Advanced Review

Snow redistribution for the hydrological modeling of alpine catchments

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Modeling snow redistribution by wind and avalanches in hydrological studies in alpine catchments is important, as the spatial variability of the snow cover has an impact on timing and magnitude of the snowmelt runoff. Disregarding snow redistribution in models can lead to the formation of 'snow towers,' i.e., multi-year accumulation of snow at high elevations and an incorrect water balance. The reviewed approaches to deal with snow redistribution in hydrological models were first broadly grouped by the represented physical processes: (1) the correction of the precipitation input data to account mainly for preferential deposition, (2) the description of all wind-driven processes based on wind field data, (3) the description of gravitational transports and/or wind-driven processes based on topographic information, and (4) the statistical description of the variability of the snow water equivalent (SWE) to account for all types of snow redistribution. The review further assessed the implementation of these approaches in physically based and bucket-type hydrological models. Generally, snow redistribution consideration has improved the simulation of snow patterns and SWE and consequently the prediction of discharge in mountain catchments worldwide. Snow redistribution approaches still have some limitations and a large gap exists between the knowledge and processes in highly detailed physically based snow models and the widely used bucket-type hydrological models used for water resources and climate change studies. There is a real need to bridge this gap using the knowledge earned by snow redistribution modeling with established physically based models to develop more conceptual approaches for the application in bucket-type models.

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INTRODUCTION

Snow and ice can play an important role for temporary water storage in many regions with seasonal climates worldwide as they shift winter precipitation to runoff during the spring to summer melt period. This is particularly relevant in alpine catchments, which provide lowland areas with water during drier seasons.[1,2] A good understanding of snow processes in alpine catchments is therefore important for water management now and in the future and there is a real need for robust modeling of snowpack in hydrological models.

Snowpacks in alpine catchments are characterized by a high spatial variability of the associated

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water stored in them, i.e., the snow water equivalent (SWE), and that variability can impact the snowmelt hydrograph at the catchment outlet.[3] Snow cover distribution influences the energy balance of the catchment, the timing, and the magnitude of snowmelt runoff.[3–5] If snow is evenly distributed on the ground, melt processes occur simultaneously and uniformly for the same energy input. In contrary, in case of uneven distribution of snow, differences in melt rates will occur. Areas with little snow cover might become snow free sooner than areas with a large amount of snow, where more energy is needed for the melting processes and where water is therefore stored longer in the snowpack.[4,5] Such differences in snowmelt are particularly visible at the end of the ablation season when mountains are covered with patchy snow. As a result, the snowmelt hydrograph is dampened and the peak is delayed[6] (Figure 1). The impact of the spatial distribution of the snow cover on the snowmelt runoff hydrograph is influenced by the spatial scale of the studied area.[7,8] The heterogeneity of a snow cover may also impact the amount of particles and solutes from atmospheric deposition trapped in snowpack and later released to runoff.[9] Furthermore, several studies showed that snow cover variability influences spatial variability of vegetation cover, as well as growth rate and maximal plant height in alpine catchments as, e.g., in the central European Alps,[10,11] in central Norway,[12] or in Wyoming (USA).[13]

The processes responsible for spatial variability in snow accumulation on the ground can be classified into five main processes which vary in their spatial scale[4]: (1) variable snow deposition due to the forest canopy, (2) snow trapping by tall shrubs, (3) preferential deposition of snow in sheltered areas as well as erosion and deposition of snow by wind, (4) sloughing and avalanching and variability in freezing levels, and (5) variable ablation due to variable melt energy due to topography. In alpine catchments, snow redistribution (3 and 4) occurs frequently as such regions are characterized by steep slopes, strong winds, and low vegetation cover. These processes can induce snow cover variability at a spatial scale up to 1000 m[4,14] and can be relevant for runoff-generation processes. As an example, model results obtained by Ragettli et al.[15] showed that 5% of the annual water inputs to the hydrological system in the glacierized upper Langtang catchment in the Himalayas (Nepal) were due to snow redistribution by avalanches. Snow redistribution also plays an important role in glacier formation and conservation, as glaciers are usually located in areas with higher snow accumulation, often due to the steep topography surrounding the glaciers.[14] These processes can even explain the survival of some small glaciers at unusually low elevations in the European Alps.[16] Snow erosion from steep slopes also influences the albedo and reflected shortwave radiation on the slope surface and impacts the melt processes on areas surrounded by such slopes.[17] Furthermore, snow redistribution influences the amount of snowmelt retention in the snowpack,[5] the snow sublimation at wind-exposed mountain ridges,[7,18] the

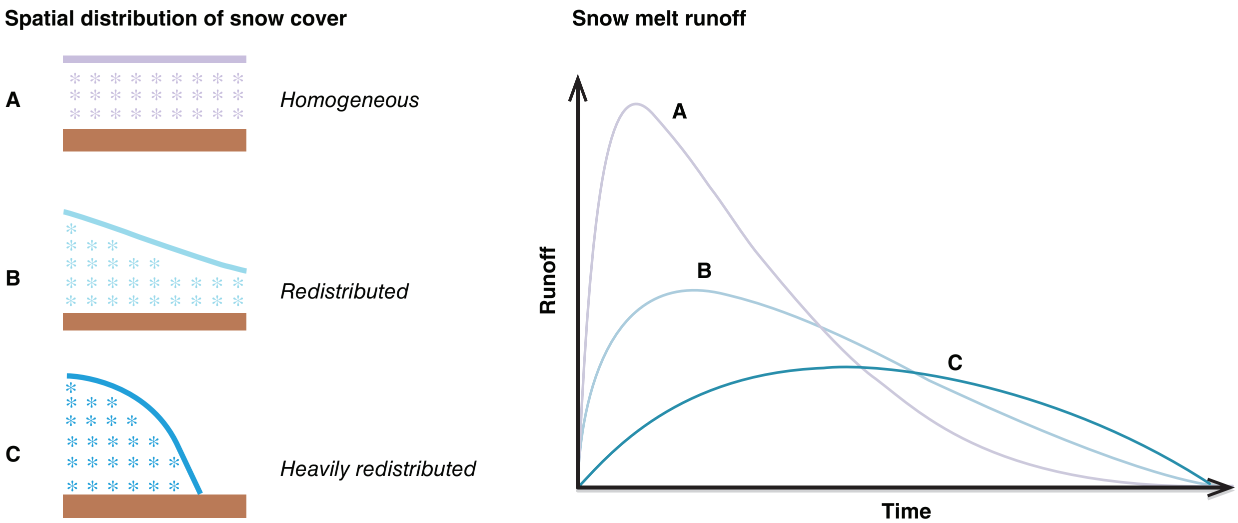

FIGURE 1 | Hypothetical impact of snow redistribution on runoff generation. In case A, snow is evenly distributed on the ground and melt processes occur simultaneously and uniformly. In cases B and C, snow was redistributed and is therefore unevenly distributed leading to a shift in the melting of the snow. One part of the area is at some point not snow covered anymore and does not generate snowmelt, while the other part is still snow covered and will need more energy and time to continue melting and to release the same water volume.

humidity and heat fluxes in the lower atmosphere boundary layer,[19] and the vegetation cover.[20] Thus, snow redistribution needs to be accurately represented in hydrological models in order to compute runoff and glacier mass balance adequately.

Snow redistribution processes can also be observed at low altitudes in low relief landscapes in cold and continental mid- and high-latitude climates as, e.g., in the Canadian Prairies, the USA Great Plains, or across the Arctic. These regions are characterized by extremely strong winds and cold snow. Whereas snow redistribution processes in these regions are primarily driven by the strength of the winds and the snow quality, in alpine catchments snow redistribution processes are mainly influenced by a strong interaction between wind and steep topography. The challenges in snow redistribution modeling are hence different for the different regions. This review focuses only on existing approaches for snow redistribution in hydrological models for use in alpine catchments in mid-latitude, mountain regions.

Over the past decades, several approaches that describe the controlling processes of snow redistribution have been developed for all kinds of hydrological models; essentially they describe the relationship among between terrain properties, meteorology, and snow cover. This review paper describes briefly the processes leading to snow redistribution and the consequences in hydrological modeling if these processes are ignored in mountain areas, before reviewing approaches to represent snow redistribution in hydrological models. Altogether, around 65 relevant studies and model descriptions were considered. This review groups and summarizes the approaches used and the way they are implemented and applied within hydrological modeling studies.

MECHANISMS BEHIND SNOW REDISTRIBUTION

Processes leading to snow redistribution in mountains are complex as they are influenced not only by both, terrain properties and wind fields, but also by snow age, snow quality, and vegetation cover.[21,22] Furthermore, snow redistribution usually takes place in remote areas with complex topography and extreme weather conditions making measurements of precipitation, wind fields, and other meteorological factors difficult. The amount of recording stations therefore decreases with elevation and there is a lack of spatially representative measurement data in those areas.[23–25] Thus, snow cover heterogeneities often need to be assessed by some form of modeling.

There are three major processes leading to snow redistribution, i.e., gravitational process and two different wind-driven processes. They all start when the vegetation snow holding depth is exceeded (Figure 2). Gravitational processes occur in the form of avalanches when a critical amount of snow is reached on steep slopes, usually depending on snow holding capacity of the vegetation cover (depending on vegetation height), aspect, slope angle, and on snow quality and age.[21] In this case, snow is redistributed by gravitation to the slope base. Wind-driven processes transport snow from wind-exposed (windward) mountain crests to wind-sheltered (leeward) areas. The wind-driven processes can occur during snowfall as preferential deposition[22] or once the snow is on the ground as snow erosion and redeposition.[26] In the first case, snow particles are shifted from their original trajectories by turbulences in the lower boundary layer of the atmosphere and are deposited in wind-sheltered areas when wind speed and updraft decrease.[22,27] In the second case, snow is eroded windward, transported first via saltation and then suspension,[18] and redeposited leeward. Saltation starts when wind speeds at the surface of the snow cover exceed a threshold shear stress. This process strongly depends on snow quality as freshly fallen snow is lighter and therefore more easily eroded than older snow.[22] Finally, the three processes influence each other, as wind-driven snow redistribution can reinforce gravitational processes by loading the top of steep slopes in wind-sheltered areas with large amounts of snow.[22,28]

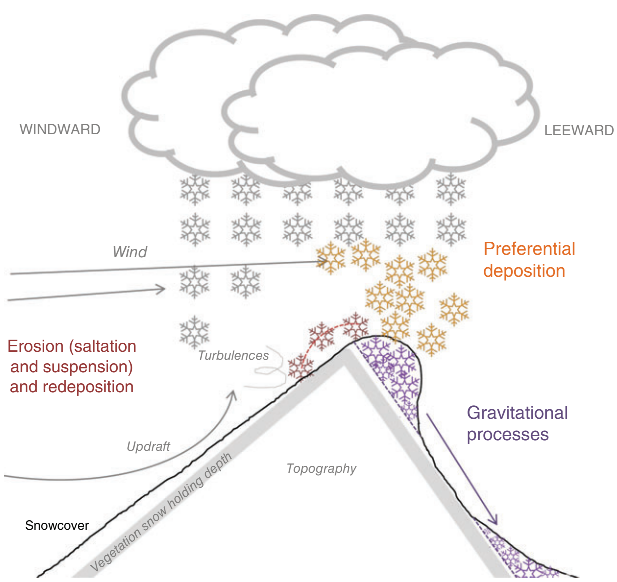

FIGURE 2 | Schematic representation of the three major processes causing snow redistribution.

As a consequence of snow redistribution, exposed mountain crests and steep slopes are often nearly snow free in the accumulation season. In the opposite, wind-sheltered areas, surface depressions, bases of steep slopes or cliffs, and glaciers receive large amounts of snow. Snow redistribution can occur at the microscale as well as at the large scale (up to 1000 m).[4,14] Clark et al.[4] reviewed methodologies for modeling snow cover and identified the spatial scale of snow cover variability induced by snow redistribution as (1) less than 5 m (microscale) for redistribution induced by shrubs, (2) 10–100 m (hillslope scale) for preferential deposition and erosion of snow from the ground and redistribution to wind-sheltered areas, and (3) 10–1000 m for sloughing and avalanching. The spatial differences in snow depths in alpine catchments can be extremely high. For example, Grünewald et al.[29] measured snow depths between 0 and 9 m within 0.6 km^2 in the alpine Albertibach catchment (Switzerland). Similarly, Hiemstra et al.[13] observed snow depth variations of 0–7 m at a ridge (3200 m a.s.l.) in the Medicine Bow Mountains in Wyoming (USA). In contrast, the spatial variability of snowpack at the catchment scale (100–10,000 m) is mainly influenced by the variability in melt energy, i.e., elevation, slope, aspect, and radiation loading.[4,30,31] However, snow redistribution highly depends on snow quality and climatic conditions, with a colder and drier snowpack being more likely to be eroded and redistributed. Some studies showed that wind-driven snow redistribution increases sublimation at mountain crests,[18] while avalanches decrease sublimation amounts.[7]

SNOW TOWERS IN HYDROLOGICAL MODELS

Disregarding snow redistribution in hydrological modeling of alpine catchments does not only impact the timing and magnitude of modeled snowmelt, but also prevents closure of the catchment water balance. As air temperature decreases with elevation, snowfall events may occur all year around in alpine headwater catchments. Overall, more snow may accumulate in high-elevation areas than can be melted during the warm season. Therefore, unrealistic amounts of snow at high elevations, so-called snow towers, are not an uncommon model artifact (Figure 3). In reality, however, summits, cliffs, and very steep slopes are often nearly snow free. Due to wind-induced and gravitational snow redistribution, snow is barely able to accumulate above certain inclinations. Such large amounts of snow represented in a hydrological model would be realistic on glacier areas, where accumulated snow over time is transformed to firn and ice. In other areas, the large snow accumulation lasting over the summer season and leading to snow towers is not realistic. Water stored in such snow towers is then no longer available for runoff generation and is thus removed from the long-term catchment water balance, i.e., added to an increasing storage term. Such issues with snow towers may even go unnoticed in short-term modeling studies (years to decades), while they become particularly evident in long-term modeling (decades to centuries) when they lead to an evidently unrealistic representation of the snow cover.

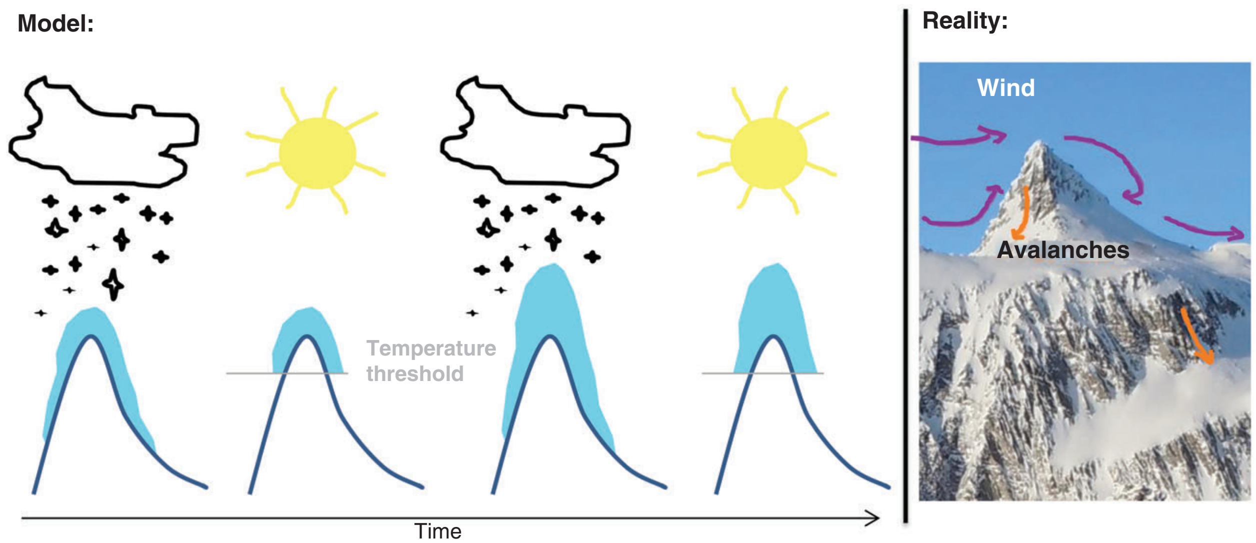

FIGURE 3 | Schematic representation of modeled snow cover resulting after several years in a snow tower at high elevation if snow redistribution is ignored in hydrological models.

To illustrate this snow tower phenomenon, SWE was simulated for the alpine catchment Alpbach in Switzerland (area: 20.7 km^2, mean elevation: 2194 m a.s.l., elevation range: 1022–3192 m a.s.l., glacier coverage: 30%) for the time period 1901–2006. SWE values were calculated with the semi-distributed bucket-type model HBV-light,[32] which uses a temperature-index approach within its snow accumulation and melt routine. HBV-light was applied in two ways, first without incorporating any snow redistribution (Figure 4(a)) and second with a simple snow redistribution approach (Figure 4(b)) as described by Stahl et al.[33] In this latter approach, part of the snow from the elevation zones above a critical elevation was equally redistributed to the lower areas and the glacier areas of the catchment, assuming that those represent preferred snow accumulation sites. For model validation, daily discharge at the catchment outlet as well as daily seasonal (1.11–31.5) interpolated SWE maps from 1971 to 2006 was available.[33] While the model version with snow redistribution performed better in terms of simulated runoff, both model runs lead to simulated hydrographs with satisfactory Nash–Sutcliffe efficiencies (0.77 and 0.84, respectively; see Figure 4). The model without snow redistribution built large amounts of snow over years that it was unable to melt (Figure 4(a)). After 100 years of simulation, the accumulated snow depth was around 550 mm SWE, while the mean observed SWE value was around 250 mm. For the unit representing the catchment area in the highest elevation zone (3100–3200 m a.s.l.) with northern aspect, the simulated SWE values without incorporating snow redistribution even amounted to a snow tower of 110,500 mm (ca 110 m) over the period of 106 years. In contrary, simulated SWE of the model including snow redistribution in Figure 4 (b) was much more realistic and no snow tower was observed for the mean SWE of the catchment. The simulated catchment means of SWE agreed better with the observations. Mean error (ME_{SWE}) and correlation coefficient (r_{SWE}) of SWE were clearly improved with ME_{SWE} of 431.5 mm improved to 79.3 mm and r_{SWE} of 0.95 improved to 0.96 from modeling without to with snow redistribution, respectively.

This model comparison illustrates the challenges linked to snow towers in hydrological modeling, how snow towers may go unnoticed in the model performance measures due to compensating

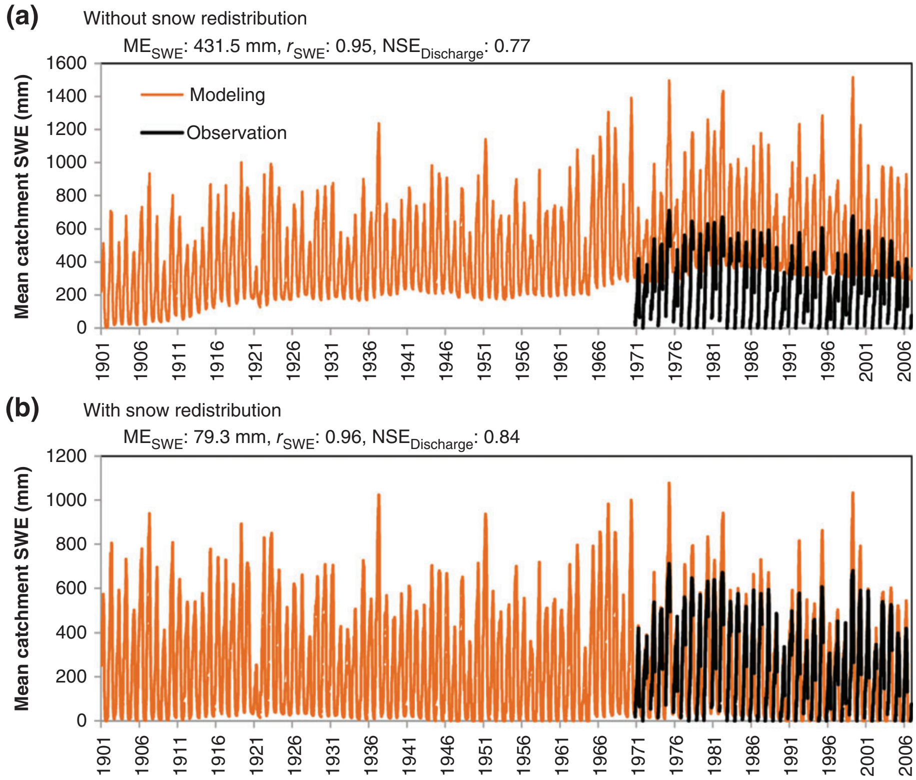

FIGURE 4 | Comparison of modeled and observed mean SWE values for the Alpbach catchment for the period 1901–2006. The model was used (a) without snow redistribution and (b) with snow redistribution. Mean error (ME_{SWE}) of SWE, correlation coefficient (r_{SWE}), and Nash–Sutcliffe efficiency for the discharge ($NSE_{Discharge}$) are given for both model runs.

effects of parameters in the calibrated model, and how important the consideration of snow redistribution is for realistic runoff modeling. Bucket-type models, as used in this comparison, are most likely to result in simulations with large snow towers, due to the overall simplicity of the temperature-index model used in the snow routine. However, snow towers are likely to be built in any type of model, where elevation zones are explicitly simulated and snow redistribution is not taken into account. If there are only a few or no elevation zones in a model, there is an implicit redistribution of the snow, as SWE is considered as a mean for the entire modeled area. Although many modelers are aware of the artifact of snow towers, this is rarely shown in the validation and discussed little in the literature. To our knowledge, snow towers in the context of hydrological modeling have been explicitly mentioned only by Koboltschnig et al.,[34] Frey and Holzmann,[35] and Skaugen and Weltzien.[36]

MODELING APPROACHES FOR SNOW REDISTRIBUTION

To model snowmelt runoff generation, hydrological models (or snowmelt runoff models) used in alpine catchments include snow routines of differing complexity. Several approaches for modeling snow redistribution have been developed and a summary of those considered in this review is given in Table 1. Tables S1–S3 (Supporting information) provide more details and synthesis with reviewed snow redistribution approaches either implemented into the snow routine of a hydrological model (Table S1), part of a snow evolution model (Table S2), or presented independently of any established snow or hydrological model (Table S3).

TABLE 1 | Summary of Reviewed Studies and Models

	Number of Studies	Number of Models
Snowmelt runoff/hydrological models		
Physically based	23[1]	10
Bucket-type	14[1]	8
Snow evolution models		
Physically based	8	2
Snow redistribution approaches (described independently from models)		
Physically based	12	
Conceptual	1	
Statistical	8	
Total number of studies	66	

[1] Subgrid variability was considered in three studies with physically based models and in two studies with bucket-type models.

Hydrological models can have different levels of complexity, spatial and temporal resolution, and can be divided in physically based and bucket-type models, as done here. In physically based models such as ALPINE3D[37] or SnowModel,[38] relevant processes and the snow cover is usually modeled with consideration of all energy fluxes. These models are generally distributed, very detailed, highly complex, and have a high spatial and temporal resolution. Their use is thus limited by the amount of available data and the computational time, which makes them applicable mostly for small catchments or plot scale and for short time periods (few winter seasons) or for events only. Less complex, distributed, physically based models such as SES,[39] AMUNDSEN,[40] WaSIM-ETH,[41] RHESSys,[6] TOPKAPI-ETH,[42,43] LARSIM,[44] or UEB[45] are more widely used for hydrological studies. In these models, extended temperature-index approaches that include spatially distributed solar radiation are frequently used,[46,47] reducing the computational effort.

Bucket-type hydrological models are widely used for large-scale (multi-basin) modeling studies or in regions with poor data availability, as many processes are conceptualized and parameterized. Bucket-type snow models are usually based on a temperature-index approach,[46] for which a direct relationship between temperature and snow accumulation and melt is assumed. The majority of these models are spatially aggregated in areas with similar hydrological response, called hydrological response units (HRUs) or grouped response units (GRUs), leading to faster computational times and requiring less input data. HRU or GRU are defined depending on soil properties, land use, and vegetation type but can also be divided in elevation zones, slope, or aspects. Typical bucket-type hydrological models are HBV,[32,48,49] COSERO,[35,50] PREVAH,[51] CEQUEAU,[52] GERM,[53] or OEZ.[14]

This classification into physically based and bucket-type is not unambiguous as models often use physically based approaches for some and simplifying approaches for other processes. The classification is therefore only indicative.

According to this classification, 10 physically based hydrological models accounting for snow redistribution were described in 23 reviewed studies, whereas snow redistribution was applied in 8 different bucket-type models that were described in 14 studies (Table 1). Of the bucket-type models accounting for snow redistribution, only five were described in peer-reviewed publications, three of them have been described in reports and model documentations (gray literature) or by personal communication. The large difference between the number of studies for physically based and bucket-type models is notable, as bucket-type models are also widely used in hydrology, especially in regions with poor data availability.

Overall, the reviewed approaches for modeling snow redistribution can broadly be divided into four categories of the processes they represent and the data they utilize (Figure 5):

(A1). the correction of the precipitation data, which is mainly used to account for preferential deposition;

(A2). the description of all wind-driven snow redistribution processes based on wind field data;

(A3). the description of gravitational transports and/or wind-driven processes based on topographic information; and

(A4). the statistical description of snow cover variability to include all three types of snow redistribution processes.

These categories are not mutually exclusive, as an approach can, e.g., use topographic information to define a correction factor for precipitation. We first describe these different approaches in detail and then provide some examples how they are implemented into hydrological models.

A1: Preferential Deposition

The correction of the precipitation data is applied to account for snow redistribution by wind, especially preferential deposition. Dettinger et al.[54] observed orographic influence in precipitation in Sierra Nevada (USA) that was different from storm to storm. They improved their simulations by correcting the precipitation data with topography. Jackson[55] developed a method to correct precipitation data in order to especially assess for preferential deposition and redistribution of snow. He used a location-dependent snow multiplier to create a predefined spatial precipitation matrix that was applied to every snow precipitation event in the Reynolds Creek catchment (USA). This approach was later applied in the alpine catchment of the Dammagletscher (Switzerland) using lapse-rate photography to define the precipitation matrix.[56] Dadic et al.[17] successfully parameterized preferential deposition at the Haut Glacier d'Arolla (Switzerland) from the correlation between the wind speeds and the snow depth during the period when threshold shear stress conditions for saltation or suspension were not reached. Kuhn,[14] e.g., used in the OEZ model a constant correction factor estimated from observations to increase snow input on a glacier in the Paznaun catchment (Austria) that improved the modeled glacier balance (Box 1).

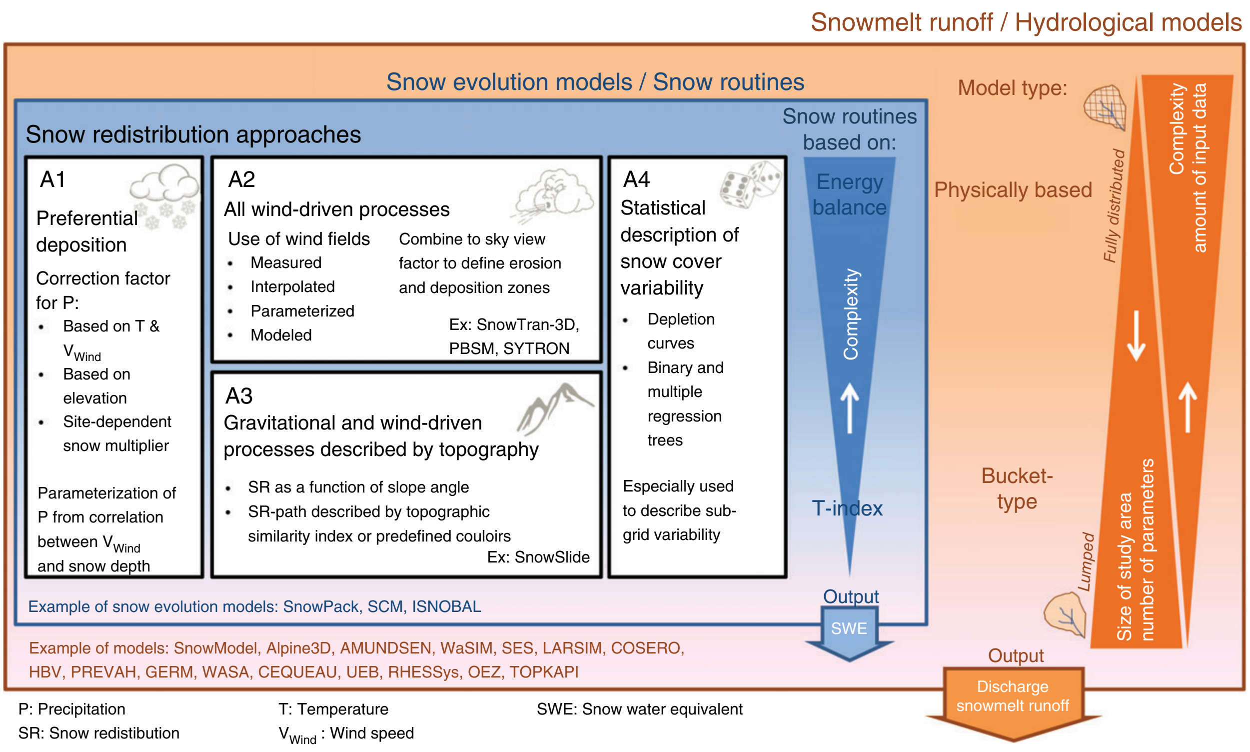

FIGURE 5 | Implementation of the snow redistribution approaches A1–A4 in snowmelt runoff or hydrological models.

BOX 1

CORRECTION OF PRECIPITATION DATA TO ACCOUNT FOR UNDERCATCH

Accurate measurements of precipitation at high elevations are difficult due to complex topography, dominance of solid precipitation, and strong winds. Measurements at weather stations need to be corrected for undercatch of precipitation due to wind transport processes, i.e., preferential deposition around the measurement station.[57] Sevruk,[57] e.g., developed a method to correct precipitation data based on monthly mean temperature and wind speeds. He found large regional differences in precipitation corrections needed in Switzerland and estimated that the undercatch at weather stations increases with elevation and could reach up to 40% in the Alps. Snow correction factors can also be calculated based on the terrain curvature during model calibration.[58] Other methods fitted precipitation measurements to observed streamflow data and water balance estimations.[33] Precipitation correction is commonly applied in nearly all hydrological models, in particular in mountain areas, to correct for precipitation undercatch. However, such a correction may also implicitly account for import or export of snow from outside the topographical catchment boundaries, and therefore may also represent cross-catchment snow redistribution.

A2: Wind-Driven Snow Processes

Wind-driven snow redistribution can be described using wind field data, which allows for representing in a physical way the transport paths of the snow particles. Wind fields are used to describe all wind-induced snow redistribution processes, i.e., preferential deposition as well as saltation and suspension. Snow transport starts when a critical wind speed is reached and deposition occurs when wind speeds decrease.

The Prairie Blowing Model[26,59] followed by SnowTran-3D[60] were developed in the Arctic and were the first physically based snow redistribution models capable of describing wind-driven snow transport and producing spatially distributed maps of SWE taking snow redistribution into account. Essery and Pomeroy[59] and Liston and Sturm[60] were able to relate the calculation of wind speeds to vegetation and more complex topography, allowing the first application of SnowTran-3D in mountain environments in the Rocky Mountains in Colorado (USA)[61] and in the Upper Sheep Creek in Idaho (USA).[62] These models later inspired SYTRON3[63] that has been developed as snow drift module for the Safran–Crocus–Mepra model chain, which is based on the snow evolution model CROCUS.[64,65]

The accuracy of such models fully depends on the accuracy of the wind speed and wind direction fields, which are very variable in alpine catchments as they strongly interact with the complex topography. For this aim, snow redistribution approaches were developed based on wind field measurements,[60] interpolation,[66] or simulations from circulation or atmospheric models[67–69] and using nonlinear turbulence models to downscale the simulated wind patterns.[17,70,71] As wind field measurements and modeling require large amount of data and are computationally intensive, methods were developed to parameterize wind fields using terrain-based information[66,72] or main wind directions.[73] Lehning et al.[37] and Dadic et al.,[17] e.g., used the main flow characteristics from complex wind fields from the advanced regional prediction system atmospheric model[74] at a resolution of 10th of meter to model snow redistribution in two glacierized catchments in the Austrian and Swiss Alps with ALPINE3D. The description of snow redistribution processes with wind fields remains data intensive and is nearly only applied in fully distributed hydrological models with a high complexity level.

A3: Gravitational and Wind-Driven Processes Described by Topography

Snow redistribution processes can also be described using topographic information alone. Anderton et al.[75] used bivariate screening to analyze the importance of terrain properties in controlling snow cover variability in the Pyrenees (Spain). They came to the conclusion that snow redistribution by wind is mostly influenced by topography. This was also confirmed by many studies that observed consistent snow patterns over years.[22,76–79] Therefore, topographic information is not only useful to describe gravitational snow redistribution processes, i.e., avalanches and sloughing, but has also been used to describe in a simpler approach the complex wind-driven snow redistribution processes. The observed correlation between snow redistribution patterns and topography therefore allowed the development of accurate modeling approaches of snow redistribution for all kinds of hydrological models.

Blöschl[80] modeled gravitational snow redistribution as a function of the slope under consideration of a minimum and maximum slope angle. With the topographic similarity index[6] that was inspired from the wetness index,[81] gravitational snow transport is assumed to follow the water path. Similarly, the mass transport and deposition (MTD) algorithm developed by Gruber[82] is a mass-conservative model to redistribute snow along predefined couloirs as a function of topography. In this model, snow is redistributed from steep slopes to the bottom of the slope.

In some physically based models (e.g., SnowModel,[83] WaSIM-ETH,[84] or AMUNDSEN[18]), the MTD algorithm was often implemented in combination with wind-driven approaches from A2 to model gravitational processes. In LARSIM, snow is redistributed to the bottom of the valley only depending on the slope and on an SWE threshold[44] In combination with wind fields from A2, topographic information can be used to identify areas where snow is eroded or deposited using, e.g., a sky view factor,[18,84] or topographic openness.[79,85] In bucket-type hydrological models, A3 approaches are used to describe all snow redistribution processes. Frey and Holzmann[35] developed a methodology similar to the MTD algorithm to redistribute precipitation from the steepest slopes to the neighbor slopes and determined the amount of snow to be redistributed depending on slope, snow age, and land cover for the distributed model versions of HBV and COSERO at a resolution of 1 km. Huss and Fischer[16] used a dimensionless factor derived from terrain characteristics as described by Farinotti et al.[56] to describe wind-driven snow redistribution to the glacier area in the model GERM. For avalanches and snow drift, they linearly reduced snow accumulation from 100 to 0% for slopes between 40 and 60°.

For the approaches A3, the parameters critical slope and critical snow depth need to be defined to initialize snow redistribution in the model. These approaches are based on topographic information and therefore do not need as many input data as A2, where wind field data are needed. They can therefore be applied to a broad range of models and are less computationally expensive.

A4: Statistical Description of the Snow Cover Variability

The statistical description of snow cover variability is used for model representations of all three types of snow redistribution processes. Statistical methods assess a relation among snowfall, avalanches, and terrain properties, usually using spatial probability density functions of SWE. Some bucket-type hydrological models use stochastic approaches for the representation of snow redistribution. This is the case in the CEQUEAU model, where snow-covered area was computed for the Nechako River catchment (Canada) using a depletion curve following a three-parameter beta distribution calibrated on satellite images.[86] Skaugen and Randen[87] used in HBV a two-parameter gamma distribution for modeling the spatial variability of SWE in the Norefjell catchment (Norway).

The approaches A4 usually do not specifically model snow redistribution processes but describe the overall spatial variability of the snow cover in a catchment (Box 2) and are also often used in large-scale hydrological models to describe the subgrid variability of the snow cover. Especially snow redistribution processes often occur at smaller spatial scales (less than 100 m) than the resolution of many large-scale hydrological models. Clark et al.[4] therefore stressed the importance of incorporating subgrid variability. This can be done by a statistical description of the snow cover at the subgrid scale, by the use of depletion curves[88–90] or a log-normal distribution of snow during a snow event within a model grid cell.[91]

BOX 2

EMPIRICAL ANALYSIS OF THE SPATIAL VARIABILITY OF SNOW

Different methods have been developed to empirically analyze the spatial distribution of the snow-covered area and/or of the SWE. The results of such analysis can be used to improve hydrological modeling. Statistical models are used to describe the overall variability of the snow cover, usually not specifically considering snow redistribution processes. Binary and multiple regression trees were developed to explain the SWE distribution in relation to different topographic parameters, such as elevation, slope, aspect, or curvature.[29,75,92] These models were applied to different catchments around the world and could explain up to 90% of the spatial variability of snow cover. Bavera et al.[93] compared the modeled SWE from two statistical models to interpolate snow data on a grid with modeled SWE from the physically based ALPINE3D model for an alpine catchment in Grisons (Switzerland) and observed overall good agreement among the three models. However, Grünewald et al.[78] tested the transferability of statistical models using high-resolution snow depth data from different alpine sites in Europe and Canada. They concluded that their 'global model' could only explain 23% of the spatial variability of snow cover and therefore that local statistical models, despite being simple, are site specific and are generally not transferable.

Synthesis

In Figure 6, the different types of hydrological models are classified by their spatial resolution and the type of snow redistribution approaches used. Fully distributed, physically based snowmelt runoff and hydrological models mainly use approaches A2, which allow for physical description of all wind-driven snow redistribution processes. They sometimes include approaches A3 to identify erosion and deposition areas and/or to assess gravitational snow redistribution. The development of several methods to derive wind speed and wind direction fields using topographic information and/or atmospheric models has clearly improved the modeling of snow redistribution in alpine catchments and reduced the computational efforts. In addition, it allowed to assess the relevance of snow sublimated at high elevations.[18,94,95] However, Musselman et al.[8] found that the simulated snow mass budget and the sublimation amounts were sensitive to the chosen windflow model and that the more physically based windflow models reduced the uncertainty of the simulated snow. The representation of the complexity of snow redistribution processes and the high spatial and temporal resolutions became clear practical limitations for many hydrological model applications. Wind speeds are usually assumed to be stationary within a time step (usually 1 h), which can lead to small over- or underestimation of the amount of snow transported within grid cells.[22] Zwaaftink et al.[94] observed that the snow redistribution model in ALPINE3D, e.g., sometimes overestimated transport for grid cells with little snow cover as it was unable to predict if a grid cell would have enough snow for transport over the entire time step.

In bucket-type hydrological models, snow redistribution is represented using combinations of approaches A1, A3, and A4. Based on the correlation between wind main directions and topography,[79,85] topography can be used as a proxy to explain all snow redistribution processes and there is therefore no need for wind field data. However, snow is usually redistributed in these models from the top of the mountain to the bottom of the valley using slope information leading to unrealistically large avalanches sliding down mountains over kilometres. Another limitation of conceptualized snow redistribution approaches is that snow is mostly only redistributed downwards, while in reality, wind-driven snow redistribution can also occur upwards. However, the spatial resolution of such bucket-type models is usually larger than 1 km and at this scale upwards snow redistribution might be negligible. In spite of their simplicity, snow redistribution approaches used in bucket-type hydrological models have improved runoff modeling, avoided the formation of snow towers[33–35] and improved glacier mass balance simulations.[16]

The implementation of subgrid variability in physically based and bucket-type hydrological models improves snow cover simulations at the subgrid

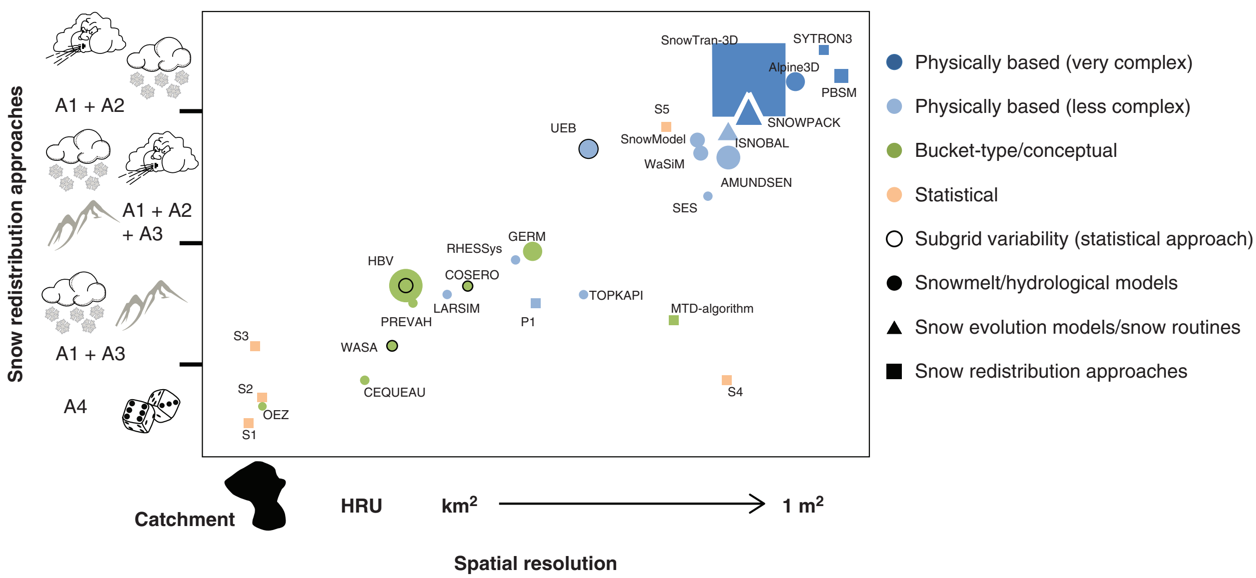

FIGURE 6 | Classification of all reviewed studies based on their spatial resolution and the types of model approaches used, i.e., correction of precipitation input data, use of measured or parameterized wind fields, use of topographic information, and statistical approaches. The size of the circles, triangles, and squares represents the number of reviewed publications with a given model explicitly taking snow redistribution into account. For a list of the model labels, see Tables S1–S3.

scale, but limitations in adequately capturing spatial variability across large elevation gradients should be considered.[4]

THE NEED TO BENCHMARK SNOW REDISTRIBUTION MODELS

Remotely sensed datasets are often used for the calibration and/or validation of hydrological models to assess the accuracy of the simulated snow cover. They can help assess model improvement after the implementation of snow redistribution approaches, but do not necessarily allow differentiating the processes leading to spatial snow cover variability, i.e., processes related to vegetation cover, snow redistribution, or energy balance. Dozier et al.[96] give a broad overview of possible methods to assess snow cover variability using remote sensing. Physically based and bucket-type models were successfully calibrated and/or validated with satellite images as, e.g., MODIS,[35,86,97,98] LANDSAT,[58,99] AVHHR,[37] or LiDAR.[17] These datasets are useful to obtain information on the extent of the snow cover, but do not provide any information on the amount of snow. With airborne laser scanning, it is possible to assess both snow-covered area and snow depth and therefore it is possible to observe the extent of snow redistribution. This has been used in different studies[79,100] but this observation method is very expensive and can usually only be used for several days and for small catchments, so the information of the actual process resulting in changes on snow depth is often missing. Schöber et al.[101] assessed the uncertainty of SWE estimates from airborne laser scanning as 15%, while meteorological data have uncertainties up to 40%.[57] LiDAR data were also directly assimilated in hydrological models for the assessment of the spatial distribution of the snow cover,[79,100,102] but these data products are still expensive. Beside satellite products, digital photography has also been used to assess the occurrence of avalanches[56] or to statistically analyze the development of the snow cover during the snowmelt season on a mountain crest.[90] Recent developments in remote sensing offer opportunities to clearly improve the representation of spatial snow cover variability in hydrological modeling.

CONCLUSION

This review on snow redistribution in hydrological modeling stressed the importance of the representation of snow cover heterogeneities in alpine catchments. Representing snow redistribution processes adequately does not only lead to improved discharge modeling, but can also improve the estimation of snow sublimation, avoid unrealistic snow towers in models, enable closure of the water balance, and improve the representation of vegetation responses.

Modelers have to deal with the complexity of snow redistribution processes and tackle the poor data availability in alpine catchments. A useful categorization of approaches is therefore based on the snow redistribution processes represented, the kind of data needed, and the application in hydrological model types. Overall, the approaches used in physically based models enable a good representation of snow redistribution, especially wind-driven redistribution processes. The limitation of these approaches lies in the large amount of data needed for the representation of the wind fields. Bucket-type models in contrast usually describe all snow redistribution processes based on topographic information or statistical description of spatial variability. Mostly, snow is redistributed from the top to the bottom of the mountain in these models. When applying too simplified snow redistribution approaches, this can lead to unrealistic scales of snow transport. These conceptualized approaches strongly depend on model parameterization and available data for model calibration. Statistical approaches have been applied in several types of models. In cases of a spatial resolution of the model that was coarser than that of relevant snow redistribution processes, statistical approaches proved to be useful to describe the subgrid variability of snow cover. Statistical approaches may serve as efficient solution given adequate data and localized parameterization or/and calibration, but questions relate to their transferability. Considerable improvement in representing spatial snow cover variability in hydrological modeling including snow redistribution effects has been reached with the incorporation of data from remote sensing. A variety of satellite products have become available providing useful information on the spatial variability of the snow cover. Whereas such datasets presently mainly allow assessing snow-covered area, new observational developments clearly offer opportunities for further improvements for understanding snow redistribution processes.

Hydrological modeling of high mountain areas has made progress in the last decades. Partially, this progress is due to the improved consideration, implementation, and combination of different snow redistribution approaches. An issue that has hardly been addressed in the reviewed studies is the relevance of snow redistribution across topographic catchment borders. The reviewed studies also suggest a remarkable difference between approaches implemented in widely used bucket-type hydrological models and approaches implemented in more complex snow models that cover explicitly wind-driven processes. Whereas the latter may capture the high complexity of snow redistribution in alpine catchments and foster a better understanding of driving processes, in many cases their application in practice is constrained. Less complex, computationally and data efficient, hydrological models are applied more widely and needed particularly for multi-basin hydrological modeling in alpine catchments and for long-term climate modeling. The incorporation of snow redistribution in such models is still in an early stage with approaches often not well documented 'ad hoc fixes.'

This review revealed a lower availability of information on snow redistribution approaches implemented in bucket-type models, in comparison to the wide literature on approaches used in physically based hydrological models or snow evolution models specifically developed for modeling alpine catchments. This contrast is also reflected in the number of model variants. This review shows that a better documentation and more scientific discussion about adequate snow redistribution approaches for widely applicable hydrological models is highly needed to make further progress. The cause may benefit from targeted efforts to bridge the gap between these distinct groups of models and approaches. A starting point may be to explore the potential of snow redistribution modeling with established physically based models for the identification of main drivers, cross-comparison with conceptual or statistical approaches, or generating other outcomes that could feed into the development of (conceptual) approaches tailored to the requirements of widely applicable hydrological models for alpine catchments.

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