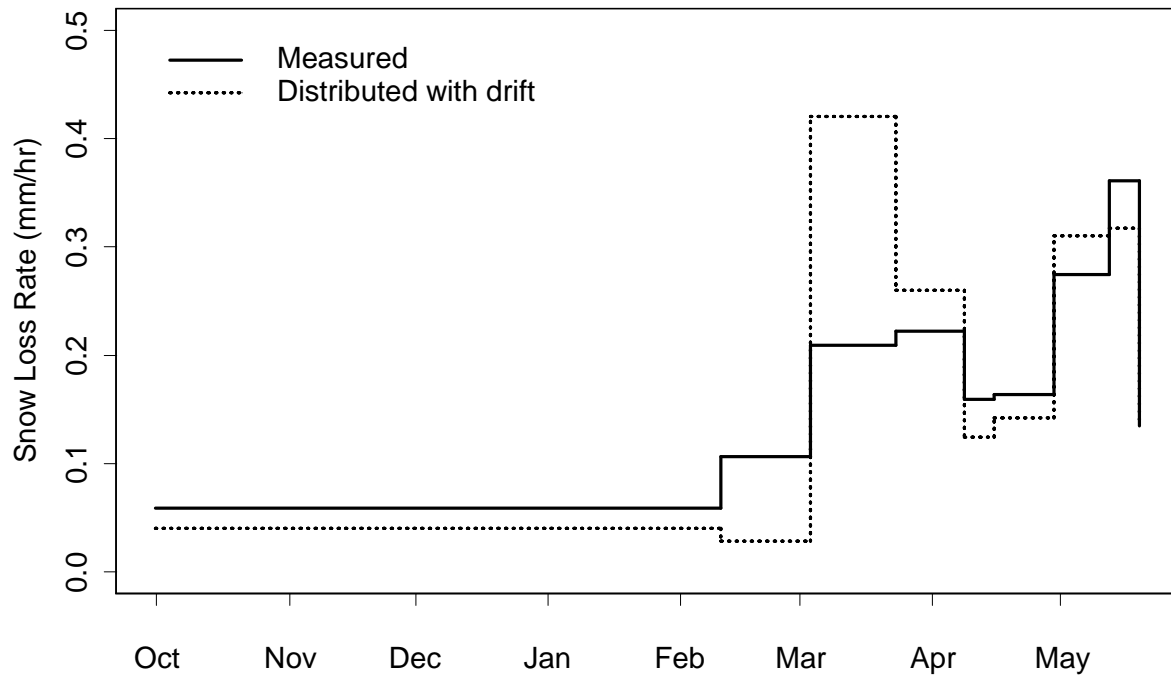date. The line through each plot is the 1:1 line

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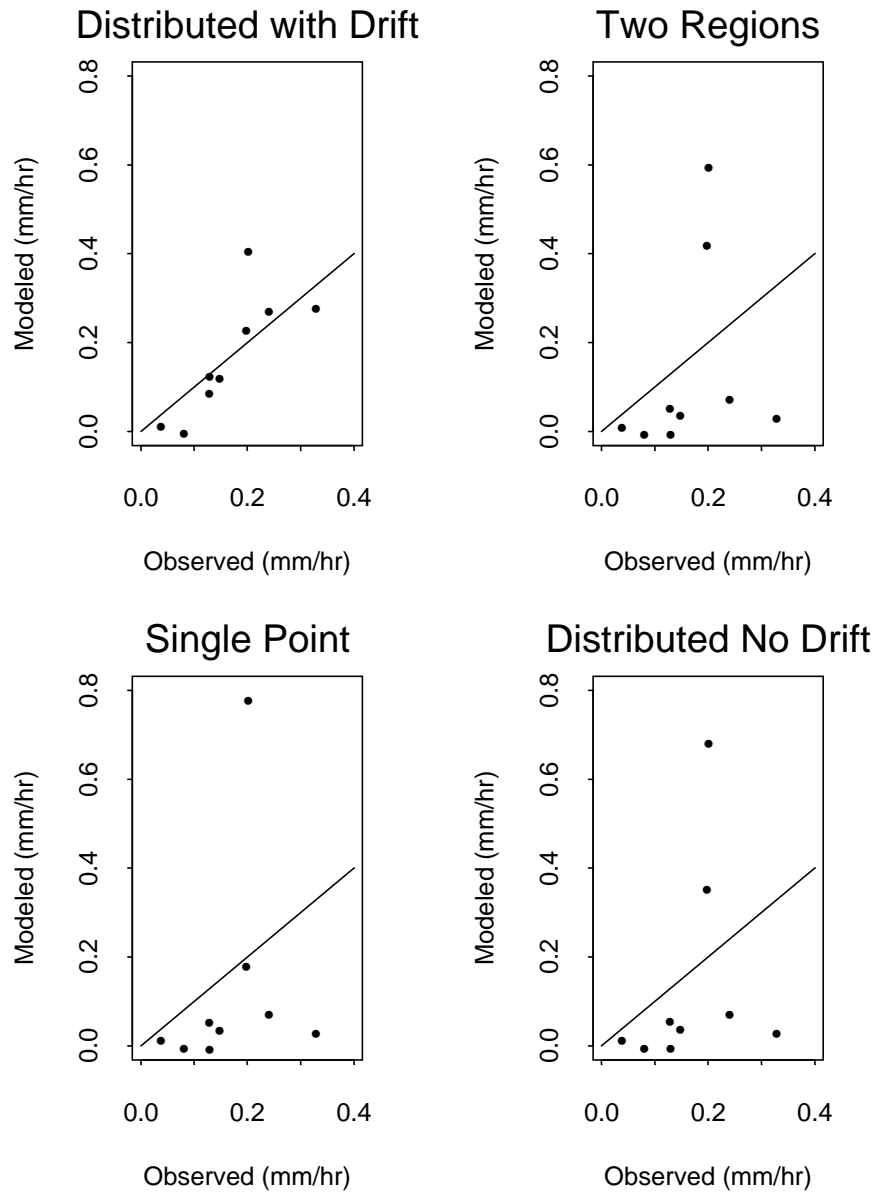
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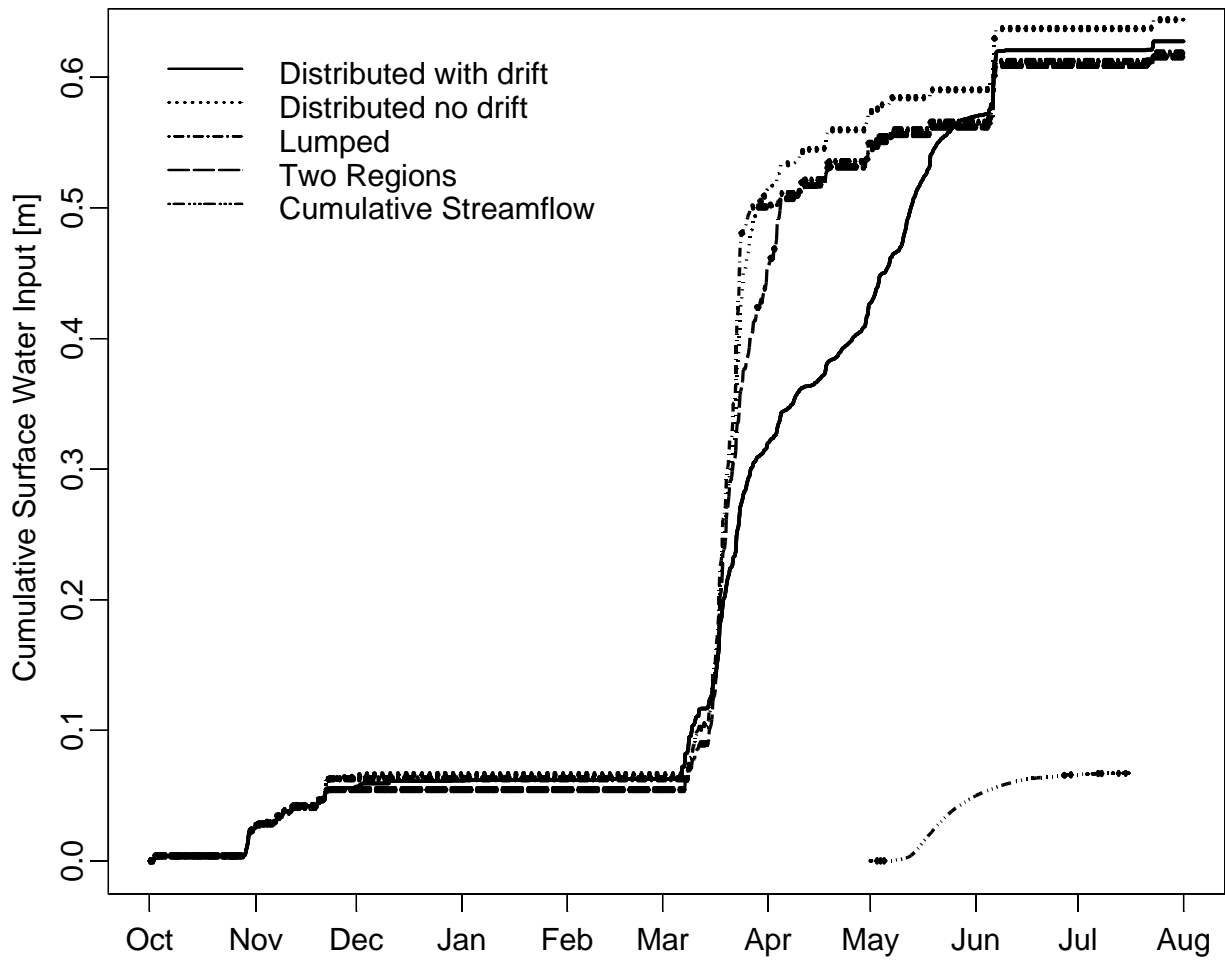
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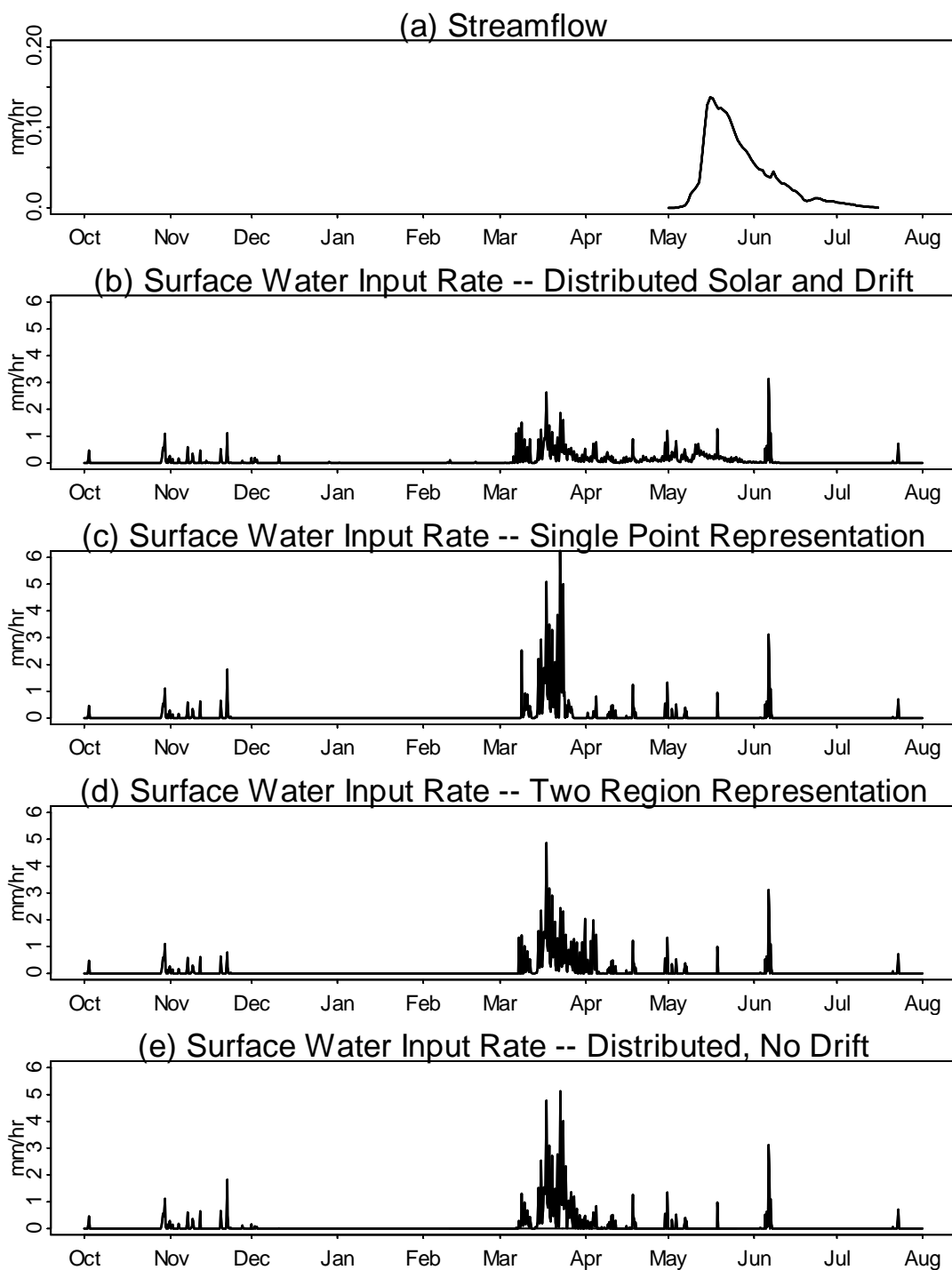
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