Table 1. Error in Computed n Using Eq. (4) of Michel's Discussion

	Nash parameter (n)			Error (%)=100×(actual–computed)/computed	
β	Actual	Eq. (8) (original paper)	Eq. (4) of Michel's discussion	Eq. (9) (original paper)	Eq. (5) of Michel's discussion
0.0421	1.05	1.06195	1.047983	–1.138093	0.192114
0.2420	1.50	1.501197	1.487887	–0.079832	0.807520
0.3679	2.00	2.000082	1.987401	–0.004103	0.629960
0.4625	2.50	2.504786	2.488031	–0.191422	0.478772
0.5265	2.90	2.902878	2.888539	–0.099229	0.395221
0.5413	3.0	3.002550	2.988654	–0.084992	0.378192
0.6102	3.5	3.501417	3.489160	–0.040495	0.309705
0.6721	4.0	4.000783	3.989562	–0.019565	0.260955

$$\beta = \frac{n-1}{\sqrt{2\pi(n-1)+1/6}} \tag{1}$$

or

$$n \cong 1 + \pi\beta^2 + \beta\sqrt{1+(\pi\beta)^2} \cong 7/6 + 2\pi\beta^2$$

Singh's viewpoint that Eq. (1) in his discussion is more flexible in inversion is not entirely true, and it can be shown by rewriting Eqs. (8) and (9) of the original paper as a function of n to compute β, as follows:

$$\beta = [(n-1.04)/5.53]^{1/1.75}; \quad 0.01 < \beta < 0.35 \tag{2}$$

$$\beta = [(n-1.157)/6.29]^{1/1.998}; \quad \beta > 0.35 \tag{3}$$

The error in computing β is given in Table 2. It is clear from Table 2 that the use of Eq. (1) in Singh's discussion yields significantly higher error than Eqs. (2) and (3) of this closure. In addition, the computation of β is not possible when n nears 1. Thus, Eqs. (2) and (3) are more flexible, and the resulting error is comparatively less. Nevertheless, all the formulas derived so far by various authors exhibit approximate relations rather than exact analytical solutions of Eq. (1) of the original paper. The error in computing n from λ by using Eqs. (4) of Michel's discussion and (7) of Singh's discussion is more compared with Eqs. (10) and (11) of the original paper, as shown in Table 3.

Table 2. Error in computation of β.

	β			Error (%)=100×(actual–computed)/computed	
N	Actual	Eq. (1) of Singh's discussion	Eqs. (2) and (3) of this closure	Eq. (1) of Singh's discussion	Eqs. (2) and (3) of this closure
1.05	0.04	CNC[a]	0.03	—	—
1.50	0.24	0.23	0.24	4.81	0.20
2.00	0.37	0.36	0.37	1.00	0.59
2.50	0.46	0.46	0.46	0.41	0.18
3.00	0.54	0.54	0.54	0.22	0.07
4.00	0.67	0.67	0.67	0.09	0.01
5.00	0.78	0.78	0.78	0.05	0.00

[a]CNC=Cannot be computed.

Table 3. Error in Computed λ Using Eq. (4) of Michel's Discussion.

	Nash parameter (λ)			Error (%)=100×(actual–computed)/computed	
λ	Actual	Original paper	Eq. (4) of Michel's discussion	Original paper	Eq. (4) of Michel's discussion
0.501994	1.3	1.381105	1.472417	–6.238860	–13.2629
0.466714	1.5	1.466809	1.571511	2.212737	–4.767380
0.366091	2.0	2.009828	2.028371	–0.491390	–1.418560
0.308175	2.50	2.522848	2.516656	–0.913910	–0.666250
0.270837	3.0	3.005101	3.010563	–0.170030	–0.352120
0.244354	3.50	3.502728	3.506369	–0.077950	–0.181980
0.224346	4.00	4.001325	4.002993	–0.033130	–0.074820
0.195682	5.00	4.999876	4.997235	0.002473	0.055306

Authors also assert that λ may not be required in obtaining an SUH as such.

Relation among *n*, λ, and β

It will be appreciated that β is a product of q_p and t_p, therefore, it will not be the same for different (real) storms of different q_p and t_p values. However, there can be a number of q_p–t_p sets for which β is the same. The question of whether β varies with storm characteristics needs more research for a rational explanation. However, with reference to Eq. (12) of the original paper, for a constant value of q_p for a storm, t_p can be related to λ (=q_pK) or K by the following relation:

$$\lambda = \frac{0.636}{1+4.13(\beta)^{1.52}} + 0.029; \quad \beta \geqslant 0.54, \lambda \leqslant 0.27 \tag{4}$$

Therefore, since K is influenced by the incipient moisture conditions and in situ basin storage, β will also be influenced by these factors.

Unit of *q*

In the original paper, the discharge or runoff (q) is taken as the equivalent depth of instantaneous flow per unit time step, and its unit is mm/hr/mm or inch/hr/inch. Such a definition helps make the term β nondimensional.

Finally, the authors gratefully acknowledge that typographical errors were inadvertently introduced and therefore suggest that the readers incorporate the corrections pointed out by the discusser.

Discussion of "Simple Snowdrift Model for Distributed Hydrological Modeling" by M. Todd Walter, Donald K. McCool, Larry G. King, Myron Molnau, and Gaylon S. Campbell

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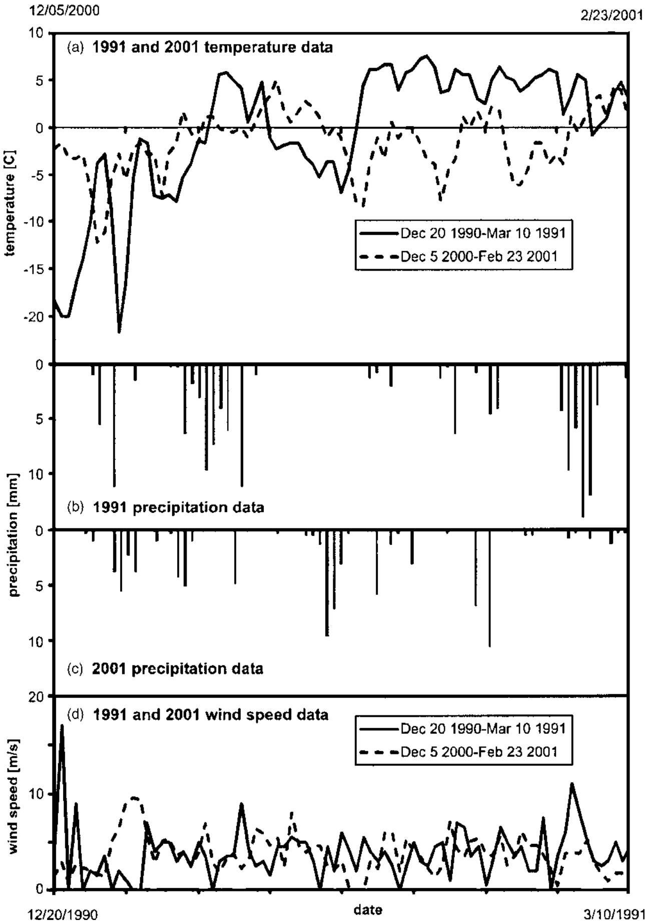

Fig. 1. Summary of the Walter et al. (2004) study period (1990–1991) to the comparison study period (2000–2001): (a) temperature; (b) and (c) precipitation; and (d) wind-speed data when humidity data were available

Although there has been extensive research on snow drifting, specifically its importance in water resources and the understanding of the process, it has received limited use and implementation in hydrological modeling. Many wintertime distributed models have traditionally limited the scope to snow accumulation and snowmelt, and the authors give several examples (DVHSM, SHE, SWAT). Wind movement of snow into, out of, and within a watershed can substantially alter the distribution of snow, and decrease the net mass of snow through sublimation losses during transport. In open terrain, the movement and sublimation of snow has been shown to be significant (Pomeroy and Li 2000). Winstral et al. illustrated that changes in topography in the upwind direction can be used to model the distribution of snow.

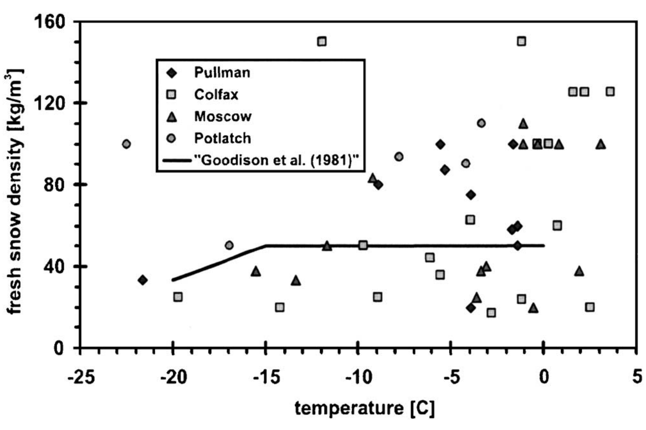

Fig. 2. Fresh-snow density estimates for the Walter et al. (2004) study sites and surrounding locations

The authors present a simple snowdrift model that is meant to be easier to use than more complex models, such as PBSM (Pomeroy et al. 1993), Piektuk (Déry et al. 1998), and SNOWTRANS-3D (Liston and Sturm 1998). The main purpose is to be able to incorporate the snow-blowing process into a distributed hydrological model with an emphasis on "*simplicity… to avoid overly complex parameterization*" (Walter et al. 2004).

The author's snowdrift model can move any fresh snow that is on the ground (drift of falling snow is not considered) if the wind speed exceeds a threshold that is based on the snow's shear velocity, which is a function of the square root of the fresh snow density. The fresh snow density is computed from Goodison et al. (1981); for air temperatures (T_a) warmer than $-15°C$ it is set at 50 kg/m^3 and for colder temperatures it is computed as $50+3.4$ (T_a+15). Snow leaves the surface at disruptions in the wind profile, in particular on the lee side of a hill or end of vegetation. The model uses a two-layer snowpack where new snow overlays old snow; upon densification greater than 150 kg/m^3, new snow is incorporated into the old snow layer and is not available for movement. When drifting occurs, the model assumes sublimation from the snowpack surface, which can be up to twice the snow flux moved by drifting. The model was applied to an isolated hill 10 km northeast of Pullman, Wash., for the period from December 20, 1990, through March 10, 1991, and is compared to a series of eight days of snowpack measurements. The forcing meteorological data for the study was taken from a station 3 km Northwest of Pullman. The model accumulates snow at air temperatures colder than $0°C$ from precipitation data that has not been corrected for snowfall-measurement inaccuracies, such as wind undercatch.

The results presented in Fig. 3 of Walter et al. (2004), illustrate that the model tends to underestimate snow water equivalent (SWE) except in areas of drift accumulation. The snowdrift model matched the observed spatial and temporal trends across the study hill slope with an r^2 of 0.95, compared with a no-drift simulation correlation of 0.33. The differences between measured and observed snowdrift results were the same magnitude as modeled snowmelt errors. The results of the sensitivity analysis found the most important factor to be fresh-snow density.

The authors ignore snowfall undercatch due to wind, which can be very important in windswept environments. Sublimation from the snowpack may have been overestimated, which could have contributed to the overall underestimation of snow accumulation upwind and downwind of drift accumulation areas. The density of fresh snow was estimated at 50 kg/m^3 since there was no precipitation measured on either day that was colder than $-15°C$. This may be an underestimation of density that would yield a lower threshold wind speed from Kind's (1981) threshold shear velocity equation, which would overestimate the amount of snowdrift. These issues will be presented in this discussion.

The authors use 81 days of daily data that are the same as those recorded at the Pullman 2NW National Weather Service (NWS) COOP station (ID 456789) (archived at NCDC 2004). As humidity data were not available at this site for the same period, a period of similar meteorological conditions (temperature, precipitation, and wind speed) from December 5, 2000, through February 23, 2001, from the nearby Pullman/Moscow airport (Fig. 1) was used to compute the snowpack sublimation, hereafter called the comparison study period.

The average daily wind speed for the 81 days of the study period is 3.8 m/s with 9 days of no wind. Assuming that the precipitation is measured by a precipitation gauge shielded with an Alter-shield, the total precipitation over the study period would increase from 142.5 to 161.3 mm, or 12.9% by considering wind undercatch, as per Goodison et al. (1998), and assuming that daily trace events contributed half of the measurable amount of precipitation, i.e., 0.127 mm. For the 81 days in 2000–2001, the increase would be from 91.3 to 136.7 mm, or 49.7%.

Sublimation from the snowpack can be estimated using the latent heat-flux equation, i.e., using wind speed and vapor-pressure deficit with the assumption that surface vapor pressure is saturated and can be computed from the ambient air temperature (Fassnacht 2004). A surface roughness height of 0.01 m was used, as per Walter et al. (2004). From the comparison study, the snowpack sublimation was computed to be 26.5 mm (0.327 mm/day) and occurred 37.5% of the time. Since the humidity is high in the area (the average relative humidity is 91.2%), the sublimation is likely vapor-pressure limited (the average vapor-pressure deficit was 0.468 mb). Even if the process was not vapor-pressure limited, then the latent heat flux would be an overestimate.

While Walter et al. (2004) do not present the sublimation rates, the computed snow fluxes were only a portion of the snowpack sublimation computed from the latent heat flux.

The formulation used to estimate fresh snow density could not be found in Goodison et al. (1981). Other formulations exist in the literature, as summarized by Fassnacht and Soulis (2002), all of which use higher densities than the formulation presented by the authors. While The authors' formulation decreases at temperatures colder than $-15°C$, Fassnacht and Soulis (2002) suggested that the density of fresh snow may actually increase at temperatures colder than $-16°C$ due to a general decrease in snow crystal size at cold formation temperatures. Using a fresh snow density, such as presented by Hedstrom and Pomeroy (1998), resulted in only 23.4% of the snowdrifting flux computed by Walter et al. (2004).

Snow data are available from the Pullman, Wash., site. Using these data and data from surrounding NWS stations, the observed SWE was divided by the snow depth to compute an approximate fresh snow density (Fig. 2). The plot illustrates that there is a large variation in fresh snow density, with few daily observations of 50 kg/m^3 fresh snow density.

Based on the average daily air temperature, precipitation can fall as snow at air temperatures warmer than 0°C (Fassnacht and Soulis 2002). This would increase snow accumulation.

The authors corroborate the model's snowmelt performance by comparison to observed snowmelt at four sites (Danville, Vt., Bloomville, N.Y., Easton, Minn., Troy, Ind.). However, the snowdrift model is not used in these areas, and while it is used for Pullman, the snowmelt component of the model is not used. A simulation of the model's snowpack performance for snowdrifting plus accumulation and snowmelt at the same site would better illustrate the model's capabilities and the integration of the simple snowdrift formulation within the distributed hydrological model, as per the paper's title and its objectives.

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Closure to "Simple Snowdrift Model for Distributed Hydrological Modeling" by M. Todd Walter, Donald K. McCool, Larry G. King, Myron Molnau, and Gaylon S. Campbell

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We appreciate the discussion of Fassnacht and Brazenec, which emphasizes the difficulty in parsimonious modeling on snow processes and suggests some potential improvements to the approaches we used in our snowdrift study. They speculate that our study may have underestimated snowfall, overestimated snowdrift, and overestimated sublimation. While these may be true, our methods were not without justification, as discussed below.