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Review

Spatiotemporal Variations in Snow and Soil Frost—A Review of Measurement Techniques

Angela Lundberg [1,*], David Gustafsson [2], Christine Stumpp [3], Bjørn Kløve [4,†] and James Feiccabrino [5,†]

[1] Civil, Environmental and Natural Resources Eng., Luleå University of Technology (LTU), SE-971 87 Luleå, Sweden
[2] Research and Development, Swedish Meteorological and Hydrological Institute (SMHI), SE-601 76 Norrköping, Sweden; David.Gustafsson@smhi.se
[3] Helmholtz Zentrum München, German Research Center for Environmental Health—Institute of Groundwater Ecology, Ingolstädter Landstraße 1, D-857 64 Neuherberg, Germany; christine.stumpp@helmholtz-muenchen.de
[4] Water Resources and Environmental Eng. Research Group, University of Oulu, FI-900 14 Oulu, Finland; bjorn.klove@oulu.fi
[5] Department of Water Resources Eng., Lund University, SE-221 00 Lund, Sweden; jfeiccab@norwich.edu
* Correspondence: Angela.Lundberg@ltu.se; Tel.: +46-920-491207
† These authors contributed equally to this work.

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Abstract: Large parts of the northern hemisphere are covered by snow and seasonal frost. Climate warming is affecting spatiotemporal variations of snow and frost, hence influencing snowmelt infiltration, aquifer recharge and river runoff patterns. Measurement difficulties have hampered progress in properly assessing how variations in snow and frost impact snowmelt infiltration. This has led to contradicting findings. Some studies indicate that groundwater recharge response is scale dependent. It is thus important to measure snow and soil frost properties with temporal and spatial scales appropriate to improve infiltration process knowledge. The main aim with this paper is therefore to review ground based methods to measure snow properties (depth, density, water equivalent, wetness, and layering) and soil frost properties (depth, water and ice content, permeability, and distance to groundwater) and to make recommendations for process studies aiming to improve knowledge regarding infiltration in regions with seasonal frost. Ground-based radar (GBR) comes in many different combinations and can, depending on design, be used to assess both spatial and temporal variations in snow and frost so combinations of GBR and tracer techniques can be recommended and new promising methods (auocostics and self potential) are evolving, but the study design must be adapted to the scales, the aims and the resources of the study.

Keywords: snow; seasonal frost; spatiotemporal variation; measurement techniques

1. Introduction

Increased air temperature will change snow accumulation and melt patterns, influence seasonal frost thickness and duration, snowmelt infiltration and recharge patterns Barnett, et al. [1–4]. Climate change will also impact snow cover and soil frost processes causing more dynamic freeze/thaw periods. Changes in climate and the related changes in snow hydrology influence water resources in many ways, affecting water quantity and quality. Snowmelt water dominates river runoff and aquifer recharge providing the main source of water in many regions. Snowmelt contains nutrients and pollutants [2,5] and pollutant flux processes are central elements of environmental risk assessment. Better understanding of snowmelt infiltration and recharge processes are thus needed to understand

and adapt to climate change and recognize impacts of future land management schemes on water resources. This is essential for understanding consequences and for effective implementation of the protective actions required by the European Commission Water Framework Directive [6], Floods Directive [7] and Groundwater Directive [8] to meet good water quantity and quality. Quantifying future evolution of infiltration and recharge in northern climates thus requires both, trustworthy forecasting of future climatic variables, and knowledge about spatiotemporal variations in present recharge processes.

Important snow resources in high latitudes and mountains with seasonal snow and frost are relatively unknown parts of the hydrological cycle with quite few high quality measurements. This is alarming as mountain regions receive high amounts of precipitation and thus also greatly contribute to runoff and groundwater recharge. In these environments, changes in spatiotemporal patterns of snow accumulation and melt are principal controls on hydrologic responses to climate change [9]. How valleys and mountaintops are influenced by climate change seems to vary. Some studies of mountain climate show faster warming of high elevations than of lower elevations (western European Alps [10]) while the high elevations have been cooling lately in the Rocky Mountains, Colorado, US [11]. Most studies conclude that less snow will fall in a warmer climate [12–15]. However, effects of warmer climate on snowfall will depend on regional factors. Warmer climate generally means shorter snow season and thus decreasing snowfall. On the other hand, snowfall is more frequent and more intense at air temperatures just below zero than at colder temperatures, (maximum air humidity increases with air temperature), increasing snow accumulation for such climatic conditions [16]. Depending on which process becomes predominant, snow accumulation may increase or decrease as an effect of warmer climate [17]. Based on simulations of 21st century climate and using 20 global climate models, Räisinen [16] showed, that even if peak snow water equivalent (SWE) generally decreased, it increased in the coldest areas. Snow depth trends over northern Eurasia are increasing in the northeast and decreasing in the west [18]. An overview of the complicated pattern of observed changes in snow cover duration and maximum snow depths in different climatic regions is provided by Brown and Mote [19], indicating that snow cover duration was the snow variable with the strongest climate sensitivity varying with altitude and climate regime. Long-term records of annual snow accumulation in Alpine regions advise that substantial, regional scale shifts in snowpack features have occurred with associated changes in the frequency and timing of freeze–thaw cycles [5].

Changes in snow covers will influence soil frost and recharge which is important for groundwater renewal and storm flow quantity and quality. There is no direct relation between frost depth and infiltration or recharge amount since infiltration depends on both snowmelt mass and soil ice content. Winters with shallow frost do not typically produce more infiltration than winters with deep frost since winters with shallow frost usually have thicker snow cover [20–22] When frost indicators and snowmelt runoff were compared in small catchments no proof for larger or faster runoff for winters with deep frost were found [23]. Even if studies on seasonally frozen ground show that frost can limit or totally prevent infiltration, this is far from always the case, and to only focus on frost depth is not enough. Frozen soil is seldom impermeable, and many studies show that infiltration takes place also through thick frost layers if the soil surface contains air filled pores [24–26]. However, if snowmelt or rainwater freezes, forming an ice layer at top of the soil surface, this blocks infiltration even if the ice layer is thin [22,27–29]. Frozen soil infiltration capacity decreases drastically with the ice content of the soil [30,31]. The ice content of the frozen soil and especially of the topsoil is thus important to access when studying the impact of seasonal frozen ground on infiltration and recharge. As the water content of soil also influence ice content, wet soils form more impermeable soils. The behavior of groundwater in seasonal frozen ground regions is thus dominated by the spatiotemporal extent of hydraulic isolation between the water on top of and below the near-surface frozen zone [32]. The close relationship between snow and frost depths to control the snowmelt separation into infiltration (and recharge) or runoff should be better understood [33]. To increase process understanding a combination of well-designed field experiments and modeling studies is of importance [32].

Topography, soil properties and vegetation cover influence snowmelt and infiltration in complex, unexpected ways. Sandy south-facing hill slopes were for example found to generate greater surface runoff than north-facing slopes and finer-textured soils [34]. Snowmelt input to groundwater recharge can thus display systematic and significant spatial variability due to the influences of elevation, slope, aspect and forest cover on both snow accumulation and snowmelt processes [35]. Turbulent flux dominated sites melt faster than sheltered sites [35]. And snow accumulation and melt was shown to differ significantly between clear-cut, juvenile, and mature stands, and amongst juvenile stands with distinctive structural differences [36]. Vegetation and topography impact on snow energy exchanges can thus result in de-synchronization of snowmelt in a basin [37,38] complicating the space-time patterns of snowmelt and therefore also on the separation of meltwater into surface runoff or infiltration. Further details regarding the complex interplay between physiographic variables sometimes exert contrasting influences on snowmelt runoff can be found in Smith et al. [35]. According to Smith et al. [35] most snowmelt studies exploring groundwater-related dynamics are made in small catchments (<50 ha) and have limited elevation ranges (<200 m) (such as [39]). The small scales have probably restricted the spatial variability in the timing and intensity of snowmelt inputs and associated impacts on groundwater and runoff response patterns. Few studies thus deal with groundwater response when meltwater from different part of a basin occur at different times (asynchronous) [35,40–43].

Laboratory and field studies on soil core scale consistently show decreased infiltration capacity with increasing ice content [44–47]. Some plot field studies also report reduced infiltration with increasing ice content [29,48], while others indicate no or minor impact [22,26,49]. Since seasonally frozen ground is mainly studied with focus on runoff processes, the effects on infiltration and recharge mostly have to be indirectly deduced. Catchment runoff studies often rely on numerical simulations and some studies suggested and successfully used a classification where the infiltration capacity of seasonally frozen ground was divided into different soil and frost types [50,51]. However a similar approach for a forested catchment found little improvement by including soil frost in the simulations [52]. In addition, no impact of frozen soil on runoff was found in a large catchment [23]. The importance of frost thus seems to decrease with increasing spatial scale and a number of possible reasons why this could be the case are suggested by Lundberg et al. [2]. Partitioning of meltwater during initiation of spring freshet into vertical versus lateral flux (due to intensity, timing and quantity) of melt seems to overwhelm the influence of topographic convergence on runoff source area dynamics in mountain areas [35]. The spatiotemporal distribution of snow and frost thus seems to lack influence on magnitude and timing of basin runoff but the limitations regarding the sizes and altitude ranges of presented studies mentioned above cannot be dismissed.

Additional knowledge regarding spatiotemporal variation in snow and frost processes is therefore needed in order to predict how global warming will influence these processes [2]. This in turn calls for appropriate knowledge on available measurement techniques to get information about relevant snow and soil frost parameters. The purpose with this paper is therefore to review different methods to measure properties of snow (depth, density, water equivalent, wetness, and layering) and soil frost (depth, water and ice content, permeability, and distance to groundwater) and to make recommendations for instrumentation of process studies aiming to improve knowledge regarding infiltration in seasonally frozen ground regions. Specific focus is on spatiotemporal distribution of snow and frost properties, which influence infiltration. Satellite based techniques can also be used to map snow and frost properties but they typically have low spatial and temporal resolution and are beyond the scope of this review. Snow and frost measurement techniques are evolving quickly so there is a risk for unavoidable omissions of some publications and this review is thus far from complete.

2. Measurement Techniques

There are existing reviews on ground based measurement techniques focusing on snow depth [53], SWE [54,55], snow density [56], forest snow [57–59], frost depth [60] and automated snow techniques [61]. However, no review focusing on the spatiotemporal variations in snow and frost properties seems to exist and the progress in measurement techniques is rapid. Current access to new cheap, wireless digital sensors allow continuous measurements of many meteorological and hydrological parameters [62,63].

First, systems to measure many relevant parameters are reviewed; electrical/dielectrical, tracer and temperature based techniques are, for example, deployed in both snow and frost studies. Then follow the review of techniques primarily used in snow studies and finally the review of methods usually used for soil frost recharge studies.

2.1. Snow Processes and Parameters and Associated Common Methodological Problems

Snow related processes that are essential in hydrological measurements include precipitation, snow depth and SWE. Besides these snow density, layering and albedo are important in some snow studies and applications. As forests effect frost and snow accumulation, vegetation cover needs special attention in snow measurements. In addition, snow packs are dynamic and particularly, the phase is important for snowmelt infiltration studies since rain on snow might refreeze at the base of the snowpack forming a more or less impermeable ice layer preventing infiltration [29], and there is an on-going trend to replace meteorological observers with automated systems, many of which lack precipitation discriminators [64].

All types of sensors located less than about 0.5 m under snow surface are likely to absorb more solar radiation than the snow itself, and this causes risk for local melt around the device and erroneous measurements [2,65]. However, thin, small and white installations cause small or negligible disturbances. If a part of the measuring device is buried in the snow and a part is extending above the snow surface there is also risk of air pockets forming around the device during high wind events by vibrations (particularly if the wind exposed area is large) causing similar problems.

2.2. Dielectrical and Electrical Techniques

The dielectrical techniques are based on variations in dielectric constant (permittivity) of the material, which differ markedly between liquid and frozen water. The permittivity (K) of wet and dry snow as well as of wet, dry and frozen soil can be calculated with a mixing model using the dielectric permittivity (ε) and the volume fractions (θ) of the different components [66]. For wet snow, the relation becomes

$$\varepsilon_{WS} = (\theta_W \varepsilon_W^\alpha + \theta_I \varepsilon_I^\alpha + \theta_A \varepsilon_A^\alpha)^{\frac{1}{\alpha}}$$

where $_{W,\,I,\,A}$ denotes liquid water, ice and air, respectively. The contribution from air is small and is usually neglected. For frozen soil the volume fractions and the dielectric permittivity of the soil itself $\left(\theta_{Soil}\varepsilon_{Soil}^\alpha\right)$ should be included [66]. A good fit over the whole range of liquid volume fraction ranging from 0 to 1 using the α-value 0.5 for soils was found [67], and this values has also been applied for snow [68]. For common frequencies the dielectric constant for liquid water is about 80, while values for ice and dry soil are about 3. Methods based on differences in dielectric properties between ice, water, soil and air have many different applications for studies of spatiotemporal variations in snow and ground frost. Radar systems, time domain reflectometry (*TDR*), 3-D tomography, LiDAR, and the "snow fork" are examples of such techniques.

2.2.1. LiDAR

Terrestrial laser scanning, also known as LiDAR or laser altimetry techniques, can give spatially detailed ground surface altitude information, and snow depth can be retrieved when the technique is applied on both bare and snow covered soil [69–72]. The development of LiDAR applications for snow depth mapping has exploded in recent years, and is now also used for investigating snow distribution below forest canopies [72]. The accuracy of the LiDAR technique is high but is hard to generalize since it depends on many factors; the measurement set-up (distance to the observed surface), the used method (beam divergence), the scanning speed, the quality check, etc. [71]. However, a skilled operator is required to perform data acquisition and post processing (to achieve trustworthy results). The purchase cost of the equipment is around 70,000–120,000 Euros [71]. Ground-based systems usually deliver millimeter-scale range accuracy and sub-meter point spacing over several kilometers for smooth and open terrain while the accuracy is lower in complex and forested terrain [53]. The technique has also been used to identify depressions exposed to concentrated infiltration in frozen soil [73].

2.2.2. Radar Systems

Ground penetrating radar, (GPR), also known as georadar, has been used for a variety of applications for snow soil and frost research, and exists in many different designs (systems with different antenna frequencies, with one or several frequencies, with one or several channels). The radar can be operated from vehicles, such as helicopters, airplanes or snow mobiles and can thus cover large lateral distances in short times, or it can be mounted stationary and monitor temporal changes [61]. *GPR*-techniques have been applied to determine the spatial distribution of snow depths [74–78], snow density [77,79], SWE [80], snow layering and stratigraphy [78,81,82], wet snow properties [83], soil frost depth [84–87], depths to thawing front and shallow freeze and thaw processes [85,86,88–92], soil water content [93,94] and depths to the water table [95,96].

Frequency-modulated continuous wave (FMWC) radar systems transmit a continuous signal where the frequency linearly increases over a time step and records the reflected waves, the minimum and maximum frequencies and the total sweep time. Usually, these systems generate frequencies of up to 40 GHz, resulting in a vertical resolution of 1–3 cm. These high radar-frequency systems are less expensive than impulse radars since the received signal only needs to be sampled with kilohertz frequency, i.e., several orders of magnitude lower than that of the transmitted signal. An overview of FMCW radar technology and its application for snow research can be found in Marshall et al. [97]. In these systems the received signal is mixed with a replica of the transmitted signal, (computer-generated or recorded by a radar antenna), and Fast Fourier Transform is used to determine the frequency difference between them. This difference along with the total sweep time and the frequency range (the difference between the maximum and minimum frequencies) are used to calculate the radar wave two-way travel time (TTWT) [98]. As for the impulse radar, snowpack depth is attained from the TTWT if the radar wave propagation velocity is known or estimated from independently measured snow density. This depth and the snow density are then finally used to calculate SWE. A limitation with this method is the requirement to perform measurements on dry snow or to determine and take into account the liquid water content (*LWC*). If the density varies substantially throughout the snowpack the accuracy of SWE estimates will be lower.

Snowpack stratigraphy can also be assessed by FMCW radar with high resolution [99]. When FMCW radar is combined with manual snow pit measurements, ice layers identified in the pit can be followed through the length of the line radar measurements. For dry snow covers with varying snow densities the propagation velocity can be calculated from the snow density for each layer and a good estimate of snow cover depth and snow density, and, therefore also SWE, can be acquired from the TTWT [100]. A discrete version of FMCW systems named step-frequency continuous wave (SFCW) radar systems, transmit a continuous signal which steps through a number of equidistant frequencies with constant step length, so the total sweep time is known [101]. SFCW radars have the same limitations as FMCW systems.

Field scale shallow soil moisture profiles using full-waveform inversion of GPR data were mapped [102], and Jadoon et al. [91] monitored temporal variations in freeze–thaw cycles on a snow covered agricultural field using a stationary mounted step-frequency radar and judged the method promising for real-time mapping of soil frost at the field scale. Steelman and Endres [85] used the development of high-frequency *GPR* direct ground wave propagation and could detect thinner frozen layers than when using the radar wave reflection from the frozen-unfrozen boarder. Steelman et al. [86]

illustrated that this technique could be used to monitoring spatiotemporal dynamics of shallow freezing and thawing events.

Peak SWE is often the most important parameter for infiltration and recharge studies, and *GPR* measurement might then need to be performed on melting snowpacks. However, the traditional *GPR* technique is not well adjusted for measurements on melting snow, since SWE-values might be overestimated by about 20% for wet snowpacks [103]. Methods to improve the accuracy of SWE measurements using *GPR* on wet snow and to estimate snow wetness based on amplitude damping of the emitted pulse have been published [80,104]. However, the available methods and technologies for estimating snow properties such as density, wetness, and internal structure directly from GPR data, is still dependent on advanced methods of antenna configurations and analysis and have not yet been shown to be applicable for larger scale operational snow surveys. In the latter case, the application of GPR is probably still most efficiently made using manual snow depth and snow density observations as reference to calibrate the GPR data. The development and use of a stationary mounted upward looking GPR, placed at the ground at the beginning of the snow season to record temporal variations in snow-pack depth, layering and snow wetness are reported in literature [81,83,105,106]. An upward looking design as the one discussed above based on L-band FMCW radar for snow cover monitoring is presented by Okorn et al. [107].

2.2.3. TDR

In-situ time domain reflectometry (TDR) measurements are also based on differences in dielectrical constant between water, soil, air and liquid water. TDR has been used for registration of temporal changes in liquid water content (*LWC*) for frozen soils [46,67,108–113] and snow [46,114,115] as well as for density of dry snow [77]. The TDR technique determines dielectric permittivity (dielectric constant) of the material by measuring the delay in time between the emitted and the reflected electromagnetic wave using wave-guides (pair of stainless steel rods) installed in the material. The permittivity can then be converted to volumetric water content for soils and for snow to density (if the *LWC* is known) or to *LWC* (if the density is known or can be assumed to be constant) [114]. The main advantages of TDR techniques are high temporal resolution, rapidity acquisition (about 20 s) and the repeatability of the measurements [116]. A major disadvantage with the technique when applied to snow is the sensitivity to air gaps forming around the wave-guides. Wave-guides absorb more solar radiation than the surrounding snow and might melt the surrounding snow thus forming air gaps around the guides. TDR has been adapted to fit on mobile platforms, primarily for agricultural applications [116]. Recent TDR measurement of freezing and thawing curves on soils in western Canada showed significant hysteresis and mechanisms for this and possible influence on the interpretation of published datasets are discussed by He and Dyck [117]. The TDR technique is applied in the commercially available water content reflectometers (WCR) (Campbell Scientific Inc.) used by for example Iwata et al. [118]. A thermo-time domain reflectometry (T-TDR) probe monitors both soil temperature and *LWC* [119].

2.2.4. Additional Electrical Techniques

Impedance tomography has been applied to get a 3-D picture of the infiltration process [120,121] and electrical resistivity imaging (ERI) has been used to give spatial distribution data regarding infiltration [122–124]. An oscillating circuit and a sensing part embedded in the material are used by capacitance based techniques. The dielectric permittivity of the medium is determined by measuring the charge time of a capacitor, which uses the medium as a dielectric capacitor. Different dielectric operating frequency are applied to different media [116]. The nuclear magnetic resonance (NMR) method has been used to measure unfrozen water content in frozen soil [125]. The underlying principle is that hydrogen protons resonate when subjected to an oscillating magnetic field of the right frequency. Limitations with this technique are that it measures small sample sizes that it is difficult to sustain the desired temperature of the NMR device, and the device is expensive [126]. Self-potential (streaming potential) theory has been applied for many hydrological applications for example for mapping of seepage in embankment dams [127–129]. A new theory and numerical model of electrical self-potential (SP) signals associated with unsaturated flow in melting snow have been developed and tested using laboratory column experiments [130]. The SP signals primarily depend on the temporal growth of snow porosity and meltwater flux, electrical conductivity and pH [130]. The authors conclude that non-intrusive SP measurements can serve as proxies for meltwater fluxes and that the acquisition methods could bridge the widely acknowledged gap in spatial scales between satellite and point measurements of snow properties. The technique has been applied to track meltwater fluxes in-situ snowpacks [131].

2.3. Temperature Based Techniques

Recent advances in fiber optics allow for rapid and accurate temperature measurements along lengthy fiber cables. High resolution temperature information (1 m, 10 s, and 0.1 °C) from fiber-optic distributed temperature sensing technology was for example employed by Tyler at el. [132] to map soil surface temperatures during melt out. Distributed temperature sensors (also called iButtons or Miniature Thermochron dataloggers) placed a few cm below or above the soil surface offer direct spatial information of soil temperatures and frozen ground and indirect information about presence or absence of snow, since diurnal temperature variations are much larger for bare than for snow covered ground [133,134]. iButtons were also used to get distributed data on the dates for snowpack basal ripening and for melt out [135] and to assess the likelihood of ice lenses formation in the snow pack [62]. Unfortunately these dataloggers are not waterproof, which can cause data loss, so one option is to seal them by coating them with plastic, and when comparing unmodified iButtons with iButtons modified in this way, Rznik and Alford [136] found small temperature differences (0–1.3 °C) and they conclude that coating iButtons with plastic is an reliable and affordable method to waterproof the data loggers. Thermistor strings are also used to maps snowpack temperature variations. Infrared thermal imager has been used for snow pit temperature measurements and to assess snow surface temperature [137]. However, it was pointed out [138] that during windy and cold conditions snow surfaces within a snow pit will quickly approach air temperatures thus limiting the use of infrared thermal imager for this type of application.

2.4. Tracer Techniques

Beside temperature, environmental tracers as well as artificial tracers are good tools to identify and quantify frost and snow processes and their impact on recharge rates and flow paths. A review of tracer studies aiming to increase the understanding of flow paths and residence times in northern catchments is presented by Tetzlaff et al. [139]. Artificial tracers can give information of a specific process at specific initial or boundary conditions of an experiment itself. Dye was used as a tracer to show that meltwater drip from trees seep more or less vertically through the snowpack to the soil but that water from different melt events follow different preferential flow channels [140]. Dyes were also used to visualize and quantify snowpack percolation [141]. Here, complex percolation patterns were observed by dye staining, highlighting the influence of ice layers and preferential flow paths in the snowpack. Similar findings were identified from the artificial application of rare earth elements to identify redistribution processes within the snowpack [142]. Ice layers within the snowpack acted as solute barriers and diurnal variability of melting processes were identified. Bromide in combination with electrical resistivity tomography has often been used to track infiltration pathways [20,122,124]. Salt tracers like bromide change the freezing point though and thus, their application as conservative tracers for snow and frost related processes are limited.

For more general applications, and on larger scales, environmental tracers have been used to estimate flow pathways in snowpacks, observe redistribution of water within the snowpack, mark the infiltration patters of melt water into soils, and quantify fractions of melt water in surface water or groundwater recharge [110,143–148]. Particularly, the stable environmental isotopes $\delta^{18}O$ and $\delta^{2}H$ are suited for providing information about meltwater infiltration in areas with frost and seasonal snow cover. Due to the temperature-isotope dependence, δ-values in snowfall and meltwater are lower compared to groundwater and annual mean of precipitation [149,150]. When snow reaches tree branches or the ground, the initial isotope signal can be modified by rain, condensation, sublimation, partial melting and percolation of meltwater. Meltwater isotopic signatures are for example influenced by the presence of forests, and Koeniger et al. [151] showed that heavy isotopes in the snowpack were progressively enriched as canopy stand density increased. During aging of the snow pack, isotope fractionation processes alter the isotope ratios of fresh snow [152]. For example, enrichment in $\delta^{18}O$ of meltwater can occur during percolation through the snow cover. Such enrichment can either be due to sublimation effects [150] or due to isotopic exchange between water and ice during percolation [153]. Both processes result in slopes of $\delta^{18}O/\delta^{2}H$ relationships that are significantly lower compared to the isotopic composition of precipitation. From the variability of the linear relationship between $\delta^{18}O$ and $\delta^{2}H$ due to water-ice interactions, Lee et al. [153] concluded on the melting history. To obtain snowmelt infiltration and recharge, melt water should therefore be collected and analyzed for water isotopic composition [149,154]. A solution is to use snow lysimeters like passive capillary samplers (PCS), earlier used to sample soil water. PCS were modified and placed at the snow soil interface to collect snowmelt water representative for the isotopic composition of the water infiltrating into the soil [155]. Penna et al. [156] state that PCS are low-cost, easy to install and can collect representative integrated snowmelt samples throughout the melt period or during single melt events. They are thus suitable for flow path determinations.

2.5. Techniques Focusing on Snow Parameters

2.5.1. Snow Precipitation

Most precipitation gauges collect less snowfall than the surrounding ground due to wind losses. Different types of wind shields and correction coefficients (functions of wind speed and air temperatures) have therefore been developed to compensate for this [157]. However, it is still a challenge to measure snow precipitation at wind exposed sites. Additional sources of errors are blockage of the gauge orifice by snow capping and accumulating on the side of the orifice walls. Heating the gauge eliminates capping and accumulation issues, however, heated gauges are prone to undercatch caused by updrafts over the gauge orifice and evaporation; particularly the latter should be avoided when using stable water isotopes as tracers. The survey by Nuti et al. [158] indicates that many automatic precipitation gauges varying in configuration, capacity, orifice area sensitivity and windshield are presently used for the measurement of solid precipitation. The use of a variety of gauge designs and approaches complicates intercomparison, and a harmonized measurement approach for snow research was called for [159]. Results from the WMO Solid Precipitation InterComparison (WMO-SPICE) to assess the quality of automated data [160] are now being published and readers are referred to other studies for details [156,158,161–178]. It is however worth mentioning that the two dimensional video disdrometers (2DVD) offer a novel technique which matches precipitation types based on images from two orthogonal cameras using supervised classification [179]. This allows for determination of both precipitation phase and precipitation density and thus of SWE for short time intervals. Examples of different precipitation types are shown in Figure 1.

Most automated methods to discriminate between rain and snow use ((I) Doppler radar; (II) optical sensors; (III) hotplates; or (IV) two dimensional video disdrometers (2DVD)) have been introduced without an in-depth intercomparison, which raises the question of their quality, consistency, compatibility, and representativeness [158].

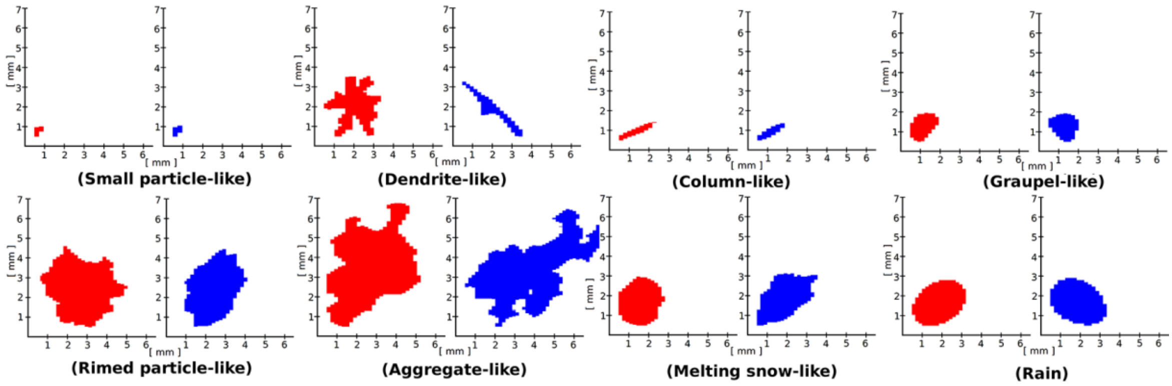

Figure 1. Examples of images from two orthogonal cameras showing the eight precipitation types identified by the 2DVD (with permission from [179]).

2.5.2. Snow Depth

The temporal and spatial evolution of snow depth in the early winter is especially important since shallow snow depths during the first cold spells often create thick frost. Ultrasonic sensors are extensively used to monitor temporal changes in snow depths for example at several SNOTEL sites [180], and they have an accuracy around ±1 cm [181]. SNOTEL is an automated system in Western US to measure snowpack and related meteorological parameters operated by the US Natural Resources Conservation Service (NRCS). Long-term trends (since 1928) of snow depths have been studied using snow stakes in the Austrian Alps [182]. Placed in view of time lapse cameras, they have been used to automatically record snow depth variation [183]. A snow depth probe combined with an inbuilt GPS giving positions with ±10 m (absolute value) and with ±2 m on repeated surveys can be ordered from the company SnowHydro [184]. By this technique several kilometers of observations with 2 m spacing can be obtained in just a few hours and downloaded to a computer at the end of the observations. However, information about how thick snow packs can be probed and how the device works with ice crust is lacking [184]. Detailed temperature profiles can be used to determine snow depth by analyzing the daily temperature amplitude (small variations within snow-pack, large above it). GPS receivers are today installed in numerous locations to provide precise positions for various scientific studies and this recent explosion of GPS networks means that daily data from thousands of GPS receivers are now available from public archives. Geodetic-quality GPS systems can be used to record average snow depths in an area of about 1000 m^2 around the GPS antenna in the depth range 0 to 150 cm [185–188].

2.5.3. Snow Water Equivalent (SWE)

SWE is the most essential parameter for assessing available water before spring melt which often is needed in hydrological forecasting related to hydropower, floods or recharge. SWE is the best indicator of the potential infiltration from snowmelt in spring, and the spatial variations in SWE give information about possible spatial variation in snowmelt volume. All methods to determine snow depths, mentioned above, can in combination with density be converted to SWE by multiplying with the density. The snow density can be measured (gravimetric snow sampling or retrieved from snow pits), estimated based on snow depth (maximum SWE in regions not exposed to midwinter melt [189]), on regional climate [190] or on season, snow depth, altitude, and location [191]. GPS depths were for example converted into SWE by SNOTEL site measured densities [188], however the spatial variation in snow density is large, see [192–195] for additional information regarding spatial and temporal variations in snow density. Temporal changes in SWE in one location can be recorded by snow pillows, weighing plates, attenuation of radioactivity or by attenuation of GPS signals or by repeated snow courses.

Snow courses: A snow course is a fixed transect in the terrain where snow depth and density are measured at fixed spatial intervals by snow tubes. Design criteria for them depend on study objectives and type of terrain [196]. Many evaluations of different snow tube designs are made and a recent comparison of two snow tube designs can be found in Dixon and Boon [197].

Snow pillows: A typical snow pillow is a big bladder filled with a non-toxic antifreeze liquid solution, installed under the snow, in level with the ground, with the weight of the snow (SWE) sensed by pressure transducers. They function well in fairly flat areas without freeze and thaw events. However, they are not suited for use in snowpacks with freeze thaw cycles forming ice sheets bridging the pillows, neither for dense forests nor steep terrain since it is difficult to dig foundations for them there. They are not suited for snowmelt infiltration studies since they block water transport into the soil. Furthermore, dark pillows should be avoided since they may absorb more solar radiation than the surrounding ground and therefore delay the onset of autumn snow accumulation [198,199]. There is also risk for leakage of antifreeze liquid. Recommendations for size, type of antifreeze liquid, etc. can be found in a Technical Report [200]. Impermeable weighing plates (SWE pressure sensors) suffer from similar weaknesses as snow pillows, but require less maintenance [201]. Tips on how to identify and correct SWE pressure sensor errors are presented in Johnston et al. [202]. Recent development and tests of different designs of permeable weighing plates better suited for infiltration studies can be found elsewhere [55,203].

Techniques based on radiation attenuation: That snowpack (more strictly hydrogen) attenuates radioactive radiation has long been used for SWE measurements [204] and at least three different applications have been used: (A) attenuation of radiation from an active radioactive source placed on the ground under the snowpack; (B) attenuation of the natural background radiation of the soil and rocks; and (C) attenuation of the natural cosmic radiation. Use of radioactive sources (active neutron sources) in a cased borehole, or access tube have been used previous to determine total water content in soils [205] but seems to have been more or less abandoned due to difficulties in gaining permission to handle, transport and leave radioactive sources in remote locations [206]. Soils and overburden emits natural gamma radiation and the strength depends on the type of soil and rock [207]. The attenuation of this radiation can after first measuring the background radiation without snow be related to SWE by a calibration function using the sensor CS 725 [208,209]. When the sensor is located about 3 m above the ground it measures an area of 50 to 100 m^2 (according to the manufacturer). This technique was tested and recommend [55,210] for non-alpine Norwegian regions (with melt and freeze cycles); however, the authors point out that it is not suited for SWE larger than 600 mm and that it should be connected to a power grid. A similar device run by solar power is presented by Martin et al. [209]. Cosmic gamma radiation also reaches the ground and incoming and attenuated cosmic radiation has been used to monitor SWE in Japan [211,212]. Between 1998 and 2004 about 40 Cosmic-ray snow sensors were installed in the mountainous regions of France giving satisfying SWE measurements [213]. However, local calibration seems to be needed and sometimes, the surrounding soil humidity has a strong influence on the SWE measurement and a specific sensor has been designed to solve this problem [213]. Today, a commercial product named SnowFox is accessible [214]. The cosmic radiation and the neutron probe techniques are similar so obstacles with identifying the measurement volume and with separating soil water and SWE could be expected. As mentioned earlier radar techniques can give line information about SWE.

2.5.4. SWE with Additional Snow Parameters

SAS2: Kinar and Pomeroy presented a non-destructive and time saving method based on acoustic reflectometry theory to determine SWE [215], and this method has later been upgraded to an electronic sensing system (SAS2) [216] to simultaneously measure LWC, snow density, and snow temperature and achieve images of the snowpack stratigraphy. Acoustic waves sent into and reflected from the snowpack by the SAS2 system and a sound propagation theory was used to acquire acoustic measurements of snow and images of the snowpack. Both stationary and portable versions of the SAS2 system were installed and tested and SWE could be determined quicker and more accurately than with a gravimetric snow tube [216].

SnowPack Analyzer/SnowPower: The SnowPack Analyzer system (also known as SnowPower) is based on low-frequency impedance measurements on a flat cable sensor for simultaneous measurement of snow density and liquid water content [217,218]. In combination with a snow depth sensor, it can also be used to measure SWE. The system measures the dielectric constant of snow at multiple frequencies in the kHz range using a newly developed low frequency impedance analyzer, and optionally also in the MHz range using an ordinary TDR analyzer. The dielectric constant of ice has a strong frequency variation in the kHz range, which enables determination of the volumetric content of both frozen and liquid water. The sensor consists of a 5 to 25 m long flat PVC-band cable, which can be mounted horizontally at some distance from the ground, to monitor conditions at a specific layer of the snow, or sloping from the ground to a position above the snow surface, to give integrated information over the entire snow profile. TDR measurements on the sensor cable may be further utilized to investigate the spatial variation of liquid water in the snowpack by inverse modeling of the Telegraph equation [219]. However, the low frequency measurements are enough for determination of the average density, SWE, and wetness; therefore the TDR measurements are not included in the later versions of the SnowPack Analyzer system. The sensor has been tested for instance in high-alpine Swiss test site [83,218], agricultural fields in Canada [217], mountain sites in Scandinavia, and forest sites in Germany and USA [220,221]. According to these tests the sensing system was quite robust with regard to the impedance analyzer and the horizontally mounted sensor cables. However, several tests indicated practical problems with the sloping installation such as wind-induced air pockets around the cable [218], running water along the sloping cable [83], and damages to the cable sensor [220]. The analysis if the sloping cable is also highly sensitive to the fraction of the cable covered by snow, which needs to be estimated for instance by an assumed geometry and snow depth observations. Due to these problems, the sloping cable installation is no longer recommended by the manufacturer (Wolfram Sommer, personal communication 2015). On the other hand, the field tests also showed that data from horizontal sensors mounted, either at the base of the snow pack, or at specific depths of the snowpack give reliable and useful information compared to manual snowpack measurements and numerical modeling of SWE, and LWC variation and snowmelt infiltration [83,218,220,221]. The Canadian study also accentuates the importance for the estimation accuracy on the choice of low frequency and the algorithm for the snow temperature extrapolation [217,218,221].

2.5.5. Snow Layering

Snow layering into different density layers has an effect on, for example, snow stability, which is important in avalanche research. Snow layering is important for spatial distribution of snowmelt and rain, which can be transported tens of meters along layers in the snow. Snow pit excavations are frequently used to determine vertical density variations and to identify snow layers and track water movement in snow [81,222]. How to dig and refill a snowpit without disturbing the snow is described in Williams et al. [223]. The penetrometer (SnowMicroPen) can be carried in a rucksack and can give extremely detailed information about snow structure profile (snow pack layering) [65,114,224]. A "snowguillotine" was used to produce high-resolution (1 cm^3), 3-D-information regarding meltwater flow through a snowpack by combining the measurements with image processing and geostatistical analysis [225]. The radar and acoustic techniques mentioned above can give line and area information about snow layers. Snow stratigraphy may also be observed using photographs of translucent snow profiles obtained by excavating a snow snowpit profile from two sides [226].

2.5.6. Liquid Water Content

The first snowmelt does not necessarily leave the snowpack but is held by capillary forces in the snow. Therefore, it is important to measure the temporal and spatial variations in liquid water content (LWC) to be able to know when and where snow is ripe (saturated LWC) and water is ready to leave the snowpack. Infrared radiation_sensors can be used to measure snow surface temperature [227] and thus give information about if the snow is melting or not since melting snow has the constant temperature of 0 °C. The "snow fork" is a hand-held device which consists of a two-pronged wave guide that is inserted into the snow to determine its density (for dry snow) and wetness (if density is known) [228]. A similar design as the snow fork, said to have higher spatial resolution and accuracy, was presented by Kendra et al. [229]. A capacitive radio-frequency device was used to record snow density and LWC at several different levels [230]; a similar approach used a monopole antenna [231]. However, all these devices are not suited for stationary registration since they will absorb solar radiation creating air pockets around the probes. LWC measured by the snow fork was consistently 1.5 times greater than by the Denoth meter [232]. The spatial variations in LWC for snow and seasonally frozen ground are needed in order to assess if and how common preferential flow is. Radar, TDR, SnowPack Analyzer and electrical resistivity techniques mentioned before can also be used to monitor snowpack wetness.

2.5.7. Melt Water Collection and Separation

Many different types of lysimeters are used to collect meltwater [62,233,234], and the design is influenced by the purpose of the study. Design to measure snowmelt separation into surface, subsurface and deep percolation can be found in Bayard et al. [21]. Teflon-coated acid washed snowmelt lysimeters were used for measuring volumes, melt intensity and isotopic composition of the snowmelt [39]. Lysimeters in materials with low thermal conductivity and high albedo (plywood and white fiber glass) approximating the thermal characteristics of the snowpack are described by Winkler et al. [36]. Lysimeters are widely used in hydrograph separation studies either using volume weighted average value or sampling at different time steps throughout the melt event [235]. The earlier mentioned passive capillary samplers (PCS) can also be used.

2.5.8. Forest Snow Parameters

Forests reduce snowfall (evaporation and sublimation of canopy intercepted snow) and cause small-scale distribution of throughfall, thus causing uneven frost. Measurement techniques for canopy snow forests storage processes have been reviewed earlier [58,236]. Ideal canopy process studies should include continuous measurements of intercepted mass and throughfall with high time resolution and not disturb the meteorological conditions function and the method should work during periods of both melt and sublimation. However, all methods have individual drawbacks [57]. Winter season canopy forest sublimation has been determined as difference between peak snow accumulation in open and forested areas [237,238]. Sublimation/evaporation processes of canopy snow has been estimated by eddy covariance techniques [239,240] and by deuterium and oxygen 18 isotopes [151,241]. The eddy covariance technique has also been applied in studies of snow sublimation below forested canopies [242]. Canopy (tree crown) intercepted mass has been estimated using branch displacement by tensiometers [243], photos [240], digitized video images of branch deflection [244], tree weighing devices [58,236,237,245] and tree stem compression [246]. Throughfall has been measured using sealing of ground by tarpaulin [247], by weighing devices [58,248] and by non-weighing snow-melt lysimeters i.e., troughs equipped with tipping buckets [62]. The lysimeter troughs designed to record drip from tree crowns during rain on snow events seem well suited for the task for snowpacks <1 m. They were buried in the ground and stuffed with coniferous branches in order to prevent icing and blockages and the associated tipping bucket was enclosed and also buried in the ground to prevent freezing [62]. Frost measurements using radar techniques with a snow mobile in forests might be difficult due to poor accessibility. In special conditions, terrestrial laser scanning can also be used for detailed mapping of sub-canopy snow depth distribution [72].

2.6. Techniques Focusing on Soil and Groundwater Parameters

Several of the radar techniques are well suited to record spatial variations in frost depths, and depths to the thawing front, and a surface to surface application have also been used to map temporal variations in soil moisture [249]. The temperature techniques discussed above can also be used to assess frost depths [87]. Frost depth is important for the infiltration but even more crucial is the ice content of the frost (in reality it is the open pore space that matters). Most infiltration measurement methods deal with determining infiltration capacity (tension disks and pressure ring infiltrometers) while techniques to measure actual infiltration rates seem more rare. Infiltration rates may be estimated from measurements of increase in water content at various soil depths using combinations of dielectrical sensors. For example TDR-techniques, which can give unfrozen water content, and gamma or neutron scattering techniques, which gives total water content (liquid and frozen). Frost depth tubes filled with methylene blue solution [87], which changes color when frozen, are often used to monitor frost temporal development and their precision was, according to Iwata et al. [60] around ±3.5 cm, and thaw depths were overestimated by the tubes but could be calibrated using a linear equation.

As TDR are commonly used in hydrological studies to monitor soil moisture content, TDRs can provide additional information to many hydrological studies on soil freezing time or freezing front movement. Sun et al. [250] tested a frequency domain dielectrical sensor designed for use in access tubes to measure in-situ soil freeze–thaw cycle dynamics and concluded that the sensor was easier to operate than TDR-equipment, rapid, fairly accurate, non-destructive and more cost effective since a single sensor could be used at multiple sites. Yoshikawa and Overduin [251] who tested soil moisture probes based on electromagnetic properties in frozen soils showed that each sensor had a unique response to soil type and temperature changes, thus requiring unique calibrations. Wu et al. [252] presented a laboratory test using the complex resistivity method to monitor freeze–thaw transitions. They claim that their study provided a basis for exploring the potential of this method to monitoring spatiotemporal variations of freeze–thaw transitions over field-relevant scales. For neutron scattering [111,205] and gamma attenuation techniques a radioactive source is used (the gamma source is stronger) to measure the volumetric water content. The source is inserted into a vertical cased tube and winched up and down to quickly measure the moisture content at different depths. However, the use of radioactive sources requires training of staff, monitoring and regulation of shipping and handling [116] and has limited the use of the these methods. These techniques have been used in combination with TDR techniques where the latter technique is used to measure LWC and the total water content (ice and water) is measured by neutron [111,253,254] and gamma ray [126] scattering methods respectively. Errors for the gamma ray and TDR technique of 2% and 1% by volume (m^3/m^3) are reported [126].

Thermally insulated tensiometers designed for monitoring the potential of unfrozen soil below the frozen soil layer are described and used by several studies [14,29,118,255,256]. These tensiometers should be installed horizontally to minimize the soil disturbance. For recommendations on how to install and use piezometers and groundwater wells to monitor groundwater response to recharge see for example Rosenberry et al. [257]. For snow and frost applications, special attention must be paid to avoiding use of metal tubing, which might cause local enhanced frost around the observation wells. The soil freezing characteristic and soil moisture characteristic plays a key roles in soil frost modeling and a portable dielectric tube sensor along with a set of temperature sensors were successfully used for in situ determination of soil freezing characteristic and soil moisture characteristic [258].

3. Summary and Future Recommendation on Measurement Techniques

The spatial variability of both snow and soil frost seem to be the most distinguished requirement for enhancing our understanding of the snowmelt infiltration processes at the spatial scale important for runoff generation. Thus, measurement techniques that enable observations of the spatial distribution with high spatial variability are to be recommended foremost, in other words, space-continuous techniques such as ground penetrating radar have a high potential to provide new insights. On the other hand, the quantitative uncertainties are rather high in radar techniques, unless it is combined with other observation types to reduce these uncertainties. In the following, we summarize the pros and cons of the various measurement techniques included in this review:

Ultrasonic sensors and snow sticks (with or without time laps cameras) are inexpensive methods suited to monitor temporal changes in snow depths. GPS systems can be used to record average SWE over larger areas but with lower accuracy. There are many different methods used to map temporal variations in SWE (see Table 1) and they all have their individual advantages and disadvantages (see references for details) but methods that do not block the melt water entrance into the soil should be used for infiltration and recharge studies so snow pillows and impermeable electronic weighing devices should be avoided.

Table 1. Summary of methods to register temporal variations in snow water equivalent (SWE).

Method	Obs. Area *	Additional Snow Parameters	Refs
Snow pillows			
Bladders or Steel containers	≈3–10 m^2	-	[200,259]
Electronic weighing devices			
Impermeable Johnson	≈10 m^2	-	[198,260]
Permeable Johnson	≈1.5–9 m^2	-	[203]
Permeable Moen 2525	≈25 m^2	-	[55]
Gamma radiation attenuation techniques			
Artificial source	Point	-	[204]
Natural ground	≈75 m^2	-	[55,208,209]
Natural cosmic	≈75 m^2	-	[211–214] 2015, Hydroinnova
Stationary up-ward looking radar techniques			
Single frequency	Point	LWC, density, layers	[81,83,105,106]
Step frequency	Point	LWC, density, layers	[107]
Low Frequency Impedance Band (SnowPower)	≈5–25 m		[218,261]
SAS2 Electronic sensing system using acoustics	<45 m^3	LWC, density, temp, layers	[216]

* Observed area when applicable is given as observed distance or observed volume and for the Johnson et al. electronic devices is it the area of the weighing panels which are given, these panels are surrounded by eight equally sized panels.

Ground based radar comes in many different designs (systems with single or varying antenna frequencies, with one or several channels) and can be mounted stationary to record temporal changes or on a vehicle to assess spatial variations. Radars applying high frequencies can for example identify thin ice layers but have shallow penetration depths while radars with low frequencies can penetrate deeper but might fail to identify thin layers. Both the travel time for the radar pulse, and the attenuation of its amplitude could preferably be used to assess properties of the snow and the frozen soils. The recent development, of upward looking stationary mounted radars, has been used to successfully record temporal variations in snowpack properties (SWE, depth, LWC). Radars mounted on vehicles have fruitfully been used to map spatial distribution of snowpack properties (depth, SWE and ice layers) and frozen soil properties (depth of frozen soil, depth of thawing layer, soil LWC). The radar applications providing information of SWE, density and layers would have many applications. A combination of an upward looking stationary radar system, and another radar system for spatial surveys at (a) the time of maximum SWE; (b) towards the end of snowmelt; and (c) at the time of maximum thaw would give information about the temporal development and spatial distribution of snow, as well as spatial distribution of frost depth and thawing depth provided that soil conditions are favorable for radar measurements (preferably sandy soils, and not clay soils). As long as snow bulk properties are of interest, ground based radar systems could well be the optimal measurement techniques to collect snow information for studies on infiltration patterns in frozen soils. However, it must be noted that derivation of snow properties such as density and liquid water content from the radar signal without other reference data comes with large uncertainties, and it is recommended to always combine the radar data with for instance manual snow density and snow depth samples to reduce these uncertainties.

Time domain reflectometry (TDR) works well for determination of LWC in snow and soil, but large care has to be made to assure that airgaps are not formed around the probes. The thermo-time domain reflectometry (T-TDR) probe monitors both temperature and LWC. High resolution temperature information (1 m, 10 s, and 0.1 °C) can be achieved from fiber-optic distributed temperature sensing technology and inexpensive coated iButtons and thermistor strings can also be useful to map soil and snow temperatures.

The low frequency impedance sensor system (SnowPack Analyzer/SnowPower) has the advantage over conventional TDR of determining both liquid and frozen water content, and the influencing area around the sensor is larger making it less sensitive to air gaps. On the other hand, the size of the sensor is both a problem and a potential strength of the system. The low frequency impedance measurements require the sensor cable to be at least about 5 m long. Low-frequency measurements will thus integrate over a larger volume, which might be preferable, but this length also causes problems with regard to the deployment in the snow, especially for sloping configurations. Thus far, the SnowPack Analyzer system seems to be most reliable and unique with regard to liquid water content measurements, and using the horizontal deployment of the sensor cable in the snow.

For flow path information some kind of tracer is recommended. Dye has been used to map meltwater paths along different flow paths in the snowpack and artificial application of rare earth elements were used to identify redistribution process within the snowpack. Electrical resistivity tomography in combination with bromide has often been used to track infiltration path ways. The stable environmental isotopes $\delta^{18}O$ and $\delta^{2}H$ are suited since the δ-values in snowfall and meltwater are lower compared to groundwater and annual mean of precipitation and thus giving information about snowmelt infiltration. However, meltwater isotopic signatures are influenced by phase change processes (freezing, melting and evaporation) and melt water leaving the snow pack should therefore be collected and analyzed for water isotopic composition by for example passive capillary samplers (PCS) or lysimeters. Design of lysimeters for collection and separation snowmelt into shallow flowing soil water and percolating water has to be adapted to the purpose and location of study. When water quality is of interest teflon-coated acid washed snowmelt lysimeters are recommended and material with thermal conductivity and albedo approximating those of the snowpack are recommended for use in the snowpack. The recent application of self-potential (SP) to map melt water flow paths seems to have large potential and so does the acoustic method, which also gives additional information.

Terrestial laser scanning technique (LiDAR) can preferably be used to identify possible locations for focused infiltration.

Recommended techniques for snowmelt infiltration studies:

- Electronic sensing system using acoustics, stationary upward mounted radars or low impedance band for temporal information about snow (LWC, SWE and layers).
- Mobile radars with different designs for spatial information about snow (LWC, SWE and layers) and soil (frost depth, water content, and thawing depth).
- Permeable weighing sensor for temporal variations in SWE.
- Natural or artificial tracers and Self-potential for flow paths in snow.
- TDR and Low-Frequency impedance sensor measurements for LWC in snow and soil.
- Neutron methods for total (liquid and frozen) water in soils.
- Fiber optics, thermistor strings or coated iButtons for temperature.
- Frost tubes for frost depth.
- Lysimeters designed for the study and SPC samplers to measure snowmelt.
- LiDAR to identify likely locations for focused infiltration.
- If precipitation gauges are used to measure snowfall, is it important to use a suitable design or to correct for wind losses.

4. Recommendation for Future Collaborative Research

A collaborative research effort is recommended to obtain more information on snow and frost hydrology. Processes related to spatial and temporal variation of snow and soil frost and its interplay with recharge and runoff are crucial in hydrology, but relatively poorly understood and not well incorporated in hydrological models. With climate warming, changes in snow and frost occurrence will be a major change in hydrology of high latitudes and future climate change scenarios should urgently assess changes in hydrological process. The demand for such information is obviously needed for many sectors and communities (water supply, flood protection, agriculture, traffic, environmental protection, etc.) Information is needed on different scales and on different processes depending on application, e.g., small scale stability is crucial for avalanches, small scale accumulation of snow is needed for traffic and roof snow loads but large scale accumulation is more important for flood prediction and infiltration/overland flow partitioning (water quality), and recharge (groundwater renewal). Knowledge on spatial distributions of snow and frost will be especially urgent in regions that rely on snowmelt runoff and snow related groundwater renewal for water supply and irrigation. As soil frost and snowmelt have an effect on transport pathways, knowledge is also needed to assess climate change related changes in solutes transport such as DOC, nitrate, pesticide and phosphorous leaching. To cover the complexities linked to snow hydrology, experts with different specializations should work closely together to increase process understanding, share experiences in novel measurement techniques and integrate knowledge and raise awareness on the importance of snow hydrology.

We recommend a stronger future collaboration in hydrological research, data sharing and learning. Such joint research could focus on different type of catchments to cover the variability and gradients in climate, topography, geology and land cover. This should bring new insight into the importance of snow and seasonal soil frost processes on spatial and temporal distribution of snowmelt infiltration (and thus on the distribution of the nutrients and pollutants in the snowmelt) could be achieved with study design adjusted to the aim, the scale, and the means of the study using more than one technique to assess the spatiotemporal variations of the key parameters. Ground based radar, stationary mounted for temporal variations, and mounted on vehicles for spatial variations of snow and frost parameters is a useful tool in this context and the acoustics and the self-potential techniques, recently adjusted for snow measurements, seem very promising for this type of studies. Isotopic techniques and airborne methods linked to data assimilation could also be important. Collaboration across current experimental sites, establishing new sites and adding more detailed information on currently monitored sites is recommended. Some sites such as ICOS on green house gas fluxes currently monitor evapotranspiration and energy fluxes in seasonally snow covered regions (https://www.icos-ri.eu). For these sites hydrological studies could relatively simply be added to existing measurement set-ups to provide more detailed information on hydrological processes where all component to understand the hydrological dynamics and close the water balance. The ICOS network could be a model for future collaboration. As snow has wide implication on many sectors of society, experimental sites need to be established on a range of different land uses and soils.

Collaborative research and data sharing can have great potential to improve the knowledge in this field. To our knowledge, national monitoring networks on snow depth are under evaluation as new techniques have emerged. A common network on experts and experimental catchment could outline future recommendation regarding national monitoring efforts. The snow studies should be linked to catchments and groundwater hydrological studies with stronger links to experts on geophysics and airborne techniques to measure snow dynamics at appropriate spatial and temporal scales.

National monitoring set-ups could benefit from more detailed studies on snow where novel techniques that capture the complex temporal and spatial patterns of snow accumulation and melt as well as hydrological process of infiltration, overland flow, recharge and runoff generation are developed.

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References

1. Barnett, T.P.; Adam, C.J.; Lettenmaier, D.P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **2005**, *438*, 303–309. [CrossRef] [PubMed]
2. Lundberg, A.; Ala-Aho, P.; Eklo, O.; Klöve, B.; Kværner, J.; Stumpp, C. Snow and frost: Implications for spatiotemporal infiltration patterns—A review. *Hydrol. Process.* **2016**, *30*, 1230–1250. [CrossRef]
3. Rasmus, S. *Snowpack Structure in Finland: Measurement and Modelling*; University of Helsinki: Helsinki, Finland, 2005.
4. Kreyling, J. Winter climate change: A critical factor for temperate vegetation performance. *Ecology* **2010**, *91*, 1939–1948. [CrossRef] [PubMed]
5. Edwards, A.C.; Scalenghe, R.; Freppaz, M. Changes in the seasonal snow cover of alpine regions and its effect on soil processes: A review. *Quat. Int.* **2007**, *162*, 172–181. [CrossRef]
6. EC. Directive 2000/60/ec of the european parliament and of the council establishing a framework for community action in the field of water policy. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=URISERV%3Al28002b (accessed on 20 Februay 2015).
7. EC. Directive 2007/60/ec on the assessment and management of flood risks. Available online: http://ec.europa.eu/environment/water/flood_risk/ (accessed on 20 Februay 2015).
8. EC. Directive 2006/118/ec of the european parliament and of the council on the protection of groundwater against pollution and deterioration. Available online: http://eur-lex.europa.eu/eli/dir/2006/118/oj (accessed on 20 Februay 2015).
9. Tague, C.; Grant, G.E. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. *Water Resour. Res.* **2009**, *45*, W07421. [CrossRef]
10. Beniston, M.; Diaz, H.; Bradley, R. Climatic change at high elevation sites: An overview. *Clim. Chang.* **1997**, *36*, 233–251. [CrossRef]
11. Pepin, N.; Losleben, M. Climate change in the colorado rocky mountains: Free air versus surface temperature trends. *Int. J. Climatol.* **2002**, *22*, 311–329. [CrossRef]
12. Hardy, J.P.; Groffman, P.M.; Fitzhugh, R.D.; Henry, K.S.; Welman, A.T.; Demers, J.D.; Fahey, T.J.; Driscoll, C.T.; Tierney, G.L.; Nolan, S. Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. *Biogeochemistry* **2001**, *56*, 151–174. [CrossRef]
13. Groffman, P.M.; Driscoll, C.T.; Fahey, T.J.; Hardy, J.P.; Fitzhugh, R.D.; Tierney, G.L. Colder soils in a warmer world: A snow manipulation study in a northern hardwood forest ecosystem. *Biogeochemistry* **2001**, *56*, 135–150. [CrossRef]
14. Iwata, Y.; Hayashi, M.; Suzuki, S.; Hirota, T.; Hasegawa, S. Effects of snow cover on soil freezing, water movement, and snowmelt infiltration: A paired plot experiment. *Water Resour. Res.* **2010**, *46*, W09504. [CrossRef]
15. Choi, G.; Robinson, D.A.; Kang, S. Changing northern hemisphere snow seasons. *J. Clim.* **2010**, *23*, 5305–5310. [CrossRef]
16. Räisänen, J. Warmer climate: Less or more snow? *Clim. Dyn.* **2008**, *30*, 307–319. [CrossRef]
17. Lundberg, A.; Beyerl, H. Ash on snow a tool—A tool to prevent flooding? *Nord. Hydrol.* **2001**, *32*, 195–214.
18. Popova, V. Winter snow depth variability over northern eurasia in relation to recent atmospheric circulation changes. *Int. J. Climatol.* **2007**, *27*, 1721–1733. [CrossRef]
19. Brown, R.D.; Mote, P.W. The response of northern hemisphere snow cover to a changing climate. *J. Clim.* **2009**, *22*, 2124–2145. [CrossRef]
20. Bayard, D.; Stähli, M. *Effects of Frozen Soil on the Groundwater Recharge in Alpine Areas*; Wiley: Chichester, UK, 2005; pp. 73–83.

21. Bayard, D.; Stähli, M.; Parriaux, A.; Flühler, H. The influence of seasonally frozen soil on the snowmelt runoff at two alpine sites in southern switzerland. *J. Hydrol.* **2005**, *309*, 66–84. [CrossRef]
22. Nyberg, L.; Stähli, M.; Mellander, P.E.; Bishop, K.H. Soil frost effects on soil water and runoff dynamics along a boreal forest transect: 1. Field investigations. *Hydrol. Process.* **2001**, *15*, 909–926. [CrossRef]
23. Shanley, J.B.; Chalmers, A. The effect of frozen soil on snowmelt runoff at sleepers river, vermont. *Hydrol. Process.* **1999**, *13*, 1843–1857. [CrossRef]
24. Johnsson, H.; Lundin, L.-C. Surface runoff and soil water percolation as affected by snow and soil frost. *J. Hydrol.* **1991**, *122*, 141–159. [CrossRef]
25. Stähli, M.; Jansson, P.E.; Lundin, L.C. Soil moisture redistribution and infiltration in frozen sandy soils. *Water Resour. Res.* **1999**, *35*, 95–103. [CrossRef]
26. Sutinen, R.; Hänninen, P.; Venäläinen, A. Effect of mild winter events on soil water content beneath snowpack. *Cold Reg. Sci. Technol.* **2008**, *51*, 56–67. [CrossRef]
27. Stein, J.; Proulx, S.; Lévesque, D. Forest floor frost dynamics during spring snowmelt in a boreal forested basin. *Water Resour. Res.* **1994**, *30*, 995–1007. [CrossRef]
28. Jones, H.; Pomeroy, J. Early spring snowmelt in a small boreal forest watershed: Influence of concrete frost on the hydrology and chemical composition of streamwaters during rain-on-snow events. In Proceedings of the Eastern Snow Conference, Ottawa, ON, Canada, 17–19 May 2001; pp. 209–218.
29. Iwata, Y.; Nemoto, M.; Hasegawa, S.; Yanai, Y.; Kuwao, K.; Hirota, T. Influence of rain, air temperature, and snow cover on subsequent spring-snowmelt infiltration into thin frozen soil layer in northern Japan. *J. Hydrol.* **2011**, *401*, 165–176. [CrossRef]
30. Espeby, B. Tracing the origin of natural-waters in a glacial till slope during snowmelt. *J. Hydrol.* **1990**, *118*, 107–127. [CrossRef]
31. Flerchinger, G.; Lehrsch, G.; McCool, D. Freezing and thwing processes. In *Encyclopedia of Soils in the Environment*; Hillel, D., Ed.; Elsevier, Ltd.: Oxford, UK, 2005; pp. 104–110.
32. Ireson, A.M.; van der Kamp, G.; Ferguson, G.; Nachshon, U.; Wheater, H.S. Hydrogeological processes in seasonally frozen northern latitudes: Understanding, gaps and challenges. *Hydrogeol. J.* **2013**, *21*, 53–66. [CrossRef]
33. Stadler, D.; Wunderli, H.; Auckenthaler, A.; Flühler, H.; Bründl, M. Measurement of frost-induced snowmelt runoff in a forest soil. *Hydrol. Process.* **1996**, *10*, 1293–1304. [CrossRef]
34. Redding, T.; Devito, K. Aspect and soil textural controls on snowmelt runoff on forested boreal plain hillslopes. *Hydrol. Res.* **2011**, *42*, 250–267. [CrossRef]
35. Smith, R.; Moore, R.; Weiler, M.; Jost, G. Spatial controls on groundwater response dynamics in a snowmelt-dominated montane catchment. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 1835–1856. [CrossRef]
36. Winkler, R.; Spittlehouse, D.; Golding, D. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern british columbia. *Hydrol. Process.* **2005**, *19*, 51–62. [CrossRef]
37. Ellis, C.; Pomeroy, J.; Essery, R.; Link, T. Effects of needleleaf forest cover on radiation and snowmelt dynamics in the Canadian Rocky Mountains. *Can. J. For. Res.* **2011**, *41*, 608–620. [CrossRef]
38. Jost, G.; Moore, R.D.; Smith, R.; Gluns, D.R. Distributed temperature-index snowmelt modelling for forested catchments. *J. Hydrol.* **2012**, *420*, 87–101. [CrossRef]
39. Laudon, H.; Seibert, J.; Kohler, S.; Bishop, K. Hydrological flow paths during snowmelt: Congruence between hydrometric measurements and oxygen 18 in meltwater, soil water, and runoff. *Water Resour. Res.* **2004**, *40*, W03102. [CrossRef]
40. Boyer, E.W.; Hornberger, G.M.; Bencala, K.E.; McKnight, D.M. Response characteristics of doc flushing in an alpine catchment. *Hydrol. Process.* **1997**, *11*, 1635–1647. [CrossRef]
41. Deng, Y.; Flerchinger, G.; Cooley, K. Impacts of spatially and temporally varying snowmelt on subsurface flow in a mountainous watershed: 2. Subsurface processes. *Hydrol. Sci. J.* **1994**, *39*, 521–533. [CrossRef]
42. Hinckley, E.L.S.; Barnes, R.T.; Anderson, S.P.; Williams, M.W.; Bernasconi, S.M. Nitrogen retention and transport differ by hillslope aspect at the rain-snow transition of the Colorado front range. *J. Geophys. Res. Biogeosci.* **2014**, *119*, 1281–1296. [CrossRef]
43. Kuras, P.K.; Weiler, M.; Alila, Y. The spatiotemporal variability of runoff generation and groundwater dynamics in a snow-dominated catchment. *J. Hydrol.* **2008**, *352*, 50–66. [CrossRef]
44. Burt, T.; Williams, P.J. Hydraulic conductivity in frozen soils. *Earth Surf. Process.* **1976**, *1*, 349–360. [CrossRef]

45. Andersland, O.B.; Wiggert, D.C.; Davies, S.H. Hydraulic conductivity of frozen granular soils. *J. Environ. Eng.* **1996**, *122*, 212–216. [CrossRef]
46. Kane, D.L.; Stein, J. Water movement into seasonally frozen soils. *Water Resour. Res.* **1983**, *19*, 1547–1557. [CrossRef]
47. Van der Kamp, G.; Hayashi, M.; Gallen, D. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. *Hydrol. Process.* **2003**, *17*, 559–575. [CrossRef]
48. Stadler, D.; Brundl, M.; Wunderli, H.; Auckenthaler, A.; Fluhler, H. Measurement of frost-induced snowmelt runoff in a forest soil [1996]. *Hydrol. Process.* **1997**, *11*, 427–427. [CrossRef]
49. Zhao, L.; Gray, D.M.; Male, D.H. Numerical analysis of simultaneous heat and mass transfer during infiltration into frozen ground. *J. Hydrol.* **1997**, *200*, 345–363. [CrossRef]
50. Gray, D.M.; Toth, B.; Zhao, L.T.; Pomeroy, J.W.; Granger, R.J. Estimating areal snowmelt infiltration into frozen soils. *Hydrol. Process.* **2001**, *15*, 3095–3111. [CrossRef]
51. Gray, D.M.; Landine, P.G.; Granger, R.J. Simulating infiltration into frozen prairie soils in streamflow models. *Can. J. Earth Sci.* **1985**, *22*, 464–472.
52. Lindström, G.; Bishop, K.; Löfvenius, M.O. Soil frost and runoff at svartberget, northern Sweden—Measurements and model analysis. *Hydrol. Process.* **2002**, *16*, 3379–3392. [CrossRef]
53. Deems, J.S.; Painter, T.H.; Finnegan, D.C. Lidar measurement of snow depth: A review. *J. Glaciol.* **2013**, *59*, 467–479. [CrossRef]
54. Egli, L.; Jonas, T.; Meister, R. Comparison of different automatic methods for estimating snow water equivalent. *Cold Reg. Sci. Technol.* **2009**, *57*, 107–115. [CrossRef]
55. Bache Stranden, H.; Lirhus Ree, B.; Moen, K. *Recommendations for Automatic Measurements of Snow Water Equivalent in Nve*; NVE Publisher: Oslo, Norway, 2015; p. 33.
56. Proksch, M.; Loewe, H.; Schneebeli, M. Density, specific surface area, and correlation length of snow measured by high-resolution penetrometry. *J. Geophys. Res. Earth Surf.* **2015**, *120*, 346–362. [CrossRef]
57. Lundberg, A.; Halldin, S. Snow interception evaporation. Review of measurement techniques, processes, and models. *Theor. Appl. Climatol.* **2001**, *70*, 117–133. [CrossRef]
58. Lundberg, A. Evaporation of intercepted snow—Review of existing and new measurement methods. *J. Hydrol.* **1993**, *151*, 267–290. [CrossRef]
59. Lundberg, A.; Halldin, S. Snow measurement techniques for land-surface-atmosphere exchange studies in boreal landscapes. *Theor. Appl. Climatol.* **2001**, *70*, 215–230. [CrossRef]
60. Iwata, Y.; Hirota, T.; Suzuki, T.; Kuwao, K. Comparison of soil frost and thaw depths measured using frost tubes and other methods. *Cold Reg. Sci. Technol.* **2012**, *71*, 111–117. [CrossRef]
61. Lundberg, A.; Granlund, N.; Gustafsson, D. Towards automated 'ground truth' snow measurements—A review of operational and new measurement methods for Sweden, Norway, and Finland. *Hydrol. Process.* **2010**, *24*, 1955–1970. [CrossRef]
62. Floyd, W.; Weiler, M. Measuring snow accumulation and ablation dynamics during rain-on-snow events: Innovative measurement techniques. *Hydrol. Process.* **2008**, *22*, 4805–4812. [CrossRef]
63. Pohl, S.; Garvelmann, J.; Wawerla, J.; Weiler, M. Potential of a low-cost sensor network to understand the spatial and temporal dynamics of a mountain snow cover. *Water Resour. Res.* **2014**, *50*, 2533–2550. [CrossRef]
64. Feiccabrino, J.; Gustafsson, D.; Lundberg, A. Surface-based precipitation phase determination methods in hydrological models. *Hydrol. Research* **2013**, *44*, 44–57. [CrossRef]
65. Schneebeli, M.; Coleou, C.; Touvier, F.; Lesaffre, B. Measurement of density and wetness in snow using time-domain reflectometry. *Ann. Glaciol.* **1998**, *26*, 69–72.
66. Roth, K.; Schulin, R.; Fluhler, H.; Attinger, W. Calibration of time domain reflectometry for water-content measurement using a composite dielectric approach. *Water Resour. Res.* **1990**, *26*, 2267–2273. [CrossRef]
67. Watanabe, K.; Wake, T. Measurement of unfrozen water content and relative permittivity of frozen unsaturated soil using NMR and TDR. *Cold Reg. Sci. Technol.* **2009**, *59*, 34–41. [CrossRef]
68. Lundberg, A. Laboratory calibration of TDR-probes for snow wetness measurements. *Cold Reg. Sci. Technol.* **1997**, *25*, 197–205. [CrossRef]
69. Egli, L.; Jonas, T.; Grunewald, T.; Schirmer, M.; Burlando, P. Dynamics of snow ablation in a small alpine catchment observed by repeated terrestrial laser scans. *Hydrol. Process.* **2012**, *26*, 1574–1585. [CrossRef]
70. Grunewald, T.; Schirmer, M.; Mott, R.; Lehning, M. Spatial and temporal variability of snow depth and ablation rates in a small mountain catchment. *Cryosphere* **2010**, *4*, 215–225. [CrossRef]

71. Prokop, A. Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements. *Cold Reg. Sci. Technol.* **2008**, *54*, 155–163. [CrossRef]
72. Revuelto, J.; López-Moreno, J.I.; Azorin-Molina, C.; Vicente-Serrano, S.M. Canopy influence on snow depth distribution in a pine stand determined from terrestrial laser data. *Water Resour. Res.* **2015**, *51*, 3476–3489. [CrossRef]
73. Kværner, J.; Eklo, O.M.; Solbakken, E.; Solberg, I.; Sorknes, S. An integrated approach for assessing influence of agricultural activities on pesticides in a shallow aquifer in south-eastern Norway. *Sci. Total Environ.* **2014**, *499*, 520–532. [CrossRef] [PubMed]
74. Marchand, W.D.; Bruland, O.; Killingtveit, A. Improved measurements and analysis of spatial snow cover by combining a ground based radar system with a differential global positioning system receiver. *Nord. Hydrol.* **2001**, *32*, 181–194.
75. Richardson, C.; Holmlund, P. Spatial variability at shallow snow-layer depths in central Dronning Maud Land, East Antarctica. *Ann. Glaciol.* **1999**, *29*, 10–16. [CrossRef]
76. McGrath, D.; Sass, L.; O'Neel, S.; Arendt, A.; Wolken, G.; Gusmeroli, A.; Kienholz, C.; McNeil, C. End-of-winter snow depth variability on glaciers in Alaska. *J. Geophys. Res. Earth Surf.* **2015**, *120*, 1530–1550. [CrossRef]
77. Previati, M.; Godio, A.; Ferraris, S. Validation of spatial variability of snowpack thickness and density obtained with GPR and TDR methods. *J. Appl. Geophys.* **2011**, *75*, 284–293. [CrossRef]
78. Singh, K.K.; Datt, P.; Sharma, V.; Ganju, A.; Mishra, V.D.; Parashar, A.; Chauhan, R. Snow depth and snow layer interface estimation using ground penetrating radar. *Curr. Sci.* **2011**, *100*, 1532–1539.
79. Forte, E.; Dossi, M.; Colucci, R.R.; Pipan, M. A new fast methodology to estimate the density of frozen materials by means of common offset GPR data. *J. Appl. Geophys.* **2013**, *99*, 135–145. [CrossRef]
80. Sundström, N.; Gustafsson, D.; Kruglyak, A.; Lundberg, A. Field evaluation of a new method for estimation of liquid water content and snow water equivalent of wet snowpacks with GPR. *Hydrol. Res.* **2013**, *44*, 600–613. [CrossRef]
81. Heilig, A.; Schneebeli, M.; Eisen, O. Upward-looking ground-penetrating radar for monitoring snowpack stratigraphy. *Cold Reg. Sci. Technol.* **2009**, *59*, 152–162. [CrossRef]
82. Harper, J.T.; Bradford, J.H. Snow stratigraphy over a uniform depositional surface: Spatial variability and measurement tools. *Cold Reg. Sci. Technol.* **2003**, *37*, 289–298. [CrossRef]
83. Mitterer, C.; Heilig, A.; Schweizer, J.; Eisen, O. Upward-looking ground-penetrating radar for measuring wet-snow properties. *Cold Reg. Sci. Technol.* **2011**, *69*, 129–138. [CrossRef]
84. Ma, Y.; Zhang, Y.; Zubrzycki, S.; Guo, Y.; Farhan, S.B. Hillslope-scale variability in seasonal frost depth and soil water content investigated by GPR on the southern margin of the sporadic permafrost zone on the Tibetan plateau. *Permafr. Periglac. Process.* **2015**, *26*, 321–334. [CrossRef]
85. Steelman, C.M.; Endres, A.L. Evolution of high-frequency ground-penetrating radar direct ground wave propagation during thin frozen soil layer development. *Cold Reg. Sci. Technol.* **2009**, *57*, 116–122. [CrossRef]
86. Steelman, C.M.; Endres, A.L.; van der Kruk, J. Field observations of shallow freeze and thaw processes using high-frequency ground-penetrating radar. *Hydrol. Process.* **2010**, *24*, 2022–2033. [CrossRef]
87. Butnor, J.R.; Campbell, J.L.; Shanley, J.B.; Zarnoch, S.J. Measuring soil frost depth in forest ecosystems with ground penetrating radar. *Agric. For. Meteorol.* **2014**, *192*, 121–131. [CrossRef]
88. Westermann, S.; Wollschlager, U.; Boike, J. Monitoring of active layer dynamics at a permafrost site on svalbard using multi-channel ground-penetrating radar. *Cryosphere* **2010**, *4*, 475–487. [CrossRef]
89. Wollschlager, U.; Gerhards, H.; Yu, Q.; Roth, K. Multi-channel ground-penetrating radar to explore spatial variations in thaw depth and moisture content in the active layer of a permafrost site. *Cryosphere* **2010**, *4*, 269–283. [CrossRef]
90. Pan, X.; You, Y.; Roth, K.; Guo, L.; Wang, X.; Yu, Q. Mapping permafrost features that influence the hydrological processes of a thermokarst lake on the Qinghai-Tibet plateau, China. *Permafr. Periglac. Process.* **2014**, *25*, 60–68. [CrossRef]
91. Jadoon, K.Z.; Weihermller, L.; McCabe, M.F.; Moghadas, D.; Vereecken, H.; Lambot, S. Temporal monitoring of the soil freeze-thaw cycles over a snow-covered surface by using air-launched ground-penetrating radar. *Remote Sens.* **2015**, *7*, 12041–12056. [CrossRef]

92. Brosten, T.R.; Bradford, J.H.; McNamara, J.P.; Gooseff, M.N.; Zarnetske, J.P.; Bowden, W.B.; Johnston, M.E. Estimating 3D variation in active-layer thickness beneath arctic streams using ground-penetrating radar. *J. Hydrol.* **2009**, *373*, 479–486. [CrossRef]
93. Huisman, J.; Hubbard, S.; Redman, J.; Annan, A. Measuring soil water content with ground penetrating radar. *Vadose Zone J.* **2003**, *2*, 476–491. [CrossRef]
94. Ardekani, M.R.M. Off- and on-ground GPR techniques for field-scale soil moisture mapping. *Geoderma* **2013**, *200*, 55–66. [CrossRef]
95. Doolittle, J.A.; Jenkinson, B.; Hopkins, D.; Ulmer, M.; Tuttle, W. Hydropedological investigations with ground-penetrating radar (GPR): Estimating water-table depths and local ground-water flow pattern in areas of coarse-textured soils. *Geoderma* **2006**, *131*, 317–329. [CrossRef]
96. Hengari, G.M.; Hall, C.R.; Kozusko, T.J.; Bostater, C.R. Use of ground penetrating radar for determination of water table depth and subsurface soil characteristics at kennedy space center. In Proceedings of the Earth resources and Environmental Remote Sensing/GIS Applications IV, Dresden, Germany, 23 September 2013; Volume 8893. [CrossRef]
97. Marshall, H.-P.; Schneebeli, M.; Koh, G. Snow stratigraphy measurements with high-frequency FMCW radar: Comparison with snow micro-penetrometer. *Cold Reg. Sci. Technol.* **2007**, *47*, 108–117. [CrossRef]
98. Yankielun, N.; Rosenthal, W.; Davis, R.E. Alpine snow depth measurements from aerial FMCW radar. *Cold Reg. Sci. Technol.* **2004**, *40*, 123–134. [CrossRef]
99. Koh, G.; Yankielun, N.E.; Baptista, A.I. Snow cover characterization using multiband fmcw radars. *Hydrol. Process.* **1996**, *10*, 1609–1617. [CrossRef]
100. Richardson, C. *Spatial Distribution of Snow in Antarctica and Other Glaciers Studies Using Ground-Penetrating-Radar*; Stockholm University: Stockholm, Sweden, 2001.
101. Iizuka, K.; Freundorfer, A.P.; Wu, K.H.; Mori, H.; Ogura, H.; Nguyen, V.K. Step-frequency radar. *J. Appl. Phys.* **1984**, *56*, 2572–2583. [CrossRef]
102. Minet, J.; Wahyudi, A.; Bogaert, P.; Vanclooster, M.; Lambot, S. Mapping shallow soil moisture profiles at the field scale using full-waveform inversion of ground penetrating radar data. *Geoderma* **2011**, *161*, 225–237. [CrossRef]
103. Lundberg, A.; Thunehed, H. Snow wetness influence on impulse radar snow surveys theoretical and laboratory study. *Nord. Hydrol.* **2000**, *31*, 89–106.
104. Sundström, N.; Kruglyak, A.; Friborg, J. Modeling and simulation of GPR wave propagation through wet snowpacks: Testing the sensitivity of a method for snow water equivalent estimation. *Cold Reg. Sci. Technol.* **2012**, *74–75*, 11–20. [CrossRef]
105. Heilig, A.; Eisen, O.; Schneebeli, M. Temporal observations of a seasonal snowpack using upward-looking GPR. *Hydrol. Process.* **2010**, *24*, 3133–3145. [CrossRef]
106. Schmid, L.; Heilig, A.; Mitterer, C.; Schweizer, J.; Maurer, H.; Okorn, R.; Eisen, O. Continuous snowpack monitoring using upward-looking ground-penetrating radar technology. *J. Glaciol.* **2014**, *60*, 509–525. [CrossRef]
107. Okorn, R.; Brunnhofer, G.; Platzer, T.; Heilig, A.; Schmid, L.; Mitterer, C.; Schweizer, J.; Eisen, O. Upward-looking l-band FMCW radar for snow cover monitoring. *Cold Reg. Sci. Technol.* **2014**, *103*, 31–40. [CrossRef] [PubMed]
108. He, H.; Dyck, M.F.; Si, B.C.; Zhang, T.; Lv, J.; Wang, J. Soil freezing-thawing characteristics and snowmelt infiltration in cryalfs of Alberta, Canada. *Geoderma Reg.* **2015**, *5*, 198–208. [CrossRef]
109. Oberdoerster, C.; Vanderborght, J.; Kemna, A.; Vereecken, H. Investigating preferential flow processes in a forest soil using time domain reflectometry and electrical resistivity tomography. *Vadose Zone J.* **2010**, *9*, 350–361. [CrossRef]
110. Murray, C.D.; Buttle, J.M. Infiltration and soil water mixing on forested and harvested slopes during spring snowmelt, turkey lakes watershed, central Ontario. *J. Hydrol.* **2005**, *306*, 1–20. [CrossRef]
111. Kahimba, F.; Ranjan, R.S. Soil temperature correction of field TDR readings obtained under near freezing conditions. *Can. Biosyst. Eng.* **2007**, *49*, 19–25.
112. Stähli, M.; Stadler, D. Measurement of water and solute dynamics in freezing soil columns with time domain reflectometry. *J. Hydrol.* **1997**, *195*, 352–369. [CrossRef]

113. Christensen, A.F.; He, H.L.; Dyck, M.F.; Turner, E.L.; Chanasyk, D.S.; Naeth, M.A.; Nichol, C. In situ measurement of snowmelt infiltration under various topsoil cap thicknesses on a reclaimed site. *Can. J. Soil Sci.* **2013**, *93*, 497–510. [CrossRef]
114. Schneebeli, M.; Johnson, J.B. A constant-speed penetrometer for high-resolution snow stratigraphy. *Ann. Glaciol.* **1998**, *26*, 107–111.
115. Waldner, P.A.; Schneebeli, M.; Schultze-Zimmerman, U.; Fluhler, H. Effect of snow structure on water flow and solute transport. *Hydrol. Process.* **2004**, *18*, 1271–1290. [CrossRef]
116. Lekshmi, S.S.U.; Singh, D.N.; Baghini, M.S. A critical review of soil moisture measurement. *Measurement* **2014**, *54*, 92–105.
117. He, H.; Dyck, M. Application of multiphase dielectric mixing models for understanding the effective dielectric permittivity of frozen soils. *Vadose Zone J.* **2013**, *12*. [CrossRef]
118. Iwata, Y.; Hayashi, M.; Hirota, T. Comparison of snowmelt infiltration under different soil-freezing conditions influenced by snow cover. *Vadose Zone J.* **2008**, *7*, 79–86. [CrossRef]
119. Tian, Z.; Heitman, J.; Horton, R.; Ren, T. Determining soil ice contents during freezing and thawing with thermo-time domain reflectometry. *Vadose Zone J.* **2015**, *14*. [CrossRef]
120. Gnecchi, J.A.G.; Patino, A.M.; Paramo, F.L.; Anguiano, A.D.T.; Espinoza, D.L. Investigation of wetting front propagation dynamics using soil impedance measurements: Implications for modelling and irrigation scheduling. *Water Resour. Manag.* **2015**, *29*, 197–210. [CrossRef]
121. Gnecchi, J.G.; Chávez, A.G.-T.; Campos, G.C.; Peregrino, V.O.; Pineda, E.M. Soil water infiltration measurements using electrical impedance tomography. *Chem. Eng. J.* **2012**, *191*, 13–21. [CrossRef]
122. French, H.; Binley, A. Snowmelt infiltration: Monitoring temporal and spatial variability using time-lapse electrical resistivity. *J. Hydrol.* **2004**, *297*, 174–186. [CrossRef]
123. Berthold, S.; Bentley, L.R.; Hayashi, M. Integrated hydrogeological and geophysical study of depression-focused groundwater recharge in the Canadian prairies. *Water Resour. Res.* **2004**, *40*, W06505. [CrossRef]
124. French, H.K.; Hardbattle, C.; Binley, A.; Winship, P.; Jakobsen, L. Monitoring snowmelt induced unsaturated flow and transport using electrical resistivity tomography. *J. Hydrol.* **2002**, *267*, 273–284. [CrossRef]
125. Watanabe, K.; Mizoguchi, M. Amount of unfrozen water in frozen porous media saturated with solution. *Cold Reg. Sci. Technol.* **2002**, *34*, 103–110. [CrossRef]
126. Zhou, X.; Zhou, J.; Kinzelbach, W.; Stauffer, F. Simultaneous measurement of unfrozen water content and ice content in frozen soil using gamma ray attenuation and TDR. *Water Resour. Res.* **2014**, *50*, 9630–9655. [CrossRef]
127. Boleve, A.; Revil, A.; Janod, F.; Mattiuzzo, J.L.; Fry, J.J. Preferential fluid flow pathways in embankment dams imaged by self-potential tomography. *Near Surf. Geophys.* **2009**, *7*, 447–462. [CrossRef]
128. Ikard, S.J.; Revil, A.; Jardani, A.; Woodruff, W.F.; Parekh, M.; Mooney, M. Saline pulse test monitoring with the self-potential method to nonintrusively determine the velocity of the pore water in leaking areas of earth dams and embankments. *Water Resour. Res.* **2012**, *48*, W04201. [CrossRef]
129. Panthulu, T.V.; Krishnaiah, C.; Shirke, J.M. Detection of seepage paths in earth dams using self-potential and electrical resistivity methods. *Eng. Geol.* **2001**, *59*, 281–295. [CrossRef]
130. Kulessa, B.; Chandler, D.; Revil, A.; Essery, R. Theory and numerical modeling of electrical self-potential signatures of unsaturated flow in melting snow. *Water Resour. Res.* **2012**, *48*, W09511. [CrossRef]
131. Thompson, S.; Kulessa, B.; Essery, R.; Lüthi, M. The electrical self-potential method is a non-intrusive snow-hydrological sensor. *Cryosphere Discuss.* **2015**, *9*, 4437–4457. [CrossRef]
132. Tyler, S.W.; Burak, S.A.; McNamara, J.P.; Lamontagne, A.; Selker, J.S.; Dozier, J. Spatially distributed temperatures at the base of two mountain snowpacks measured with fiber-optic sensors. *J. Glaciol.* **2008**, *54*, 673–679. [CrossRef]
133. Reusser, D.E.; Zehe, E. Low-cost monitoring of snow height and thermal properties with inexpensive temperature sensors. *Hydrol. Process.* **2011**, *25*, 1841–1852. [CrossRef]
134. Lundquist, J.D.; Lott, F. Using inexpensive temperature sensors to monitor the duration and heterogeneity of snow-covered areas. *Water Resour. Res.* **2008**, *44*, W00D16. [CrossRef]
135. Schmid, M.O.; Gubler, S.; Fiddes, J.; Gruber, S. Inferring snowpack ripening and melt-out from distributed measurements of near-surface ground temperatures. *Cryosphere* **2012**, *6*, 1127–1139. [CrossRef]

136. Roznik, E.A.; Alford, R.A. Does waterproofing thermochron ibutton dataloggers influence temperature readings? *J. Therm. Biol.* **2012**, *37*, 260–264. [CrossRef]
137. Shea, C.; Jamieson, B.; Birkeland, K.W. Use of a thermal imager for snow pit temperatures. *Cryosphere* **2012**, *6*, 287–299. [CrossRef]
138. Schirmer, M.; Jamieson, B. Limitations of using a thermal imager for snow pit temperatures. *Cryosphere* **2014**, *8*, 387–394. [CrossRef]
139. Tetzlaff, D.; Buttle, J.; Carey, S.K.; McGuire, K.; Laudon, H.; Soulsby, C. Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: A review. *Hydrol. Process.* **2015**, *29*, 3475–3490. [CrossRef]
140. Bründl, M.; Schneebeli, M.; Flühler, H. Routing of canopy drip in the snowpack below a spruce crown. *Hydrol. Process.* **1999**, *13*, 49–58. [CrossRef]
141. Campbell, F.M.A.; Nienow, P.W.; Purves, R.S. Role of the supraglacial snowpack in mediating meltwater delivery to the glacier system as inferred from dye tracer investigations. *Hydrol. Process.* **2006**, *20*, 969–985. [CrossRef]
142. Lee, J.; Nez, V.E.; Feng, X.; Kirchner, J.W.; Osterhuber, R.; Renshaw, C.E. A study of solute redistribution and transport in seasonal snowpack using natural and artificial tracers. *J. Hydrol.* **2008**, *357*, 243–254. [CrossRef]
143. Buttle, J.M.; Sami, K. Recharge processes during snowmelt—An isotopic and hydrometric investigation. *Hydrol. Process.* **1990**, *4*, 343–360. [CrossRef]
144. Stähli, M.; Bayard, D.; Wydler, H.; Flühler, H. Snowmelt infiltration into alpine soils visualized by dye tracer technique. *Arct. Antarct. Alp. Res.* **2004**, *36*, 128–135. [CrossRef]
145. Stumpp, C.; Hendry, M.J. Spatial and temporal dynamics of water flow and solute transport in a heterogeneous glacial till: The application of high-resolution profiles of $\delta^{18}O$ and $\delta^{2}H$ in pore waters. *J. Hydrol.* **2012**, *438*, 203–214. [CrossRef]
146. Dietermann, N.; Weiler, M. Spatial distribution of stable water isotopes in alpine snow cover. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 2657–2668. [CrossRef]
147. Bengtsson, L.; Lepistö, A.; Saxena, R.K.; Seuna, P. Mixing of meltwater and groundwater in a forested basin. *Aqua Fenn.* **1991**, *21*, 3–12.
148. Mueller, M.H.; Alaoui, A.; Külls, C.; Leistert, H.; Meusburger, K.; Stumpp, C.; Weiler, M.; Alewell, C. Tracking water pathways in steep hillslopes by $\delta^{18}O$ soil depth profiles of soil water. *J. Hydrol.* **2014**, *519*, 340–352. [CrossRef]
149. Rodhe, A. Snowmelt dominated systems. *Isot. Tracers Catchment Hydrol.* **1998**, *21*, 391–433. [CrossRef]
150. Clark, I.; Fritz, P. *Environmental Isotopes in Hydrogeology*; Lewis Publishers: Boca Raton, NY, USA, 1997.
151. Koeniger, P.; Hubbart, J.A.; Link, T.; Marshall, J.D. Isotopic variation of snow cover and streamflow in response to changes in canopy structure in a snow-dominated mountain catchment. *Hydrol. Process.* **2008**, *22*, 557–566. [CrossRef]
152. Herrmann, A.; Lehrer, M.; Stichler, W. Isotope input into runoff systems from melting snow covers. *Nord. Hydrol.* **1981**, *12*, 309–318.
153. Lee, J.; Feng, X.; Faiia, A.M.; Posmentier, E.S.; Kirchner, J.W.; Osterhuber, R.; Taylor, S. Isotopic evolution of a seasonal snowcover and its melt by isotopic exchange between liquid water and ice. *Chem. Geol.* **2010**, *270*, 126–134. [CrossRef]
154. Cooper, L. Isotopic Fractionation in Snow Cover. In *Isotope Tracers in Catchment Hydrology*; Elsevier Science B.V.: Amsterdam, The Netherlands, 1998.
155. Penna, D.; Ahmad, M.; Birks, S.J.; Bouchaou, L.; Brencic, M.; Butt, S.; Holko, L.; Jeelani, G.; Martinez, D.E.; Melikadze, G.; et al. A new method of snowmelt sampling for water stable isotopes. *Hydrol. Process.* **2014**, *28*, 5637–5644. [CrossRef]
156. Garrett, T.J.; Yuter, S. Observed influence of riming, temperature, and turbulence on the fallspeed of solid precipitation. *Geophys. Res. Lett.* **2014**, *41*, 6515–6522. [CrossRef]
157. Ma, Y.; Zhang, Y.; Yang, D.; Farhan, S.B. Precipitation bias variability *versus* various gauges under different climatic conditions over the Third Pole Environment (TPE) region. *Int. J. Climatol.* **2014**, *26*, 321–334.
158. Nuti, R.; Wong, K. *Instruments and Observing Methods, Cimo Survey on National Summaries of Methods and Instruments for Solid Precipitation Measurement at Aws*; World Meteorological Organization: Geneva, Switzerland, 2010; p. 57.

159. Young, K.; Bolton, R.; Killingtveit, A.; Yang, D. Assessment of precipitation and snowcover in northern research basins. *Nord. Hydrol.* **2006**, *37*, 377–391. [CrossRef]
160. WMO. Spice: Wmo Solid Precipitation Intercomparison Experiment (2012–2015). Available online: http://www.wmo.int/pages/prog/www/IMOP/intercomparisons/SPICE/SPICE.html (accessed on 20 Februay 2015).
161. Boudala, F.S.; Isaac, G.A.; Rasmussen, R.; Cober, S.G.; Scott, B. Comparisons of snowfall measurements in complex terrain made during the 2010 winter Olympics in Vancouver. *Pure Appl. Geophys.* **2014**, *171*, 113–127. [CrossRef]
162. Boudala, F.S.; Rasmussen, R.; Isaac, G.A.; Scott, B. Performance of hot plate for measuring solid precipitation in complex terrain during the 2010 Vancouver winter Olympics. *J. Atmos. Ocean. Technol.* **2014**, *31*, 437–446. [CrossRef]
163. Lee, J.-E.; Jung, S.-H.; Park, H.-M.; Kwon, S.; Lin, P.-L.; Lee, G. Classification of precipitation types using fall velocity-diameter relationships from 2D-video distrometer measurements. *Adv. Atmos. Sci.* **2015**, *32*, 1277–1290. [CrossRef]
164. Battaglia, A.; Rustemeier, E.; Tokay, A.; Blahak, U.; Simmer, C. Parsivel snow observations: A critical assessment. *J. Atmos. Ocean. Tech.* **2010**, *27*, 333–344. [CrossRef]
165. Yang, D. Double fence intercomparison reference (DFIR) vs. Bush gauge for "true" snowfall measurement. *J. Hydrol.* **2014**, *509*, 94–100. [CrossRef]
166. Yang, D.; Simonenko, A. Comparison of winter precipitation measurements by six tretyakov gauges at the valdai experimental site. *Atmos. Ocean* **2014**, *52*, 39–53. [CrossRef]
167. Grazioli, J.; Tuia, D.; Monhart, S.; Schneebeli, M.; Raupach, T.; Berne, A. Hydrometeor classification from two-dimensional video disdrometer data. *Atmos. Meas. Tech.* **2014**, *7*, 2869–2882. [CrossRef]
168. Zhang, L.; Zhao, L.; Xie, C.; Liu, G.; Gao, L.; Xiao, Y.; Shi, J.; Qiao, Y. Intercomparison of solid precipitation derived from the weighting rain gauge and optical instruments in the interior Qinghai-Tibetan Plateau. *Adv. Meteorol.* **2015**. [CrossRef]
169. Rasmussen, R.M.; Hallett, J.; Purcell, R.; Landolt, S.D.; Cole, J. The hotplate precipitation gauge. *J. Atmos. Ocean. Technol.* **2011**, *28*, 148–164. [CrossRef]
170. Theriault, J.M.; Rasmussen, R.; Ikeda, K.; Landolt, S. Dependence of snow gauge collection efficiency on snowflake characteristics. *J. Appl. Meteorol. Climatol.* **2012**, *51*, 745–762. [CrossRef]
171. Theriault, J.M.; Rasmussen, R.; Petro, E.; Trepanier, J.-Y.; Colli, M.; Lanza, L.G. Impact of wind direction, wind speed, and particle characteristics on the collection efficiency of the double fence intercomparison reference. *J. Appl. Meteorol. Climatol.* **2015**, *54*, 1918–1930. [CrossRef]
172. Rasmussen, R.; Baker, B.; Kochendorfer, J.; Meyers, T.; Landolt, S.; Fischer, A.; Black, J.; Thériault, J.; Kucera, P.; Gochis, D.; et al. How well are we measuring snow; the NOAA/FAA/NCAR winter precipitation test bed. *Bull. Am. Meteorol. Soc.* **2010**, *936*, 811–829. [CrossRef]
173. Wolff, M.; Isaksen, K.; Braekkan, R.; Alfnes, E.; Petersen-Overleir, A.; Ruud, E. Measurements of wind-induced loss of solid precipitation: Description of a norwegian field study. *Hydrol. Res.* **2013**, *44*, 35–43. [CrossRef]
174. Wolff, M.A.; Isaksen, K.; Petersen-Overleir, A.; Odemark, K.; Reitan, T.; Braekkan, R. Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: Results of a norwegian field study. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 951–967. [CrossRef]
175. Yuter, S.E.; Kingsmill, D.E.; Nance, L.B.; Loeffler-Mang, M. Observations of precipitation size and fall speed characteristics within coexisting rain and wet snow. *J. Appl. Meteorol. Climatol.* **2006**, *45*, 1450–1464. [CrossRef]
176. Naaim-Bouvet, F.; Bellot, H.; Nishimura, K.; Genthon, C.; Palerme, C.; Guyomarc'h, G.; Vionnet, V. Detection of snowfall occurrence during blowing snow events using photoelectric sensors. *Cold Reg. Sci. Technol.* **2014**, *106*, 11–21. [CrossRef]
177. Colli, M.; Lanza, L.G.; Rasmussen, R.; Thériault, J.M. Tthe collection efficiency of shielded and unshielded precipitation gauges- part II: Modeling particle trajectories. *J. Hydrometeorol.* **2015**, 231–243. [CrossRef]
178. Kane, D.L.; Stuefer, S.L. Reflecting on the status of precipitation data collection in Alaska: A case study. *Hydrol. Res.* **2015**, *46*, 478–493. [CrossRef]
179. Grazioli, J.; Tuia, D.; Monhart, S.; Schneebeli, M.; Raupach, T.; Berne, A. Hydrometeor classification from two-dimensional video disdrometer data. *Atmos. Meas. Tech.* **2014**, *7*, 2869–2882. [CrossRef]

180. Serreze, M.C.; Clark, M.P.; Armstrong, R.L.; McGinnis, D.A.; Pulwarty, R.S. Characteristics of the western United States snowpack from snowpack telemetry (snotel) data. *Water Resour. Res.* **1999**, *35*, 2145–2160. [CrossRef]
181. Brazenec, W.A. *Evaluation of Ultrasonic Snow Depth Sensors for Automated Surface Observing Systems (Asos)*; Colorado State University: Fort Collins, CO, USA, 2005.
182. Schöner, W.; Auer, I.; Böhm, R. Long term trend of snow depth at sonnblick (austrian alps) and its relation to climate change. *Hydrol. Process.* **2009**, *23*, 1052–1063. [CrossRef]
183. Garvelmann, J.; Pohl, S.; Weiler, M. From observation to the quantification of snow processes with a time-lapse camera network. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1415–1429. [CrossRef]
184. SnowHydro. Gps Depth Probe Snowhydro. Available online: http://www.snowhydro.com/products/column2.html (accessed on 20 Februay 2015).
185. Boniface, K.; Braun, J.J.; McCreight, J.L.; Nievinski, F.G. Comparison of snow data assimilation system with gps reflectometry snow depth in the western United States. *Hydrol. Process.* **2015**, *29*, 2425–2437. [CrossRef]
186. Gutmann, E.D.; Larson, K.M.; Williams, M.W.; Nievinski, F.G.; Zavorotny, V. Snow measurement by GPS interferometric reflectometry: An evaluation at niwot ridge, colorado. *Hydrol. Process.* **2012**, *26*, 2951–2961. [CrossRef]
187. Larson, K.M.; Gutmann, E.D.; Zavorotny, V.U.; Braun, J.J.; Williams, M.W.; Nievinski, F.G. Can we measure snow depth with GPS receivers? *Geophys. Res. Lett.* **2009**, *36*, L17502. [CrossRef]
188. McCreight, J.L.; Small, E.E.; Larson, K.M. Snow depth, density, and swe estimates derived from GPS reflection data: Validation in the western U.S. *Water Resour. Res.* **2014**, *50*, 6892–6909. [CrossRef]
189. Lundberg, A.; Richardson-Näslund, C.; Andersson, C. Snow density variations: Consequences for ground-penetrating radar. *Hydrol. Process.* **2006**, *20*, 1483–1495. [CrossRef]
190. Sturm, M.; Taras, B.; Liston, G.E.; Derksen, C.; Jonas, T.; Lea, J. Estimating snow water equivalent using snow depth data and climate classes. *J. Hydrometeorol.* **2010**, *11*, 1380–1394. [CrossRef]
191. Jonas, T.; Marty, C.; Magnusson, J. Estimating the snow water equivalent from snow depth measurements in the Swiss Alps. *J. Hydrol.* **2009**, *378*, 161–167. [CrossRef]
192. Bormann, K.J.; Westra, S.; Evans, J.P.; McCabe, M.F. Spatial and temporal variability in seasonal snow density. *J. Hydrol.* **2013**, *484*, 63–73. [CrossRef]
193. Zhong, X.; Zhang, T.; Wang, K. Snow density climatology across the former USSR. *Cryosphere* **2014**, *8*, 785–799. [CrossRef]
194. Rees, A.; English, M.; Derksen, C.; Toose, P.; Silis, A. Observations of late winter canadian tundra snow cover properties. *Hydrol. Process.* **2014**, *28*, 3962–3977. [CrossRef]
195. Proksch, M.; Rutter, N.; Fierz, C.; Schneebeli, M. Intercomparison of snow density measurements: Bias, precision and spatial resolution. *Cryosphere Discuss.* **2015**, *9*, 3581–3616. [CrossRef]
196. Hydrometry. *Manual Measurement of Snow Water Equivalent*; European Committee for Standardization: Brussels, Belgium, 2014; SIS/TK 432.
197. Dixon, D.; Boon, S. Comparison of the snowhydro snow sampler with existing snow tube designs. *Hydrol. Process.* **2012**, *26*, 2555–2562. [CrossRef]
198. Johnson, J.B.; Schaefer, G.L. The influence of thermal, hydrologic, and snow deformation mechanisms on snow water equivalent pressure sensor accuracy. *Hydrol. Process.* **2002**, *16*, 3529–3542. [CrossRef]
199. Trabant, D.; Clagett, G. Measurement and evaluation of snowpacks. *Cold Reg. Hydrol. Hydraul.* **1990**, 39–93.
200. CEN/TR; 15996. Hydrometry. In *Measurement of Snow Water Equivalent Using Snow Mass Registration Devices*; European Committee for Standardization: Brussels, Belgium, 2010.
201. Johnson, J.B.; Gelvin, A.; Schaefer, G. An engineering design study of electronic snow water equivalent sensor performance. In Proceedings of the 75th Annual Western Snow Conference, Kailua-Kona, HI, USA, 16–19 April 2007; pp. 23–30.
202. Johnson, J.B.; Marks, D. The detection and correction of snow water equivalent pressure sensor errors. *Hydrol. Process.* **2004**, *18*, 3513–3525. [CrossRef]
203. Johnson, J.B.; Gelvin, A.B.; Duvoy, P.; Schaefer, G.L.; Poole, G.; Horton, G.D. Performance characteristics of a new electronic snow water equivalent sensor in different climates. *Hydrol. Process.* **2015**, *29*, 1418–1433. [CrossRef]
204. Pomeroy, J.; Gray, D. *Snow Cover—Accumulation, Relocation and Management*; National Hydrology Institute NHRI: Saskatoon, Canada, 1995; p. 134.

205. Daniel, J.A.; Staricka, J.A. Frozen soil impact on ground water-surface water interaction. *J. Am. Water Resour. Assoc.* **2000**, *36*, 151–160. [CrossRef]
206. Dobriyal, P.; Qureshi, A.; Badola, R.; Hussain, S.A. A review of the methods available for estimating soil moisture and its implications for water resource management. *J. Hydrol.* **2012**, *458*, 110–117. [CrossRef]
207. Desilets, D.; Zreda, M.; Ferré, T. Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. *Water Resour. Res.* **2010**, *46*, W11505. [CrossRef]
208. Choquette, Y.; Ducharme, P.; Rogoza, J. Cs725, an accurate sensor for the snow water equivalent and soil moisture measurements. In Proceedings of the International Snow Science Workshop, Grenoble, France, 7–11 October 2013.
209. Martin, J.P.; Houdayer, A.; Lebel, C.; Choquette, Y.; Lavigne, P.; Ducharme, P. An unattended gamma monitor for the determination of Snow Water Equivalent (SWE) using the natural ground gamma radiation. In Proceedings of the Nuclear Science Symposium Conference, Dresden, Germany, 19–25 October 2008; pp. 983–988.
210. Bache Stranden, H.; Lirhus Ree, B.; Møen, K.M. *Måling av snø ved Hjelp Avgammasensor*; Norges Vassdrags-og Energidirektorat: Oslo, Norway, 2014; p. 46.
211. Kodama, M. Continuous monitoring of snow water equivalent using cosmic-ray neutrons. *Cold Reg. Sci. Technol.* **1980**, *3*, 295–303. [CrossRef]
212. Kodama, M.; Nakai, K.; Kawasaki, S.; Wada, M. Application of cosmic-ray neutron measurements to the determination of the snow-water equivalent. *J. Hydrol.* **1979**, *41*, 85–92. [CrossRef]
213. Paquet, E.; Laval, M.T. Operation feedback and prospects of edf cosmic-ray snow sensors. *Houille Blanche* **2006**, *2*, 113–119. [CrossRef]
214. SnowFox. Swe Probe. Facta Sheet. Available online: http://hydroinnova.com/reso_product.html (accessed on 20 Februay 2015).
215. Kinar, N.; Pomeroy, J. Determining snow water equivalent by acoustic sounding. *Hydrol. Process.* **2007**, *21*, 2623–2640. [CrossRef]
216. Kinar, N.J.; Pomeroy, J.W. Measurement of the physical properties of the snowpack. *Rev. Geophys.* **2015**, *53*, 481–544. [CrossRef]
217. Niang, M.; Bernier, M.; Stacheder, M.; Brandelik, A.; Van Bochove, E. Influence of snow temperature interpolation algorithm and dielectric mixing-model coefficient on density and liquid water content determination in a cold seasonal snow pack. *Subsurf. Sens. Technol. Appl.* **2006**, *7*, 1–22. [CrossRef]
218. Stähli, M.; Stacheder, M.; Gustafsson, D.; Schlaeger, S.; Schneebeli, M.; Brandelik, A. A new *in situ* sensor for large-scale snow-cover monitoring. *Ann. Glaciol.* **2004**, *38*, 273–278. [CrossRef]
219. Schlaeger, S. A fast tdr-inversion technique for the reconstruction of spatial soil moisture content. *Hydrol. Earth Syst. Sci. Discuss.* **2005**, *9*, 481–492. [CrossRef]
220. Heggli, A. Data analysis of the snow pack analyzing system tested by UCAR. In Proceedings of the 81st Annual Western Snow Conference, Jackson Hole, WY, USA, 15–18 April 2013.
221. Gustafsson, D.; Sommer, W.; Ahlberg, J. Measurement of liquid water content in snow and its application in snow hydrological modelling. In Proceedings of the XXVI Nordic Hydrological Conference: Hydrology: From Research to Water Management, Riga, Latvia, 9–11 August 2010; p. 34.
222. Eiriksson, D.; Whitson, M.; Luce, C.H.; Marshall, H.P.; Bradford, J.; Benner, S.G.; Black, T.; Hetrick, H.; McNamara, J.P. An evaluation of the hydrologic relevance of lateral flow in snow at hillslope and catchment scales. *Hydrol. Process.* **2013**, *27*, 640–654. [CrossRef]
223. Williams, M.W.; Seibold, C.; Chowanski, K. Storage and release of solutes from a subalpine seasonal snowpack: Soil and stream water response, niwot ridge, Colorado. *Biogeochemistry* **2009**, *95*, 77–94. [CrossRef]
224. Schneebeli, M.; Pielmeier, C.; Johnson, J.B. Measuring snow microstructure and hardness using a high resolution penetrometer. *Cold Reg. Sci. Technol.* **1999**, *30*, 101–114. [CrossRef]
225. Williams, M.W.; Erickson, T.A.; Petrzelka, J.L. Visualizing meltwater flow through snow at the centimetre-to-metre scale using a snow guillotine. *Hydrol. Process.* **2010**, *24*, 2098–2110. [CrossRef]
226. Gustafsson, D.; Waldner, P.A.; Stähli, M. Factors governing the formation and persistence of layers in a subalpine snowpack. *Hydrol. Process.* **2004**, *18*, 1165–1183. [CrossRef]
227. Semadeni-Davies, A.; Lundberg, A.; Bengtsson, L. Radiation balance of urban snow: A water management perspective. *Cold Reg. Sci. Technol.* **2001**, *33*, 59–76. [CrossRef]

228. Sihvola, A.; Tiuri, M. Snow fork for field determination of the density and wetness profiles of a snowpack. *IEEE Trans. Geosci. Remote Rens.* **1986**, *Ge-24*, 717–721. [CrossRef]
229. Kendra, J.R.; Ulaby, F.T.; Sarabandi, K. Snow probe for in situ determination of wetness and density. *IEEE Trans. Geosci. Remote Rens.* **1994**, *32*, 1152–1159. [CrossRef]
230. Denoth, A. An electronic device for long-term snow wetness recording. *Annales of Glaciology* **1994**, *19*, 104–106.
231. Denoth, A. Monopole-antenna: A practical snow and soil wetness sensor. *IEEE Trans. Geosci. Remote Rens.* **1997**, *35*, 1371–1375. [CrossRef]
232. Williams, M.W.; Rikkers, M.F.; Pfeffer, T.; Sommerfeld, R. Comparison of snow liquid water measurements with a denoth meter and finnish snow-fork. In Proceedings of the AGU Fall Meeting, Niwot Ridge, CO, USA, 14–16 October 1996.
233. Whitaker, A.C.; Sugiyama, H. Seasonal snowpack dynamics and runoff in a cool temperate forest: Lysimeter experiment in Niigata, Japan. *Hydrol. Process.* **2005**, *19*, 4179–4200. [CrossRef]
234. French, H.K.; van der Zee, S. Field observations of small scale spatial variability of snowmelt drainage and infiltration. *Nord. Hydrol.* **1999**, *30*, 161–176.
235. Laudon, H.; Hemond, H.F.; Krouse, R.; Bishop, K.H. Oxygen 18 fractionation during snowmelt: Implications for spring flood hydrograph separation. *Water Resour. Res.* **2002**, *38*, 1258. [CrossRef]
236. Hedstrom, N.R.; Pomeroy, J.W. Measurements and modelling of snow interception in the boreal forest. *Hydrol. Process.* **1998**, *12*, 1611–1625. [CrossRef]
237. Nakai, Y. *An Observational Study on Evaporation from Intercepted Snow on Forest Canopies*; Kyoto University: Kyoto, Japan, 1996; (In Japanese, tables and figures in English).
238. Lundberg, A.; Koivusalo, H. Estimating winter evaporation in boreal forests with operational snow course data. *Hydrol. Process.* **2003**, *17*, 1479–1493. [CrossRef]
239. Harding, R.J.; Pomeroy, J.W. The energy balance of a winter boreal landscape. *J. Clim.* **1996**, *9*, 2778–2787. [CrossRef]
240. Nakai, Y.; Sakamoto, T.; Terajima, T.; Kitamura, K.; Shirai, T. The effect of canopy-snow on the energy balance above a coniferous forest. *Hydrol. Process.* **1999**, *13*, 2371–2382. [CrossRef]
241. Claassen, H.C.; Downey, J.S. A model for deuterium and oxygen-18 isotope changes during evergreen interception of snowfall. *Water Resour. Res.* **1995**, *31*, 601–618. [CrossRef]
242. Reba, M.L.; Pomeroy, J.; Marks, D.; Link, T.E. Estimating surface sublimation losses from snowpacks in a mountain catchment using eddy covariance and turbulent transfer calculations. *Hydrol. Process.* **2012**, *26*, 3699–3711. [CrossRef]
243. Hancock, N.H.; Crowther, J.M. A technique for the direct measurement of water storage on a forest canopy. *J. Hydrol.* **1979**, *41*, 105–122. [CrossRef]
244. Bründl, M.; Bartelt, P.; Schneebeli, M.; Flühler, H. Measuring branch defection of spruce branches caused by intercepted snow load. *Hydrol. Process.* **1999**, *13*, 2357–2369. [CrossRef]
245. Montesi, J.; Elder, K.; Schmidt, R.A.; Davis, R.E. Sublimation of intercepted snow within a subalpine forest canopy at two elevations. *J. Hydrometeorol.* **2004**, *5*, 763–773. [CrossRef]
246. Martin, K.A.; Van Stan, J.T.; Dickerson-Lange, S.E.; Lutz, J.A.; Berman, J.W.; Gersonde, R.; Lundquist, J.D. Development and testing of a snow interceptometer to quantify canopy water storage and interception processes in the rain/snow transition zone of the north cascades, Washington, USA. *Water Resour. Res.* **2013**, *49*, 3243–3256. [CrossRef]
247. Lundberg, A.; Calder, I.; Harding, R. Evaporation of intercepted snow: Measurement and modelling. *J. Hydrol.* **1998**, *206*, 151–163. [CrossRef]
248. Storck, P.; Lettenmaier, D.P.; Bolton, S.M. Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resour. Res.* **2002**, *38*, 1223. [CrossRef]
249. Cassiani, G.; Giustiniani, M.; Ferraris, S.; Deiana, R.; Strobbia, C. Time-lapse surface-to-surface GPR measurements to monitor a controlled infiltration experiment. *Boll. Geofis. Teor. Appl.* **2009**, *50*, 209–226.
250. Sun, Y.; Cheng, Q.; Xue, X.; Fu, L.; Chai, J.; Meng, F.; Lammers, P.S.; Jones, S.B. Determining *in-situ* soil freeze-thaw cycle dynamics using an access tube-based dielectric sensor. *Geoderma* **2012**, *189*, 321–327. [CrossRef]

251. Yoshikawa, K.; Overduin, P.P. Comparing unfrozen water content measurements of frozen soil using recently developed commercial sensors. *Cold Reg. Sci. Technol.* **2005**, *42*, 250–256. [CrossRef]
252. Wu, Y.; Hubbard, S.S.; Ulrich, C.; Wullschleger, S.D. Remote monitoring of freeze-thaw transitions in arctic soils using the complex resistivity method. *Vadose Zone J.* **2013**, *12*. [CrossRef]
253. Yi, J.; Zhao, Y.; Shao, M.a.; Zhang, J.; Cui, L.; Si, B. Soil freezing and thawing processes affected by the different landscapes in the middle reaches of Heihe river basin, Gansu, China. *J. Hydrol.* **2014**, *519*, 1328–1338. [CrossRef]
254. Hayhoe, H.N.; Bailey, W.G. Monitoring changes in total and unfrozen water-content in seasonally frozen soil using time domain reflectometry and neutron moderation techniques. *Water Resour. Res.* **1985**, *21*, 1077–1084. [CrossRef]
255. Hirota, T.; Iwata, Y.; Hayashi, M.; Suzuki, S.; Hamasaki, T.; Sameshima, R.; Takayabu, I. Decreasing soil-frost depth and its relation to climate change in Tokachi, Hokkaido, Japan. *J. Meteorol. Soc. Jpn.* **2006**, *84*, 821–833. [CrossRef]
256. Iwata, Y.; Hirota, T. Monitoring over-winter soil water dynamics in a freezing and snow-covered environment using a thermally insulated tensiometer. *Hydrol. Process.* **2005**, *19*, 3013–3019. [CrossRef]
257. Rosenberry, D.O.; LaBaugh, J.W.; Hunt, R.J. Use of monitoring wells, portable piezometers, and seepage meters to quantify flow between surface water and ground water. *Field Techniques for Estimating Water Fluxes between Surface Water and Ground Water*; U.S. Geological Survey: Reston, VA, USA, 2008. 4-D2.
258. Cheng, Q.; Sun, Y.; Xue, X.; Guo, J. *In situ* determination of soil freezing characteristics for estimation of soil moisture characteristics using a dielectric tube sensor. *Soil Sci. Soc. Am. J.* **2014**, *78*, 133–138. [CrossRef]
259. Sorteberg, H.; Engeset, R.; Udnaes, H. A national network for snow monitoring in Norway: Snow pillow verification using observations and models. *Phys. Chem. Earth* **2001**, *26*, 723–729. [CrossRef]
260. Johnson, J.B. A theory of pressure sensor performance in snow. *Hydrol. Process.* **2004**, *18*, 53–64. [CrossRef]
261. Niang, M.; Bernier, M.; Van Bochove, E.; Durand, Y. Precision of estimated snow water equivalent (swe) derived from the new sensor snowpower in Quebec (Canada). *Houille Blanche* **2006**, 128–133. [CrossRef]