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Northwest Watershed Research Center
USDA Agricultural Research Service

Understanding the Hydrologic Behavior of a Snowmelt-Driven, Small, Semi-Arid Mountainous Watershed

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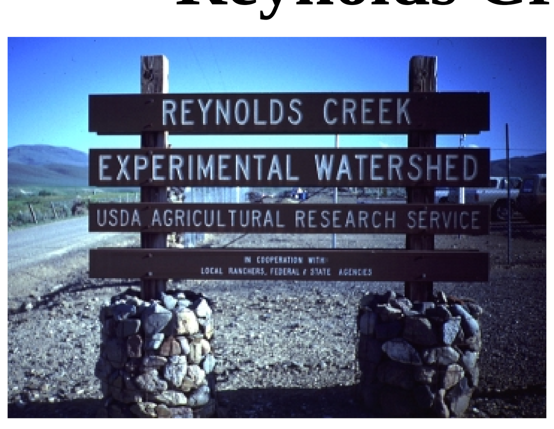
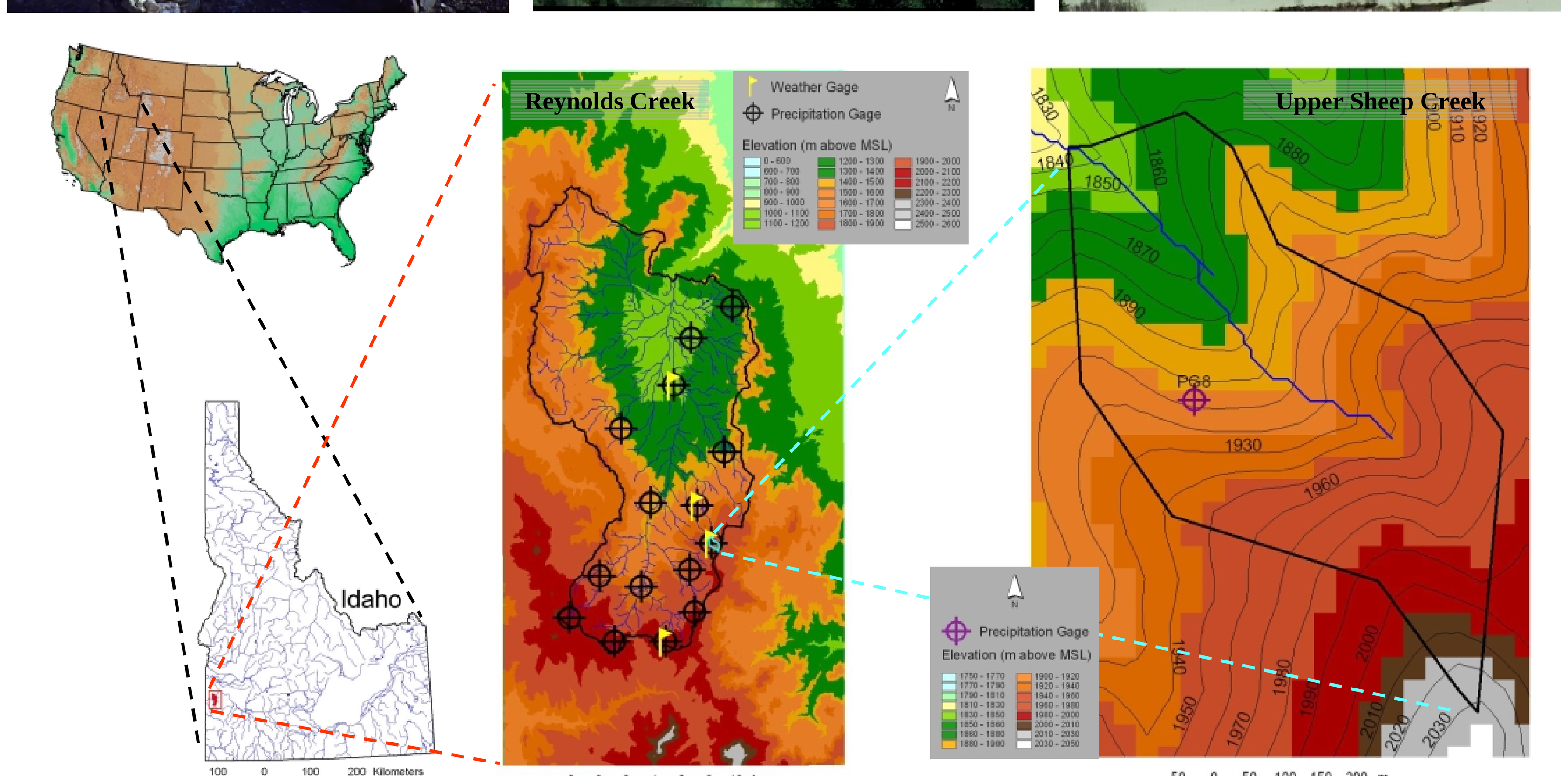
Abstract

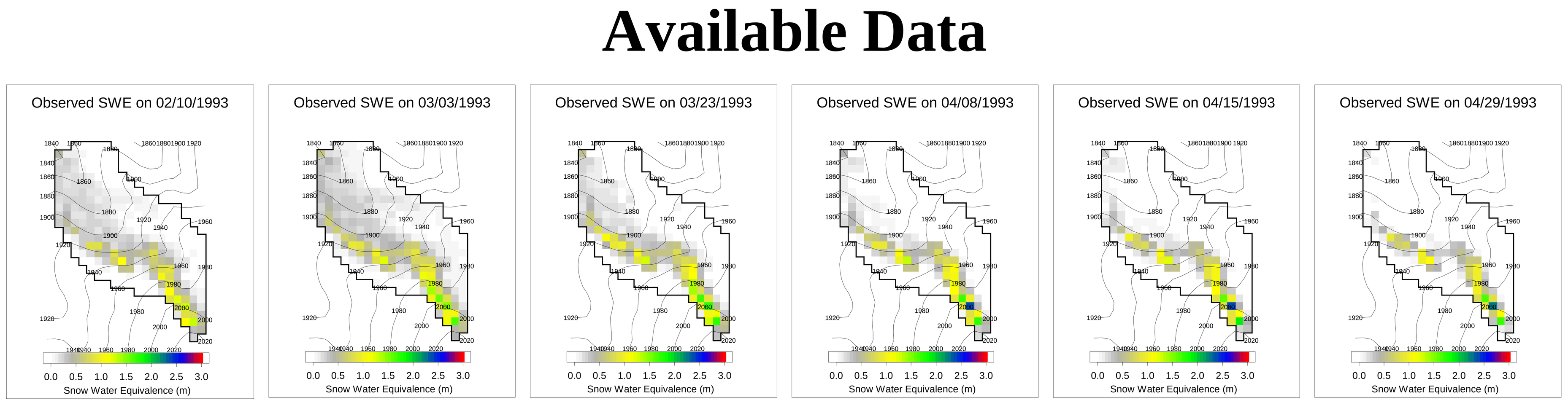
The purpose of this study is to understand hydrologic behavior at a small semi-arid mountainous watershed in order to construct a hydrologic model, which can later be scaled up to larger watersheds in the same region. We take a data intensive approach to understand the hydrologic processes acting in the watershed. Measurements used include maps of snow water equivalence surveyed manually on a 30 m grid, streamflow, precipitation, weather and radiation. Wind driven snow drifting combined with variable radiation exposure on rough terrain produces a consistent (from year to year) spatial distribution of snowpack in the watershed. Spatial variability of surface water input is identified as the dominant hydrologic process in this watershed. We use the drift factor approach to parameterize wind blown snow drifting in the watershed. The drift factors are obtained by calibration using manually surveyed snow water equivalence maps during the accumulation and drift period. Earlier studies have examined annual water balance at this watershed by dividing the watershed into three zones based on drift patterns, soil types and vegetation. We show that these zones can be obtained from the distribution of calibrated drift factors. The timing of surface water input on the zone corresponding to deep drifts on the north-facing, leeward slope corresponds closely with the timing of streamflow at the outlet. A lumped hydrologic model is developed which consists of (a) simple parameterization of evapotranspiration, (b) infiltration into the soil zone and recharge to the saturated zone, and (c) subsurface storage-discharge function. This model, applied to each of the three surface water input zones individually is shown to be sufficient to parameterize the volume and timing of runoff from this watershed.

Reynolds Creek Experimental Watershed

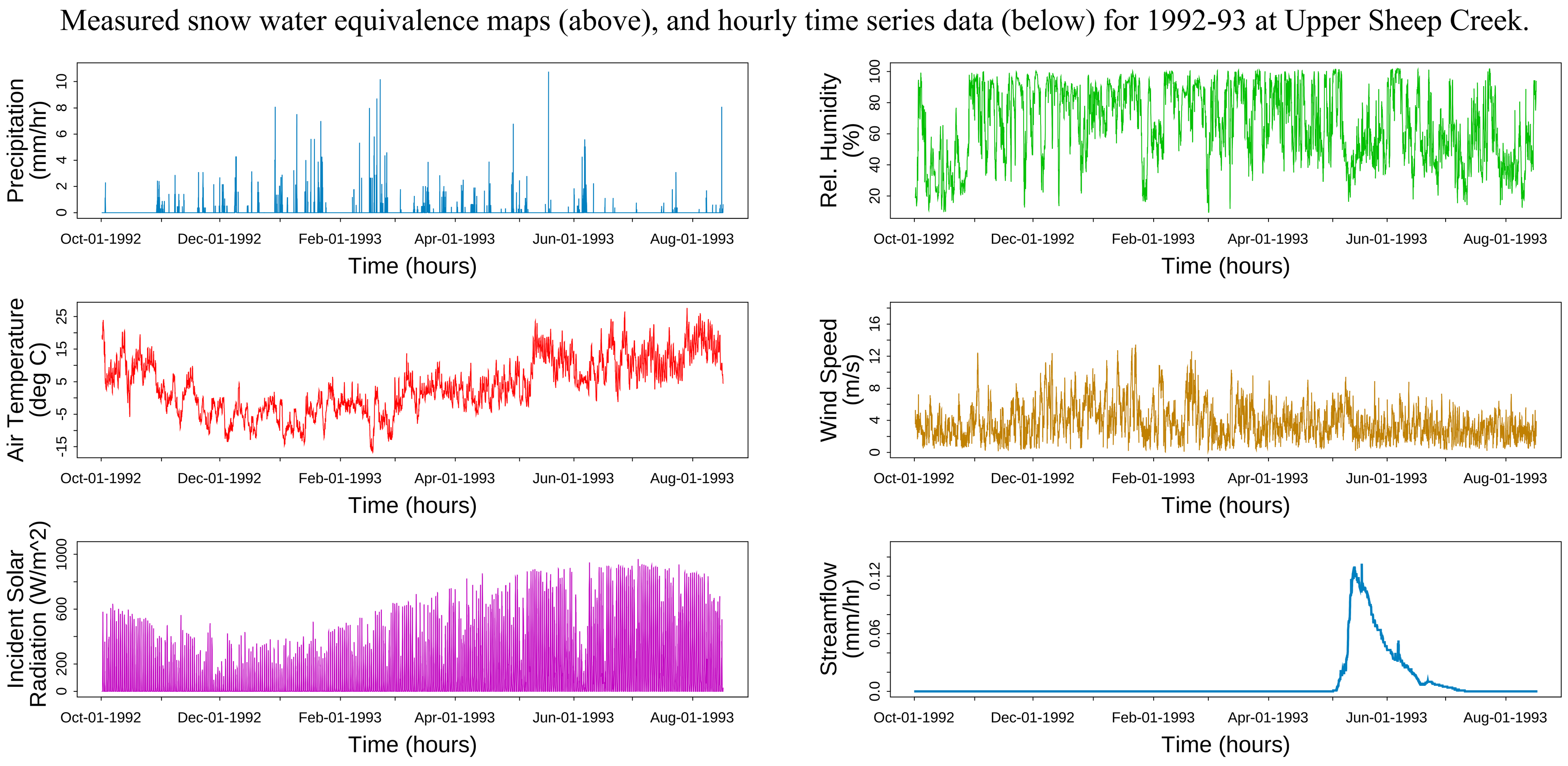




Available Data

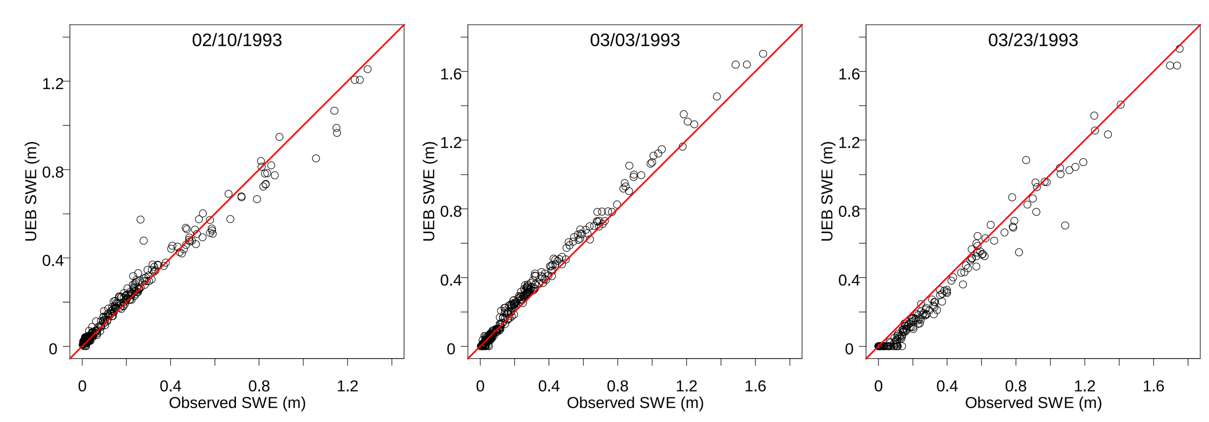


Measured snow water equivalence maps (above), and hourly time series data (below) for 1992-93 at Upper Sheep Creek.



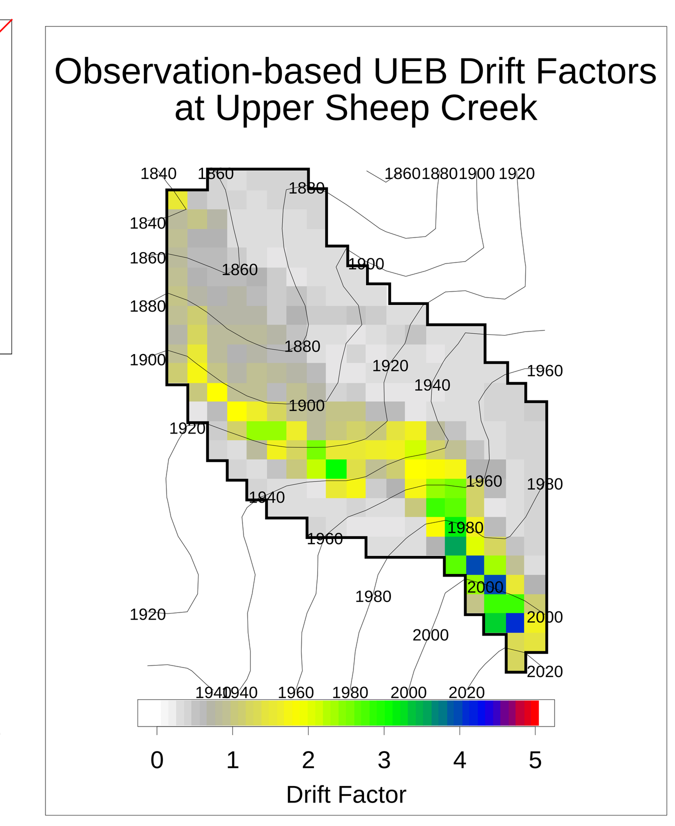
Snow Drift Factor

Snow drift factor is a spatial field which is used to parameterize wind-induced snow drifting. It is defined as a factor by which gage snowfall must be multiplied to equate measured and modeled snow water equivalence (SWE) on the ground. It describes the propensity of a location to accumulate extra snow through drifting (drift factor > 1), or to lose snow due to scouring (drift factor < 1). This approach approximates drifting which follows snowfall as occurring concurrently with snowfall. This approach also amounts to an assumption of linearity in the spatial pattern of snow accumulation. If precipitation is doubled, the spatial pattern is assumed to remain the same, while the amount of SWE doubles at each location. In order to estimate the drift factors over the watershed, a physically-based point model, the Utah Energy Balance (UEB, Tarboton et al., 1995; Tarboton and Luce, 1996) snow accumulation and melt model was applied to each grid cell at Upper Sheep Creek (USC). Using the model in this way provides an approach to account for the melt that occurs during accumulation and drifting. Snowmelt during the accumulation and drift period is usually small, yet significant. The first three manually surveyed SWE maps during 1992-93 (dates 02/10/1993, 03/03/1993 and 03/23/1993) were used to carry out a point-by-point calibration of the drift factors. The objective function used was the sum of the signed differences between modeled and measured snow water equivalence on these three dates. The objective function was monotonic with respect to the drift factor at each grid cell. Drift factor at each grid cell was thus obtained as the value which makes the objective function close to zero at that grid cell.



Date	R^2
02/10/1993	0.9737
03/03/1993	0.9774
03/23/1993	0.9687

Scatterplots of modeled vs. observed SWE at USC during 1992-93 (top). The calibrated observation based UEB drift factors are shown on right. Modeled (UEB) SWE is obtained by UEB running over the USC grid using observation-based (calibrated) UEB drift factors for parameterization of wind-induced snow drift.



Snowmelt

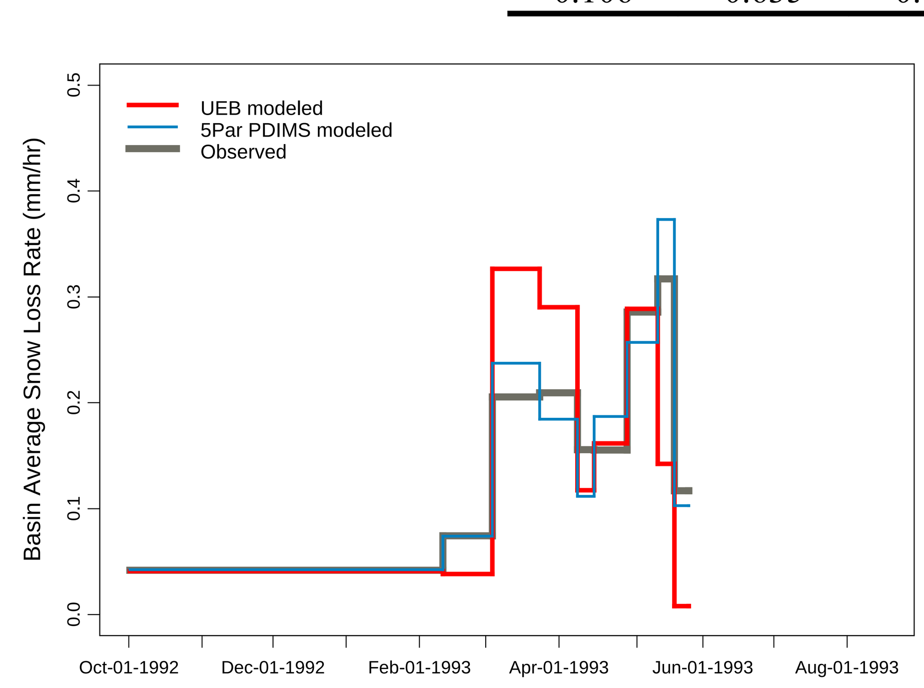
The drift factors were calibrated using UEB to estimate snowmelt during the accumulation and drift period. It was found, however, that UEB tends to overestimate melt during the melt season. Since our goal is to best estimate the spatially distributed surface water input, we chose to sidestep this discrepancy, and calibrated an index-based snowmelt model to interpolate snowmelt between observations. The Pseudo-Distributed Index-Based Model for Snowmelt (PDIMS) estimates melt as:

$$M = M_f \cdot \max[R \cdot (T_a - T_b), 0]$$

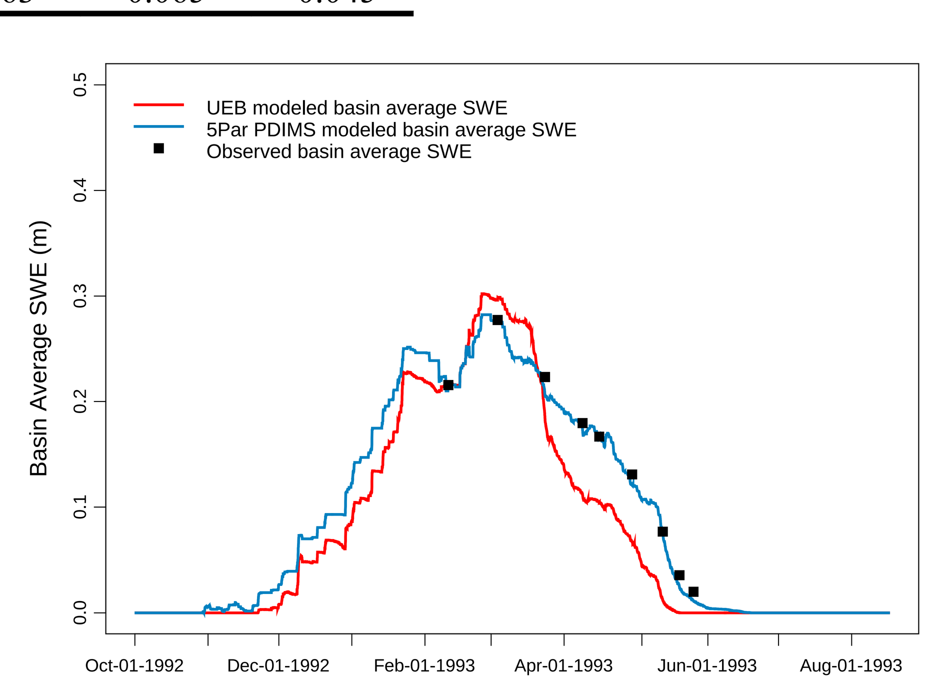
Here M is rate of snowmelt in m/hr, M_f is a parameter (the melt factor, m/hr/(W/m^2)/^{o}C), T_a is air temperature (^{o}C), T_b is a reference base temperature (0 ^{o}C) and R is net radiation (W/m^2). The melt is assumed to be influenced by spatially varying factors, which are captured by radiation, which was modeled over the terrain. Incident solar radiation was measured at hourly interval at USC. Direct and diffuse parts of the incident solar radiation were estimated as described by Erbs et al. (1982). Incoming longwave radiation was estimated using air temperature and humidity. Outgoing longwave radiation was estimated based on ground conditions (snow/bare ground). The melt factors are assumed to vary over monthly time scales, which gives us five melt factors (January through May) to calibrate. The calibration was carried out using NLFIT (Kuczera, 1994).

Calibrated melt factors at USC

January	February	March	April	May
0.106	0.635	0.063	0.065	0.045



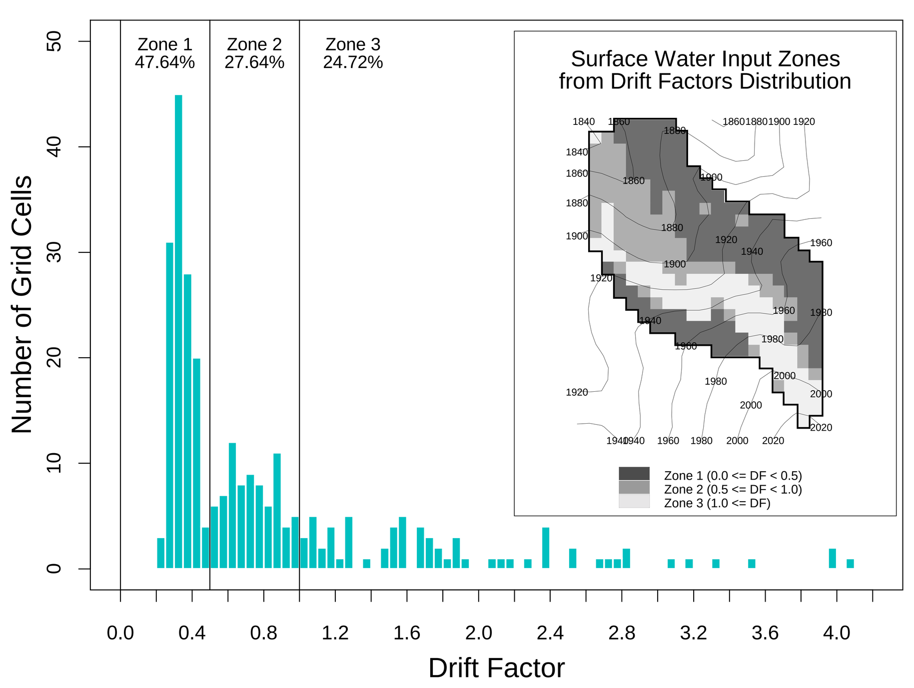
Basin average snow loss rate is the average rate at which snow is depleted (melted or blown away) from the watershed computed for each inter-measurement time period.

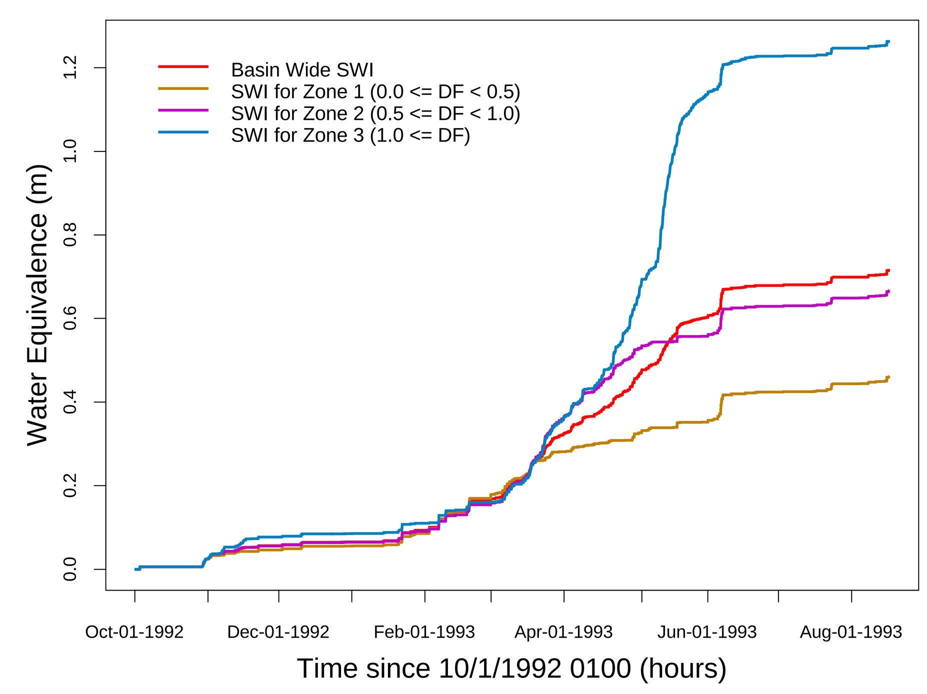


Basin average snow water equivalence (m) modeled by UEB (red line) and 5 Par PDIMS (blue line). The black rectangles are basin average SWE obtained from observations.

Surface Water Input

Surface water input (SWI) is defined as the amount of water (snowmelt + rainfall) available for infiltration into soil at any time step at any grid cell. Three SWI zones have been described to exist at Upper Sheep Creek, which correspond to locations of the snow drifts and the timing of their melt (Cooley, 1988), or a combination of soil and vegetation zones (Flerchinger et al, 1998). Here we define these zones based on the drift factors. In the figure below, three modes can be approximately identified on the histogram of drift factors at USC. The zones corresponding to these breaks are very similar to those described by earlier studies. This gives us a quantitative basis for delineating SWI zones, and also provides a description of the dominant source of hydrologic variability (distribution of SWI) within the watershed.





Comparison of the cumulative SWI time series with observed outflow revealed that the rapid rise in SWI during May on Zone 3 coincides with the appearance of streamflow at the outlet of USC. This leads us to believe that the outflow from USC occurred mostly in response to melting of the deep snowdrift on Zone 3 during May. A simple subsurface model may be able to simulate the observed hydrograph at the outlet. We developed and calibrated a simple water balance model to verify this hypothesis.

Dominant Zone Hydrologic Model (DZHM)

The model consists of four components: (1) evapotranspiration, (2) infiltration and excess runoff, (3) saturated zone recharge and (4) baseflow, described below.

Evapotranspiration: Potential evapotranspiration (*PET*) is computed from Priestly-Taylor equation. Actual evapotranspiration (*AET*) is then computed depending on moisture availability in the soil store.

$$PET = \alpha \frac{\Delta}{(\Delta+\gamma)} \frac{R_a}{\lambda \cdot \rho_w} \qquad AET = K_{veg} \cdot f_{AET} \cdot PET$$

Here α is the Priestly-Taylor coefficient [1.74 for arid climate, Shuttleworth (1992)], Δ is the gradient of the saturated vapor pressure – temperature curve at air temperature, γ is the psychometric constant at air temperature and pressure, λ is the latent heat of vaporization of water (kJ/kg), ρ_w is the density of water (kg/m^3), and R_a is a measure of available energy (net radiation, kJ/m^2/hr). The factor f_{AET} is the ratio of actual to potential evapotranspiration and is 1.0 when moisture content exceeds field capacity, and falls linearly to 0.0 as moisture content decreases from field capacity to wilting point. The coefficient K_{veg} accounts for the vegetation type.

Soil Zone: The active capacity of the soil zone is divided into components between the volumetric moisture content at saturation θ_s, field capacity θ_r and wilting point θ_w. We define $\Delta\theta_1 = \theta_s - \theta_r$, $\Delta\theta_2 = \theta_r - \theta_w$ and $\Delta\theta = \Delta\theta_1 + \Delta\theta_2$. The soil zone is characterized by a depth z_r (m), which gives a capacity parameter SOILC:

$$SOILC = z_r \cdot (\theta_s - \theta_w) = z_r(\Delta\theta_1 + \Delta\theta_2) = z_r \Delta\theta$$

The state of the soil zone is denoted by *SR* (m), and potential rate of infiltration is computed using a Green-Ampt like formulation:

$$i = K_o \cdot e^{-f \cdot z_f} \frac{z_f + \psi_f}{z_f} \qquad z_f = \frac{SR}{\Delta\theta}$$

where K_o is the hydraulic conductivity of soil at the surface (m/hr), f defines the rate of exponential decrease of K_o with depth (1/m), and ψ_f is the wetting front soil suction head (m). This assumes that for the purposes of infiltration excess calculation all moisture in the soil zone is in a saturated wedge at the surface above a wetting front. Drainage from the soil zone to the saturated zone is computed using:

$$r_d = K_o \cdot e^{-f \cdot z_r} \left(\frac{\max(0, SR - z_r \cdot \Delta\theta_2)}{z_r \cdot \Delta\theta_1} \right)^c$$

This assumes for the purposes of drainage calculations that the moisture content is uniform over the soil zone and drainage occurs when moisture content exceeds field capacity. The maximum drainage rate is assumed to be equal to hydraulic conductivity at the base of the soil zone with drainage reducing as moisture content reduces according to a pore disconnectedness parameter c. These are recognized to be gross simplifications. Nevertheless they capture the major sensitivities in a relatively simple way.

Saturated Zone (baseflow): Our analysis of saturated zone storage and measured discharge showed evidence that the saturated zone at USC acts as a bucket-like store, which overflows when storage exceeds a threshold. The relationship between storage and discharge beyond the threshold was not clearly established from analysis of data, and we chose to employ a general power-function like relationship, given by:

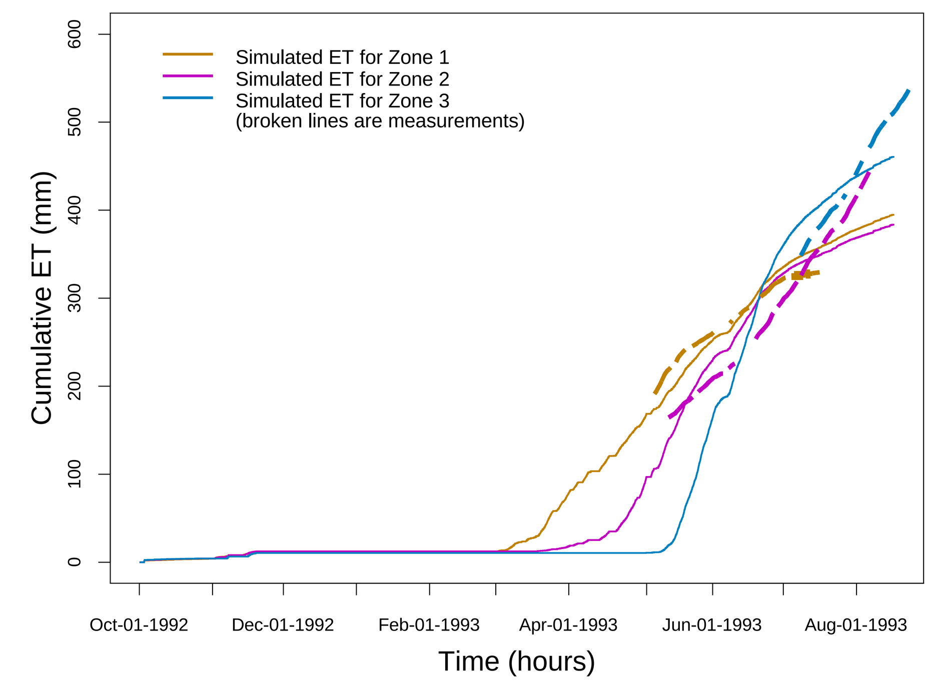
$$\begin{aligned} Q_b &= 0 & \text{if } z_i \le \bar{z} \\ &= K_o \cdot e^{-f \cdot \bar{z}} \cdot (z_i - \bar{z})^{\eta} & \text{if } z_i > \bar{z} \end{aligned}$$

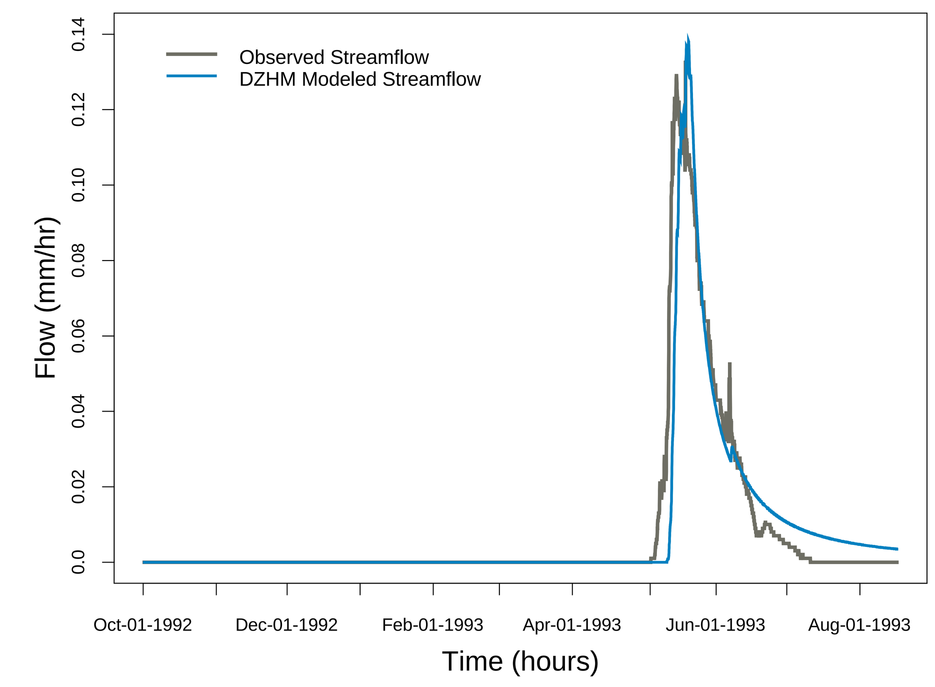
where Q_b is the baseflow (m/hr), $\bar{z}$ is the state variable denoting the average depth to the water table (m), z_i is the threshold above which "the bucket spills" (m) and η is the an exponent.

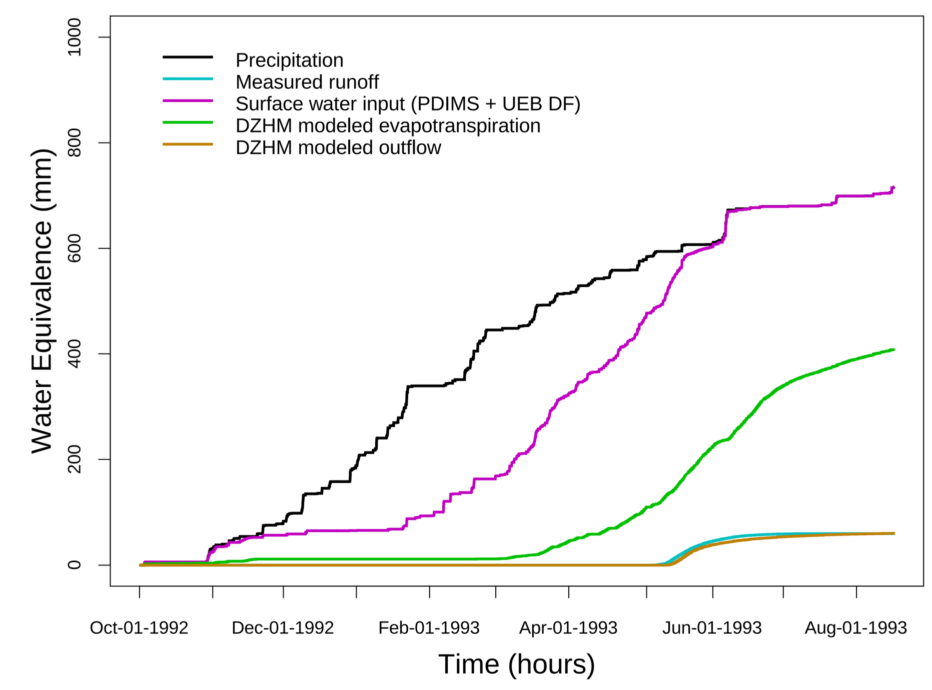
Calibration of DZHM at USC

DZHM was calibrated at USC using NLFIT (Kuczera, 1994). The calibration was carried out in two phases. In the first phase, the parameters z_r and K_{veg} were calibrated for the soil zone model, while keeping f and K_o at some nominal values. The soil zone capacity parameter z_r was assumed to be uniform across zones, while K_{veg} was different for each zone. This calibration used measured ET data at USC (Flerchinger et al., 1998). In the second phase of calibration, the saturated zone parameters z_i and η were calibrated along with K_o and f, using measured streamflow at USC outlet. Computed ET after the second phase was found to be insensitive to change in the values of K_o and f from first phase to second phase, and so we did not iterate on calibration phases. Simulated ET, simulated streamflow and mass balance component details obtained from the calibrated DZHM run are shown below.

DZHM Calibration Results







DZHM Simulated Mass Balance at USC

	Zone 1	Zone 2	Zone 3	Total
Surface Water Input (mm)	459.9	665.3	1263.2	715.2
Actual ET (mm)	394.8	383.7	460.8	408.0
Runoff (mm)	0.0	0.0	243.8	60.3
Change in Soil Storage (mm)	25.1	18.4	25.6	23.4
Change in Ground Water Storage (mm)	40.0	263.3	533.1	223.6
Measured Runoff (mm)				59.7

Top left: Comparison between simulated and modeled ET at USC. ET was measured over three plant communities at USC during 1992-93. These communities are assumed to represent the average zone behavior. Top right: Comparison between simulated and measured outflow hydrograph at USC. The timing and volume of annual streamflow are reproduced well. Bottom left: Annual cumulative mass balance components at USC. The difference between precipitation (black line) and surface water input (purple line) is surface storage as snow. Bottom right: Mass balance components at USC during 1992-93.

Summary

- Spatial pattern of snow water equivalence which results from wind-blown snow drifting is identified as the dominant source of variability within a small, snowmelt-driven, semi-arid watershed. Wind-induced drifting is parameterized by drift factors.
- Surface water input zones can be quantitatively delineated using the distribution of drift factors.
- Subdividing the watershed into surface water input zones is necessary for modeling timing of streamflow.
- A simple water balance model running on surface water input zones is sufficient to describe the annual streamflow and overall mass balance.
- This model shows contributions to total runoff from each zone.

Future Work

- Surface water input zones delineated using the distribution of drift factors can be used to extend the model to larger areas.
- Drift factors are impractical to obtain by measurement of spatial pattern of snow water equivalence on multiple dates at spatial scales much larger than that of USC. We are examining the possibility of obtaining drift factors from a blowing snow model (Liston and Sturm, 1998), which describes the transport of snow in response to wind.

Acknowledgment

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