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Winter Snowpack and Its Role in Water Resource Management and Ecosystem Function

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Abstract Winter snowpack plays a crucial role as a key water resource storage form in many regions worldwide, significantly impacting the water cycle, agriculture, industry, and ecosystem health. However, climate change is profoundly affecting the formation processes, characteristics, and regional distribution of snowpacks, posing new challenges for water resource management and ecosystem functions. This study reviews current research on winter snowpack, exploring its essential role in water storage and release, soil moisture maintenance, habitat provision, and nutrient cycling, with case studies illustrating the effectiveness of snowpack-dependent management systems. Additionally, the study analyzes the impact of climate change on snowpack dynamics, presents the latest advancements in monitoring and modeling technologies, and proposes sustainable management strategies and policy recommendations. The research aims to provide scientific evidence and strategic guidance for more effective water resource management and ecological conservation in the future.

Keywords Winter snowpack; Water resource management; Ecosystem function; Climate change; Monitoring and modeling

1 Introduction

Winter snowpack refers to the snow accumulation in mountainous regions during the winter months, acting as a natural reservoir that stores water in its frozen form and gradually releases it as meltwater during the spring and summer. This process is crucial for maintaining hydrological balance and directly impacts the health of ecosystems and human activities (Vano et al., 2020; Singh et al., 2022). Particularly in the western United States, winter snowpack is a more important component of water storage than man-made reservoirs, playing a significant role in hydropower generation, agricultural irrigation, and urban water supply (Pelak et al., 2022). The dynamics of snowpack determine the timing and quantity of water availability, making it critical for effective water resource management (Mote et al., 2018; Livneh and Badger, 2020). Additionally, snowpack influences ground temperature, light conditions, and moisture availability, which in turn affect vegetation, interactions between plants and animals, and microbial activities, thereby having a profound impact on the entire ecosystem (Rixen et al., 2022).

However, climate change poses significant challenges. Rising temperatures are leading to reduced snow accumulation and earlier snowmelt, disrupting the long-established seasonal rhythms, and threatening ecosystems and human societies (Qin et al., 2020). These changes not only increase the unpredictability of droughts but also jeopardize the water security of millions of people (Livneh and Badger, 2020; Vano et al., 2020). Moreover, the decline in snowpack is accelerating global warming through reduced albedo effects (Irannezhad et al., 2022).

This study systematically reviews the current research progress on winter snowpack, focusing on its role in water resource management and ecosystem function, analyzing the impact of climate change on snowpack dynamics, and exploring the latest advances in monitoring and modeling technologies as well as sustainable management strategies and policy recommendations. The goal is to provide scientific evidence and strategic guidance for more effective water resource management and ecological conservation in the context of climate change.

2 Winter Snowpack Formation and Characteristics

2.1 Processes of snowpack formation

Snowpack formation is a complex process influenced by various climatic and environmental factors. Snowfall, the primary contributor to snowpack, is affected by atmospheric dynamics, surface air temperature (SAT), and precipitation patterns. In colder months, sub-zero temperatures facilitate the accumulation of snow, which gradually builds up to form a snowpack. However, with global warming, there has been a notable reduction in the number of sub-zero days, leading to less frequent snowfall and more rain-on-snow events, which negatively impact snowpack accumulation (Irannezhad et al., 2022). Additionally, the spatial distribution of snowpack is influenced by factors such as upwind terrain, vegetation, solar radiation, and slope, which can cause significant variability in snow depth and snow water equivalent (SWE) across different regions (Bilish et al., 2019).

2.2 Physical and chemical properties

The physical properties of snowpack, such as depth, density, and SWE, are crucial for understanding its role in water resource management. Snowpack acts as a natural reservoir, storing water during winter and releasing it as snowmelt in spring and summer, which is vital for hydropower, agriculture, and drinking water supply (Singh et al., 2022). The chemical properties, including the isotopic composition of snow, provide insights into the hydrological processes and the contribution of snowmelt to groundwater recharge. Stable water isotopes help track the changes in isotopic composition from snowfall to snowmelt, offering a better understanding of snow hydrological processes (Beria et al., 2018). Furthermore, the presence of liquid water content within the snowpack, which can vary significantly over short timescales, influences the timing and rate of snowmelt runoff (Webb et al., 2018).

2.3 Regional variations in snowpack characteristics

Snowpack characteristics exhibit significant regional variations due to differences in climate, topography, and vegetation. For instance, in the western United States, mountain snowpack serves as a critical water source, with significant declines observed in recent decades due to warming temperatures and reduced snowfall (Mote et al., 2018). In marginal snow environments, such as the Australian Alps, snowpacks are typically warm and exhibit high variability, with frequent complete melts and re-accumulations within a single season (Bilish et al., 2019). In northern forest ecosystems, the depth and duration of snowpack strongly influence soil temperatures and ecosystem functions, with declining snowpack leading to colder and more variable soil temperatures in winter (Sanders-DeMott et al., 2019). These regional differences highlight the importance of localized studies to understand and manage snowpack resources effectively.

3 Snowpack and Water Resource Management

3.1 Role of snowpack in the hydrological cycle

Snowpack plays a crucial role in the hydrological cycle by acting as a natural reservoir that stores water during the winter months and gradually releases it as snowmelt during the spring and summer. This process is essential for maintaining river flows and groundwater recharge, which are critical for various ecosystems and human activities (Irannezhad et al., 2022; Singh et al., 2022). The snowpack's ability to store and release water helps balance the seasonal availability of water, ensuring that there is sufficient water supply during the dry months (Mote et al., 2018; Simpkins, 2018).

3.2 Seasonal water storage and release

The seasonal storage and release of water from snowpack are vital for managing water resources. During the winter, snow accumulates and stores precipitation, which is then released as snowmelt in the warmer months. This gradual release is crucial for maintaining river flows and meeting water demands during the dry season (Simpkins, 2018; Singh et al., 2022). However, climate change is altering the timing and amount of snowmelt, leading to earlier and reduced snowmelt, which can disrupt the seasonal water availability and pose challenges for water resource management (Mote et al., 2018; Qin et al., 2020; Vano, 2020).

3.3 Impact on water supply for agriculture, industry, and domestic use

Snowpack is a significant source of water for agriculture, industry, and domestic use. In regions such as the western United States, snowmelt provides a substantial portion of the water used for irrigation, municipal, and industrial purposes (Mote et al., 2018). Changes in snowpack dynamics due to climate change, such as reduced snow accumulation and earlier snowmelt, can lead to water shortages and increased competition for water resources among different sectors (Simpkins, 2018; Qin et al., 2020). For instance, in high-mountain Asia and the western US, shifts in snowmelt patterns are expected to impact agricultural water supply, necessitating the adaptation of water management practices to ensure sustainable water availability (Qin et al., 2020).

3.4 Case studies of snowpack-dependent water management systems

Several regions around the world rely heavily on snowpack for their water management systems. For example, the western United States depends on snowmelt from mountain ranges such as the Sierra Nevada, Rocky, and Cascade mountains to meet its water needs (Mote et al., 2018; Singh et al., 2022). In these areas, water managers have developed infrastructure such as dams and reservoirs to capture and store snowmelt for use during the dry season. However, declining snowpack and changes in snowmelt timing are challenging these traditional water management systems, prompting the need for innovative approaches to ensure water security (Simpkins, 2018; Pelak et al., 2022). Since the mid-20th century, there has been a significant decline in spring snowpack, which has had a major impact on snow-dependent water resource management systems. By combining observational data and hydrological models, research has found that climate warming has led to reduced snowpack, subsequently affecting various aspects such as agricultural irrigation and urban water supply (Figure 1).Another example is the high-mountain Asia region, where major river basins like the Indus and Ganges rely on snow and glacial melt for water supply. Changes in snowpack dynamics in these regions highlight the need for adaptive water management strategies to cope with the impacts of climate change (Simpkins, 2018; Qin et al., 2020).

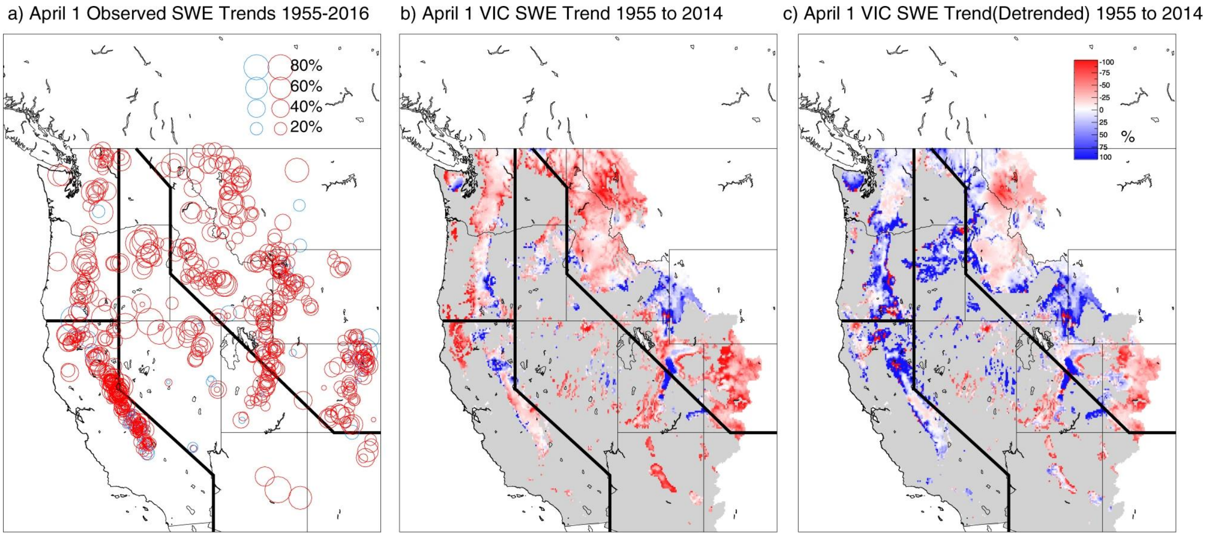
a) April 1 Observed SWE Trends 1955-2016
b) April 1 VIC SWE Trend 1955 to 2014
c) April 1 VIC SWE Trend(Detrended) 1955 to 2014

Figure 1 Linear trends in 1 Apr SWE relative to the starting value for the linear fit (i.e., the 1955 value for the best-fit line) (Adopted from Mote et al., 2018)

Image caption: (a) at 699 snow course locations in the western United States for the period 1955-2016, with negative trends shown by red circles and positive by blue circles; (b) from the simulation using the VIC hydrologic model for the period 1955-2014 (cells in gray have mean April 1 SWE less than 5 mm; areas in white are not simulated); (c) as in (b) but using temperature data in which linear trends have been removed for the 1954-2014 period. Lines on the maps divide the West into four regions for analysis shown in subsequent figuresm(Adopted from Mote et al., 2018)

4 Snowpack and Ecosystem Function

4.1 Influence on soil moisture and vegetation

Snowpack plays a critical role in regulating soil moisture and vegetation dynamics. Variations in snow depth and duration can significantly affect soil temperature and moisture levels, which in turn influence plant growth and soil microbial activity. For instance, snowpack insulates the soil, reducing temperature fluctuations and preventing deep soil freezing, which is crucial for maintaining soil moisture during winter and early spring (Sanders-DeMott et al., 2019; Wilson et al., 2020). In the sagebrush steppe, declining snowpack has been shown to reduce soil respiration and moisture, potentially altering the carbon cycle and vegetation cover (Tucker et al., 2016). Similarly, in alpine and arctic ecosystems, snowpack depth influences the timing of snowmelt, which affects soil water availability and the length of the growing season for vegetation (Harpold et al., 2016; Rixen et al., 2022).

4.2 Habitat provision for flora and fauna

Snowpack provides essential habitat for various flora and fauna, particularly in cold biomes. It creates a stable microclimate that protects plants and animals from extreme temperatures and desiccation. For example, in tundra ecosystems, snow cover determines ground temperature and moisture availability, which are critical for plant-animal interactions and microbial processes (Rixen et al., 2022). Additionally, snowpack influences the distribution and abundance of vegetation, which in turn affects habitat availability for wildlife. In the sagebrush steppe, changes in snowpack depth can alter vegetation cover, impacting habitat quality for species dependent on this ecosystem (Tucker et al., 2016).

4.3 Role in nutrient cycling and soil health

Snowpack significantly impacts nutrient cycling and soil health by modulating soil temperature and moisture, which influence microbial activity and nutrient availability. Reduced snowpack can lead to increased soil freezing, which affects soil respiration and nutrient leaching. For instance, in an alpine fir forest, snowpack reduction was found to stimulate soil nutrient leaching without significantly changing microbial biomass, indicating that soil microbes can rapidly adapt to changes in snowpack (Yang et al., 2021). In subalpine grasslands, variations in snow depth were shown to modify nitrogen-related microbial abundances and activities, affecting nutrient dynamics and soil health (Jusselme et al., 2016). Additionally, snowpack influences litter decomposition and elemental cycling, with thicker snowpacks maintaining more stable nutrient levels in forest ecosystems (Chen et al., 2018).

4.4 Case studies on ecosystem dependencies on snowpack

Several case studies highlight the dependencies of ecosystems on snowpack. At the Hubbard Brook Experimental Forest, long-term studies have shown that snowpack dynamics influence soil microclimate and ecosystem function, with implications for carbon and nitrogen cycling processes (Sanders-DeMott et al., 2019; Wilson et al., 2020). In the sagebrush steppe, snowpack manipulation experiments using snowfences demonstrated that snow depth affects soil respiration and vegetation cover, with potential impacts on the regional carbon balance (Tucker et al., 2016). In the French Alps, historical agricultural practices created terraces with varying snow depths, providing a natural experiment to study the effects of snowpack on soil microbial functioning and nutrient dynamics (Jusselme et al., 2016). These case studies underscore the importance of snowpack in maintaining ecosystem health and resilience in the face of climate change.

5 Snowpack and Climate Change

5.1 Effects of climate change on snowpack dynamics

Climate change significantly impacts snowpack dynamics by altering surface air temperatures (SAT) and precipitation patterns. Increased SAT leads to fewer sub-zero days, reduced snowfall, and more frequent rain-on-snow events, which collectively decrease snowpack accumulation and snow water equivalent (SWE) (Irannezhad et al., 2022). These changes result in earlier snowmelt and reduced springtime freshwater availability, particularly in cold climate regions (Irannezhad et al., 2022). Additionally, variations in snow depth and duration influence soil temperatures, leading to colder and more variable winter soil conditions, which have important implications for ecosystem function (Sanders-DeMott et al., 2019; Wilson et al., 2020).

5.2 Projected changes in snowpack patterns

Future projections indicate a substantial reduction in snow cover area, particularly in alpine systems. For instance, in the Sierra Nevada mountain range, snow cover is expected to decrease by an average of 60.4% by the end of the century (Collados-Lara et al., 2019). Similarly, in the Blue Mountains of Oregon, snow-dominated watersheds are projected to transition to mixed rain and snow, with high flows occurring more frequently in late autumn and winter rather than spring (Clifton et al., 2018). These changes are driven by increased temperatures and altered precipitation patterns, which will significantly modify snow dynamics and reduce snowpack accumulation (Clifton et al., 2018; Collados-Lara et al., 2019).

5.3 Implications for water resource management

The reduction in snowpack due to climate change poses significant challenges for water resource management. Snowpack acts as a natural reservoir, storing water during the cold season and releasing it during warmer months. Reduced snowpack makes drought harder to predict and jeopardizes irrigated agriculture, particularly in regions heavily dependent on snowmelt runoff, such as high-mountain Asia, Central Asia, western Russia, the western US, and the southern Andes (Qin et al., 2020; Vano et al., 2020). Effective water management strategies will need to adapt to these changes by improving current practices and developing new methods to ensure water availability throughout the year (Clifton et al., 2018; Qin et al., 2020).

5.4 Implications for ecosystem health and function

Changes in snowpack dynamics have profound effects on ecosystem health and function. Reduced snowpack and altered snowmelt patterns influence soil microclimate, affecting soil temperature and moisture levels, which in turn impact carbon and nitrogen cycling processes (Wilson et al., 2020). In northern forest ecosystems, declining snowpack depth and duration lead to colder and more variable soil temperatures, affecting soil biogeochemistry, microbial activity, vegetation, and fauna (Sanders-DeMott and Templer, 2017; Sanders-DeMott et al., 2019). Additionally, increased atmospheric humidity under warming conditions can lead to more frequent and intense winter melt events, further altering the timing and availability of water for ecosystems (Harpold and Brooks, 2018). These changes highlight the need for comprehensive climate change experiments that consider both winter and growing season dynamics to better understand and predict ecosystem responses (Sanders-DeMott and Templer, 2017).

By understanding and addressing the impacts of climate change on snowpack dynamics, water resource management, and ecosystem health, we can develop more effective strategies to mitigate these effects and ensure the sustainability of vital water and ecological resources.

6 Monitoring and Modeling of Snowpack

6.1 Techniques for snowpack measurement and monitoring

Accurate measurement and monitoring of snowpack are crucial for effective water resource management and understanding ecosystem functions. Traditional methods include in situ measurements such as snow pillows and snow courses, which provide point-specific data on snow water equivalent (SWE) (Pelak et al., 2022). However, these methods are often limited by their spatial coverage and accessibility, particularly in high mountain regions.

Recent advancements have introduced innovative techniques such as the combination of ground-penetrating radar with terrestrial LiDAR scanning to estimate the spatial distribution of liquid water content in seasonal snowpacks. This method allows for non-destructive, high-resolution measurements of snowpack properties, capturing rapid changes at sub-daily timescales (Webb et al., 2018). Additionally, the use of lake water pressure to measure changes in SWE over large areas offers a novel approach that inherently senses changes over the entire lake surface, providing data that is directly comparable to the grid cells of weather and climate models (Pritchard et al., 2021).

6.2 Advances in snowpack modeling

Snowpack modeling has seen significant advancements, particularly with the integration of data assimilation techniques. For instance, the CrocO_v1.0 system uses an ensemble data assimilation approach to ingest various snowpack observations, improving the accuracy of snowpack simulations by reducing uncertainties (Cluzet et al., 2021). Similarly, the development of the Spatial Modeling for Resources Framework (SMRF) has streamlined the process of generating input forcing data for snow models, making it computationally efficient and suitable for both research and operational applications (Havens et al., 2017).

Moreover, models that blend different data sources, such as precipitation gauge observations with snowpack measurements, have shown improved predictions of snowpack evolution. In the Kings River Basin, California, a blended scenario combining these data sources resulted in better snowpack predictions compared to models relying solely on precipitation gauges or standard gridded products (Figure 2) (Pelak et al., 2022).

6.3 Integration of remote sensing and ground-based observations

The integration of remote sensing and ground-based observations has enhanced the monitoring and modeling of snowpack. Remote sensing technologies, such as the Moderate Resolution Imaging Spectrometer (MODIS), provide valuable data on snow cover, which can be used to supplement sparse in situ measurements in data-poor regions (Sproles et al., 2016). Additionally, the assimilation of passive microwave satellite observations, such as those from the AMSR-2, into snowpack models has improved SWE estimates by updating meteorological forcing data and snowpack states without relying on surface-based data (Larue et al., 2018).

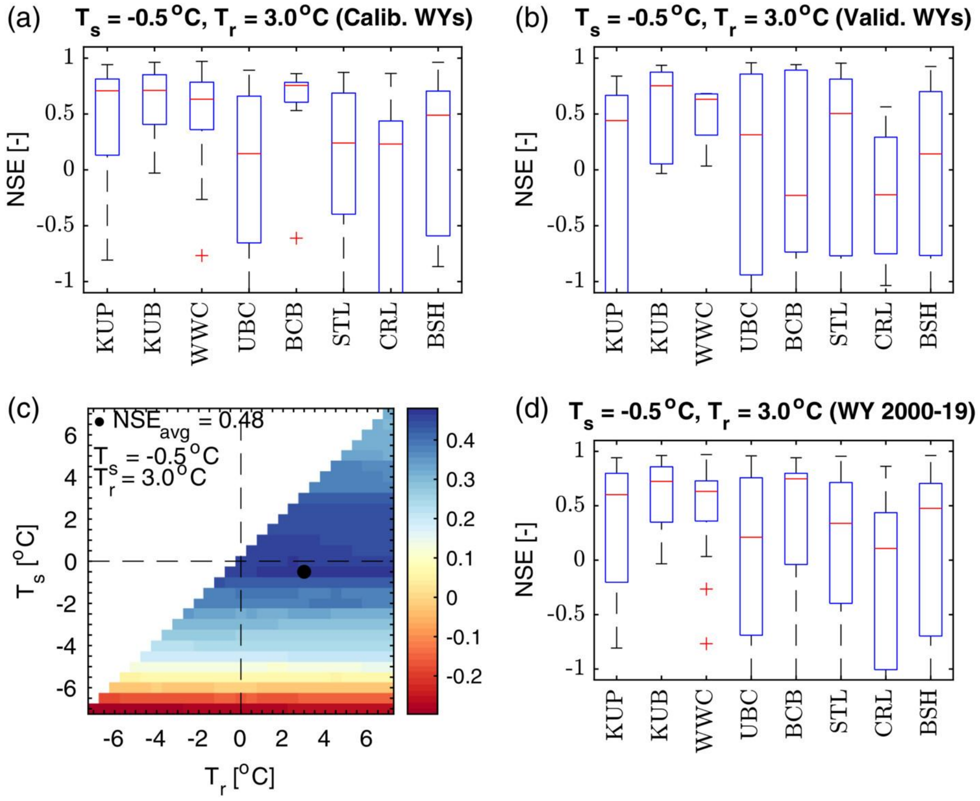

Figure 2 (a, b) Box plots showing the range of NSE values for the 8 calibration sites, for the calibration period (a) and validation period (b) for the snow threshold Ts = −0.5 °C and the rain threshold Tr = 3 °C. (c) Changes in the average NSE values as a function of Ts and Tr. Here, the median NSE values were averaged to obtain the values shown in this figure. The chosen parameter combination of Ts = −0.5 °C and Tr = 3 °C are marked by a black dot. (d) Box plot of the NSE values for each of the 8 calibration sites for the chosen thresholds over the entire study period (Adopted from Pelak et al., 2022)

Efforts to link remote sensing, hydrological modeling, and in situ observations have also been made to better understand the spatial-temporal behavior of seasonal snow cover. For example, a novel algorithm has been developed to improve the quality of remotely sensed snow datasets by incorporating ground-based meteorological observations, leading to more accurate snow cover simulations (Dong et al., 2016).

6.4 Applications in predictive water resource management

The advancements in snowpack measurement and modeling have significant implications for predictive water resource management. Accurate snowpack estimates are essential for forecasting water availability, particularly in regions where snowmelt is a critical water source. For instance, in the Elqui River watershed in Chile, a snowmelt forecast model using remotely-sensed snow cover products has been developed to predict future water availability despite minimal in situ measurements (Sproles et al., 2016).

Furthermore, the integration of data assimilation techniques into snowpack models has enhanced the ability to predict snowpack dynamics and their impact on water resources. The use of ensemble Kalman filter (EnKF) schemes to assimilate ground-based and remotely sensed snow observations has shown promise in improving model simulations and providing more reliable predictions for water resource management (Piazzi et al., 2018).

The continuous advancements in snowpack measurement and modeling techniques, along with the integration of remote sensing and ground-based observations, are crucial for effective water resource management and understanding the role of snowpack in ecosystem functions. These developments enable more accurate predictions of snowpack dynamics, which are essential for managing water resources in a changing climate.

7 Management Strategies and Policy Implications

7.1 Strategies for sustainable snowpack management

Sustainable snowpack management is crucial for maintaining water resources and ecosystem functions, especially in the face of climate change. One effective strategy is the integration of advanced snowpack monitoring technologies, such as blending precipitation gauge data with snow pillow measurements to improve snow water equivalent (SWE) predictions. This approach has been shown to enhance the accuracy of basin-scale snowpack estimates, which is vital for water resource management in mountainous regions. Additionally, improving snow observation networks at high elevations can help better represent precipitation patterns, which is critical for hydrologic modeling (Pelak et al., 2022).

Another strategy involves the use of remote sensing technologies to achieve better spatial characterization of snow cover. Combining ground observations with satellite data can provide realistic information on snowpack variability, which is essential for managing water resources in regions like the Mediterranean mountains (Fayad et al., 2017). Furthermore, understanding the role of atmospheric humidity in snowpack ablation can inform management practices. For instance, regions with higher humidity may experience more frequent midwinter melt events, necessitating adjustments in water storage and release schedules (Harpold and Brooks, 2018).

7.2 Policy frameworks supporting snowpack conservation

Policy frameworks that support snowpack conservation are essential for mitigating the impacts of climate change on water resources. Policies should focus on enhancing the resilience of snow-dependent water systems by promoting sustainable land use practices and protecting critical snowpack areas. For example, policies that encourage the preservation of forested watersheds can help maintain snowpack depth and duration, which in turn supports soil temperatures and ecosystem functions (Sanders-DeMott et al., 2019).

Moreover, policies should incentivize the adoption of advanced monitoring and modeling technologies to improve snowpack predictions and water management. This includes funding for research and development of new technologies, as well as the implementation of comprehensive snow observation networks (Pelak et al., 2022). Additionally, international cooperation and data sharing can enhance the effectiveness of snowpack management policies, particularly in regions that share transboundary water resources.

7.3 Case studies of effective snowpack management policies

Several case studies highlight the effectiveness of snowpack management policies. In the western United States, the integration of snow pillow and precipitation gauge data has significantly improved snowpack predictions, leading to better water resource management in the Kings River Basin, California (Pelak et al., 2022). This approach has been instrumental in ensuring sufficient surface water input to meet the combined estimates of natural flow and evapotranspiration in the basin.

Another example is the use of remote sensing technologies in the Mediterranean mountains, where combining ground observations with satellite data has provided valuable insights into snowpack variability. This information has been crucial for developing water management strategies that address the specific challenges of the Mediterranean climate (Fayad et al., 2017).

7.4 Recommendations for future policy directions

Future policy directions should focus on enhancing the resilience of snow-dependent water systems through a combination of technological innovation, sustainable land use practices, and international cooperation. Key recommendations include:

Investing in Advanced Monitoring Technologies: Policies should support the development and implementation of advanced snowpack monitoring technologies, such as the blending of precipitation gauge and snow pillow data, to improve SWE predictions and water management (Pelak et al., 2022).

Promoting Sustainable Land Use Practices: Policies should encourage the preservation of forested watersheds and other critical snowpack areas to maintain snowpack depth and duration, which are essential for ecosystem functions and water resources (Sanders-DeMott et al., 2019).

Enhancing International Cooperation: Transboundary water resources require coordinated management efforts. Policies should facilitate international data sharing and collaborative research to address the global challenges of snowpack conservation (Fayad et al., 2017).

Adapting to Climate Change: Policies should incorporate climate change projections into water management strategies, focusing on regions most at risk from changing snowmelt patterns. This includes developing alternative water supplies and adjusting agricultural practices to ensure water availability (Qin et al., 2020).

By implementing these recommendations, policymakers can help ensure the sustainable management of snowpack resources, thereby supporting water resource management and ecosystem functions in the face of climate change.

8 Challenges and Future Research Directions

8.1 Current challenges in snowpack research and management

One of the primary challenges in snowpack research is the accurate estimation of snow water equivalent (SWE) at basin scales. This is complicated by the low density of precipitation gauges in high mountain regions, which are often below the snowline, leading to significant spatial interpolation errors (Pelak et al., 2022). Additionally, the predictability of seasonal water resources is declining due to reduced snowpack, particularly in lower-elevation coastal areas, which are most impacted by warming (Livneh and Badger, 2020). The variability in snowmelt timing and the shift from snow to rain due to rising temperatures further complicate water resource management (Mote et al., 2018; Simpkins et al., 2018).

8.2 Gaps in existing knowledge

There are significant gaps in understanding the spatial distribution and temporal dynamics of liquid water content within snowpacks. Current methods lack the ability to non-destructively estimate these properties at fine spatial and temporal scales (Webb et al., 2018). Furthermore, the impact of atmospheric humidity on snowpack ablation and the interaction between humidity, solar radiation, and temperature in controlling snowmelt are not fully understood (Harpold and Brooks, 2018). The role of internal climate variability in future snow resource potential also remains uncertain, with many basins showing potential for both increases and decreases in snow supply (Mankin et al., 2015).

8.3 Priority areas for future research

Future research should prioritize the development of improved snow observation networks at high elevations to enhance the representation of precipitation patterns in hydrologic models (Pelak et al., 2022). There is also a need to better understand the effects of forest management practices, such as thinning, on snow accumulation and melt dynamics (Krogh et al., 2020). Additionally, research should focus on the development of robust climate risk management strategies that account for the full range of internal climate variability and the critical role of atmospheric humidity in snowpack dynamics (Mankin et al., 2015; Harpold and Brooks, 2018). Integrating interdisciplinary approaches to link climate change drivers with water-energy-food nexus and related ecosystem processes is also essential (Liu et al., 2016).

8.4 Potential technological and methodological advancements

Technological advancements such as the combination of ground-penetrating radar with terrestrial LiDAR scanning offer promising methods to estimate the spatial distribution of liquid water content in snowpacks non-destructively and at high resolutions (Webb et al., 2018). The use of process-based snow modeling combined with high-resolution LiDAR data can improve predictions of the effects of forest management on snowpack (Krogh et al., 2020). Additionally, the development of decision support tools using machine learning can help synthesize complex snow-forest interactions and inform water management practices (Krogh et al., 2020). Enhanced global observations, both in situ and remotely sensed, will be crucial for evaluating and improving climate models, thereby reducing uncertainties in snowpack predictions (Simpkins et al., 2018).

By addressing these challenges and gaps, and leveraging technological advancements, we can improve our understanding and management of snowpack resources, which are critical for sustaining ecosystems and human water needs in the face of climate change.

9 Concluding Remarks

Winter snowpack plays a crucial role in water resource management and ecosystem function. As a natural reservoir, it stores water during the winter and gradually releases it in the spring and summer, which is vital for maintaining river flows, supporting agricultural production, and supplying urban water needs. However, climate change is significantly impacting snowpack dynamics, leading to reduced snow accumulation, earlier snowmelt, and changes in the timing and availability of water. These changes pose new challenges for water resource management, as traditional practices and infrastructure often struggle to adapt to these shifts.

Snowpack is not only a key component of water resources, particularly in regions that rely on snowmelt for their water supply, such as the western United States, but it also supports ecosystem health by regulating soil moisture, recharging groundwater, and maintaining stream flows. However, changes in snowpack dynamics can disrupt these critical processes, leading to negative impacts on ecosystems and biodiversity.

In light of these challenges, there is an urgent need for integrated management approaches, improved observation networks, and predictive models to better understand and respond to the impacts of snowpack changes on water resources and ecosystems. Further research into the interactions between snowpack, atmospheric conditions, and ecosystem processes will aid in developing more effective management strategies to address the complex effects of climate change.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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