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The Essential Role of Local Context in Shaping Risk and Risk Reduction Strategies for Snowmelt-Dependent Irrigated Agriculture

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Multi-Sector Dynamics: Advancing Complex Adaptive Human-Earth Systems Science in a World of Interconnected Risks

Key Points:

- Changes to snow storage and release patterns pose localized and heterogeneous risks to irrigated agriculture, which accelerate in the future
- Potential to manage risk from less snow by augmenting water storage is limited by water supply-demand imbalances in many locations over time
- Conserving water by reducing demand could buffer irrigated agriculture against increased risk even as augmentation potential diminishes

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Essential Role of Local Context in Shaping Risk and Risk Reduction Strategies for Snowmelt-Dependent Irrigated Agriculture

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Abstract Climate change-induced shifts in snow storage and snowmelt patterns pose risks for adverse impacts to people, the environment, and irrigated agriculture. Existing research primarily focuses on evaluating these risks to irrigated agriculture at large scales, overlooking the role of local context in shaping risk dynamics. Consequently, many "at-risk" areas lack insight into how adaptation strategies for managing risk through water supply augmentation or water conservation vary across contexts and over time. To address this gap, we develop a comprehensive index for evaluating irrigated agriculture's risk and adaptation potential to changes in snow at local scales and apply it throughout the western US. Results confirm trends toward escalating risk for changes in snow storage and snowmelt patterns over the century. However, substantial heterogeneity in the extent and drivers of risk exists due to variability in localized interactions between declines in water supply (approximately −9% ± 13% by 2100) and increased agricultural demand (approximately 7% ± 5% by 2100). Despite an existing focus on supply augmentation as a critical adaptation strategy to reduce risk, we show its effectiveness diminishes for many areas over time, declining to an average of −54% of historical augmentation potential by 2100. Conserving water through historical changes in crop acreage and type emerges as a more stable adaptation measure, reducing demand by 7%–8% regardless of time. While particularly relevant for higher elevation, less intensive agricultural settings in snowmelt-dependent regions, findings underscore the need for strategies that support local-scale, context-appropriate adaptation to effectively manage escalating risk as snow changes.

Plain Language Summary Climate change-induced shifts in snow storage and snowmelt patterns threaten water supplies for irrigated agriculture, necessitating adaptation. In agriculture, adaptation requires balancing water supply and demand locally, which is often overlooked in larger-scale analyses. We develop a framework for evaluating risk and adaptation at local scales in the agricultural sector and apply it to the western US, which is broadly at risk for adverse effects (i.e., physical harm, economic losses, and socio-cultural damage) if water demand cannot be met. Changing snow dynamics negatively impact many local areas over time, although impacts can often be reduced through supply augmentation and water conservation. While the degree of risk and the effectiveness of these adaptation strategies vary across regions and time, increasing demand and supply volatility diminishes opportunities for supply augmentation. This trend underscores the importance of supporting context-appropriate adaptations for agricultural communities facing increased risk to their water supplies.

1. Introduction

Water stored in snowpacks and released as snowmelt from high mountain environments is a vital source for ~26% of the global land area, sustaining an estimated ~600 million people, ~50% of the world's biodiversity hotspots, and ~20%–40% of global rye, barley, and cotton production (Immerzeel et al., 2020; Qin et al., 2020). Water management systems in these snowmelt-dependent regions were designed to leverage snowpacks' historical

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ability to store winter precipitation and release it during months with higher water demands (Barnett et al., 2005). However, climate change is rapidly altering snow water storage and release patterns, making it challenging to meet downstream water demands within the constraints of existing infrastructure capacities and policy frameworks (Hale et al., 2023; Harpold & Brooks, 2018; Immerzeel et al., 2020; Qin et al., 2020). As the world's largest consumer of freshwater resources, irrigated agriculture is particularly at risk for adverse effects arising from climate-caused changes in snow, such as physical harm, economic losses, and sociocultural damage (Biemans et al., 2019; Immerzeel et al., 2020; Qin et al., 2020).

Traditionally, risk for changes in snow in irrigated agriculture has largely been managed through the augmentation of reservoirs and groundwater with any water supply available after downstream and local demands have been met (Kellner, 2021; Kellner & Brunner, 2021). There is, for example, longstanding interest in increasing storage capacity to capture increased winter runoff as well as optimizing reservoir operation for multiple purposes through various tools, including forecast-informed reservoir operation (Delaney et al., 2020; Kellner, 2021; Kellner & Brunner, 2021). Transitioning the storage of winter runoff from built reservoirs to groundwater through different types of managed aquifer recharge (MAR), including Flood-MAR and deep reinjection, has also been proposed as a way to circumvent challenges associated with changes in snowmelt timing under climate change. However, the effectiveness of managing risk for changes in snow via supply augmentation ultimately hinges on the timing and amount of available water, which is increasingly threatened by climate change (Li et al., 2017).

In recognition of this growing limitation, water conservation has been proposed as an adaptation strategy for managing risk to irrigated agriculture due to reduced water availability (Udall & Peterson, 2017). Among other things, water conservation can involve reducing cultivated acreage through fallowing of certain crops during periods of low supply (Malek et al., 2020; Richter et al., 2023; Tessema et al., 2019; Udall & Peterson, 2017). In some regions, water conservation can also involve a shift toward altering crop types to increase high-value crops, such as orchards, nuts, and vineyards, which yield more significant income with reduced acreage requirements (Udall & Peterson, 2017).

Prior research has primarily focused on assessing risk for climate-caused changes in snow across large areas (e.g., >10,000 km^2; Immerzeel et al., 2020; Mankin et al., 2015; Qin et al., 2020, 2022). However, there has been a notable lack of emphasis on evaluating adaptation strategies, such as supply augmentation or water conservation, to effectively manage risk (Drenkhan et al., 2023). This gap can be attributed, in part, to the fact that water management adaptations are often implemented and evaluated at much smaller scales. Local agricultural water management organizations play a crucial role in regulating water supply and demand within their jurisdictions, acting as intermediaries between individual producers and larger hydrologic units (York et al., 2019). Consequently, despite state-of-the-art risk assessments of climate change impacts, such as the International Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6; IPCC, 2022), which could be applied in snowmelt-dependent regions, information regarding risk and risk management at local scales where adaptation often occurs remains limited (Drenkhan et al., 2023; Westskog et al., 2017).

In response, we develop a comprehensive risk index for local agricultural water management areas as climate change continues to modify snow storage and snowmelt release patterns, drawing from the guidance provided by the AR6 framework for risk assessment (IPCC, 2022). We then use this index to assess the efficacy of different adaptations in managing risk guided by two research questions:

1. How does the extent of risk for changes in snow storage and snowmelt patterns vary across local agricultural water management areas in the western US?
2. When and where are supply augmentation and water conservation-based adaptations for irrigated agriculture most effective for managing risk as snow changes?

Drawing insights from existing literature, we develop several robust sub-indices to measure components of the AR6 framework (e.g., hazard, vulnerability, and adaptation as described in Section 2) with historical data (covering the period from 1979 to 2005) and future projections (covering the period from 2020 to 2100), spanning variables that include irrigation water supply, snow storage and snowmelt patterns, evaporative losses, and agricultural water demand. We use these sub-indices to construct a comprehensive risk index for adverse impacts on local agricultural water management areas. This allows us to quantify the effectiveness of supply augmentation and water conservation for managing projected risk over time.

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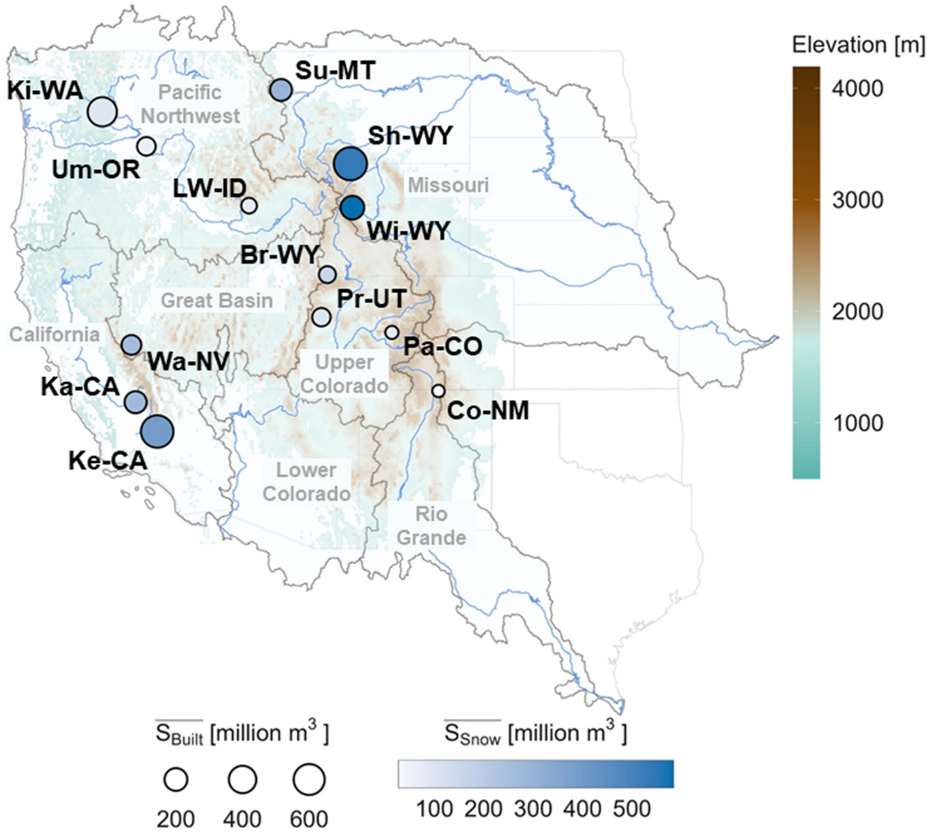

Figure 1. Map of local agricultural water management areas where Ki-WA refers to Kittitas in Washington, Um-OR to Umatilla in Oregon, LW-ID to Little Wood in Idaho, Wa-NV to Walker in Nevada, Ka-CA to Kaweah in California, Ke-CA to Kern in California, Co-NM to Costilla in New Mexico, Pa-CO to Paonia in Colorado, Pr-UT to Price in Utah, Br-WY to Bridger in Wyoming, Wi-WY to Wind in Wyoming, Sh-WY to Shohone in Wyoming, and Su-MT to Sun in Montana. Symbol coloring represents the median historical snow storage and snowmelt release (S_{snow}) as estimated by NCA-LDAS (1979–2005), symbol sizing represents the maximum reservoir storage (S_{Built}) per Table 1. Elevation is represented in the background with green capturing lower elevation areas and brown higher elevation areas.

We test our index in diverse local agricultural water management areas across the western US. Information for each of our local agricultural water management areas is built from communication with water managers and data mining of government reports, websites, and white papers to accurately capture how water is managed to meet agricultural demand at the local scale. In other words, we construct local areas to reflect the spatial boundaries of agricultural demand and how available water supplies service it given infrastructure and institutional constraints. By doing this, we showcase the effectiveness of our index in assessing the risk for changing snow storage and snowmelt patterns in irrigated agricultural settings while remaining grounded in the local context.

2. Materials

2.1. Study Sites

Headwater areas have significant implications for local and downstream water availability and are thus the focus of our evaluation. We identified 13 agricultural water management areas (Table S1 in Supporting Information S1) meeting specific criteria: substantial mountain-sourced surface water stored in unimpaired reservoirs, primary or secondary agricultural use, and a minimum 26-year supply record with <25% missing data. These areas comprised 28 irrigation organizations connected to 23 points (e.g., stream gage or reservoir outflow) of surface water supply. Demand and supply regions were delineated and combined into a single value for each of the 13 areas (Figure 1). We used each point (e.g., stream gage or reservoir outflow) to delineate the contributing source area and water district maps from various sources to delineate demand areas, communicating with local officials to ensure they were accurately joined. These delineations were then used to extract gridded data, as described below.

2.2. Data

The following data were used to evaluate the metrics, sub-indices, and index described below (Table 1):

3. Methods

We used the AR6 risk framework to assess the risk for changes in S_{Snow} in the 13 local agricultural water management areas (Section 2). We evaluated the metrics outlined below with data from Table 1 to construct hazard, vulnerability, adaptation, and risk indices. Additional details can be found in Table S2 in Supporting Information S1. The AR6 framework seeks to comprehensively evaluate climate-related risk, including physical and non-physical ones (e.g., socioeconomic). In this framing, risk arises from interrelated components that include a hazard or a specific climate-related event or phenomena (e.g., reduction in snowmelt); vulnerability, or the susceptibility of an exposure area to the impacts of a climate hazard; and exposure, or the presence people, livelihoods, species, ecosystems, and assets within each area that could be adversely affected by climate change. It also considers response and adaptation in terms of the actions and strategies that can be taken to reduce (i.e., mitigate) or manage (e.g., adapt) risk. Critically, our approach is intended to provide decision-makers with insight into managing risk and enhancing resilience as snow changes (IPCC, 2022).

Below, we outline the individual sub-indices used to evaluate each component except for exposure. Because our areas are, by design, meant to reflect the specific exposure of irrigated agriculture that directly depends upon a combination of snowmelt and reservoirs, our index assumes that exposure is a constant.

3.1. Snowmelt-Dependent Irrigation Water Supply Hazard Sub-Index

Hazard is defined as the potential occurrence of water supply stress due to declines in snow, which can result in losses, harm, and damage to people, places, and infrastructure (Cardona et al., 2012). Based on existing research, changes in two key factors were considered (Gordon et al., 2022; Regonda et al., 2005; Stewart, 2009; Stewart et al., 2004).

1. *Timing of Water Supply Mass (DoQ50)*: This represents the day of the water year when 50% of the total water has already flowed downstream. Changes in this timing can have significant implications for water supply management (Krogh et al., 2022; Stewart et al., 2004).
2. *Magnitude of Annual Water Supply*: This represents the water supply amount over the year. Changes in this volume are critical for water resource management.

To assess the hazard presented by changes to the timing of water supply availability, the following formula (Equation 1) was used:

$$\Delta DoQ_{50} = \left| \overline{DoQ_{50,corrected,future}} - \overline{DoQ_{50,observed,historical}} \right| \tag{1}$$

where $\overline{DoQ_{50,corrected,future}}$ is the median simulated day of water supply center of mass timing for future periods after bias correction (Table 1), and $\overline{DoQ_{50,observed,historical}}$ Is the median observed day of water supply center of mass timing for the historical period (1979–2005).

For the sub-index of hazard presented by changes in the magnitude of water supply (ΔQ), the following formula (Equation 2) was applied:

$$\Delta Q = \frac{\overline{Q_{WY,corrected,future}}}{\overline{Q_{WY,observed,historical}}} \tag{2}$$

Recent work by Gordon et al. (2024) reviewed different methods for standardizing and interpreting metrics, demonstrating that the appropriate use of local thresholds requires both local knowledge of the system and a strong understanding of the system's physical tipping point. Because we lacked local knowledge and a strong

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Table 1
Summary of the Data Used in Our Analysis

Variable	Definition	Temporal resolution	Sources	Description
Water supply (Q)	Includes streamflow and reservoir inflows based on documented sources	Historical (1979–2005)	United States Geological Survey (USGS), the United States Bureau of Reclamation (USBR), and the United States Army Corps of Engineers (USACE)	
		Simulated (1979–2100)	64 GCM-RCP pairs from the localized constructed analog (LOCA) coupled model intercomparison project version 5 (CMIP5) hydrologic projections (32 GCMs under both the RCP 4.5 and RCP 8.5 emission scenarios) (Vano et al., 2020)	Runoff estimates from LOCA CMIP5 downscaled hydrologic projections were routed in MizuRoute using the Kinematic Wave tracking option (Mizukami et al., 2016)
Snow storage and snowmelt release (S_{snow})	Measured as peak snow water equivalent in the snowpack (SWE)	Historical (1979–2005)	National Climate Assessment-Land Data Assimilation Unit (NCA-LDAS) (Kumar et al., 2019)	
		Simulated (1979–2100)	LOCA CMIP5 downscaled hydrologic projections (Vano et al., 2020)	SWE estimates were obtained from 64 GCM-RCP pairs
Agricultural water demand (D)	The sum of net irrigation water requirement (NIWR) for all crops and reservoir evaporation demand over the water year for each area.	Simulated (1950–2100)	USBR (Huntington et al., 2014) and bias-corrected Crop Data Layer (CDL) data from the USDA per the guidance in Lark et al. (2017)	See details in Allen et al. (2020)
			USBR (Huntington et al., 2014) and bias-corrected Crop Data Layer (CDL) data from the USDA per the guidance in Lark et al. (2017)	See details in Allen et al. (2020)
Reservoir storage (S_{Built})	The volume of built storage for each area	1979–2100	(Lehner et al., 2011; Masia et al., 2018)	

Note. Post-processing of data, including bias correction, is outlined in Table S2 in Supporting Information S1.

understanding of the physical tipping point for all areas, we omitted the introduction of local thresholds and allowed readers to interpret values more objectively. We standardized metrics for comparison by rescaling them from 1 to 10 using the following formulation (Gonzales & Ajami, 2017):

$$\textit{Rescaled Metric} = 1 + (10 - 1) \times \frac{(I - A)}{(B - A)} \tag{3}$$

where I represents the original metric and A and B are the lower and upper bounds of the original scale, respectively. This rescaling allows for consistent comparisons between different units and periods without requiring a local threshold.

After standardizing values so that a 10 is high hazard and a 1 is low, rescaled timing and magnitude metrics were then combined into a hazard sub-index for each local agricultural water management area using the geometric mean (Equation 4) to provide a comprehensive measure of the potential hazard as follows:

$$\textit{Hazard Index} = [(\textit{Rescaled } \Delta Q) \times (\textit{Rescaled } \Delta DoQ_{50})]^{1/2} \tag{4}$$

We use the geometric mean rather than arithmetic (consistent with Gonzales & Ajami, 2017) since the geometric mean avoids a high score in one metric leading to a (relatively) high final index even if the other metric is (relatively) low. To allow for comparison, we present all results with arithmetic means in SI.

3.2. Snowmelt-Dependent Vulnerability Sub-Index

In our study, vulnerability is the likelihood of adverse impacts for agricultural water security, defined as having enough water supply to meet agricultural demand. We assess vulnerability by comparing projected changes in agricultural water security to a historical threshold like other relevant work (Mankin et al., 2015). Key components of our vulnerability sub-index include:

1. *Projected agricultural water security (W)*: This metric is the projected Q to D ratio for each future period under the Business-as Usual (BAU) land use scenario, which is based on the crop acreage and type corresponding to the median historical agricultural water demand.
2. *Threshold for adverse impacts (W_o)*: This threshold is based on the historical median ratio of Q to D. It serves as the point below which adverse effects are expected for each area. We set the threshold to the historical value (W_o) to account for variations in water sources (e.g., groundwater extraction or inter-basin water transfers), focusing specifically on changes in headwater supply while keeping other water sources constant.

We calculate the vulnerability sub-index presented in Equation 5 using these components. This sub-index measures the extent to which projected changes in agricultural water security deviate from the threshold for negative impacts, allowing us to assess vulnerability to altered snowmelt-driven water supply patterns:

$$\text{Vulnerability Index} = \frac{(W - W_o)}{W_o} \tag{5}$$

where W is defined as $\frac{\overline{Q_{WY,corrected,future}}}{\overline{D_{WY,BAU,future}}}$, $\overline{D_{WY,BAU,future}}$ is the median agricultural demand from reservoir evaporation and irrigation under the BAU land use scenario over each future period, W_o is $\frac{\overline{Q_{WY,observed,historical}}}{\overline{D_{WY,historical}}}$, and $\overline{D_{WY,historical}}$ is the median historical agricultural demand from reservoir evaporation and irrigation (1950–1999). Raw values were then rescaled to the same 1–10 range as Hazard using Equation 3.

3.3. Snowmelt-Dependent Irrigation Adaptation Sub-Index

Adaptation in our study refers to actions taken to manage the harm caused by changes in S_{Snow}. We focus on two primary adaptation strategies:

1. *Water conservation*: This involves conserving water by reducing and altering crop types and areas. It represents the proportion of water demand that can be saved through historical changes in these measures based on

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the CDL (Table 1). The water conservation (WC) land use scenario is based on the crop acreage and type corresponding to the 25th percentile of historical agricultural demand.

2. *Supply augmentation*: This strategy assesses the potential increase in available water for refilling reservoirs and groundwater storage after accounting for *D*, consistent with previous research (Masia et al., 2018). We evaluate changes in each area's capacity to replenish storage compared to historical values. We assume larger declines impose more significant constraints on constructing new reservoirs or MAR. Additional details can be found in SI.

Water conservation was evaluated using Equation 6 below:

$$\text{Water Conservation} = \frac{\overline{D_{WY,BAU,future}} - \overline{D_{WY,DM,future}}}{\overline{D_{WY,BAU,future}}} \tag{6}$$

where $\overline{D_{WY,WC,future}}$ is the median agricultural demand from reservoir evaporation and irrigation under the WC land use scenario over each future period. This indicator is similar to work in urban water conservation (Gonzales & Ajami, 2017).

Supply augmentation was evaluated using Equation 7 below:

$$\text{Supply Augmentation} = \frac{\left(\overline{Q_{WY,corrected,future}} - \overline{D_{WY,BAU,future}}\right) - \left(\overline{Q_{WY,historical}} - \overline{D_{WY,BAU,historical}}\right)}{S_{Built}} \tag{7}$$

Both water conservation and supply augmentation indicators were rescaled from 1 to 10 using Equation 3, where a score of 1 represents low adaptation and a score of 10 represents high adaptation. We then combined metrics via Equation 8 to provide a comprehensive measure of the potential adaptation in each area:

$$\text{Adaptation Index} = [(\mathit{Rescaled\ Supply\ Augmentation}) \times (\mathit{Rescaled\ Water\ Conservation})]^{1/2} \tag{8}$$

3.4. Snowmelt-Dependent Irrigation Risk Index

Risk is defined as the potential for adverse impacts on human and environmental systems resulting from changes in S_{Snow}. We follow the AR6 framework and calculate risk as a function of three main components: vulnerability, hazard, and exposure (which we treat as constant). Thus, we quantify risk as the sum of our hazard and vulnerability indices.

We also evaluate the potential minimum risk, similar to the approach introduced by Luers et al. (2003), by subtracting the adaptation index (which reflects the potential for adaptation measures) from the calculated risk index. This potential minimum risk provides insight into the residual risk even after accounting for adaptation efforts.

4. Results

4.1. Snowmelt-Dependent Irrigation Water Supply Hazard Sub-Index Results

The hazard posed to water supply by changes in S_{Snow} increases throughout the century (Figure 2, Table 2 and Table S3 in Supporting Information S1). Average hazard sub-index scores, considering changes in annual streamflow volume (ΔQ) and timing (ΔDoQ_{50}), are reported in Table 2. Scores increase from a low of 3.3 ± 1.7 out of 10 from 2020 to 2050 to a high of 4.7 ± 2.2 for 2080–2100, driven by intensification in declines in Q (−9.0% ± 12.6% from 2080 to 2100 vs. −5.6% ± 6.5% from 2020 to 2050) and advances in DoQ_{50} (early by 12.9 ± 9 days from 2080 to 2100 vs. 6.5 ± 7.3 days from 2020 to 2050). Hazard results are not well correlated with S_{Snow} over the near and mid-future ($r^2 = 0.14$ and $p = 0.015$ per value in Table S3 in Supporting Information S1), which could be explained by the potential for localized physiography and climate as well as time to introduce variability and heterogeneity in water supply response to S_{Snow} under climate change (Gordon et al., 2022).

Results (Figure 2, Table 2 and Table S3 in Supporting Information S1) reveal two pathways for Western US agricultural water management areas facing changes in S_{Snow}—sustained moderate to high and initially low but

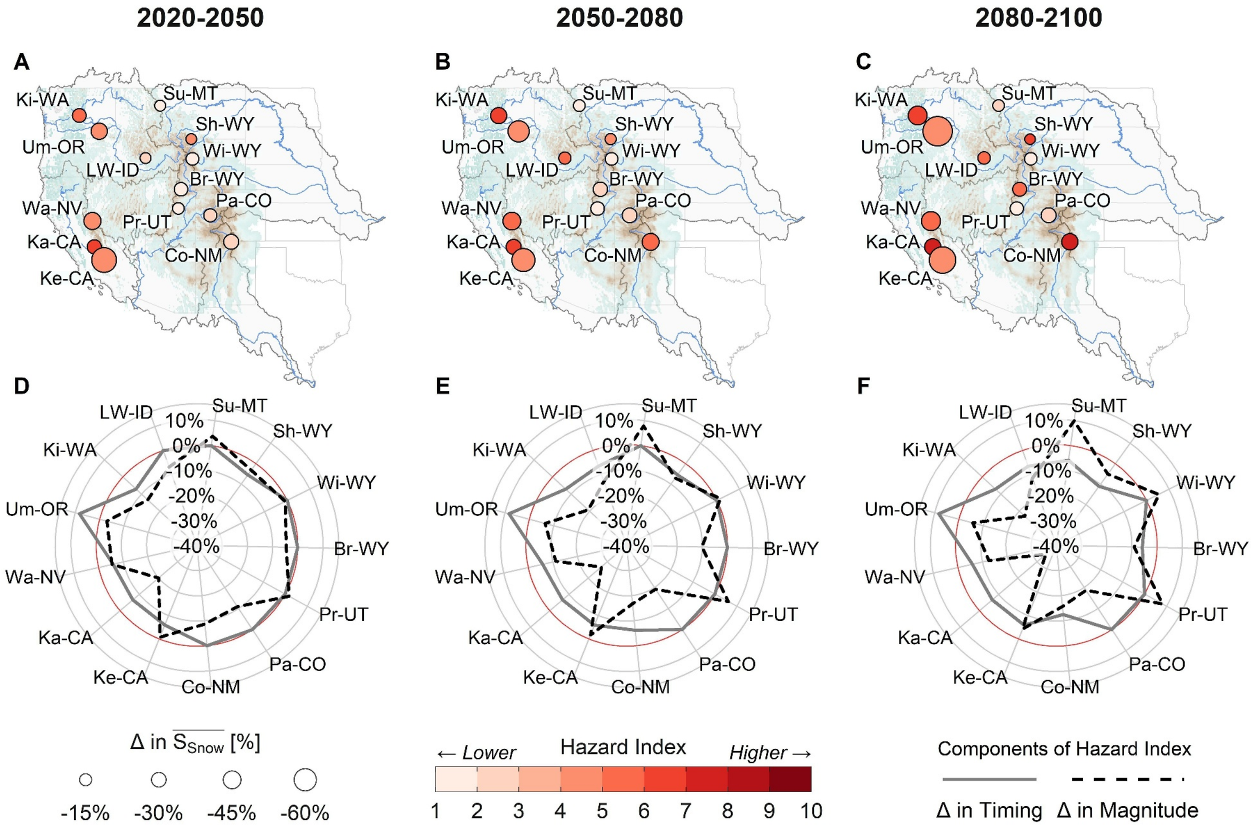

Figure 2. Hazard sub-index results for 13 local agricultural water management areas based on the geometric mean of changes in the annual volume of streamflow and DOQ_{50} timing: (a) the near future (2020–2050); (b) the mid future (2050–2080); (c) the far future (2080–2100). Large symbols indicate more significant declines in snow values and darker symbols indicate greater hazard to water supply. In (a)–(c), lower elevations are shaded in greens, with higher elevations shaded in browns. We present the raw projected changes in historical timing and magnitude components of hazard in (d)–(f). Most of these values are negative, indicating earlier timing or smaller annual flow magnitudes. Neutral or no change is indicated by a red line in (d)–(f).

intensifying hazard (Figure 2). Lower elevation and latitude areas, such as Ke-CA, Ka-CA, Wa-NV, and Um-OR, represent the sustained moderate to high hazard pathway. For instance, Ka-CA scores 6.2 from 2020 to 2050, the highest hazard score with a −20% decline in Q (compared to an average decline of −5.6% for all areas) and a 14-day advance in the timing of DoQ_{50} (compared with an average of 6.5 days for all areas) (Figure 2d). In contrast, higher elevation areas relying on snowpack from interior mountain ranges, such as LW-ID, Sh-WY, Pa-CO, Br-WY, and Co-NM, experience lower initial hazard earlier in the century, which intensifies over time. This trend is most pronounced in Co-NM, where hazard sub-index scores increase from 2.2 in 2020–2050 to 7.9 by 2050–2080 (Figure 2, Table 2 and Table S3 in Supporting Information S1).

4.2. Snowmelt-Dependent Agricultural Water Security Vulnerability Sub-Index

The vulnerability of agricultural water security to changes in S_{Snow} also increases throughout the century (Figure 3, Table 2 and Table S3 in Supporting Information S1). However, there is significant variability in scores between areas, emphasizing the importance of localized conditions and the passage of time in predicting outcomes for irrigated agriculture under climate change. Average vulnerability sub-index scores, considering the change in projected agricultural water security relative to historical values, and their standard deviation are reported in Table 2 and Table S3 in Supporting Information S1. Scores increase from a low of 3.4 ± 1.6 out of 10 from 2020 to 2050 to a high of 5.2 ± 2.9 for 2080–2100 when agricultural water security is on average −14.5% ± 13.3% less than its historical average (Figure 3). Notably, the end-of-century decline in agricultural water security is more than double the projected value from 2020 to 2050 (6.2% ± 7.5%). However, observed declines in agricultural water security are not strongly or significantly correlated with changes in S_{Snow} or hazard, with limited evidence for geographic trends across areas (Table 2 and Table S3 in Supporting Information S1).

Table 2
Summary of Results for Each of the Sub-Indices and Components Described in Section 4

	Risk	Min. Risk	Vul.	Hazard	Adapt.	Δ in S_{snow} (%)	Δ in W (%)	Δ in Q (%)	Δ in D (%)	Water Cons. (%)	Supply Aug. (%)	Δ in DoQ_{50} (days)
2020–2050												
Average	6.1	4.0	3.4	3.3	5.6	−25.6	−6.1	−5.6	0.69	−7.6	−28.1	6.5
St. Dev.	1.1	1.6	1.6	1.7	2.0	16.5	7.5	6.5	2.34	4.3	28.1	7.3
2050–2080												
Average	6.8	4.9	4.7	4.1	5.2	−32.2	−12.2	−8.9	3.93	−7.7	−47.0	8.6
St. Dev.	1.5	2.1	2.5	2.0	2.3	16.2	11.3	10.4	3.68	4.3	45.2	7.1
2080–2100												
Average	7.2	5.4	5.2	4.7	5.0	−34.4	−14.5	−9.0	6.72	−7.9	−54.5	12.9
St. Dev.	1.8	2.4	2.9	2.2	2.5	20.2	13.3	12.6	5.35	4.4	53.4	9.0
Overall (2020–2100)												
Overall Average	6.7	4.8	4.5	4.0	5.3	−30.7	−10.9	−7.8	3.78	−7.8	−43.2	9.3
Overall St. Dev.	1.5	2.0	2.4	2.0	2.2	17.5	11.2	9.9	4.58	4.2	43.3	8.0

Note. *Min. Risk* is Potential Minimum Risk, *Vul.* is vulnerability, *Adapt.* is adaptation, W is agricultural water security, Q is water supply, D is demand including irrigation and evaporation, *Water Cons.* is water conservation, *Supply Aug.* is supply augmentation, and $DoQ50$ is the center of streamflow mass timing. We present the full results by system using both a geometric mean (Table S3 in Supporting Information S1) and an arithmetic mean approach (Table S4 in Supporting Information S1). The results presented here use a geometric mean based on the reasoning in Section 3.

Findings emphasize that spatially and temporally variable interactions between irrigation water supply and agricultural water can result in heterogeneous vulnerability even within the same larger basin. For example, within the Upper Colorado River Basin, two neighboring areas, Br-WY and Pr-UT, experience similar changes in the irrigation water supply of within ±11% of each other at a maximum (Table 2 and Table S3 in Supporting Information S1). However, significant increases in agricultural water demand in Br-WY lead to a substantial divergence in vulnerability from Pr-UT over the mid and far future. The observed variability in vulnerability drivers within the same basin, combined with the potential for a wide range in vulnerability scores over time, highlights the potential for existing approaches focused on larger scales to obscure significant local-scale differences as S_{Snow} changes.

4.3. Snowmelt-Dependent Irrigation Adaptation Sub-Index

The opportunities for adapting to changes in snow through a combination of water conservation and supply augmentation decrease over the century (Figure 4, Table 2 and Table S3 in Supporting Information S1). However, the magnitude of these changes in adaptation scores over time is less pronounced than in hazard or vulnerability scores (Figure 4). Average adaptation scores are reported in Table 2. Values drop from a high of 5.6 ± 2.0 for 2020–2050 to a low of 5.0 ± 2.5 for 2080–2100 (Figure 4), mirroring projected declines in supply augmentation potential of up to −54.5% ± 53.4% by 2080–2100 despite stable and consistent opportunities to reduce BAU demand by −7.9% ± 4.4%. This reduction is the equivalent of recharging 20.5% ± 10.6% of reservoir storage through historical changes in crop type and acreage. Importantly, adaptation is not statistically significantly correlated to S_{Snow} or hazard, although it does appear to diminish as vulnerability increases in the far future ($r^2 = 0.43$).

Results indicate that water conservation could play a significant role in buffering areas against declines in supply augmentation potential. This is particularly true in less agriculturally intensive and higher elevation areas (e.g., LW-ID, Sh-WY, Wi-WY, Br-WY, Pr-UT, Pa-CO, and Co-NM). Changes in crop acreage are a more significant driver of water conservation opportunities than changes in crop type (Figures S2 and S3 in Supporting Information S1). This may be due to higher elevation settings being limited in the crops they can grow, primarily alfalfa and specific hay types, which can be temporarily taken in and out of production (Matt Yost et al., 2020).

4.4. Snowmelt-Dependent Irrigation Risk Index

The risk for adverse outcomes from changes in S_{Snow} for many local agricultural water management areas, as measured by hazard and vulnerability index scores, intensifies over the century (Figures 5 and 6; Table 2 and

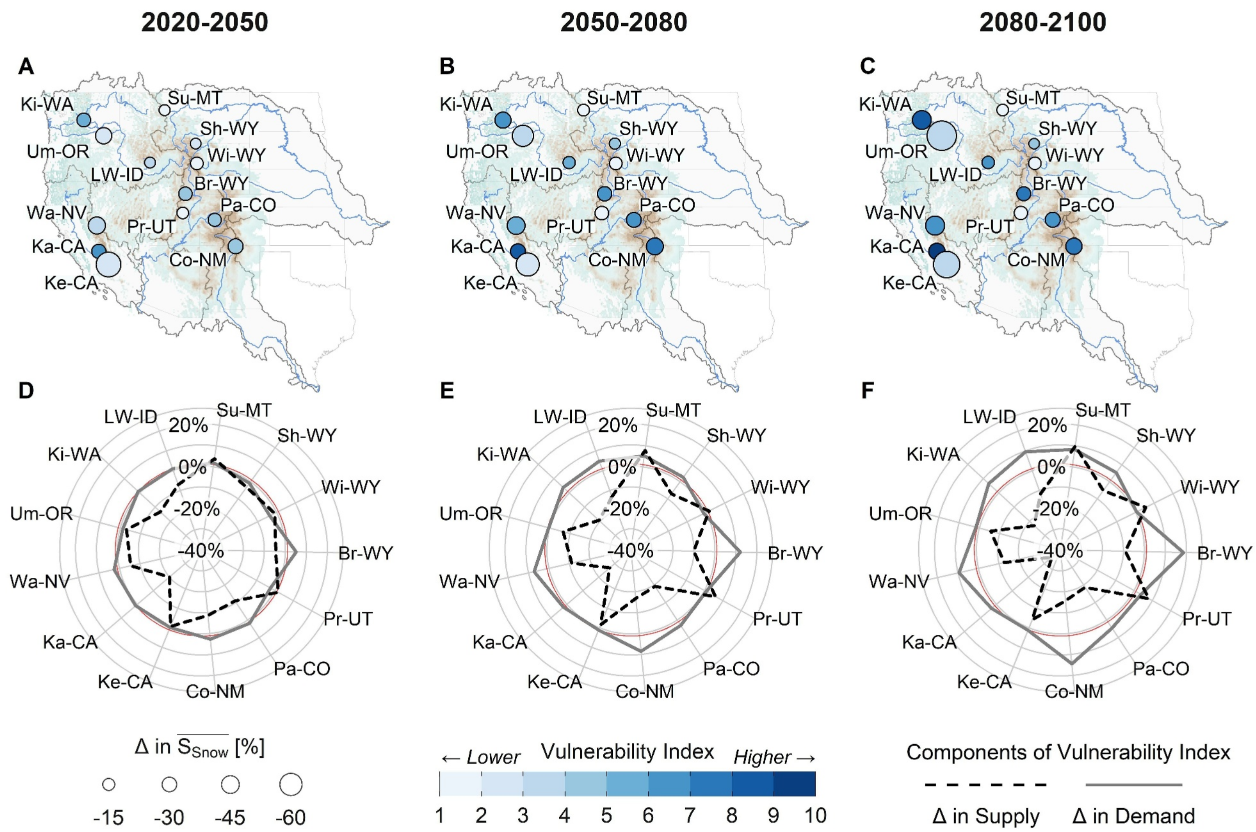

Figure 3. Vulnerability sub-index results for 13 local agricultural water management areas based on changes in agricultural water security relative to historical agricultural water security. Darker circles indicate higher vulnerability and larger circles indicate more significant declines in snow for (a) the near future (2020–2050), (b) the mid-future (2050–2080), and (c) the far future (2080–2100). We present the raw projected changes in the water supply and agricultural demand components of vulnerability in (d–f). As reflected in shading in (a)–(c), lower elevation is depicted in greens, while higher elevation is depicted in browns consistent with Figure 1.

Table S3 in Supporting Information S1). Average risk index scores increase from 6.1 ± 1.1 from 2020 to 2050 to 7.2 ± 1.8 from 2080 to 2100, although the drivers of this increase appear complex and variable across areas. Significant changes in demand drive risk in some areas (e.g., Br-WY and Co-NM), with significant changes in supply driving it in others (Ki-WA, Ka-CA) per Figure 4. Notably, an area risk (as we define it) cannot always be predicted solely from supply and demand changes. Ke-CA has a more significant risk than Um-OR by the late century despite having more minor relative changes in supply and demand. However, results suggest that lower risk is primarily attributable to increased supply/demand (see points to the right of the dashed 1:1 line in Figure 5).

The potential minimum risk in areas, which accounts for adaptation, hazard, and vulnerability scores, is uniformly lower than a "business-as-usual" approach. However, the magnitude of the difference between risk and potential minimum risk varies based on adaptation, as shown by the difference in the larger outside-colored circle (risk) and smaller inside the colored circle (minimum risk) in Figures 5 and 6d–6i, particularly by the end of the century. With that said, higher risk index scores are weakly but significantly correlated to lower adaptation index scores ($r^2 = 0.33$, $p = 0.000$), suggesting that areas with lower initial risk also tend to have more significant adaptation potential in alignment with a "rich-get-richer" dynamic observed in recent analyses (He et al., 2021).

5. Discussion

The evolving dynamics of snow storage and snowmelt patterns pose a significant risk to irrigated agriculture on a global scale, underscoring the importance of comprehensively assessing risk and potential adaptation strategies to effectively manage it. Here, we develop an approach for assessing and quantifying risk and adaptation using the AR6 framework. We collaborated with local water managers to design our study areas, focusing on local scales to better capture the nuanced dynamics between water supply and demand and accurately depict how water is

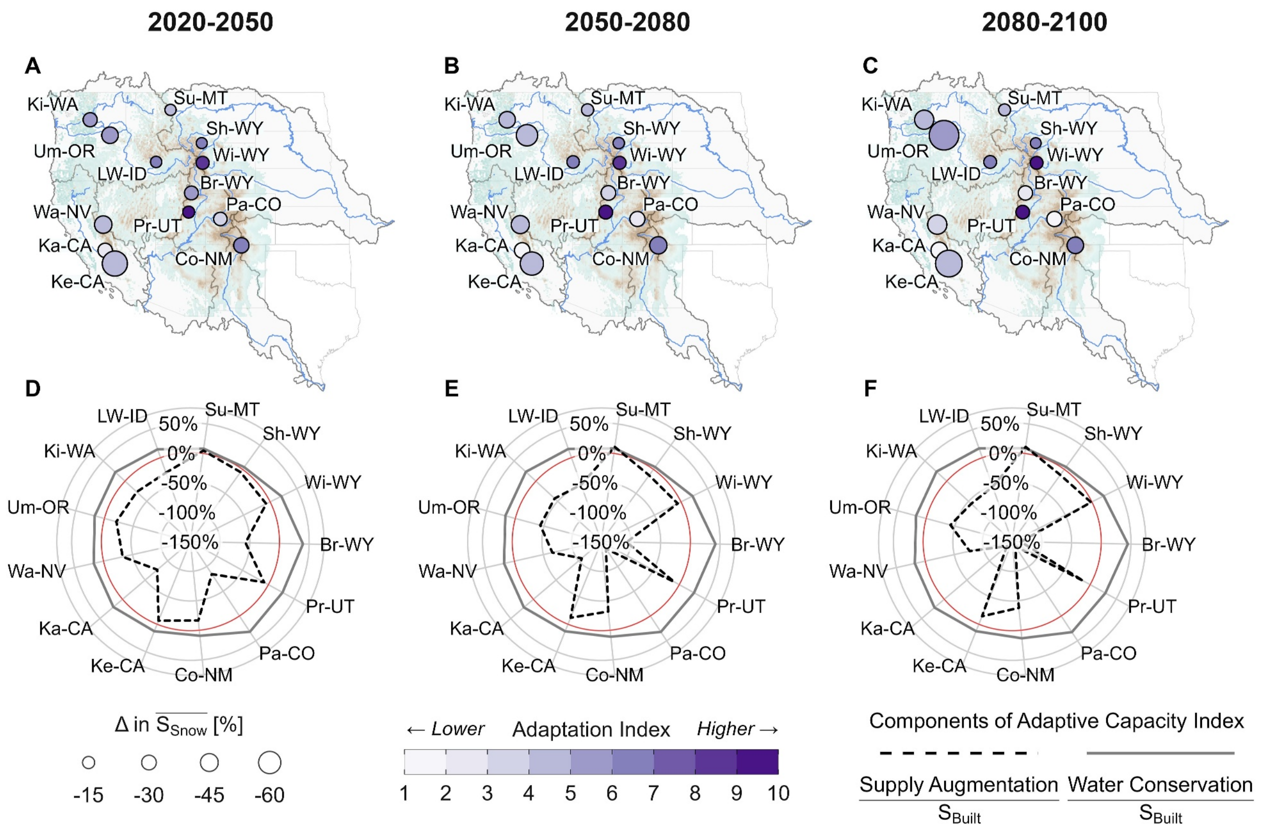

Figure 4. Supply augmentation and water conservation contributions to adaptation under declines in snow. Adaptation results for 13 local agricultural water management areas based on the geometric mean of supply augmentation and water conservation for (a) the near future (2020–2050), (b) the mid future (2050–2080), (c) the far future (2080–2100). Large symbols indicate more extensive ΔS_{Snow} values and darker coloring suggest more significant adaptation potential. Panels (d)–(f) show the individual supply augmentation and water conservation components of our adaptation sub-index relative to built storage capacity for each period. Supply augmentation in (d)–(f) shows the volume of the projected change in the amount of water available to replenish reservoir and groundwater storage relative to built storage, which can be either positive or negative depending on the area. Positive values indicate an increase in supply augmentation and vice versa. Water conservation in (d)–(f) shows that water is saved by enacting the water conservation land use scenario relative to built storage, which is always positive. Smaller numbers are thus associated with smaller volumes of water conserved relative to built storage. Re-scaled values for individual supply augmentation and water conservation indicators are presented in Figure S1 in Supporting Information S1. As reflected in shading in (a)–(c), lower elevation is depicted in greens, while higher elevation is depicted in browns consistent with Figure 1.

actually allocated to meet agricultural needs. Our findings confirm previous research indicating an escalation of risk in snowmelt-dependent agriculture while also emphasizing the necessity of considering local contexts when assessing risk and its drivers across space and time. By concentrating on local scales, where adaptation strategies are frequently implemented, we also gain valuable insights into the effectiveness of two adaptation strategies—supply augmentation and water conservation— in managing risk over the century.

Results show that over the century, risk for adverse impacts accelerates for many local agricultural water management areas in the western US (Figures 5 and 6). Most existing studies examine risk from supply or demand changes in isolation (Immerzeel et al., 2020; Li et al., 2017; Mankin et al., 2015). However, we show that risk can be driven by significant declines in water supply (in the case of Ka-CA and Ki-WA), significant increases in demand (in the case of Br-WY), or localized tradeoffs between the two (in the case of Wa-NV and Co-NM). In other cases (e.g., Ke-CA and Um-OR), the risk may arise more from substantial changes in snow, increasing pressure on built storage. Despite uniform increases in risk over the century, observed heterogeneity in *why* risk increases illuminates the pitfalls associated with focusing exclusively on supply-side changes without an attendant focus on demand dynamics (Qin et al., 2020). Our findings also illustrate the potential for localized differences in drivers of risk within the same large basin, underscoring calls to consider hydroclimatic changes at management-relevant scales (York et al., 2019).

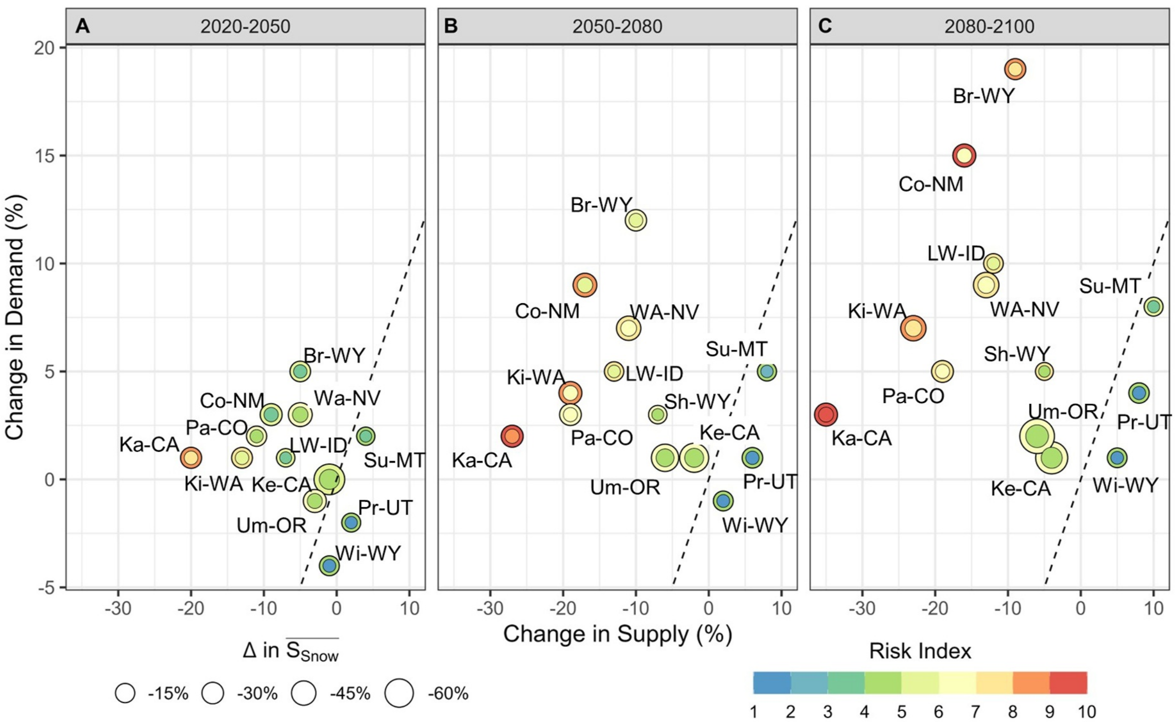

Figure 5. Risk index results for 13 local agricultural water management areas for (a) the near future (2020–2050), (b) the mid future (2050–2080), and (c) the far future (2080–2100). The exterior circle color represents risk index scores. The interior circle color represents the potential minimum risk for declines in snow values accounting for adaptation. Warm colors represent more significant risk, and cool colors represent less risk. The projected size of the decline in ΔS_{Snow} is represented by symbol size, with large symbols indicating more extensive ΔS_{Snow} values. The dashed line represents the 1:1 line between the percent change in supply and demand.

The findings also indicate temporal and spatial shifts in opportunities for irrigated agriculture to manage risk through strategies such as supply augmentation or water conservation across different local contexts. Specifically, our results provide broad evidence for declines in supply augmentation potential (>50%) for many areas in the western US (e.g., LW-ID, Ki-WA, Wa-NV, Br-WY, Pa-CO, Ka-CA, Co-NM, and Um-OR) by the middle to end of this century. Findings about the long-term constraints on supply augmentation are significant for long-term adaptation planning, given the conventional emphasis on western US reservoirs to cope with water supply volatility (Martínez-Valderrama et al., 2023). In this, results could contribute data from diverse geographies to ongoing conversations about the legal and economic dimensions of changing water management. For instance, environmental impacts can make building or expanding reservoirs expensive and contentious (Kellner, 2021). Community concerns and legal policies can further prolong implementation times (Sackett, 2022), potentially reducing the value of approaches that rely on supply augmentation for many places (Figure 4f). MAR-based strategies could offer quicker implementation options, though variability in local infrastructure may constrain this option (He et al., 2021). For example, even if supply augmentation does not decline, local agricultural water management areas with a smaller proportion of land serviced by flood irrigation (e.g., Su-MT) could have more significant limitations on how much water can be delivered to areas for recharge.

Unlike supply augmentation, adaptation to increased risk as snow changes through water conservation appears to be large time-invariant and accessible to many of the areas included in our study. This is particularly true for areas in less agriculturally intensive and higher elevation settings (e.g., Co-NM, LW-ID, Br-WY). While water conservation buffers many areas against declining supply augmentation potential, significant reductions in crop acreage (e.g., fallowing) may have economic and community impacts (Dozier et al., 2017; Howitt et al., 2015; Medellín-Azuara et al., 2022). We observed limited evidence of historical switching from higher to lower water-use crops or lower-value flexible crops to smaller acreages of higher-value crops (Figures S2 and S3 in Supporting Information S1). Although this strategy could also improve adaptation, it may also reduce opportunities for temporary fallowing and require significant investments in agronomic knowledge, livelihoods, and culture, assuming that crops other than alfalfa and hay can be grown at all (Matt Yost et al., 2020; Udall & Peterson, 2017).

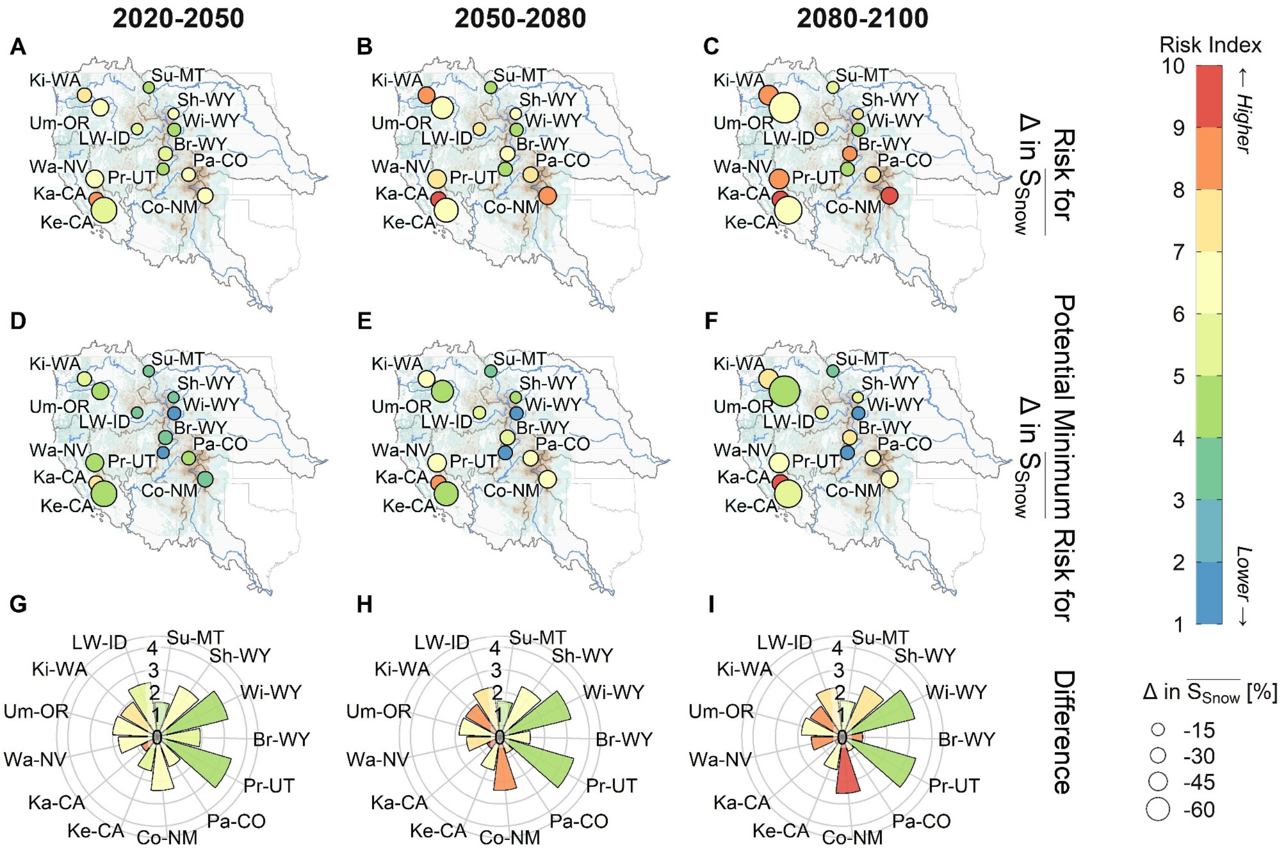

Figure 6. Risk index results for 13 local agricultural water management areas for (a) the near future (2020–2050); (b) the mid future (2050–2080); (c) the far future (2080–2100). Potential minimum risk for declines in snow values accounting for adaptation are shown for the same periods (d)–(f). We then present the difference (adaptation) in (g) through (i) with symbol colors matching those in (a) to (c). Warm colors represent more significant risk, and cool colors have less risk. Adaptation is more beneficial in systems where the difference depicted in (g)–(i) is more significant. As reflected in shading in (a)–(f), lower elevation is depicted in greens, while higher elevation is depicted in browns consistent with Figure 1.

Furthermore, functional agricultural lands provide numerous environmental services, including biodiversity and wildlife habitat (Donnelly et al., 2019; Gigliotti et al., 2022; Gordon et al., 2020; Havstad et al., 2007), which would need to be carefully considered.

Our assessment of adaptation strategies to changes in snow is necessarily broad. We focused on changes in water availability for supply augmentation as a first-order constraint on several conventional (e.g., reservoir expansion or construction) and emerging (e.g., MAR) approaches. However, we did not account for outside water sources like groundwater and transfers, potentially underestimating supply augmentation. We also examined average changes in available water rather than high-flow conditions, as others explicitly focused on MAR have done (He et al., 2021). As data on alternative water sources improve, our estimates of supply augmentation potential could be refined. Likewise, our evaluation of demand-based water conservation is based on historical changes in crop type and acreage, though unprecedented changes may occur going forward. Additionally, we solicited input from water managers when constructing each local water management area; however, there is room to improve upon integrating community perspectives in these types of risk analysis. For example, future work could more rigorously interrogate community perceptions of adaptation actions (e.g., other types of supply augmentation or water conservation not considered here) and incorporate those into this framework. Nonetheless, accounting for how water is allocated in places like the western US through communication with water managers is a step forward for analyses of risk for changes in snowmelt in irrigated agriculture that so often ignore institutional or infrastructure controls over the relationship between supply and demand.

There are several opportunities for future work to build on our efforts. We tested our approach in the western US due to its rich data sets; however, future work could evaluate adaptations in other hotspots such as western Russia, central and high-mountain Asia, and the southern Andes (Qin et al., 2020, 2022). Additionally, there is a substantial opportunity to incorporate more comprehensive measures of adaptation and its unintended consequences for risk, per future directions noted in IPCC (2022), in the context of local agricultural water management. For instance, developing indicators to assess tradeoffs between crop changes and wildlife habitat could enhance planning for multiple benefits under imbalances between snowmelt-driven supply and agricultural demand, as seen in places like California (Donnelly et al., 2019). Our comprehensive risk index for local agricultural areas and a unique data set merging supply and demand in said agricultural areas offers a roadmap for integrating these diverse considerations into future global analyses.

6. Conclusions

Global studies have underscored increasing risk to irrigated agriculture as climate change alters snow storage and release patterns, which includes the potential for physical harm, economic losses, and sociocultural damage. Our analysis confirms substantial declines in snow storage across all study areas, with a projected average decline of −34.4% by the century's end despite regional variability: some areas could experience smaller declines (−5.5% by 2100 for Shoshone in Wyoming) and others larger ones (−67.7% by 2100 for Kern in California). Consistent with existing research, we find that these changes correspond to intensifying risk for adverse outcomes in irrigated agriculture over the century. However, our results also reveal the limitations of the research community's persistent focus on quantifying water supply-side risk at basin scale. For example, we show that some local areas could experience higher risk for changes in snow because of projected increases in demand (18.7% by 2100 for Bridger in Wyoming) despite more modest declines in supply (−9.1% by 2100). By concentrating on the interplay between supply and demand at local scales, we show that risk can stem from variable and localized changes in supply and demand.

While there is consensus that robust and locally appropriate adaptation strategies are necessary to manage risk as climate change alters snow storage and release patterns, few studies have explicitly evaluated adaptation strategies for irrigated agriculture at smaller scales, where changes in water management are often implemented. Our findings help to address this gap by offering insight into the spatial and temporal distribution of potential strategies across the western US over the course of the century. Considerable attention has been devoted to the potential of supply-side adaptations, such as constructing or augmenting reservoirs, which remain a dominant strategy for many basins around the world. However, we uncover widespread potential for significant reductions in the ability to enhance reservoirs and groundwater storage in study areas including Kaweah in California, Paonia in Colorado, and Bridger in Wyoming. Even as some supply-side adaptations diminish, we show that many local areas could manage risk by implementing routine changes in demand. This is particularly true for areas in the intermountain west including Little Wood in Idaho, Shoshone in Wyoming, Wind in Wyoming, Bridger in Wyoming, Price in Utah, Paonia in Colorado, and Costilla in New Mexico. In this, our results underscore the urgent need for a complementary and robust research focus on localized approaches to support water conservation in at-risk agricultural regions, such as the western US. The approach presented here is designed to assist scientists in better tailoring future research to meet the urgent need for information that supports effective adaptation planning at actionable scales.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All code to support the analyses and results presented in this manuscript can be downloaded from https://zenodo.org/doi/10.5281/zenodo.10999388. DOI: 10.5281/zenodo.10999388 (Gordon, 2023).

Except for MizuRoute water supply data per Mizukami et al. (2016), the original data products used in this study are currently available to the public. Historical observed streamflow and reservoir inflows can be retrieved from USGS (2016) and from USBR (2022), which can be accessed at: https://www.usbr.gov/rsvrWater/HistoricalApp.html where users can then select reservoirs listed in Table S1 in Supporting Information S1. Projected hydrologic data can be retrieved according to Vano et al. (2020). Historical and projected agricultural demand data can be retrieved according to Huntington et al. (2014). CropScape data can be accessed from USDA (2023).

All irrigation collective shapefiles were manually georeferenced based on publicly available at https://zenodo.org/doi/10.5281/zenodo.10999388. DOI: 10.5281/zenodo.10999388 (Gordon, 2023).

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