A low-to-no snow future and its impacts on water resources in the western United States

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Abstract | Anthropogenic climate change is decreasing seasonal snowpacks globally, with potentially catastrophic consequences on water resources, given the long-held reliance on snowpack in water management. In this Review, we examine the changes and trickle-down impacts of snow loss in the western United States (WUS). Across the WUS, snow water equivalent declines of ~25% are expected by 2050, with losses comparable with contemporary historical trends. There is less consensus on the time horizon of snow disappearance, but model projections combined with a new low-to-no snow definition suggest ~35–60 years before low-to-no snow becomes persistent if greenhouse gas emissions continue unabated. Diminished and more ephemeral snowpacks that melt earlier will alter groundwater and streamflow dynamics. The direction of these changes are difficult to constrain given competing factors such as higher evapotranspiration, altered vegetation composition and changes in wildfire behaviour in a warmer world. These changes undermine conventional WUS water management practices, but through proactive implementation of soft and hard adaptation strategies, there is potential to build resilience to extreme, episodic and, eventually, persistent low-to-no snow conditions. Federal investments offer a timely opportunity to address these vulnerabilities, but they require a concerted portfolio of activities that cross historically siloed physical and disciplinary boundaries.

Mountains are known as the water towers of the world, capturing, storing and releasing water for downstream use[1,2]. In the western United States (WUS), as in many global regions[2], this natural service largely occurs through seasonal mountain snowpacks (FIG. 1a), storing approximately 200 km^3 or 162 million acre-feet (MAF) of water annually[3,4], as quantified through snow water equivalent (SWE). In places such as California, for example, average 1 April snowpack water storage (21 km^3 or 17 MAF) nearly doubles the amount of surface water reservoir storage (29 km^3 or 23.5 MAF)[5]. The springtime and summertime melt of these seasonal snowpacks is fundamental to water infrastructure and operations, supplying water during times of precipitation scarcity and when agricultural, ecological and municipal water demands are high[6]. Over the last century, observations and models reveal that anthropogenic climate change has substantially reshaped WUS water resources, including a declining snowpack[7–9,10–17]. For instance, observed 1 April snowpack decline since the mid-twentieth century ranged between 15 and 30% or 25 and 50 km^3 (REF.[15]).

Future mountain snowpacks are further projected to decline, and even disappear, but at unknown rates[4]. While the complete loss of snow is the worst-case scenario, a plausible situation informed by estimates of historical low-snow conditions (FIG. 1b) would be a WUS-wide reduction in SWE and seasonal snow, and a shift from rare or short-term to more persistent low-to-no snow occurrences.

The potential for persistent low-to-no snow to disrupt the WUS water system is substantial, potentially even catastrophic. Water storage and conveyance infrastructure was designed and is now managed using spring snowmelt as a central criterion for operations[5,18–22]. These water management decisions are predicated on the assumption of a stationary climate[19,23], which is an unintended, yet, critical, oversight. Moreover, water rights allocations for many major WUS rivers were made in the late nineteenth and early twentieth century at the end of the Little Ice Age (AD 1400–1900)[24–28], a period that is among the wettest in the past 4,000 years[29–32]. Given the high confidence that continued warming will result in

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Key points

- Mountain snowpacks in the western United States (WUS) have historically acted as large, natural reservoirs of water; yet, they are now harbingers of a changing climate through their signalling of a low-to-no snow future.
- Models projecting the time horizon of low-to-no snow in the WUS lack spatiotemporal consensus due to differences in definitions, metrics, methods and regionally specific analyses.
- Low-to-no snow will impose a series of cascading hydrologic changes to the water–energy balance, including vegetation processes, surface and subsurface water storage and, ultimately, streamflow that directly impacts water management.
- A re-evaluation of long-standing hydroclimatic stationarity assumptions in WUS water management is urgently needed, given the impending trickle-down impacts of a low-to-no snow future.
- Observational and modelling advances are needed to better understand the implications of a low-to-no snow future on water resources and to evaluate the trade-offs among a wide array of potential adaptation strategies that can address both water supply availability and water demands.
- Co-production of knowledge between scientists and water managers can help to ensure that scientific advances provide actionable insight and support adaptation decision-making processes that unfold in the context of significant uncertainties about future conditions.

decreased river flows in the WUS, of which snow-loss is a major contributor, warming will challenge the ability to meet water demands under allocations that did not include climate change risk management[17].

Societies established on freshwater availability and seasonal storage capacity in mountainous snowpack could, therefore, face multibillion-dollar implications, with costs dependent on the time horizon of a low-to-no snow transition[4]. For example, assuming a WUS-wide loss of 66.6 km^3 or 54 MAF of annual snow storage valued at \$200 per acre-foot, with low-to-no snow conditions emerging in the next 50–100 years, WUS snow loss is estimated to reach a cumulative cost of US\$120–850 billion[4]. Of course, economic impact assessments of snow loss are complicated by water values that depend on time, location and supply abundance, as well as the nonlinear changes in the value of water during severe drought. Yet, despite these complications, such estimates demonstrate the dire situation of a low-to-no snow future with little to no action.

Uncertainties in the time horizon of snow loss also have practical implications and challenges for the diverse set of water users, including for the agricultural and municipal sectors[33,34]. Future snowpack losses will be detrimental to long-term water stores typically reserved for emergencies[35,36] and become increasingly difficult to manage as transitions between low-to-no snow periods move from extreme (single year), to episodic (multi-year), to persistent (decades) conditions. Moreover, the disappearance of snow in the WUS has important hydrologic ramifications on both natural and managed systems. Changes in the seasonal snow cycle influences the timing and magnitude of groundwater recharge, vegetation dynamics and stream discharge, which then directly impacts water availability. These processes occur simultaneously and demonstrate nonlinear and heterogeneous behaviour[37–40].

Thus, there is a real need to understand the time horizons, spatial extents and magnitudes of snowpack changes to inform what can be gained through climate change mitigation. This information needs to be provided at decision-relevant scales and conducted with use-inspired science that is informed by a diverse stakeholder group[41,42]. Ultimately, water policy and governance needs to be constrained by the spatiotemporal limits of the water cycle to avoid the prior pitfalls of assuming climate stationarity. This approach of being proactive rather than reactive to a low-to-no snow future will safeguard already limited natural and financial resources, and aid in building resilience to a low-to-no snow future.

In this Review, we provide a call to action and forewarn the dire implications of a low-to-no snow future, given its central role in mountainous watershed behaviour, ecosystem function and, ultimately, downstream water availability. We begin by synthesizing observational evidence of snowpack disappearance in the WUS, followed by the propagating impacts of those changes on the hydrologic cycle. We follow with discussion of adaptation strategies necessary to reduce the economic and ecosystem impacts of low-to-no snow. We end with recommendations for future research, including the need for concerted efforts to cross historically siloed physical and disciplinary boundaries, as well as the scientific practitioner divide. While other hydrometeorological variables have important bearing on WUS water resources, emphasis is placed on snowpack changes, owing to the historic reliance on snowpack by water resources management as a seasonal natural reservoir, and due to a strong, inverse relationship with temperature[17] compared with precipitation[43–45], which lacks consensus on whether future conditions in the WUS will be wetter, drier or remain the same.

A declining mountain snowpack

Prior to assessing future projections of WUS snowpacks in the face of anthropogenic climate change, it is crucial to provide context on the historical and contemporary changes of snowpack and the observational networks used to measure them.

Observational networks and their limitations. Observational networks of WUS snowpack are some of the most extensive in the world, including centennial-length snow courses, decadal-length manual and

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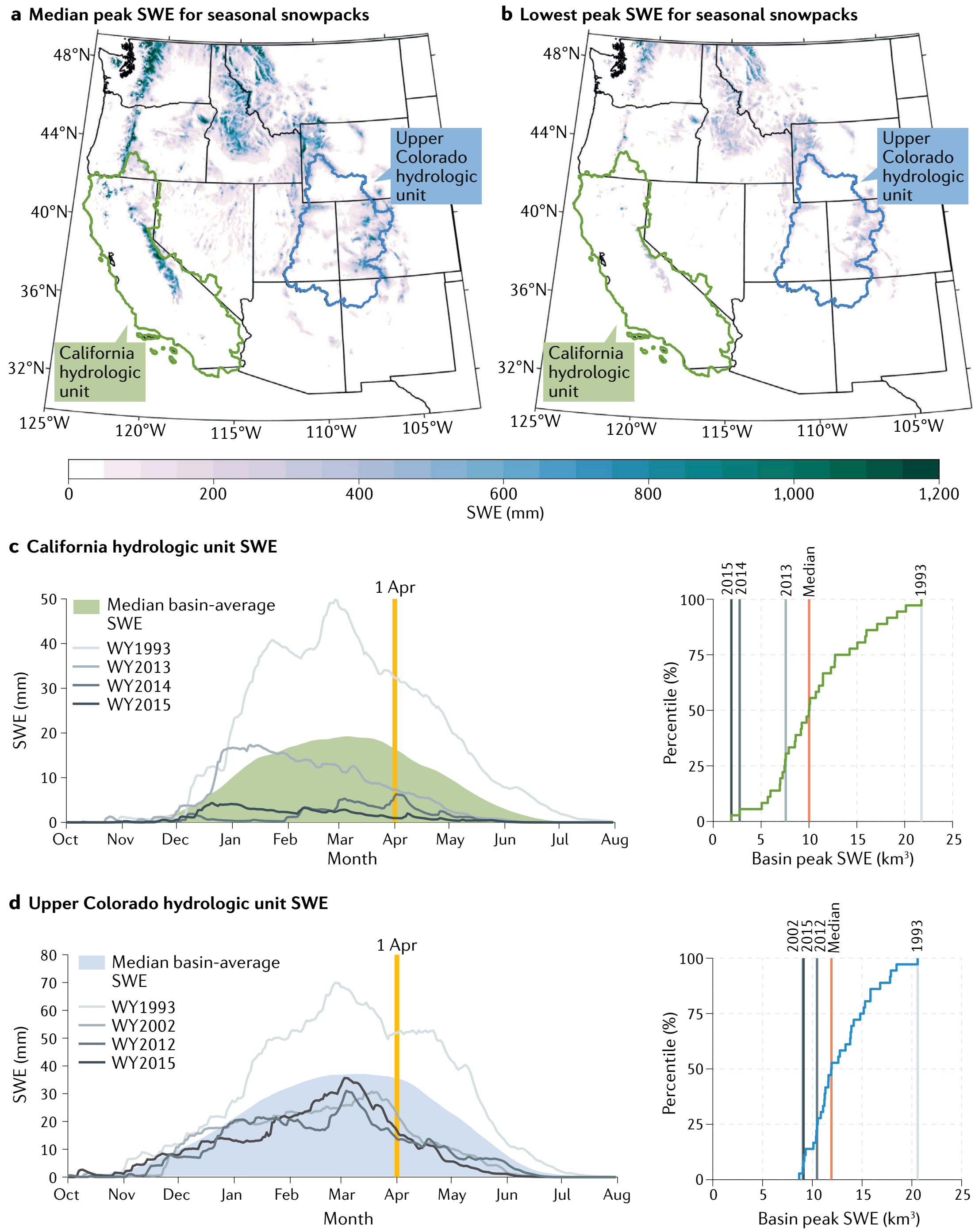


Fig. 1 | **Spatiotemporal variability in western United States seasonal snowpack. a** | Median peak snow water equivalent (SWE) for seasonal snowpacks of the western United States over 1982–2016 (REF.[255]). California and Upper Colorado hydrologic units, as defined by the United States Geological Survey, are distinguished by green and blue contours, respectively. **b** | As in panel **a**, but the minimum peak SWE for seasonal snowpacks. **c** | The temporal evolution of mean and historic high-snow and low-snow water years (WY) for the California hydrologic unit (left), and the cumulative distribution function of peak SWE water storage volume (right). Vertical bars in the right panel indicate peak SWE and median SWE for the time series illustrated in the left panel. **d** | As in panel **c**, but for the Upper Colorado hydrologic unit. Interannual differences in SWE conditions can proximally serve as an indicator of future low-to-no snow conditions.

automated in situ measurements, and multi-year airborne and remotely sensed products.

An important observation date for WUS snow observations is 1 April. While somewhat arbitrary, this date results from monthly manual snow surveys established early in the twentieth century[46,47], and is codified into water management as an indicator of warm season streamflow[35]. However, depending on location and hydroclimatic variability[48], 1 April SWE does not necessarily represent the total amount of water stored as snow in a given water year[49] (FIG. 1c,d), nor can it capture the warming-induced earlier shift in the peak timing of SWE[50,51]. Peak SWE can better quantify the total amount of meltwater available and identify when the melt season might begin, but it cannot fully characterize the temporal evolution and spatial variation of annual water storage and release[12,29,52,53], especially in lower elevation, ephemeral snowpacks that have multiple peaks in the water year life cycle of SWE[54]. In the Rocky Mountains, 1 April SWE underestimates peak SWE by 12%[55]. Both variables are, thus, often needed to assess whether snowpack changes represent an absolute loss or a temporal shift.

Other metrics are also used to characterize SWE. SWE centroid accounts for coarser temporal data (monthly) and snowpacks with multiple SWE values[50], but it inherently provides a more constrained estimate of meltwater totals and can artificially influence other management-relevant metrics, such as the snowmelt season start date, snowmelt season length and/or spring snowmelt rates[18]. SWE centroid and peak SWE also fail to account for SWE changes at daily-to-subseasonal scales[56]. 'Snow drought' refers to a historically low snowpack in a particular time in the water year, or over multiple water years, created by either anomalously low precipitation (dry snow drought) and/or anomalously high temperatures during precipitation events or driving midwinter melt (warm snow drought)[29,57,58]. The concept has gained momentum and enables a better understanding of the drivers of low-to-no snow conditions and the identification of when snow conditions begin to diverge from normality.

Interannual variability that drives differences between peak SWE and 1 April SWE, as well as changes in snow accumulation and persistence as a result of anthropogenic climate change, highlight the importance of observational networks in providing real-time monitoring of current snowpack conditions. Yet, the utility of these observational networks is limited by instrument measurement biases and spatiotemporal gaps[59–61]. A spatially incomplete in situ network, especially at high-elevation headwater regions, creates challenges as warming continues to drive the freezing line upslope, which inhibits the accumulation and persistence of seasonal snowpack, particularly at mid-elevations[14,62,63]. Loss of snowpack can further reduce the ability of in situ networks to provide skilful drought prediction, given a strong relationship between snowmelt and runoff[22].

To address challenges associated with monitoring gaps and extreme events, various statistical and model-based interpolation methods have been developed, so as to provide spatially distributed information. However, assumptions made in interpolation methods produce 40–66% differences in estimates of WUS-wide peak SWE, limiting direct applications to water resource management[64]. Blending traditional approaches, such as snow sensors and expanded snow course surveys[47], with novel techniques like airborne lidar[65], remotely sensed observations[53,66,67] and citizen science[68], can offset some of these limitations. Nevertheless, heterogeneity in mountainous environments limit the ability to obtain perfect snowpack observations, necessitating the use of models[61].

Estimates of change. Despite observational challenges, estimates of contemporary changes have been widely documented, revealing significant reductions in WUS mountain snowpacks and their persistence (FIG. 1c,d). Indeed, observed reductions in both peak SWE and 1 April SWE provide two lines of evidence for a declining snowpack[15,69] (Supplementary Table 1). Peak SWE timing, for instance, has shifted 8 days earlier per degree of warming[51], while peak SWE losses of −2.8 mm per year across 25% of stations have been estimated[69]. Moreover, 1 April SWE depths have decreased by 21% across 90% of reporting stations over 1955–2016, representing a snow loss equivalent to the storage capacity of Lake Mead, the largest reservoir in the WUS[15]. Below-normal conditions have further increased in likelihood in sequential years[1,51,57,70,71].

While WUS mountains are dependent on extreme precipitation and snowfall events to build snowpacks, they are also susceptible to changes in precipitation characteristics, contributing to some of the observed changes alongside warming. Atmospheric rivers, for example, which are commonly associated with snowpack accumulation, are warming, intensifying and producing more rainfall and thus, rain-on-snow events[35,36,72–74]. Since the 1980s, rates of minimum temperature warming in WUS mountains ranges have increased from 0.17 to 0.7 °C per decade, with greater warming (0.8–1.2 °C per decade) across more locations on wet days[72,75]. Warming temperatures push the snowline upslope, nonlinearly altering the amount of water that can be stored as snow[63,76]. Warming also causes snowpacks to ripen earlier in the season, increasing snowpack susceptibility to rain-on-snow events[77]. Deposition of light-absorbing particles — including dust and black carbon — further lower snow albedo, increase solar energy absorption and accelerate snow depletion by 31–51 days, so as to result in earlier peak runoff timing[60,78–80]. Increasing wildfire activity[81] and land-use change[79] are enhancing the deposition of light-absorbing particles on WUS snowpacks, though regional impacts of these particles on the snowpack energy balance remain uncertain[82,83].

Given the strong reliance on an increasingly volatile source of water, resource managers in the last decade have proactively turned to innovative strategies to retain higher reservoir levels via advances in hydrometeorological forecasting[84]. Low snowpack and, more broadly, drought have also motivated landmark policy changes, such as the Sustainable Groundwater Management Act in California[85].

A low-to-no snow future

With observed contemporary changes in the WUS snowpack and projected continuation of anthropogenic climate change, there is high-to-very high confidence that WUS-wide snowpack will continue to decline and peak earlier in the water year[17]. However, for various reasons, little consensus exists regarding when snowpack disappearance becomes particularly detrimental, when the time-to-emergence of low-to-no snow might arise and how the spatial extent of a low-to-no snow future will materialize, as will now be discussed.

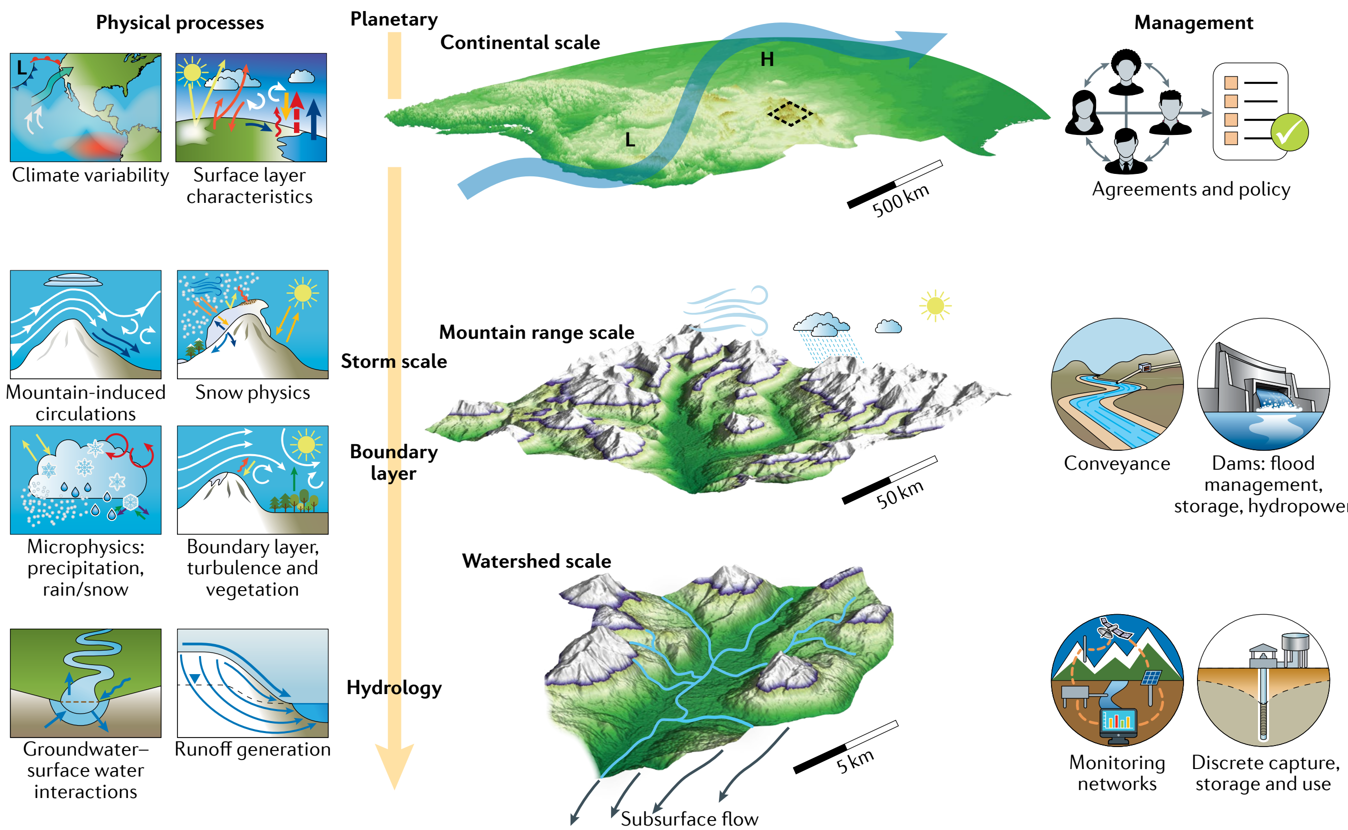


Fig. 2 | **A multiscale perspective of the mountainous hydrologic cycle.** Earth system spatial scales (continental, mountain range and watershed) as they pertain to western United States water and their influences from physical processes (left) and management strategies (right), which also vary by scale. The dashed black box in the continental scale schematic is representative of a typical Earth System Model gridcell (~100 km), sometimes equivalent to an entire mountain range, encapsulating substantial land and subsurface heterogeneity. These cross-scale and cross-discipline considerations are required for a holistic assessment of water management in the western United States.

Challenges of producing snow projections. Snowpack is an emergent property of cross-scale interactions involving temperature, precipitation, radiation, topography and land-surface characteristics, all of which span spatial scales of the globe to hillslopes and temporal scales of centuries to seconds[86] (FIG. 2). For decades, a lack of cross-scale theory, as well as siloed sciences, sparse observational data and computational limitations, constrained advances in modelling mountain environments with high fidelity. Although Earth System Model (ESM) capabilities have dramatically evolved in the last century[87], particularly their strengths as large-scale, centennial-length projection tools, ESMs lack some key process representations needed to accurately simulate mountainous environments, particularly at decision-relevant scales (BOX 1). Indeed, a fully coupled bedrock-through-atmosphere system remains a scientific grand challenge, given limitations in resolving spatial and temporal heterogeneity of atmospheric and land-surface hydrological processes (ranging from tens to hundreds of metres), the substantial disparity in model scales between scientific communities (sub-kilometre to hundreds of kilometres) and the uncertainties around the physical coupling, or lack thereof, between models and/or model components (FIG. 2).

Recent breakthroughs in supercomputing (for example, Exascale and GPU computing)[88–90], benchmarking of models to high-spatiotemporal-resolution observations (including remotely sensed and readily deployable in situ observational networks)[91–94] and the growing field of artificial intelligence[95,96] are accelerating ESM development and their ability to represent the mountainous hydrologic cycle. These breakthroughs combined with the use of variable and/or adaptive mesh refinements to aid in scale-awareness across resolutions[97–103], mountain-focused parameterizations[104,105], more flexible and modular codes[106,107], determination of when and where two-way coupling is needed between models and submodels[108], and utilization of machine learning to better constrain parameter uncertainty or lack of cross-scale theory[95] will inevitably reduce the wide range of estimates in future projections of mountain snowpack.

The use of a hierarchy of models, namely, intermediate-scale (single to tens of kilometres) integrated process models (IPMs), can further inform assumptions made in ESMs and their ability to project future snow loss. IPMs are computationally less expensive, can more realistically represent important model lower boundary features and can be more easily benchmarked with and/or periodically updated by observations[109,110]. Most importantly, they can be used to interrogate the process assumptions made in ESMs by systematically removing process fidelity in the IPM for those found in ESMs. However, considerations

Box 1 | **Mountainous hydrologic cycle process uncertainty in Earth System Models**

The mountainous hydrologic cycle provides a unique test for Earth System Models. The mosaic of cross-scale interactions and emergent behaviour stress the validity of model assumptions, particularly subgrid parameterizations. Indeed, process representation in atmospheric, land-surface and subsurface systems — needed to characterize the partitioning, stores and fluxes of the mountainous hydrologic cycle — remains a grand challenge, specifically under impending low-to-no snow conditions. Earth System Model limitations include:

- Simplified microphysical and macrophysical representations of dominant hydrometeor processes that can bias the magnitude and elevational gradients in mountain precipitation[256,257], and often do not account for wind redistribution and sublimation during or after precipitation[111,258].
- Parameterization omission of terrain influences on shortwave and longwave radiation, which impacts the spatial heterogeneity and lifetime of snowpack[259–261].
- Assumptions in parameterization choice (such as aerodynamic roughness length) can decouple the atmosphere–land interface, particularly during the winter season, resulting in a rapid surface cooling effect that leads to large biases in surface temperature[257,262].
- Prescription of snowpack density and snow cover fraction by empirical functions based on discrete temperature ranges applied uniformly across mountain ranges, ignoring the influences of relative humidity[263] and wind redistribution[258], impacting surface albedo, water storage and energy fluxes.
- Under-representation of the multiple interacting gradients needed to resolve vegetation dynamics (for example, topographic, biogeographic, disturbance), impacting vegetation processes during cold season precipitation (such as canopy interception) and growing season evapotranspiration[107].
- Neglected or crude representation of subsurface processes, including vadose zone dynamics, lateral flow and geological heterogeneity, influencing infiltration–runoff partitioning and groundwater recharge[264].

should also be made for how to minimize bias propagation between coupled models and benchmarks that ensure that added value is actually provided with more costly, complex simulations. Lastly, systematic model intercomparison projects, such as the Snow Model Intercomparison Project (SnowMIP)[111], will be pivotal in providing directions for other important community and model development needs.

Projections of mountain snowpacks, therefore, become a computational balance between limiting the physical process representation at a particular scale (model resolution versus subgrid-scale parameterization); the length of the simulation (a single water year versus multiple decades); the assessment of climate internal variability and statistical robustness (single versus multiple ensemble members); and/or the number of emissions scenarios assessed. These constraints yield an extensive and diverse literature, with a wide range of descriptive metrics, projection methods, time periods and regional specificity (Supplementary Table 1).

Literature synthesis of WUS snow projections. As a result of these limitations, particularly the difficulty in comparing different metrics and widespread use of a single, high-emissions scenario, syntheses of WUS snowpack projections must be taken with caution. Nevertheless, bringing together 18 analyses[3,7,21,104,105,112–124] of snowpack changes across the WUS and four major WUS mountain ranges reveals continued snow loss (FIG. 3; Supplementary Tables 1,2).

In particular, WUS-wide average SWE decline (and their 95% confidence intervals, both rounded to the nearest 5%) is ~25 ± 5% by 2050, ~35 ± 10% by 2075 and ~50 ± 10% by 2100 (FIG. 3a). The large spread in projected changes at mid-century to end of century highlights the lack of consensus on the time to emergence of low-to-no snow. The spread also highlights challenges about how to best characterize SWE loss and standardize SWE projection methods, such that scientific findings can be transformed into actionable information for water managers adapting to the rapid rate of snow-loss brought about by anthropogenic climate change[41,42,125,126]. This actionable information is particularly pertinent for the maritime mountains of the WUS (the Cascades and the Sierra Nevada) (FIG. 3b,d), where ~45% losses are expected by 2050, compared with 20–30% for the continental mountains (the Rockies and the Wasatch/Uinta) (FIG. 3c,e). Additional projections and analyses are also needed in understudied mountains within, for example, the Great Basin and the Colorado Plateau.

Defining low-to-no snow. Declining SWE on a more frequent, persistent and widespread basis[3,7,9,113], albeit with regional variabilities (FIG. 3), is, thus, a hallmark of a projected shift to low-to-no snow in the WUS. Specifically defining low-to-no snow, however, is challenging owing to a multitude of considerations, including the metrics available to quantify snowpack decline.

In developing a quantitative definition of low-to-no snow, two critical points emerge. First, the definition should characterize conditions under which low-to-no snow becomes physically meaningful. Second, the snow conditions should represent deviations from ‘normal’ that result in challenges or failures in water management, recreational value and/or ecosystem services. The definition needs to be both broadly understood and regionally specific, while remaining applicable across WUS mountains and downstream water management paradigms. Precise definitions of low-to-no snow depend on the physical characteristics of snowpack (for example, volume of water stored in seasonal and ephemeral snow, peak timing of water storage, and runoff rate and timing) and the dependence of historic management paradigms.

From a physical perspective, low-to-no snow can be defined by its lowest bound (zero snow). Although not impossible, it is unlikely that a complete disappearance of snow in the WUS will occur before the end of the twenty-first century, even under a high-emissions scenario (FIG. 3), and deleterious impacts to resource management and ecosystems would likely occur before zero-snow conditions. Alternatively, a definition utilizing historic percentiles of peak SWE, akin to the US Drought Monitor[127], has been successfully applied to identify snow drought conditions[9,12]. This approach provides a guide to defining low-to-no snow when combined with the strengths of the peak SWE metric. Within this percentile context, low snow is defined as conditions in which peak SWE falls between the 30th and 10th percentiles, and (effectively) no snow is defined as peak SWE conditions within the lowest 10th percentile.

Emergence of low-to-no snow. ESMs can be used to explore the time to emergence of low-to-no snow. They simulate the spatiotemporal scales necessary to assess

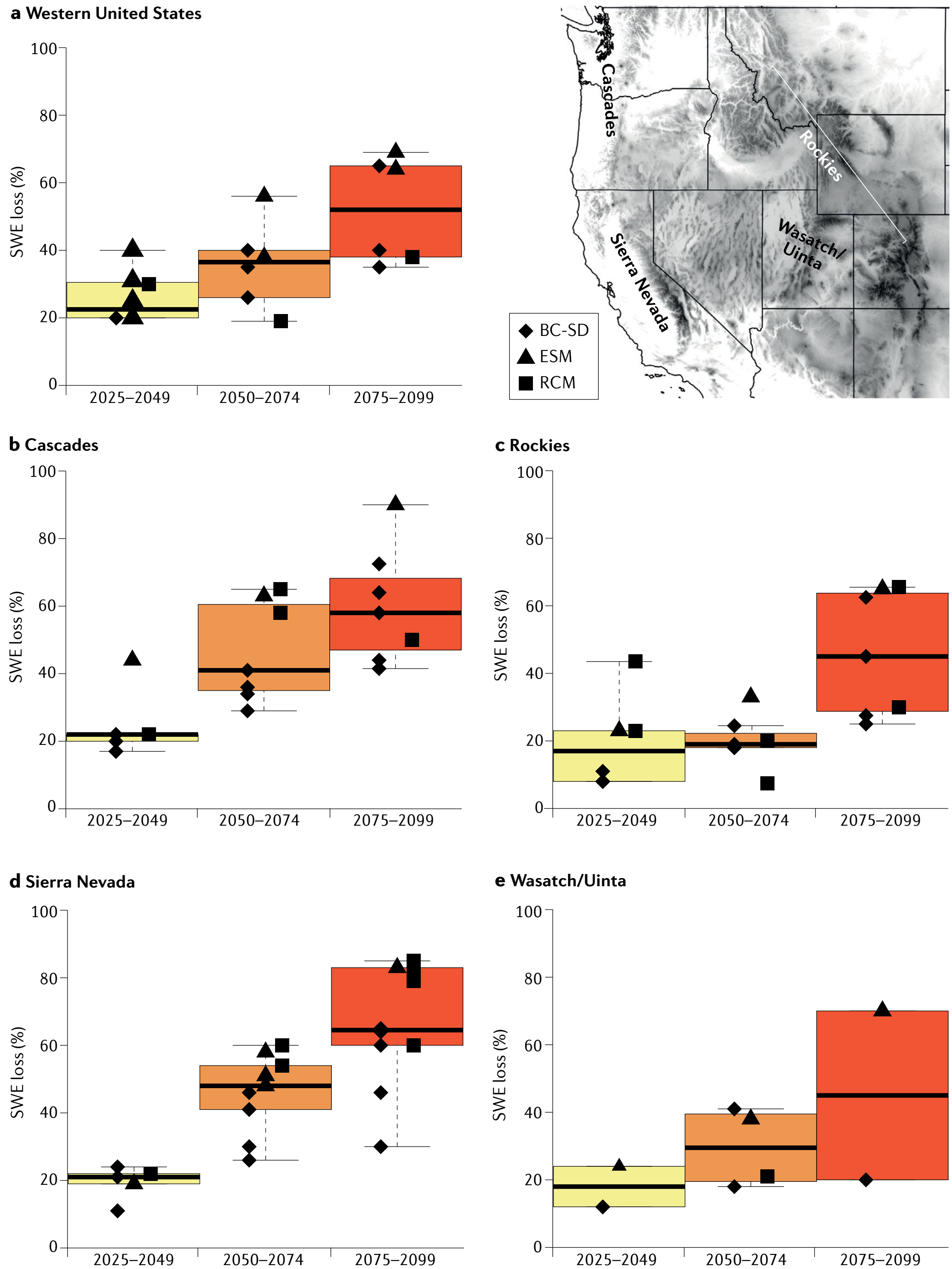
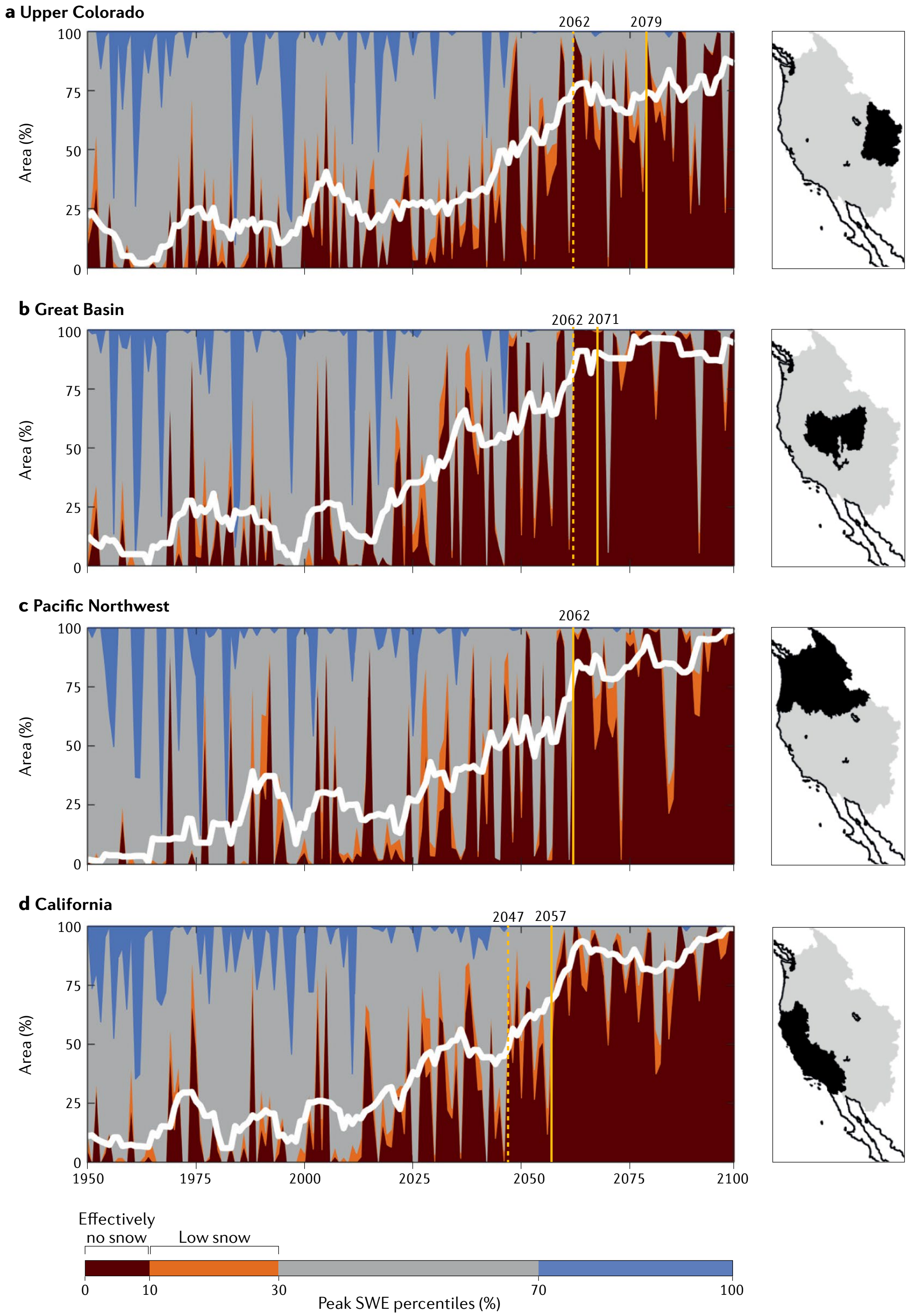


Fig. 3 | **Ranges of projected twenty-first century snowpack loss. a** | Projected snow water equivalent (SWE) loss across the mountainous western United States for the near future (2025–2049; yellow), mid-century (2050–2074; orange) and end of century (2075–2099; red), as derived from published literature[3,7,21,104,105,112–124]. Percent SWE loss considers 1 April, peak SWE and/or seasonal SWE. Projection methods include Earth System Models (ESMs), bias-corrected statistically downscaled ESMs (BC-SD) and regional climate models (RCMs), incorporating analyses under RCP4.5 and RCP8.5, and, in some instances, older high-emission scenarios (SRES A2) (Supplementary Information). Box plots represent the standard minimum, maximum, upper and lower quartiles, and median projected SWE changes. **b** | As in panel **a**, but for the Cascades. **c** | As in panel **a**, but for the Rockies. **d** | As in panel **a**, but for the Sierra Nevada. **e** | As in panel **a**, but for the Wasatch/Uinta. The map at the top right illustrates the areas considered for the regional analyses, with 'western United States' encapsulating the entire domain. Heterogeneity in projected snowpack changes exists across mountain ranges and for different modelling approaches, but generally indicate agreement in decreases by the end of the century.



the timing, amount, phase and location of storms that deliver precipitation[87]; capture alterations in the surface energy budget and the fluxes and stores of water; and avoid limitations associated with assumptions of stationarity[19] through the use of emissions scenarios and land-use change. While acknowledging the outstanding limitations in ESM process representation in mountains (BOX 1), the uncertainty in individual model projections[128], the value of large ensembles[129] and the varying plausibility of emission scenarios[130], exploration of the timeline to low-to-no-snow emergence is valuable, even within a single simulation as a proof of concept. Here, a 20-km-resolution simulation spanning 1950–2099 (REF.[131]) as part of the High Resolution Model Intercomparison Project (HighResMIP)[132] is used for that purpose, adopting the

◀ Fig. 4 | **Snow disappearance based on a low-to-no snow definition. a** | Temporal evolution of the Upper Colorado hydrologic unit (see map on the right) categorized by peak snow water equivalent (SWE) percentiles. The white line indicates the 10-year running average of basin area (both snow and non-snow gridcells) considered low-to-no snow, that is, where an individual year's peak SWE ≤ 30th historical peak SWE percentile. Data are from a single ensemble member of the 20-km-resolution MRI-AGRCM3-2-S Earth System Model[131] under RCP8.5 (Supplementary Information). Vertical dashed and solid lines indicate the time-to-emergence of episodic and persistent low-to-no snow conditions, respectively, as defined by the onset of 5 and 10 sequential years with low-to-no snow conditions over ≥50% of the basin. **b** | As in panel **a**, but for the Great Basin. **c** | As in panel **a**, but for the Pacific Northwest. **d** | As in panel **a**, but for California. Although illustrative of a single simulation, projections such as these demonstrate the utility of the 'low snow' and 'effectively no snow' definitions, as well as the time-to-emergence concepts.

≤30th percentile of historical peak SWE low-to-no snow definition (FIG. 4).

Through the middle and end of the twenty-first century, an increasing fraction of the WUS is impacted by SWE deficits relative to the historical period (FIG. 4; Supplementary Fig. 1). In particular, only 8–14% of years are classified as low-to-no snow over 1950–2000, compared with 78–94% over 2050–2099. In all regions, an abrupt transition occurs in the mid-to-late twenty-first century. For example, the onset of episodic low-to-no snow — the first time that five consecutive years of ≥50% of the basin area experience low-to-no snow — occurs in the 2060s for most basins, but in California, emerges in the late 2040s. Persistent low-to-no snow — the first time that 10 consecutive years of ≥50% of the basin area experience low-to-no snow — occurs as early as the late 2050s in California and as late as the end of the 2070s in the Upper Colorado (FIG. 4). Indeed, from 2070 to 2099, 80–97% of years meet the definition of persistent low-to-no snow. Projections indicate that situations can also arise where the shift from extreme to episodic conditions is rapid, such as in the Pacific Northwest, essentially skipping the episodic low-to-no snow regime[133]. Therefore, if global emissions continued unabated, there is ~35–60 years before low-to-no becomes persistent across the WUS.

Propagating impacts to the hydrologic cycle

In a low-to-no snow climate, several key hydrologic processes controlling the spatiotemporal partitioning of water will be altered (FIG. 5), including precipitation stores (surface water, soil moisture and groundwater) and fluxes (evapotranspiration (ET), runoff and streamflow). Furthermore, deviations from 'normal' snow years can have direct and indirect impacts on hydrologic processes. These impacts are now discussed.

Evapotranspiration. Snowmelt is a significant source of water for vegetation in the WUS[134]. Changes in snowpack are, therefore, expected to have direct, near-term influences on soil moisture profiles[3,134] and ET fluxes. Anthropogenic warming enhances evaporative demand[135], which, subject to water availability, will increase ET. Yet, changing snowpacks can dramatically alter water availability, particularly during early spring and summer. Together, the increased evaporative demands along with changing water availability can make contemporary droughts similar in severity to Medieval megadroughts[136,137]. However, there are several mediating factors influencing and complicating snow change influences on ET, including: plant physiological changes[138,139]; water-limitation caps to ET[140,141]; vegetation access to water due to snowmelt timing shifts; and the degree to which subsurface storage can buffer changes in above ground snow. For example, assuming access to deep (>2 m) rooting zones and associated storage[142], a warmer climate is anticipated to increase ET by 28% across a western Sierra Nevada watershed by the end of the century[143], with similar declines in streamflow. In contrast, other projections indicate reductions in ET by up to 40% for mid-latitude Sierra catchments, owing to earlier snowmelt and truncated water availability into the growing season[144]. At longer, multi-year timescales, changes in the timing and magnitude of water availability for ET will both influence and respond to changes in the density and species composition of vegetation.

Groundwater. Groundwater recharge in mountainous systems, either diffuse (via direct percolation of precipitation into the subsurface) or focused (via surface water bodies), is expected to change, given alterations to snowpack[145]. In general, snowmelt more effectively infiltrates into the subsurface when compared with rainfall[146]. Thus, a phase change in future precipitation can result in less mountainous groundwater diffuse recharge. Furthermore, upward elevation shifts in the snowline will decrease the surface area over which snowmelt can occur[76], reducing snowmelt infiltration into lower permeability material and, thereby, decreasing overall recharge. If more snowpack becomes focused at higher elevations, there is potential for deeper snowpacks to accumulate, which melt later and faster[122]. However, low-permeability alpine snowmelt drives substantial groundwater interflow because ET demands in these regions are also low, enabling a substantial contribution of groundwater to subalpine vegetation — a potential climate-change-resilient mechanism for groundwater recharge[147]. If changes in groundwater do occur, they can have cascading effects on subsurface weathering rates, chemical export[148] and discharge for groundwater gaining streams and rivers, with subsequent implications for groundwater-dependent ecosystems[149]. There is, thus, a critical need to understand mountain groundwater in a future climate[40].

Runoff and streamflow. On average, snowmelt produces more runoff than rainfall[115,150,151] and more attenuated peak flows than rainfall runoff[152]. Models suggest that more than half of runoff in the WUS originates from snow, despite snowfall representing only one-third of total precipitation. Snowmelt contributions to runoff in the mountains are even larger, up to 70%[115], indicating that projected snowfall changes will influence streamflow.

Generally, a shift in precipitation phase from snow to rain leads to significant decreases in annual streamflow, reflecting increases in ET[150]. However, as noted, the direct effects of a low-to-no snow future on ET in winter wet–summer dry systems can include both decreases and increases in ET. More water-limited areas might show decreases and higher elevation temperature-limited areas

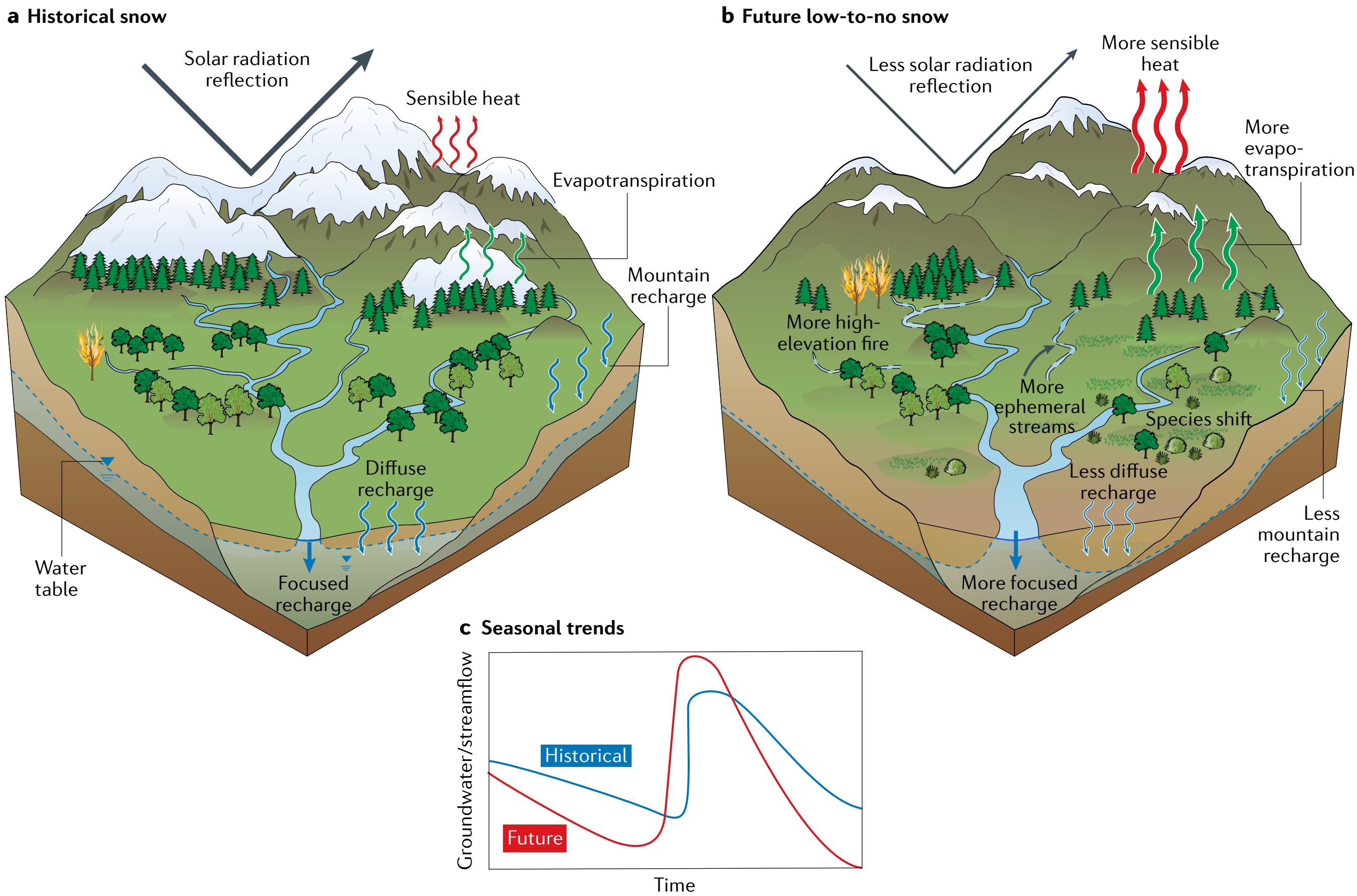


Fig. 5 | **Changes in mountain environments under persistent low-to-no snow conditions. a** | Physical and biological processes as observed in mountain systems with seasonal snowpack. **b** | Shifts in the behaviour of mountain systems under future low-to-no snow. **c** | Seasonal trends of groundwater and streamflow throughout a single water year (beginning 1 October), where the blue line represents historical conditions and the red line represents hypothesized future conditions. Although predictions of many co-evolving hydrologic processes as a result of low-to-no snow conditions are difficult to infer, changes in both above and below ground future watershed behaviour is expected.

might show increases, and these changes will evolve with changes in vegetation distribution and type. Thus, while overall streamflow is likely to decrease, there could be locations where annual streamflow might increase with shifts from snow to rain. Yet, some projections reveal that mean future flows will remain stable, but that peak flows will increase and low flows will decrease[153]. Changes to WUS hydrographs, however, should be contextualized relative to the low-to-no snow transition. For instance, in a warmer future where snowpack remains, it is expected that slower snowmelt rates will yield less streamflow[154]. In a transitional future where both snow and rain exist, there is also increased potential for flood hazards due to rain-on-snow events[77,155]. Rain-on-snow events effectively enhance runoff efficiency, where streamflow contributions from winter rainfall can surpass snowfall contributions[156].

At sub-annual timescales, seasonal low flow, fed predominately by late spring snowmelt and groundwater in gaining streams, is an important consideration, given its role in sustaining ecological habitats and water demands in Mediterranean climates, where annual peak water supply demands correspond to precipitation-free months. Historical evaluation of snowpack and resulting streamflow relationships during low-discharge conditions reveals that, for every 10% decrease in peak SWE, annual minimum flows could decrease on the order of 9–22% and occur several days earlier[157]. Shorter snowmelt seasons imply longer low-flow periods, which results in reduced low flows[158] (FIG. 5c). The translation of changes in the timing of snowmelt into low flows is strongly influenced by geological factors that influence watershed response times. Slower draining, deep groundwater-dominated watersheds such as the High Cascades in Oregon, for example, could show greater reduction in late-season flows relative to faster draining watersheds, such as steep granitic watersheds in the California Sierra Nevada or volcanic watersheds in the Western Oregon Cascades[158,159]. As streamflow responses to changes in the magnitude and timing of snowmelt are strongly mediated by geologic factors that control recession characteristics, heterogeneity in geology, even within regions such as the California Sierra Nevada, will be an important consideration in hydrologic model applications to predict low-flow responses to changing snow[157].

Longer term and indirect hydrologic changes. At multi-year timescales, snowpack changes will impact the co-evolution of hydrologic and land-surface processes, such as the amount and type of vegetation present. For example, forest productivity in the California Sierra Nevada increases with snow accumulation, particularly for more water-limited mid-elevations[160], and earlier snowmelt reduces carbon uptake in the Colorado Rockies[161], reflecting loss of water to support late summer productivity. Longer term species changes with warming are also expected[162], along with increases in forest mortality with drought[163,164] and disease[165,166]. How changes in vegetation structure (including leaf area, rooting depth and biomass) and composition (water use access and water use efficiency) translate to changes in ET–streamflow partitioning remains poorly constrained in models, and is likely to vary with geoclimatic settings.

Changing vegetation structure can also feed back on the snowpack. For instance, denser forest canopies can increase snow interception losses through sublimation and increase snowmelt via greater longwave radiation. Denser canopies, however, can also slow snowmelt by reducing incoming shortwave radiation at the snow surface, and lessen sensible and latent heat fluxes into the sub-canopy snowpack[167]. The relationship between forest cover and snow dynamics can also vary with local climate conditions and landscape morphology. Regionally, mean winter temperature is an indicator of where forest cover will act as an insulator to snow cover or enhance its melt; regions with December through February temperatures >−1 °C reduce seasonal snow duration on the order of 1–2 weeks[168].

Changes in wildfire frequency, severity and timing are particularly catastrophic consequences of a low-to-no snow future. Indeed, alongside continued warming, a shift towards a no-snow future is anticipated to exacerbate wildfire activity, as observed[169,170]. However, in the longer term, drier conditions can also slow post-fire vegetation regrowth, even reducing fire size and severity by reducing fuels. The hydrologic (and broader) impacts of fire are substantial, and include: shifts in snowpack accumulation, snowpack ablation and snowmelt timing[171]; increased probability of flash flooding and debris flows[172,173]; enhanced overland flow; deleterious impacts on water quality[174,175]; and increased sediment fluxes[176,177]. Notably, even small increases in turbidity can directly impact water supply infrastructure[178,179]. Vegetation recovery within the first few years following fire rapidly diminishes these effects, but some longer term effects do occur, as evidenced with stream chemistry[180] and above and below ground water partitioning both within and outside of burn scars[181].

Integrated cascading responses. Projecting the propagation of changing snow dynamics onto ET, groundwater and surface water involves integrating cascading responses and their coupling with changing land-surface properties. Time horizons of these expected hydrologic and land-surface changes depend on the degree of low-to-no snow intermittency and other climate drivers, in turn, impacting the degree of system rebound. The potential consequences of different changes in annual to sub-seasonal snowpack on major hydrologic stores and fluxes are substantial and difficult to infer, given simultaneous changes in temperature and precipitation (FIG. 6).

Regional-to-continental-scale estimates of the cascading effects of future low-snow scenarios on runoff are available for the WUS[3,115]. However, the hydrologic models used for such analyses generally do not account for potential feedbacks related to changes in vegetation and land-surface characteristics, which are vital for longer range forecasts. Empirical analysis of hydrologic responses to wildfires[182] show substantial regional variation within the WUS. Similarly, expected trajectories of changing wildfire regimes vary both within and between WUS regions[183]. Coupled models must, therefore, resolve parameters and processes that drive not only significant spatial patterns in snow and hydrology but also spatial patterns of changing vegetation and its cascading impacts on water.

Hypothetical sequencing of low snow years can conceptually define transition times between conditions that are extreme, episodic or persistent (FIG. 6b), depending on their frequency and order. The occurrence of these transitions can subsequently impact the hydrologic dynamics. For example, groundwater response signals during high snow years can alleviate stresses of previous years during the extreme low-snow regimes, but not during episodic or persistent regimes (FIG. 6b). Hydrologic deviations from expected (or historic) responses will be dependent on the resilience of each component of the system, and the co-evolution and interaction of processes simultaneously. Thresholds in system response could then be reached more quickly, given disturbances (for example, fire or vegetation mortality induced by disease or insects).

Climate change adaptation strategies

In a future characterized by low-to-no snow, creative and flexible strategies to adapt to variable water supplies will be critical to reduce economic and ecosystem impacts, particularly in light of 71% of water experts believing that current water management strategies would be insufficient and the need for a better understanding of climate-change-induced uncertainties[33].

Vulnerabilities of the WUS water system. Over the last century, a complex engineered system has been developed in the WUS alongside the natural river network and snowpack storage to meet diverse water demands, including: rural, urban, residential, tribal, commercial, industrial, agricultural and hydroelectric power (FIG. 7). This system includes reservoirs for surface storage, canal and pump structures to move water long distances across basins and over mountains, groundwater pumps to augment surface supplies and hedge against dry years, run-of-river and reservoir-based hydropower to generate electricity, and water efficiency technologies and conservation practices to reduce water needs. In addition to ensuring reliable water supply, this system mitigates flood risk from high-water events and provides environmental flows for ecosystem benefits. Together, these systems have been designed to facilitate the movement of water from water-surplus to water-limited regions, to manage

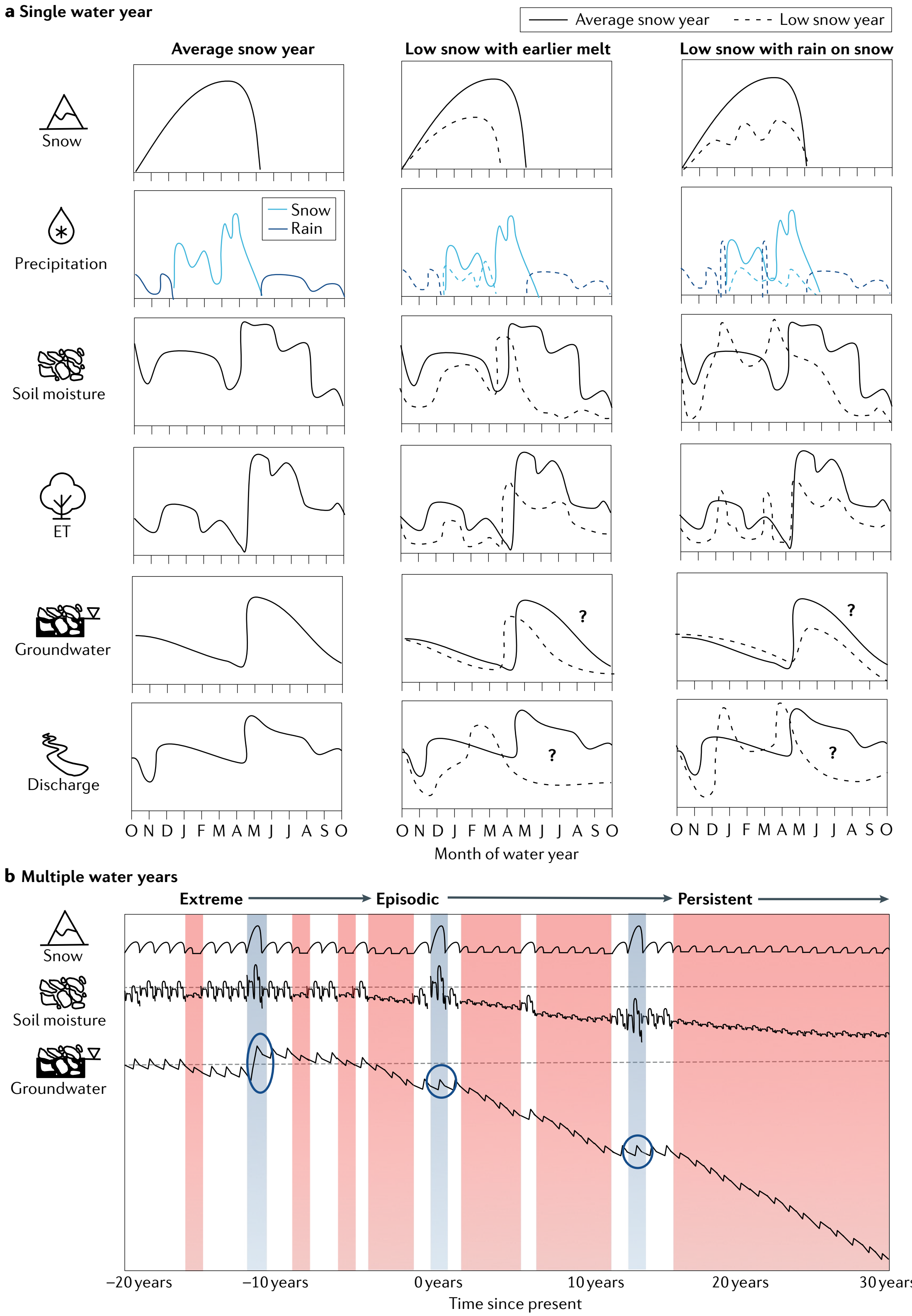


Fig. 6 | **Cascading above and below ground impacts of snowpack changes. a** | Temporal dynamics of annual water partitioning for hypothetical variations (average snow year, low snow with earlier melt and low snow with rain on snow) in average and low snow years. With the exception of the rain-on-snow scenario, these illustrations assume no additional compensation from rain. Question marks denote scenarios where inferring potential changes are more uncertain. **b** | Sequencing effects of multi-year low-to-no snow conditions indicating transitions between extreme, episodic and persistent system behaviour. Red shading indicates low snow years and blue shading indicates high snow years. Inferences in system behaviour such as rebounds after single or sequential low snow years are difficult, given interactions across the atmosphere–bedrock continuum, warranting the use of physically based models. ET, evapotranspiration.

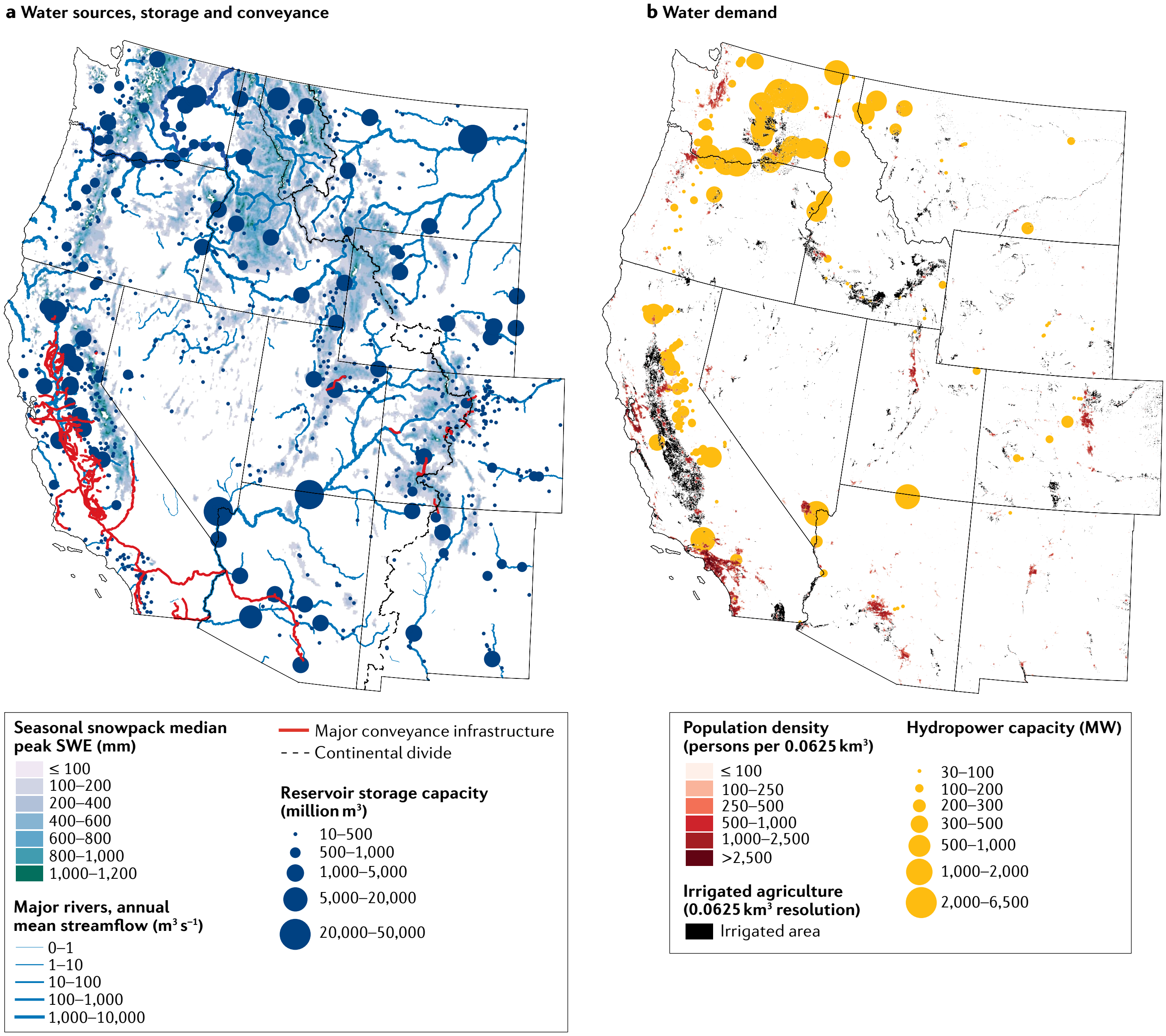


Fig. 7 | **Supply and demand connections between the natural and managed WUS water systems. a** | Water sources, storage and conveyance across the western United States (WUS). **b** | Water demands across the WUS. This combination of natural and engineered systems illustrates the interconnected nature of WUS water and the long travel distances of water moved away from mountains to support urban and agricultural water end users and to power run-of-river and reservoir-based hydropower generation. Note that groundwater aquifers, another major water source in the region, are not included in this figure for clarity of visual representation. See Supplementary Information for the data sources. SWE, snow water equivalent.

the natural spatiotemporal variability that is inherent in the WUS precipitation patterns and the locational and timing mismatch between water availability and human water demands across multiple sectors[184,185]. The high value placed on water in these regions, particularly during times of scarcity, drives this movement of water across basins, despite the great financial and energy cost of doing so[186]. A complicated set of legal commitments regulate much of the physical infrastructure, including long-term water compacts, interbasin transfers, water rights, water quality standards, and environmental water and species protection mandates. These physical and legal structures are managed together in response to changing water demands across daily, yearly and decadal scales.

While WUS water management has adapted to inter-annual variability in water supply, fundamentally, the water infrastructure, legal framework of water rights[187] and management institutions were built with the expectation that supply variability would be contained within a stationary range of known possible conditions[19]. However, changes in the seasonality and variability of the mountainous hydrologic cycle has important direct and indirect implications for the management of WUS water resources that extend beyond just changes in the historical mean and variability of annual runoff. For example, under a low-to-no snow future, it will be more challenging to capture earlier snowmelt in reservoirs required to maintain early season flood control capacity[188] or to gauge reservoir releases in order to prepare for secondary or tertiary peaks in inflow.

These changes will affect water availability for urban water suppliers, for example, in Southern California, a region heavily dependent on imported water from the snowpacks of the Sierra Nevada and Colorado River Basin[189]. There will be increased pressure on agricultural water users in the WUS[190], who have come to rely on snowmelt stored in reservoirs to irrigate during the summer growing season[6,191]. Rural community water systems, such as in the Central Valley of California, could become more reliant on already stressed and overdrafted groundwater sources, particularly those that already have water quality violations[192]. Climate change impacts, including declining snowpack, could create water supply availability and quality challenges in some tribal areas that exacerbate socio-economic vulnerabilities[62,193,194]. In addition, a low-to-no snow future will affect the WUS energy sector; high-elevation hydropower generators that have small reservoirs designed around stationary snowpack storage will likely decrease their electricity production, particularly during the summer[195–197]. Given that conveyance infrastructure connects disparate natural systems across hundreds of miles and between basins (FIG. 7), such impacts of low-to-no snow conditions in one region can have far-reaching impacts that disrupt the WUS water system across a diverse group of stakeholders with different economic values, water use priorities and legal mandates. These connections further compound existing pressures on water supplies from ageing infrastructure, population growth, increased demands from energy production and land-use change[184,198].

A path forward. A number of potential adaptation strategies to a low-to-no snow future can be pursued to address both water supply availability and water demands, with, for example, hard infrastructure (including dams, canals and new supplies) and soft management approaches (including better forecasting to inform operations, managed aquifer recharge (MAR) and conservation)[199]. It is likely that a diversified portfolio of both supply-side and demand-side strategies will be needed to flexibly adapt to a low-to-no snow future, and overcome implementation barriers and physical limits of any one approach[17,200].

Physical surface storage and conveyance infrastructure (for example, dams, pipelines and aqueducts) serve to smooth the variability of water supplies in time and space. Proposed future adaptation strategies include building new surface storage capacity (for example, the Sites Reservoir in California)[201], retrofitting existing reservoirs to increase capacity (for example, raising Shasta Dam in California)[202,203] and constructing large new conveyance projects (for example, Utah's proposed Lake Powell Pipeline on the Colorado River)[204]. However, dams and large conveyances are expensive, slow to develop relative to the speed of anthropogenic climate change and can have significant negative ecosystem impacts, including obstructing and changing other physical aspects of fish habitats[205,206], trapping sediment[207] and changing water quality. Planning of these new systems and associated water governance is also challenging because large infrastructure is designed, built and maintained on the multidecadal scale and includes trade-offs such as cost versus capacity, requiring decision frameworks and optimization paradigms that can account for multiple factors[208,209].

Besides new infrastructure, there is some flexibility to adapt existing surface storage infrastructure to new conditions through innovative reservoir operations. Forecast-informed reservoir operation (FIRO) is a relatively new concept in which weather and hydrologic forecasts are used to selectively retain or release water from reservoirs, as opposed to conventional release schedules based on rule curves, which are estimates of allowable maximum daily storage to reduce downstream flood risk[84,210]. Advances in sub-seasonal to seasonal weather forecasting have made it possible for reservoir operators to more effectively balance water supply and flood control objectives (for example, avoid releasing water supply for flood preparedness if large precipitation events are unlikely in the near future). A modelling case study on Lake Mendocino showed the potential to increase water storage by 33%[84]. Such strategies are invaluable as the need to capture spring snowmelt becomes less reliable in the water year. Enhanced monitoring networks can further support critical management decisions during these high-impact events[211].

Groundwater reservoirs can also provide significant storage capacity to offset snow loss. For example, California groundwater basins are estimated to have between 850 million to 1.3 billion acre-feet (1,048 to 1,604 km^3) of storage, compared with an annual average of 23.5 MAF or 29 km^3 of surface water reservoir storage (with an upper bound of 50 MAF or 62 km^3)[5,212]. Therefore, MAR, whereby excess surface water is conveyed to flood-permeable landscapes to infiltrate into groundwater aquifers or stormwater is captured and stored in urban areas[213], could be another important climate adaptation strategy[214]. Conveyance can transport water to locations suitable for groundwater recharge either at times when there is excess conveyance capacity or when coupled with FIRO to provide more storage space in reservoirs without 'losing' water from the managed system. Importantly, these potential new groundwater stores must be managed conjunctively, or in coordination with surface water, to allow critically overdrafted basins to recover and be maintained at more sustainable levels[215].

There are also potential approaches to increase total supply by bringing 'new' water into the system. These approaches can be natural-engineered hybrid approaches such as forest and vegetation management to reduce ET and increase snow storage, runoff and recharge[216]. However, forest management for water could conflict with other desired forest management outcomes, and must consider a range of other objectives, including wildfire hazard, terrestrial carbon storage, habitat refugia, recreation impacts and economics of its scalability, again highlighting inherent trade-offs among competing societal objectives[217,218]. Cloud seeding is another hybrid system that has been pursued historically but carries with it controversy[219]. Fully engineered approaches such as seawater and brackish desalination and recycled water for potable and non-potable reuse are also possibilities and face their own challenges in terms of cost, energy usage, social acceptance, implementation lags and capacity[220–223].

Water demand management can complement the aforementioned supply-side approaches. Agricultural water use can be reduced by improved irrigation efficiency, more precise water use versus yield estimates for crops, integrated crop water management, crop switching and land repurposing[224–227]. Ideas for reducing water use in urban sectors include more water-efficient appliances, reduced outdoor irrigation, leak detection, rainwater capture and localized storage[185,228]. Additionally, changes in agricultural and urban water markets and pricing could be powerful tools to manage demand and respond to scarcity[229]. All of these approaches could help to increase WUS water system resilience, but their implementation would be more optimal with an improved understanding of the spatiotemporal dynamics of a low-to-no snow future.

Decision-making under uncertainty and co-production. Evaluating the risks and trade-offs among alternative climate adaptation strategies presents a scientific and policy challenge, given the highly variable, multiscale, interconnected and nonlinear nature of built infrastructure systems and the natural systems that they are embedded within. Upgrading water infrastructure so that it is prepared to respond to these types of changes and challenges will require enormous investment. For example, the American Society of Civil Engineers projects US$1 trillion are needed to maintain and expand the nation's drinking water systems, which have received a grade of 'D' in their 2017 infrastructure ranking[230]. Determining which investments are worthwhile to pursue is a process that is informed by scientific and technical knowledge about hydroclimatic and infrastructure systems. For example, operational decision support models can be combined with economic[231] and bedrock through atmosphere modelling capabilities[232], to explore physically plausible future scenarios with consideration of mitigation strategies and water supply and demands. However, additional or improved scientific information is, by no means, the only barrier to adaptation[233,234], and related decision-making is fundamentally a social process that must resolve the trade-offs among multiple objectives arising from different communities, actors and institutions.

There is an extensive social science literature on climate adaptation that examines, for instance, institutional, cultural, behavioural and political aspects of decision-making[235,236], including which stakeholders have a voice in planning (often referred to as procedural justice)[237] and who benefits from adaptations (often referred to as distributive justice)[238,239]. There are several promising scientific developments that can serve to narrow uncertainties regarding a low-to-no snow future. These include real-time modelling and monitoring networks, and the development of observationally informed coupled modelling strategies that represent key human and natural system processes in a self-consistent manner. While such advances in science can reduce uncertainty regarding future conditions, some degree of irreducible uncertainty will always remain[240]. Thus, at the same time that science evolves to increase predictive understanding of the mechanisms of hydroclimatic change, management practice must evolve to accommodate uncertainty regarding the changing patterns of current and future hydrologic variability. Developing a robust strategy and selecting investment options that balance competing societal objectives and multisectoral interactions (such as the interaction among water and energy[186] or water and carbon[207] reduction goals) requires new approaches to integrate water resource planning. Frameworks and planning methods for decision-making under deep uncertainty that acknowledge and accommodate imperfect knowledge regarding the probabilistic range of possible future conditions such as decision scaling[241], robust decision-making, dynamic adaptation pathways[242] and scenario planning can identify scientifically informed adaptive strategies that leverage best available science without overstating its confidence[243].

For instance, the United States Bureau of Reclamation and water management agencies within the Colorado River Basin engaged in a robust decision-making study that identified a range of potential future climate conditions under which water delivery obligations would be vulnerable. Portfolios of adaptation strategies aimed at demand reduction (including agricultural, municipal and industrial conservation) and supply augmentation (including reuse, desalination and water import) were evaluated for their ability to alleviate these vulnerabilities and for their trade-offs in cost, yield, technical feasibility, legal risk and other criteria. The portfolios generally increase system robustness but have a wide range of implementation costs, especially under the declining supply conditions, and vary between the Upper Basin and the Lower Basin[244].

Making science usable for decision-making requires strong trust between the parties[245]. This trust often develops over deliberate, long-term collaboration[246], with mutual understanding of the science, models and tools being discussed and demonstration of the credibility, saliency and legitimacy of the new approach(es)[247]. Institutional, technical and financial capacity to implement these approaches must also be overcome[233]. Scientists must also recognize that practitioners are often directly responsible, sometimes even personally liable, for the outcomes of decisions made, which makes them hesitant in the application of new climate science[236], especially if perceived as not fitting with existing knowledge or policy goals[233,248].

A path forward can be made by including Earth scientists, infrastructure experts, decision scientists, water management practitioners and community stakeholders, in a collaborative, iterative process of scientific knowledge creation through a co-production framework[41,42,249,250]. This process helps to ensure that new science is suited to challenges at hand and can provide meaningful input into decision-making processes, enabling more efficient, flexible and robust solutions. For example, an interdisciplinary, social and hydroclimatic co-production project between the Eastern Shoshone and Northern Arapaho tribes of the Wind River Indian Reservation in Wyoming, university partners and more than a dozen government agencies helped to develop early-warning tools for drought and to support climate adaptation planning at scales relevant to local water managers, in response to climate information needs identified by the tribes[62]. In such collaborations, boundary spanners or information brokers, organizations and/or individuals who can facilitate the co-production process play critical convening and translating roles in increasing the usability of new climate science for adaptation planning[234,248,251,252].

Summary and future perspectives

The WUS water sector built its infrastructure and developed its management practices under the assumption of an abundant winter snowpack that reliably melts prior to peak water demands in summer months. Observations highlight multiple lines of evidence indicating a historically declining snowpack that peaks and melts earlier. Models further project a continuation of this decline, with equivalent snowpack losses on the order of ~35 ± 10% by mid-century and ~50 ± 10% before the end of the twenty-first century, should emissions continue unabated. Exact timelines of snowpack declines are uncertain, shaped by projection methods, emission scenario and metrics used. To standardize community efforts to understand the time to emergence of snow loss, a new low-to-no snow definition is provided based on historical peak SWE percentiles, ≤30th percentile (low snow) and ≤10th percentile (effectively no snow). This low-to-no snow definition helps characterize when snow loss becomes particularly detrimental, which is likely regionally specific and will be a function of the sequencing of low snow years and the response of the hydrologic system to those low snow years. The implications of these snowpack changes include perturbations to groundwater recharge, streamflow dynamics and ET fluxes, and are complicated by simultaneous, nonlinear processes from the bedrock through the canopy, as well as disturbance such as wildfire. Owing to the expansive and interconnected nature of WUS water storage and conveyance, particularly to differential snow loss in various mountain regions, several vulnerabilities to the existing WUS water system will require innovative adaptation approaches that can be supported by new modes of usable, decision-relevant knowledge production.

Of the many uncertainties imposed by climate change on the hydrologic cycle, the high confidence in snowpack decline enables proactive planning. From a water storage perspective alone, a shift in precipitation from snow to rain will result in a failure to meet water demands, given limitations in existing reservoir storage capacity. Strategies could include additional surface and subsurface storage, diversifying supply options and conservation. A re-evaluation of the operation and design of WUS water systems is timely, given current plans for large-scale federal investments in infrastructure and the American Society of Civil Engineers' recent declaration of 'chronically underinvested' US drinking water systems[230]. This re-evaluation also presents an opportunity to proactively plan for snow-related water failures. Snow loss is often less of a priority relative to other investments made retroactively to a changing climate, for example, Texas' winterization from the national electric grid or the US coastal flood defence from storm surges and sea level rise[253]. For water management, the urgency of implementation for the planning, permitting, construction and/or retrofitting of storage and conveyance systems is immediate, but the realization of benefits is on the order of several decades[184]. Thus, decisions and investments made today will extend multiple generations, operate for half-centuries or more, and need to function within rapidly changing hydroclimatic conditions. To avoid pitfalls of assuming stationarity again, investments should not solely focus on hard infrastructure but also the potential for soft management approaches and continuous optimization of the hard infrastructure investments, such as MAR and FIRO, as environmental conditions change.

In combination with hard infrastructure and soft management investments, additional investments in maintaining and expanding observational networks and supporting the implementation of frameworks to develop co-produced, use-inspired research will be instrumental as snow disappears. Gaps between operational and research models need to be addressed. Future ESM development aimed at enhancing the fidelity of integrated mountainous hydrologic cycle processes should also be considered a scientific grand challenge. The overall goal being that future models that can reliably translate projections of planetary-to-regional-scale changes in the Earth's climate system to the scales relevant to the mountainous hydrologic cycle is, in turn, better suited to isolate existing natural and managed system vulnerabilities and assess the efficacy and scalability of climate adaptation strategies.

Finally, a paradigm shift in the science community is also needed, where those studying climate change will need to not only look for a single mode of hypothesis-driven research but also towards a problem-oriented framework[254]. Likewise, water agencies will need to be amenable to new technologies, approaches and develop non-traditional relationships to inform new protocols for operations. This more holistic approach that accepts nonstationarity while considering both the natural physical system and the managed one can help to ensure that systems are less vulnerable to longer term hydroclimatic change and short-term hydrometeorological extremes. A concerted, community-wide effort is needed to support the funding mechanisms, legal and research institutions, incentive structures, co-production teams and/or boundary organizations to represent a diverse set of stakeholder needs. The overall goal of these investments and interactions would be WUS-wide resilience to ongoing snow loss and the imminent onset of a persistent low-to-no snow future if anthropogenic climate change continues unabated.

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