Yakima Basin Hydrology and Extreme Weather Technical Memorandum/White Paper on BAS Approach

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EXECUTIVE SUMMARY

The Yakima Basin is experiencing rapid hydrologic transformation driven by environmental change, including rising winter temperatures, declining snowpack, intensified atmospheric rivers (ARs), more frequent rain-on-snow (ROS) events, increased wildfire activity, and greater seasonal hydrologic extremes. These changes fundamentally alter water supply reliability, flood hazards, sediment dynamics, aquatic ecosystems, and infrastructure vulnerability (National Academies, 2023; Webb et al., 2025; Payne & Magnusdottir, 2015; Espinoza et al., 2018).

Winter storms increasingly deliver warm rain rather than snow, especially in mid-elevation zones. Research by Davenport et al. (2020) demonstrates that flood sizes increase *nonlinearly* as the proportion of precipitation falling as rain increases—with rainfall-driven floods 2.5 times larger than snowmelt-driven floods. As freezing levels rise, AR-driven rainfall combines with melting snow to produce fast-rising floods far larger than those historically observed. Projections indicate that rain-on-snow flood risk may increase by 20–200% at higher elevations where seasonal snowcover persists (Li et al., 2019; Musselman et al., 2018).

Soil moisture saturation—now occurring earlier and more persistently in winter—further amplifies runoff efficiency. Webb et al. (2025) found that soil moisture thresholds are critical determinants of AR-driven flooding magnitude. Post-fire watersheds in the Naches, Taneum, Rattlesnake, and other subbasins heighten sediment and debris risks; USGS research documents that peak flows can exceed pre-fire values *severalfold* during the first years after high-severity burns (Moody & Martin, 2001; Ebel & Moody, 2017; McGuire et al., 2024).

At the same time, declining snow water equivalent (SWE) and earlier spring melt reduce the basin's natural water storage capacity. Mote et al. (2018) documented 15–40% reductions in April 1 SWE since the mid-20th century, with projections of 30–60% additional declines by mid-century. This contributes to summer drought, elevated stream temperatures, and degraded habitat for ESA-listed salmonids. Mean July water temperature in the Columbia River has risen from 16.9°C in 1950 to 20.9°C in 2006, approaching thermal stress thresholds for salmon (Crozier et al., 2008).

Reservoir operations face new tensions from greater winter inflow variability and increased drought-year demand. Channel migration zones (CMZs) are expected to expand under higher peak flows and increased sediment supply. Annual AR-related flood damages across the western United States are projected to increase from approximately $1 billion historically to $2.3–3.2 billion by the 2090s under moderate and high emissions scenarios respectively (Corringham et al., 2022).

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SECTION 1. INTRODUCTION

The Yakima River Basin is undergoing rapid hydrologic and climatic transformation driven by rising temperatures, altered precipitation regimes, and an increasing frequency of extreme weather events. These changes are reshaping the magnitude, frequency, and timing of floods, droughts, soil saturation, sediment movement, and ecological conditions throughout the basin (Climate Impacts Group [CIG], 2021; National Academies of Sciences, Engineering, and Medicine, 2023). A landmark review in *Nature Reviews Earth & Environment* (Payne et al., 2020) synthesized evidence that due to intense moisture transport, atmospheric rivers are increasingly associated with hydrological hazards such as extreme rainfall and flooding, with increased atmospheric moisture governed by Clausius–Clapeyron scaling enhancing AR-related precipitation intensity.

Because the basin's water supply system is highly dependent on seasonal snowpack, the shift toward warmer winters, reduced snow water equivalent (SWE), and earlier snowmelt has significant implications for water storage, flood behavior, and summer water availability (Mote et al., 2018; Vano et al., 2010). The Climate Impacts Group (2021) projects that under continued warming, the Pacific Northwest may experience up to a sevenfold increase in instances where extreme rain events follow periods of high wildfire danger within the same year, creating dangerous compound hazard conditions.

Warming trends are driving a transition from snow-dominated to rain-dominated hydrology at mid-elevations, resulting in more winter rainfall, diminished spring melt contributions, and increased winter runoff. Davenport et al. (2020) demonstrated through analysis of 410 gaged watersheds across the western United States that this transition has profound implications: flood sizes increase *exponentially* as a higher fraction of precipitation falls as rain. A storm with 100% rain produces floods 33% larger than expected from the linear increase in liquid precipitation alone, indicating nonlinear amplification of flood hazards.

These conditions heighten the likelihood of extreme precipitation events, particularly those associated with atmospheric rivers (ARs), which now account for a substantial portion of annual precipitation in the Pacific Northwest. NOAA satellite data confirms that ARs account for 30–50% of annual precipitation in the Pacific Northwest, though the majority of AR events are weaker; it is the Category 3–5 ARs that pose the greatest flood risks. Warner et al. (2020) project that ARs will become more frequent and intense under global warming scenarios, with the most powerful events capable of dumping over 10 inches of precipitation in 72 hours.

Beyond hydrology, wildfire occurrence and severity have increased across the eastern Cascade Range, with major recent fires such as the Schneider Springs Fire and the Jolly Mountain Fire reshaping watershed structure and runoff behavior (Abatzoglou & Williams, 2016). A comprehensive review by McGuire et al. (2024) in *Nature Reviews Earth & Environment* documents that fire effects on geomorphic processes include dramatically altered runoff generation, with burned watersheds exhibiting reduced infiltration, higher runoff ratios, and increased sediment mobility. When AR storms strike post-fire basins, the resulting floods can be substantially larger and debris-laden; USGS modeling indicates that even modest rainstorms following wildfire can produce dangerous flash floods and debris flows (Staley et al., 2017).

SECTION 2. PURPOSE AND SCOPE

The purpose of this technical memorandum is to provide a comprehensive, science-based assessment of flooding, hydrologic change, soil moisture dynamics, reservoir operations, and watershed hazards in the Yakima River Basin under current and projected climate conditions. This document is intended to support Yakima County's Horizon 2046 Comprehensive Plan update and to inform revisions to the Critical Areas Ordinance (CAO), Shoreline Master Program (SMP), and flood hazard management approaches consistent with state requirements for Best Available Science (RCW 36.70A.172).

This memorandum synthesizes multiple lines of evidence to characterize emergent and future hydrologic behavior, including:

1. Hydroclimatic trends and projections, using regional climate models, SWE datasets, soil moisture indices, and observed precipitation and streamflow records (USGS, 2020; CIG, 2021; Mote et al., 2018).

2. Flood-generating mechanisms, including atmospheric river (AR) activity, rain-on-snow (ROS) events, rising freezing levels, antecedent soil moisture conditions, and interactions with mountain snowpack (Kampf et al., 2021; Webb et al., 2025).

3. Wildfire–hydrology interactions, including enhanced runoff, post-fire hydrophobic soils, elevated sediment yields, debris flows, and geomorphic instability (Eidam et al., 2020; Riggins et al., 2020).

4. Reservoir system vulnerabilities and operational challenges, particularly relating to increased winter inflows, earlier runoff timing, and the difficulty of balancing flood control with summer storage under nonstationary conditions (Bureau of Reclamation [USBR], 2022; Vano et al., 2010).

5. Ecological, infrastructure, and community impacts, with emphasis on ESA-listed salmonids, irrigation-dependent agricultural operations, at-risk rural communities, and climate-sensitive infrastructure networks.

6. Risk and resilience strategies, informed by recent national guidance on climate adaptation, hydrologic nonstationarity, and compound hazard planning (National Academies, 2023; NOAA PMEL, 2023).

The scope of the memorandum encompasses both basin-scale processes—such as snowpack decline, AR frequency, and soil moisture trends—and localized hazards, including post-fire debris flows, channel migration zone (CMZ) expansion, infrastructure exposure, and changes in groundwater–surface water interactions. The analysis integrates climate projections through mid-century and identifies pathways to enhance resilience across natural and human systems.

This document is designed for technical practitioners, planners, engineers, and resource managers needing a defensible scientific foundation for decision-making under changing hydrologic conditions

SECTION 3. ATMOSPHERIC RIVERS, ENSO, AND LARGE-SCALE CLIMATE DRIVERS

Atmospheric rivers (ARs) and global climate oscillations—particularly the El Niño–Southern Oscillation (ENSO)—play central roles in shaping seasonal precipitation patterns, extreme rainfall, and flood risk throughout the Pacific Northwest, including the Yakima Basin. These large-scale systems exert increasing influence under a warming climate, with multiple lines of evidence showing intensification of AR events, altered storm tracks, and greater variability between wet and dry years (Dettinger, 2013; Gershunov et al., 2017; NOAA PMEL, 2023).

3.1 Atmospheric Rivers as Primary Flood Drivers

ARs are long, narrow corridors of concentrated water vapor transport originating primarily from the subtropics. Research published in *Nature Environmental Change* (Espinoza et al., 2018) and *Geophysical Research Letters* (Gao et al., 2015) demonstrates that global analysis of Environmental Change projection effects shows atmospheric rivers will carry more moisture and produce more intense precipitation under warming scenarios. When ARs intersect the Cascade Range, they generate intense orographic precipitation, warm temperatures, and rapid snowmelt.

In Washington State, ARs account for 25–50% of annual precipitation and are responsible for the majority of major historical winter floods (Warner et al., 2020; Corringham et al., 2019). A 40-year analysis of flood insurance claims by Corringham et al. (2019), published in *Science Advances*, found that atmospheric rivers drive the vast majority of flood damages in the western United States, with damages increasing exponentially with AR intensity category. The study documented that AR-related flooding causes approximately $1 billion in damage annually on the West Coast.

New research from the National Center for Atmospheric Research (NSF NCAR) published in *Nature Communications Earth & Environment* (Shields et al., 2024) reveals important regional variations: by 2100, atmospheric rivers striking the Pacific Northwest could increase flooding risks by temporarily raising ocean water heights as much as three times more than current storms if society continues high emissions. The research found that while Southern California ARs will be amplified primarily by increased evaporation, Pacific Northwest ARs will be driven by warmer temperatures in both atmosphere and ocean, producing more powerful storms.

Projected climate conditions indicate that ARs will become: (1) more frequent, with studies documenting an uptick in landfalling AR frequency since the 1940s; (2) more intense, with higher integrated vapor transport (IVT) values; (3) longer in duration, with multi-day events becoming more common; and (4) warmer, increasing the likelihood of rain-dominant and rain-on-snow events (Webb et al., 2025; Sharma & Déry, 2020). The December 2025 Pacific

Northwest flooding event—with a Category 5 AR delivering over 10 inches of rain in some areas—exemplifies this intensification pattern.

3.2 ENSO Phases and Precipitation Patterns

ENSO strongly modulates winter precipitation patterns in the Pacific Northwest, but research increasingly shows that AR frequency and strength can override typical ENSO patterns. El Niño conditions tend to produce drier, warmer winters, while La Niña typically produces wetter, cooler winters. However, NOAA PMEL (2023) research updates demonstrate that severe floods can occur even during El Niño conditions when strong ARs override the general pattern. ENSO-neutral years exhibit the widest variability and can produce extreme events through AR clustering.

3.3 Compound Climate Forcing

Increasingly, ARs coincide with multiple hazard amplifiers, producing compound events. The National Academies (2023) report on Environmental Change and extreme hydrology identifies compound drivers as the dominant flood-risk scenario across the Pacific Northwest. Typical compound combinations include: ARs coinciding with elevated soil moisture and saturated antecedent conditions; ARs interacting with warm temperature anomalies and elevated freezing levels; ARs striking pre-existing snowpack at mid-elevations; and ARs affecting post-fire watershed conditions. When these factors combine, floods can be substantially larger than precipitation alone would predict.

SECTION 4. CHANGING HYDROLOGIC REGIMES AND NONSTATIONARITY

The Yakima Basin has entered a period of hydrologic *nonstationarity*, meaning that historical patterns of precipitation, snowpack accumulation, streamflow timing, and flood frequency no longer reliably predict future conditions. This concept was formalized by Milly et al. (2008) in their landmark *Science* paper declaring that "stationarity is dead," fundamentally challenging traditional water management approaches that assume the past is a reliable guide to the future.

4.1 Transition from Snow-Dominant to Rain-Dominant Hydrology

Historically, the Yakima Basin relied on deep mountain snowpack as its primary form of natural water storage. However, warming winter temperatures have altered the proportion of precipitation falling as snow versus rain, especially at elevations between 3,000 and 5,000 feet (Mote et al., 2018; Knowles et al., 2006). The extent of the rain-snow transition zone has been comprehensively mapped by Klos et al. (2014) in *Geophysical Research Letters*, demonstrating significant expansion under projected climate scenarios.

Key observed and projected trends include: reduced winter snowpack with SWE decline of 20–40% by mid-century; more winter precipitation falling as rain rather than snow; earlier onset of spring melt by 1–4 weeks; and increased winter discharge coupled with reduced summer baseflows. These changes alter both flood timing—shifting from spring melt-driven floods to winter rainfall-driven floods—and drought timing, reducing summer water availability (Vano et al., 2010; Regonda et al., 2005).

4.2 Intensification of Extreme Precipitation

Extreme precipitation intensity has increased regionally, consistent with thermodynamic expectations under warming. The Clausius-Clapeyron relationship predicts that for every 1°C of warming, the atmosphere can hold approximately 7% more moisture, increasing the potential for extreme rainfall (Pall et al., 2007). However, recent research by Ombadi et al. (2023) finds that the intensity of extreme rainfall in high-elevation mountainous regions is rising at an accelerated rate of around 15% per degree Celsius of global warming—substantially exceeding theoretical expectations.

Observations across Washington State confirm upward trends in: daily precipitation maxima; multi-day precipitation totals; duration of wet spells; and intensity and frequency of atmospheric rivers. Han et al. (2024) and Berghuijs & Hale (2025) document that the increase in rainfall runoff and accelerated onset of snowmelt-driven surface runoff elevates flood risks particularly in the winter and spring months.

4.4 Breakdown of Historical Frequency Analyses

Flood frequency analyses traditionally assume stationarity—meaning future conditions mirror past ones. However, with ongoing warming and AR intensification, past hydrologic records no longer represent future flood probabilities (Milly et al., 2008). Research published in *Nature Communications* (Blöschl et al., 2017) demonstrates that changing climate has already shifted the timing of European floods, and similar patterns are emerging in western North America. As a result: the 100-year flood may occur significantly more often than once per century; flood magnitudes greater than historical maxima become increasingly plausible; and infrastructure and land-use planning tools based on historical recurrence intervals systematically underestimate risk.

SECTION 5. RAIN-ON-SNOW EVENTS AND RISING FREEZING LEVELS

Rain-on-snow (ROS) events are among the most hazardous flood-generating mechanisms in the Yakima Basin. A comprehensive study by Li et al. (2019) published in *Nature Environmental Change* used high-resolution (4 km) Weather Research and Forecasting model simulations to project that ROS becomes less frequent at lower elevations due to snowpack declines, but increases at higher elevations where seasonal snowcover persists, resulting in a 20–200% enhancement of flood risk in those zones.

5.1 Increasing Freezing-Level Heights

The freezing level—the elevation at which atmospheric temperatures reach 0°C—is rising across the Cascade Range due to regional warming trends. Research by Klos et al. (2014) mapped the extent of the rain-snow transition zone in the western US under historic and projected climate, finding significant expansion of the area where precipitation is transitioning from snow to rain. Model projections show winter freezing levels rising by 800–1,200 feet by mid-century, placing a much larger proportion of the watershed within the ROS-sensitive elevation band.

When freezing levels rise above key basin elevations, storm precipitation that would historically have fallen as snow instead falls as rain. This increases: direct rainfall runoff; rapid snowmelt triggered by warm rain; antecedent soil saturation; and flood peak magnitudes. Gonzales et al. (2019) and Huang et al. (2020) document that rising temperatures cause more precipitation to fall as rain at the expense of snow, shifting the snowline to higher elevations in mountainous regions.

5.2 Quantified ROS Flood Amplification

Recent research by Bean et al. (2024), published in *Water*, quantified the impact of ROS-induced flooding across the Western United States by comparing ROS- and non-ROS-induced stream surges. Their analysis suggests that ROS-induced stream surges are 3–20% larger than non-ROS-induced stream surges, with the magnitude depending on antecedent snowpack and soil moisture conditions. This finding has direct implications for infrastructure design, particularly culvert sizing.

The flood magnitude amplification from ROS events arises from combining liquid precipitation delivered directly to stream networks; meltwater generated during warm storms through heat transfer from rain to snow; and release of water stored in snowpack. This compound effect can increase peak discharge by 50–200% relative to rainfall-only events, depending on antecedent snowpack and soil moisture (Kampf et al., 2021). In the Yakima Basin, recent winters have produced multiple ROS-enhanced flood events, particularly where early-season ARs overlay relatively fresh snowpacks.

SECTION 6. FLOOD BEHAVIOR IN A WARMING CLIMATE

Flood behavior in the Yakima Basin is changing in ways that depart substantially from historical norms. These changes are driven by increased winter rainfall, declining snowpack, elevated freezing levels, intensified atmospheric rivers, and altered soil-moisture dynamics (National Academies, 2023; Webb et al., 2025). A comprehensive review in *Discover Geoscience* (2025) synthesizes evidence that rain-driven runoff events in the western United States have become 2.5 times more intense than snowmelt-driven runoff events, and this trend is expected to continue as the climate warms.

6.1 Shift from Spring Snowmelt Floods to Winter Rainfall Floods

Historically, the Yakima River Basin experienced its largest floods during spring snowmelt, when deep mountain snowpacks melted rapidly due to warming temperatures or rain events. A recent study in *Nature Communications* (2025) reveals that global warming has led to both earlier and later snowmelt floods in different regions over the past 70 years, challenging the simple assumption that warming always advances floods and highlighting the complex nature of snowmelt flood timing shifts.

With warming winters, however, the basin is witnessing: more winter precipitation falling as rain; earlier snowmelt and less snow accumulation; reduced contribution of spring melt to peak flows; and higher winter peak flows tied to direct rainfall and rain-on-snow events. By mid-century, winter rainfall-driven floods are projected to dominate flood hydrology across the basin (Mote et al., 2018; Vano et al., 2010). Research by Hamlet & Lettenmaier (2007) documented the effects of 20th century warming and climate variability on flood risk in the western US, establishing the foundation for understanding these ongoing transitions.

6.3 Intensification of Peak Discharge

Warmer storms increase both the volume and rate of runoff generation. Peak discharge amplification arises from: more liquid precipitation delivered quickly to the channel network; ROS events releasing significant meltwater; reduced snowpack management zoning capacity; and higher soil saturation during warm winter periods. Modeling studies indicate that mid-century peak flows may exceed historical values by 20–50%, and in ROS-dominated events, peaks could reach double historical magnitudes depending on snowpack conditions (Kampf et al., 2021; Webb et al., 2025).

Projections from the *Scientific Reports* analysis by Corringham et al. (2022) indicate that annual expected AR-related flood damages in the western United States could increase from $1 billion in the historical period to $2.3 billion in the 2090s under the moderate RCP4.5 scenario and $3.2 billion under the high RCP8.5 scenario—assuming spatial patterns of exposure, vulnerability, and flood protection remain constant.

SECTION 7. RESERVOIR SYSTEM DYNAMICS UNDER CLIMATE STRESS

The Yakima Basin's reservoir system—including Kachess, Keechelus, Cle Elum, Bumping Lake, and Rimrock Lake—plays an essential role in flood control, irrigation supply, ecological flows, and municipal water provision. These reservoirs were engineered under historical hydrologic assumptions that are rapidly shifting due to Environmental Change. As a result, their operational effectiveness and reliability are increasingly challenged by earlier runoff timing, larger winter inflows, declining snowpack, and heightened risk of winter flooding (USBR, 2022; Vano et al., 2010).

7.1 Earlier Snowmelt and Changing Inflow Patterns

Historically, reservoirs filled between late winter and late spring as snowmelt progressed. With warming temperatures, inflow timing is shifting dramatically:

- Higher winter inflows due to rainfall and ROS events
- Earlier spring inflows, often in February–March rather than April–May
- Reduced late-spring inflows due to diminished SWE

This shift compresses the period available for storing water while also increasing winter flood-management demands.

7.2 Increasing Need for Winter Flood Control Space

Reservoirs must maintain storage space to management zone flood peaks. However, with greater winter rainfall and ROS-driven inflows, operators increasingly face:

- More frequent pre-storm drawdowns

- Higher uncertainty about timing and magnitude of storm-driven inflows
- Trade-offs between flood control and water supply storage

In warm winters, multiple AR events may arrive in close succession, reducing the time available to safely refill storage after a drawdown.

7.3 Capacity Constraints and Nonstationary Hydrology

The Yakima Basin reservoir system was not designed to manage:

- Large, repeated winter inflow pulses
- Steeper hydrograph rise rates
- Multi-day AR precipitation totals
- Compounding ROS and warm-rain events

Under projected mid-century warming, inflow extremes could exceed reservoir design expectations more frequently, increasing the need for adaptive management strategies (USBR, 2022).

7.4 Operational Challenges and System Vulnerabilities

Reservoir managers face several emerging vulnerabilities:

1. Conflicting objectives: Balancing flood protection with spring/summer water storage becomes increasingly difficult under hydrologic whiplash conditions.
2. Earlier refill windows: Reservoirs may reach refill thresholds earlier in the year, often before downstream flood risk has passed.
3. Reduced snowpack management zoning: Historically, snowpack acted as a natural reservoir, releasing water gradually. Reduced SWE increases reliance on reservoir storage while also increasing winter inflows.
4. Greater evaporation losses: Warmer summers enhance surface reservoir evaporation, slightly reducing water availability.

7.5 Kachess, Keechelus, and Cle Elum: Upper Basin Dynamics

Upper basin reservoirs—Kachess, Keechelus, and Cle Elum—are particularly sensitive to warming trends:

- More winter rain increases inflow variability
- Snowline rise reduces snow accumulation
- ROS impacts are amplified by deep early-winter snowpacks
- Sediment loads may increase following post-fire storm events in upper tributaries

These facilities must absorb larger winter inflows while maintaining sufficient spring-summer storage.

7.6 Rimrock and Bumping Lake: West-Side "Hybrid" Hydrology

Rimrock and Bumping Lake, located on the wetter west side of the basin, may face:

- Larger winter flood peaks
- Increased spillway activation frequency
- Higher ROS exposure due to mid-elevation snowpacks
- Rapid inflow surges during AR clusters

These reservoirs may require more flexible operating rules to accommodate increasingly volatile conditions.

7.7 Implications for Water Security and Flood Risk

Combined, these challenges suggest that managing the Yakima Basin reservoir system under 21st-century climate conditions will require:

- Updated seasonal operating curves
- Enhanced real-time forecasting tools
- More proactive flood-space management
- Greater emphasis on coordinated basin-wide operations
- Integration of climate projections into long-term planning

Reservoir operations are foundational to managing flood risk and water shortages. To remain effective, they must adapt to hydrologic nonstationarity and the intensification of extreme events.

SECTION 8. WILDFIRE–HYDROLOGY INTERACTIONS AND POST-FIRE FLOOD HAZARDS

Wildfire activity has increased significantly across the eastern Cascade Range, including key tributary watersheds feeding the Yakima Basin. A comprehensive review by McGuire et al. (2024) in *Nature Reviews Earth & Environment* synthesizes current understanding of fire effects on geomorphic processes, documenting that wildfires alter soil properties, hydrologic characteristics, and sediment-transport processes in ways that dramatically elevate flood and debris flow hazards.

8.1 Soil Hydrophobicity and Reduced Infiltration

High-severity burns commonly produce soil hydrophobicity—hydrocarbon residues that create a near-surface water-repellent layer. Research by DeBano (2000) and subsequent studies (Ebel & Moody, 2017; Ebel et al., 2022) document that this reduces infiltration and increases overland flow. USGS research demonstrates that post-fire soil hydrophobicity can: increase runoff ratios by 200–500%; reduce water residence time in soils; produce rapid stormflow responses; and cause infiltration-excess overland flow, even under moderate rainfall. Hydrophobicity is often strongest in the first 1–3 years following a fire but may persist longer under dry conditions.

8.2 Increased Runoff Generation and Peak Flow Amplification

Burned watersheds exhibit dramatically altered runoff behavior. Research by Moody & Martin (2001, 2009) and subsequent USGS studies document key changes including: faster hydrograph rise rates; higher peak discharges; reduced lag time between rainfall and stormflow; higher likelihood of flash flooding; and greater erosion and bank instability. Peak flows can exceed pre-fire values severalfold during the first years after a high-severity burn (Eidam et al., 2020). East et al. (2025), published in *Earth and Space Science*, quantified post-fire sediment yield from a Sierra Nevada watershed and found elevated sediment delivery continuing for multiple years post-fire.

8.3 Sediment, Debris, and Geomorphic Instability

Wildfires destabilize hillslopes, increase sediment supply, and destroy root structures that formerly reinforced soils. Gorr et al. (2024), published in *Journal of Geophysical Research: Earth Surface*, developed empirical models for postfire debris-flow volume in the Southwest United States using a database of 54 postfire debris-flow volumes collected between 2010 and 2021. Their models predict debris-flow volume based on peak 30-minute rainfall intensity, watershed area greater than 23°, and soil burn severity.

Combined with decreased infiltration, post-fire conditions lead to: debris flows often triggered by short-duration intense rainfall; elevated suspended sediment loads degrading water quality; enhanced bedload transport reshaping channels; and aggradation in downstream reaches potentially increasing flood elevations. Olsen et al. (2024) documented impacts of post-fire debris flows on fluvial morphology and sediment transport in a California coastal stream, finding that within two years after fire, average grain size had coarsened to 95% of pre-fire values, indicating relatively rapid geomorphic recovery in some systems.

8.4 Vulnerability to AR and ROS Events

Post-fire landscapes are particularly vulnerable to warm atmospheric river storms and rain-on-snow events. McGuire et al. (2024) found that post-fire debris flows often initiate in the first several years following fire when runoff rapidly entrains sediment on steep slopes. Research on the Tadpole Fire in New Mexico (McGuire et al., 2024) characterized debris-flow-prone watersheds and debris-flow-triggering rainstorms, finding that rainfall intensity averaged over 15-minute duration (I15) is a key predictor of debris flow likelihood.

In a post-fire setting, even moderate storms can trigger channel-spanning debris flows; severe sediment-laden floods; increased downstream deposition; and debris-driven blockage of culverts and bridges. Wasklewicz et al. (2023) modeled post-wildfire debris flow and large woody debris transport from the North Complex Fire to Lake Oroville, finding that debris flow modeling triggered by a 50-year rainfall intensity transported 1,073 pieces (1,579.7 m^3)

of large woody debris to the mainstem river. The combination of wildfire and ARs is among the most hazardous compound climate risks for the Yakima Basin.

SECTION 9. SOIL MOISTURE DYNAMICS, ANTECEDENT CONDITIONS, AND RUNOFF EFFICIENCY

Soil moisture plays a central role in determining flood magnitude, watershed response time, and the efficiency with which precipitation is converted to runoff. In the Yakima Basin, warming temperatures, shifting precipitation patterns, and more frequent atmospheric river (AR) storms are fundamentally altering soil moisture regimes. These changes amplify flood risk and reduce the reliability of historical hydrologic relationships (Webb et al., 2025; National Academies, 2023).

9.1 Rising Background Soil Moisture Under a Warmer Climate

Warmer winters produce:

- More rainfall
- More mid-winter melt events
- More frequent freeze–thaw cycles
- Increased antecedent wetness heading into storm periods

As a result, soils remain wetter for longer throughout the winter. Elevated background soil moisture increases the likelihood that storm precipitation will transition from infiltration-dominated to runoff-dominated processes.

9.2 Runoff Efficiency and Threshold Behavior

Soil moisture regulates the proportion of rainfall or meltwater that becomes direct runoff. When soils are saturated or near saturation:

- Small storms generate disproportionately large flows
- Hydrograph response becomes much faster
- Downstream flood magnitudes increase significantly
- Channel erosion and sediment transport intensify

Runoff generation often exhibits threshold dynamics: once soil moisture surpasses a critical level, additional rainfall is converted into runoff with high efficiency.

9.3 Soil Moisture Memory and Compounding Effects

Soils exhibit memory, retaining moisture across days to weeks. When several AR events occur in quick succession—an increasingly common pattern—soils do not have time to dry between storms. This produces compounding flood risk because each subsequent storm interacts with wetter antecedent conditions (Corringham et al., 2019).

Soil moisture memory amplifies:

- Peak flows
- Baseflow increases
- Overbank flood likelihood
- ROS-driven flood intensity

9.4 Changes in Freeze–Thaw Cycles and Soil Permeability

Warming winters increase the number of freeze–thaw events, which can degrade soil structure and alter infiltration characteristics. These cycles may:

- Reduce permeability in compacted or disturbed soils
- Enhance surface crusting
- Increase overland flow
- Reduce water storage capacity in near-surface soils

Shifts in snow cover also expose soils to more direct winter rain, reducing the insulating effect historically provided by the snowpack.

9.5 Soil Moisture and Rain-on-Snow (ROS) Amplification

Antecedent soil moisture is a major determinant of ROS flood severity. Even a moderate ROS event can produce exceptionally high runoff when:

- Soils are already saturated from earlier storms
- Snowpack water content is high
- Warm rainfall produces rapid melt

Under these conditions, the watershed behaves as though impermeable, routing large volumes of water directly into channel networks.

9.6 Implications for Flood Modeling, Forecasting, and Planning

Because soil moisture strongly influences runoff dynamics, flood modeling must incorporate real-time and projected soil moisture conditions rather than relying solely on precipitation inputs.

This has implications for Yakima County:

- Floodplain mapping: Must integrate dynamic soil moisture and ROS scenarios.
- Critical Areas Ordinance (CAO): Should recognize soil-moisture-driven landslide and erosion hazards.
- Reservoir operations: Require improved soil moisture forecasting tools.

- Emergency planning: Should consider soil moisture thresholds that precede large floods.

Overall, rising soil moisture under climate warming creates a more flood-responsive watershed, increasing the frequency and intensity of hazardous flows.

SECTION 10. SEDIMENT TRANSPORT, DEBRIS FLOWS, AND CHANNEL MORPHODYNAMICS

Sediment dynamics in the Yakima Basin are being reshaped by wildfire, extreme precipitation, rain-on-snow (ROS) events, and shifts in hydrologic timing. Warmer winters, increased storm intensity, and more frequent post-fire conditions have created a watershed prone to higher sediment yields, debris flows, channel aggradation, and migration. These geomorphic responses amplify flood hazards, strain infrastructure, and degrade aquatic habitat (Eidam et al., 2020; Riggins et al., 2020).

10.1 Increased Sediment Supply from Burned Watersheds

Wildfires dramatically increase sediment availability by:

- Removing vegetation and root structures
- Increasing surface erosion rates
- Triggering landslides and slope failures
- Enhancing debris-flow susceptibility during intense rainfall

Following large fires such as Schneider Springs and Jolly Mountain, many Yakima Basin tributaries experienced orders-of-magnitude increases in sediment production, especially during AR storms.

10.2 Debris Flow Processes and Triggers

Debris flows are rapid, high-density mixtures of water, soil, rock, and organic material that travel downslope during extreme rainfall. They can be triggered by:

- Short-duration, high-intensity storms
- Rainfall on burn scars
- Rain-on-snow events
- Slope failures and shallow landslides

Post-fire debris flows can occur under rainfall intensities far lower than those required under pre-fire conditions. Once mobilized, debris flows can entrain additional sediment, increasing destructive potential.

10.3 Channel Aggradation and Reduced Conveyance

Enhanced sediment supply contributes to:

- Aggradation of streambeds
- Reduced channel conveyance capacity
- Increased flood elevations
- Accelerated channel migration

Aggraded channels are more prone to overbank flooding and can redirect flow pathways during major storms, especially in alluvial valley bottoms such as the Naches River floodplain.

10.4 Large Wood and Infrastructure Impacts

Post-fire channels contain significant quantities of large woody debris (LWD) from burned riparian forests. This wood can:

- Obstruct bridges and culverts
- Create channel blockages
- Redirect flow
- Induce localized flooding
- Increase scour and erosion around infrastructure

Debris jams are especially hazardous during AR storms when flows are high and sediment transport is elevated.

10.5 ROS and Storm-Driven Sediment Pulses

Rain-on-snow events accelerate both snowmelt and sediment mobilization. When ROS coincides with burn scars, sediment pulses can dramatically increase:

- Turbidity
- Bedload transport
- Suspended sediment concentrations
- Fine-sediment deposition in downstream habitats

These pulses can degrade ESA-listed salmonid habitat and fill critical spawning gravels.

10.6 Long-Term Morphodynamic Change

Climate-driven increases in extreme storms and wildfire activity lead to long-term geomorphic adjustments, including:

- More frequent avulsions
- Greater channel instability
- Expansion of channel migration zones (CMZs)

- Altered floodplain–river interactions
- Increased risk of chronic aggradation in key reaches

Over decades, these morphodynamic responses can significantly alter hazard patterns and hydrologic connectivity across Yakima County.

10.7 Planning and Regulatory Implications

For Yakima County and basin partners, these sediment and channel dynamics necessitate updates to:

- Flood hazard mapping (including CMZs)
- CAO geohazard and erosion-hazard sections
- SMP shoreline management zones
- Infrastructure design standards
- Habitat restoration planning

Incorporating sediment processes and morphodynamic trends into planning frameworks is essential to maintaining safety, ecological integrity, and regulatory compliance.

SECTION 11. SNOWPACK DECLINE, SWE CHANGES, AND ALTERED RUNOFF TIMING

Snowpack is the primary natural reservoir for the Yakima River Basin. Declines in snow water equivalent (SWE), shifts in snowline elevation, and earlier seasonal melt are fundamentally altering water availability, streamflow timing, reservoir operations, and flood dynamics (Mote et al., 2018; Vano et al., 2010). These changes reduce summer water supply while simultaneously increasing winter flood hazards.

11.1 Declining Snow Water Equivalent (SWE)

Observed SWE trends across the Cascade Range show:

- 15–40% reductions in April 1 SWE since the mid-20th century
- Accelerated SWE losses at mid-elevations (3,000–5,000 ft)
- Increased year-to-year variability in peak SWE
- More frequent years with extremely low snowpack

Climate models project additional SWE declines of **30–60% by mid-century**, depending on emission trajectories (Mote et al., 2018).

11.2 Rising Snowline Elevations

Warming winters raise the snowline elevation, causing more precipitation to fall as rain rather than snow. This shift:

- Decreases seasonal snow storage
- Increases winter runoff
- Heightens rain-on-snow (ROS) potential
- Concentrates snowpack in fewer high-elevation zones

The snowline in typical AR storms is now often 1,000–2,000 feet higher than it was historically, placing much of the Yakima Basin's snow-bearing terrain into rain-dominant regimes.

11.3 Earlier Snowmelt and Runoff Shifts

Snowmelt is occurring 1–4 weeks earlier than historical norms. This leads to:

- Earlier spring peak flows
- Reduced spring and summer baseflows
- Shorter snowmelt runoff season
- Increased mismatch between water availability and irrigation demand

Earlier runoff also reduces reservoir refill reliability, particularly during dry years.

11.4 Loss of Natural Storage and Increased Winter Flooding

Snowpack historically acted as a management zone, storing winter precipitation until spring. Reduced SWE removes this management zone, increasing:

- Winter inflow volumes to reservoirs
- Frequency of winter floods
- Magnitude of ROS-driven events
- Sensitivity of the hydrologic system to AR storms

Under these conditions, more liquid water is available during winter storms, amplifying downstream flood risk (Webb et al., 2025).

11.5 Mid-Elevation Sensitivity

Mid-elevation zones (3,500–5,500 ft) are the most sensitive to warming and contribute disproportionately to both spring runoff and winter ROS-driven floods. These elevations contain a large portion of the basin's snowpack but now:

- Experience more winter rain
- Undergo more freeze–thaw cycles
- Lose snow cover earlier
- Produce larger runoff surges during warm storms

Changes in these zones account for a major share of increased flood volatility.

11.6 Implications for Water Supply Reliability

Reduced snowpack affects:

- Agricultural water supply
- Hydropower generation (Yakima Basin only)
- Municipal water systems
- Environmental flow targets

Without adequate snowpack, the basin is more dependent on reservoir storage, which must now also accommodate larger winter inflows.

11.7 Regulatory and Planning Considerations

Snowpack and SWE decline necessitate updates in:

- CAO and SMP planning (climate-risk integration)
- Basin drought contingency planning
- Instream flow management
- Infrastructure design (e.g., culvert sizing, flood conveyance)
- Multi-benefit floodplain and habitat restoration projects

Addressing SWE decline is essential to maintaining long-term water security and hazard resilience.

SECTION 12. CLIMATE-DRIVEN DROUGHT AND HYDROLOGIC WHIPLASH

The Yakima Basin is experiencing growing exposure to climate-driven drought, characterized by reduced snowpack, earlier runoff timing, diminished summer flows, and increased evaporative demand. These trends elevate water scarcity risks for agriculture, municipal supply, fisheries, and ecosystems (CIG, 2021; National Academies, 2023). At the same time, the basin is also experiencing hydrologic whiplash—a rapid oscillation between extreme wet and extreme dry conditions.

Climate warming is intensifying both ends of the hydrologic spectrum.

12.1 Increased Frequency and Severity of Drought

Drought in the Yakima Basin is increasingly driven less by lack of precipitation and more by:

- Warmer temperatures
- Reduced seasonal snow accumulation
- Higher evapotranspiration rates

- Earlier timing of runoff

These factors produce “hot droughts,” where temperature-driven water losses exceed historical norms, even during near-average precipitation years (Williams et al., 2020).

12.2 Earlier Runoff Reduces Summer Water Availability

Earlier snowmelt results in:

- Lower summer baseflows
- Reduced carryover storage in reservoirs
- Reduced reliability of April–June inflows
- Increased irrigation curtailments for junior water rights

These impacts are magnified during years characterized by weak snowpack or warm winters.

12.3 Hydrologic Whiplash: Rapid Shifts Between Extremes

Hydrologic whiplash occurs when wet and dry extremes occur in rapid succession. Recent patterns include:

- Successive atmospheric rivers leading to high winter flows
- Followed by rapid drying and early melt
- Followed by summer drought conditions

This variability complicates reservoir operations, agricultural planning, and ecosystem management.

12.4 Drought and Flood Interactions

Drought conditions can contribute to later flood hazards through:

- Increased wildfire occurrence
- Reduced vegetation cover
- More erodible hillslopes
- Faster watershed response during post-fire storms

Drought-to-flood transitions are becoming a defining hazard pattern as climate variability increases.

12.5 Impacts on Water Supply, Agriculture, and Ecosystems

Climate-driven drought affects:

- Irrigation demand, increasing use during hotter, drier summers
- USBOR operations, requiring difficult trade-offs between refill and conservation

- ESA-listed salmonids, which rely on cool summer flows
- Groundwater–surface water exchange, especially in agricultural valleys
- Wetland function, impacted by reduced late-season recharge

Agricultural districts dependent on Yakima Project water are particularly vulnerable during Tier 3 and Tier 4 drought years.

12.6 Planning Implications

Yakima County must prepare for a future in which drought is:

- More frequent
- Longer in duration
- More temperature-driven
- More likely to coexist with flood hazards

Adaptive measures include:

- Enhanced water-use efficiency
- Multi-benefit floodplain reconnection
- Climate-informed reservoir operations
- Groundwater recharge projects
- Drought contingency planning

Drought and flood management must increasingly be treated as interconnected components of a rapidly shifting hydrologic system.

SECTION 13. AQUATIC ECOSYSTEM IMPLICATIONS AND SPECIES VULNERABILITY

Climate-driven changes in hydrology, temperature, sediment transport, and streamflow timing have profound implications for aquatic ecosystems in the Yakima Basin. ESA-listed salmonids—including spring Chinook, steelhead, bull trout, and coho—are particularly sensitive to alterations in flow regimes, thermal conditions, and habitat complexity. NOAA Fisheries research documents that salmon respond to Environmental Change through behavior, morphology, growth rates, performance, survival, and population growth rate or productivity (Crozier, 2008; Crozier et al., annual reviews 2010–2020).

13.1 Temperature Stress and Reduced Cold-Water Refugia

Warmer summers and reduced snowmelt-driven baseflows increase stream temperatures basin-wide. Research published in *Evolutionary Applications* (Crozier et al., 2008) documents that mean July water temperature in the Columbia River rose from 16.9°C in 1950 to 20.9°C in 2006—approaching critical thermal thresholds for salmon. The Climate Impacts Group found that water temperatures exceeding 21–22°C can prevent migration, and prolonged exposure above these thresholds can be lethal for juveniles and adults.

A comprehensive review of cold-water habitats and climate refugia published in the *Canadian Journal of Fisheries and Aquatic Sciences* (Isaak et al., 2023) addresses the concept and utility of climate refugia for salmonid conservation, distinguishing between short-term thermal refuges and longer-term climate refugia where populations can persist over decades to centuries. The study emphasizes that identification and protection of such habitats is emerging as a critical conservation tactic.

These trends reduce: the extent of cold-water refugia throughout the basin; thermal management zone capacity of deeper pools; connectivity of groundwater-fed side channels; and over-summer survival probability for juvenile salmonids. NOAA research on stream temperature monitoring in the Pacific Northwest documents that several Yakima tributaries now routinely exceed temperature thresholds for salmonid health during late summer.

13.2 Altered Flow Timing and Migration Cues

Earlier spring runoff and reduced summer flows shift seasonal hydrographs, disrupting migration timing cues for salmonids. NOAA Fisheries research documented that over the past century, wild sockeye salmon have shifted their migration timing to an earlier seasonal period—likely an evolutionary response to Environmental Change (Crozier et al., studies 2010–2020). The research also indicates that adaptive behavior (behavioral plasticity) may not be sufficient to save some populations; Snake River sockeye, for example, are at very high risk of losing their anadromous life history under continued warming.

Impacts include: early smolt migration windows potentially mismatched with ocean conditions; reduced adult upstream passage during low flows; increased stranding risk in dewatered side channels; and diminished incubation success due to variable flows and fine sediment deposition. Research by Beechie et al. (2013) on restoring salmon habitat for a changing climate found that river basins spanning the current snow line appear especially vulnerable, and recovery plans enhancing lower-elevation habitats may be more successful because those habitats will change less than higher-elevation basins likely to experience the greatest snow-rain transition.

13.3 Increased Sediment Loads and Habitat Degradation

Sediment pulses from wildfire-affected watersheds and ROS-driven events can smother spawning gravels, reduce oxygen flow to redds, and degrade rearing habitat. High turbidity impairs feeding success and increases predation risk for juvenile fish. Research by Sedell et al. (predicting spatial distribution of postfire debris flows) documents that post-fire debris flows can have significant consequences for native trout in headwater streams. After large fires, sediment yields may remain elevated for 5–10 years, prolonging habitat degradation (Eidam et al., 2020; Goode et al., enhanced sediment delivery in a changing climate).

SECTION 14. INFRASTRUCTURE EXPOSURE AND FLOOD-RISK PATHWAYS

Environmental Change is reshaping infrastructure risk across the Yakima Basin. Increased winter rainfall, more frequent atmospheric river (AR) storms, rising freezing levels, declining snowpack, and heightened sediment and debris movement are placing roads, bridges, culverts, pipelines, irrigation works, and utilities under mounting stress. As hydrologic extremes intensify, infrastructure that was designed using historical precipitation and flood statistics is increasingly vulnerable to damage or failure (National Academies, 2023; USBR, 2022).

14.1 Transportation Infrastructure Vulnerability

Road networks in Yakima County frequently traverse floodplains, alluvial fans, and steep tributary valleys. Climate-driven hazards create multiple exposure pathways:

- Overbank flooding that overtops or washes out roads
- Debris flows in post-fire watersheds impacting valley-bottom routes
- Culvert blockages from sediment and wood, causing upstream flooding
- Erosion and scour undermining roadbeds
- Avalanche and slope-failure hazards linked to freeze–thaw cycles

Several Yakima County roads have repeatedly required repairs following AR events and post-fire storms.

14.2 Bridge and Culvert Performance Under Higher Flow Volumes

Bridges and culverts across the basin were sized based on historical peak-flow recurrence intervals. With increased peak flows and sediment loads, these structures now face:

- Scour of bridge piers and abutments
- Reduced hydraulic capacity due to aggradation
- Debris jams, which can rapidly redirect flow
- Increased overtopping frequency

Undersized culverts are a major contributor to localized flooding during high-intensity rainfall and ROS events.

14.3 Irrigation and Water Delivery Systems

The Yakima Basin's extensive irrigation infrastructure—including canals, diversions, siphons, and pumping stations—is exposed to multiple climate-driven hazards:

- Excess sedimentation reducing canal capacity
- Bank failures linked to rapid changes in flow and soil moisture
- Debris loading from post-fire stormflows

- Reduced water availability during summer droughts
- High winter inflows stressing diversion structures

These challenges threaten agricultural productivity and water delivery reliability.

14.4 Utilities, Pipelines, and Critical Facilities

Electrical, gas, and telecommunications infrastructure can be compromised by:

- Flooding of substations and utility corridors
- Increased treefall from saturated soils
- Landslides triggered by prolonged winter rain
- Debris flows intersecting utility corridors

Critical facilities—including hospitals, emergency operations centers, and water treatment plants—require updated risk assessments under future flood scenarios.

14.5 Channel Migration Zones (CMZs) and Lateral Erosion Hazards

Rivers across the Yakima Basin exhibit dynamic channel migration, especially during high flows. CMZ hazards increase under climate warming due to:

- Higher peak flows
- Increased sediment supply
- More frequent avulsions
- Reduced floodplain roughness following fires

Infrastructure located within CMZs faces heightened long-term risk.

14.6 Post-Fire Infrastructure Hazards

Burn scars dramatically elevate risk to downstream infrastructure through:

- Flash flooding
- Debris flows
- Increased erosion
- Rapid aggradation
- Woody debris impacts on bridges and culverts

Even moderate storms can cause significant damage in the first 1–5 years after a fire.

14.7 Implications for County Planning and Design Standards

Infrastructure design must evolve to remain effective under nonstationary hydrology. Key recommendations include:

- Updating stormwater and bridge design criteria to reflect future peak flows
- Incorporating ROS and AR scenarios into hydrologic design
- Expanding CMZ mapping and setbacks
- Enhancing culvert screening and debris management capacity
- Prioritizing nature-based solutions to reduce downstream flood impacts
- Evaluating redundancy and resilience within utility systems

Climate-resilient infrastructure planning is essential to support Yakima County's long-term safety, economic stability, and compliance with BAS requirements.

SECTION 15. COMMUNITY IMPACTS AND SOCIOECONOMIC CONSIDERATIONS

Climate-driven changes in flooding, drought, wildfire, and water supply reliability have significant implications for the health, safety, economy, and social well-being of communities throughout the Yakima Basin. Rural areas, agricultural sectors, and tribal communities face disproportionate exposure to climate hazards, while limited infrastructure capacity and historic development patterns heighten vulnerability (CIG, 2021; National Academies, 2023).

15.1 Differential Exposure and Vulnerability Across Communities

Flood and drought impacts are not evenly distributed. Communities facing higher exposure include:

- Rural agricultural areas along flood-prone lowlands
- Unincorporated communities with limited infrastructure investment
- Tribal lands where natural-resource access is highly sensitive to hydrologic change
- Low-income populations with fewer resources for hazard mitigation or relocation

Mobile home parks and older housing stock located in floodplains often face a higher risk of damage during extreme events.

15.2 Public Health Implications

Climate-related hazards can increase public health risks through:

- Water contamination during high flows
- Hazardous debris and sediment deposition
- Increased vector-borne and heat-related illnesses
- Dust and air quality effects following wildfires
- Loss of access to clean drinking water during drought

Flood events can also disrupt emergency services and access to hospitals or evacuation routes.

15.3 Economic Impacts to Agriculture and Labor

Agriculture accounts for a major share of the Yakima Basin's economy. Climate impacts include:

- Reduced water availability for irrigation
- Greater variability in crop yields
- Increased risk of frost damage during altered spring timing
- Heat stress for outdoor laborers
- Flood-related damage to fields, equipment, and storage facilities

Water-short years can trigger economic losses across processing, logistics, and labor markets.

15.4 Impacts to Tribal Rights and Resources

Tribal nations depend on the Yakima River and its tributaries for:

- Salmon harvest
- Cultural practices
- Subsistence food systems
- Treaty-reserved rights

Changes in flow timing, temperature, sediment, and habitat complexity directly affect salmonid populations and thus tribal sovereignty and cultural continuity.

15.5 Housing, Transportation, and Community Services

Flooding and wildfire impacts can disrupt:

- Housing stability
- School operations
- Utility service
- Access to employment
- Transportation corridors

Communities with fewer financial and institutional resources have greater difficulty recovering from repeated climate-related disruptions.

15.6 Equity and Environmental Justice Considerations

Climate adaptation strategies must account for the disproportionate burden carried by communities with:

- Lower incomes
- Limited English proficiency
- Less political influence
- Higher exposure to physical hazards
- Critical dependence on climate-sensitive economic sectors

Integrating equity considerations into planning—consistent with state and federal environmental justice frameworks—is essential for meeting long-term community needs.

15.7 Implications for County Planning

Yakima County's planning frameworks should incorporate:

- Community-centered hazard mitigation
- Climate-resilient housing policies
- Improved evacuation and emergency communication systems
- Investment in rural infrastructure and flood defenses
- Partnerships with tribal nations and underserved communities
- Incentives for climate-adaptive agricultural practices

A community-focused, equity-informed approach will ensure that adaptation strategies distribute benefits and burdens fairly across the basin.

SECTION 16. POLICY AND REGULATORY IMPLICATIONS

Climate-induced changes in hydrology, flood behavior, soil moisture, wildfire, sediment transport, and water supply have direct implications for Yakima County's regulatory frameworks, including the Critical Areas Ordinance (CAO), Shoreline Master Program (SMP), flood hazard regulations, and long-range planning under the Growth Management Act (GMA). Incorporating Best Available Science (BAS) is essential to ensure that policies remain protective, legally defensible, and aligned with emerging climate realities (RCW 36.70A.172; WAC 365-195-900).

16.1 Integration of Nonstationary Hydrology into Planning and Codes

Traditional regulatory tools rely on historical flood-frequency analyses, which assume stationarity. These assumptions no longer hold under increasing atmospheric river (AR) intensity, rain-on-snow (ROS) events, declining snowpack, and hydrologic whiplash (Milly et al., 2008).

Policy implications include:

- Updating floodplain maps using climate-adjusted hydrology
- Revising CAO standards for geologic and flood hazards
- Expanding channel migration zone (CMZ) maps
- Integrating soil moisture and ROS dynamics into hazard delineation
- Requiring scenario-based flood analyses for new development

These updates are necessary to maintain public safety and regulatory compliance.

16.2 Shoreline Master Program (SMP) Considerations

Climate-driven changes influence shoreline processes, requiring updates in SMP provisions related to:

- Shoreline management zones, which may need expansion in areas of increased channel migration
- Bank stabilization standards, emphasizing nature-based solutions
- Habitat protection, especially for ESA-listed salmonids
- Flood hazard reduction, including setbacks and avoidance in rapidly changing reaches

BAS increasingly supports softer engineering approaches—log structures, floodplain reconnection, and riparian restoration—to accommodate dynamic river systems.

16.3 Critical Areas Ordinance (CAO) Updates

CAO requirements for wetlands, geologic hazards, fish and wildlife habitat, and flood hazard areas must reflect Environmental Changes such as:

- Increased sediment loading
- Enhanced debris flow potential
- Shifting habitat ranges for cold-water species
- Expansion of wetland boundaries due to altered groundwater
- Steeper and more erosive runoff responses

The CAO must also incorporate wildfire-driven hydrologic shifts in high-risk basins.

16.4 Comprehensive Plan and Horizon 2046 Integration

The Horizon 2046 update provides an opportunity to integrate climate considerations into:

- Land-use designations

- Infrastructure investment priorities
- Emergency management plans
- Agricultural and water resource planning
- Long-term capital facilities planning

Including climate-adaptive measures in the Comprehensive Plan ensures alignment with future risk profiles and state-level climate guidance.

16.5 Coordination with State and Federal Agencies

Yakima County intersects with multiple regulatory and resource agencies, requiring coordinated adaptation strategies with:

- Washington Department of Ecology (Ecology)
- Washington Department of Fish & Wildlife (WDFW)
- NOAA Fisheries
- U.S. Bureau of Reclamation (USBR)
- U.S. Army Corps of Engineers (USACE)
- Tribal governments

Such coordination ensures consistent application of BAS across programs and enhances funding eligibility for climate resilience projects.

16.6 Legal and Liability Considerations

Failure to incorporate climate science into local regulations may increase:

- Exposure to litigation
- Public safety risk
- Infrastructure loss
- Long-term financial liability

Courts increasingly uphold requirements that local jurisdictions consider foreseeable climate risks in land-use decisions.

16.7 Policy Recommendations

Yakima County should prioritize:

- Climate-adjusted hydrologic modeling for floodplain mapping
- Updates to CAO and SMP provisions reflecting dynamic hazards
- Nature-based and multi-benefit flood risk reduction projects

- Integration of climate risk into development review
- Strengthening of interagency partnerships
- Enhanced data collection and monitoring systems

A proactive, climate-informed policy framework is essential to protect people, ecosystems, and infrastructure as hydrologic conditions evolve.

SECTION 17. CLIMATE ADAPTATION AND RESILIENCE STRATEGIES

Adapting to hydrologic change in the Yakima Basin requires a shift from reactive flood control toward proactive, integrated climate resilience. Resilience strategies must address the full hydrologic spectrum—floods, droughts, wildfire-driven hazards, sediment dynamics, and temperature-related ecological stress (National Academies, 2023; CIG, 2021). Because climate drivers now interact in compound and cascading ways, adaptation must be multi-benefit, cross-jurisdictional, and grounded in Best Available Science (BAS).

17.1 Integrated Floodplain Management

Modern flood resilience emphasizes restoring natural floodplain functions. Effective approaches include:

- Floodplain reconnection and side-channel restoration
- Setback levees that allow greater channel migration width
- Removal or modification of constraining levees
- Riparian revegetation to stabilize banks and moderate temperatures
- Protection of cold-water refugia and thermal management zone zones

These techniques reduce flood heights, increase ecological resilience, and restore sediment transport functions impaired by channelization.

17.2 Nature-Based Solutions

Nature-based solutions provide effective alternatives to traditional engineering and are increasingly favored in federal and state guidance. Priorities include:

- Engineered log jams (ELJs) to enhance complexity and dissipate flood energy
- Beaver-dam analogues (BDAs) to increase groundwater storage
- Reconnected wetlands to slow runoff and increase floodplain storage
- Reforestation in burned basins to accelerate post-fire recovery
- Riparian management zones to reduce erosion and moderate stream temperatures

Implementing these solutions supports climate resilience while improving habitat for ESA-listed species.

17.3 Climate-Informed Reservoir Operations

Reservoir operations must be adapted to hydrologic nonstationarity. Strategies include:

- Seasonal operating rules that incorporate AR forecasts
- Dynamic rule curves that account for rising freezing levels
- Adjusted flood-space management to accommodate larger winter inflows
- Improved integration of soil moisture and SWE forecasts
- Basin-wide coordination to optimize storage, flood protection, and ecological flows

These adjustments are essential to maintain water reliability while reducing flood exposure.

17.4 Infrastructure Adaptation and Design Modernization

Infrastructure must be designed for future, not past, hydrology. Recommendations include:

- Upsizing culverts and bridges for climate-adjusted peak flows
- Designing debris- and sediment-resistant structures in post-fire basins
- Updating stormwater design standards to include AR/ROS scenarios
- Reinforcing or relocating critical facilities out of high-risk zones
- Incorporating redundancy and distributed systems to reduce cascading failures

Climate-informed engineering reduces long-term maintenance costs and hazard exposure.

17.5 Wildfire and Post-Fire Hazard Mitigation

Given the strong coupling between wildfire and flood risk, resilience strategies include:

- Fuel reduction and forest health treatments in high-risk basins
- Erosion control measures post-fire (mulching, contour felling, seeding)
- Enhanced debris-flow monitoring in burned watersheds
- Post-fire early-warning systems
- Rapid-response engineering for high-risk tributaries

Addressing wildfire risk is essential to reducing downstream flood impacts.

17.6 Water Supply and Drought Resilience

Drought resilience strategies include:

- Managed aquifer recharge (MAR) projects
- Modernization of irrigation infrastructure
- Water conservation incentives in agriculture and municipalities

- Multi-benefit water storage projects (surface + groundwater)
- Expanded drought-contingency planning
- Restoration of natural wetland storage and hyporheic systems

These actions help offset declining snowpack and earlier runoff timing.

17.7 Community and Emergency Preparedness

Resilient communities require:

- Enhanced early-warning systems for ARs, ROS, and debris flows
- Improved evacuation routes and flood access planning
- Targeted assistance to vulnerable populations
- Community education on flood and drought risk
- Post-disaster recovery frameworks emphasizing equity and rapid reoccupation

Preparedness is especially important for rural and frontline communities.

17.8 Governance, Collaboration, and Data Integration

Effective resilience requires coordinated, science-based governance. Key actions include:

- Strengthening partnerships with tribes, federal agencies, water districts, and NGOs
- Modernizing monitoring networks for snowpack, soil moisture, and streamflow
- Integrating climate projections into all major planning processes
- Applying adaptive management to continually refine strategies
- Leveraging federal and state funding for climate resilience projects

Collectively, these strategies support a basin-wide transition toward climate-informed water, land, and hazard management.

SECTION 17A. CRITICAL AQUIFER RECHARGE AREAS AND MANAGED AQUIFER RECHARGE FOR MULTI-BENEFIT RESILIENCY *(New Section)*

The Yakima Basin faces an urgent groundwater sustainability challenge that demands immediate attention and innovative solutions. Recent research by Asante-Sasu et al. (2025) published in *Groundwater for Sustainable Development* documents that the Yakima Basin is experiencing groundwater level declines of 2–3 feet per year—rates that mirror the critically stressed Odessa Subarea and threaten long-term water availability for agriculture, municipalities, and ecosystems. This landmark Washington State University study, which analyzed data from nearly 3,000 wells across the Columbia Plateau Regional Aquifer System (CPRAS), found that 73% of monitored wells exhibited declining trends between 2000 and 2020, with the Yakima Basin identified as a regional “hot spot” of particular concern.

The convergence of declining groundwater supplies, increasing climate variability, and the basin's dependence on both surface water and groundwater for its multi-billion-dollar agricultural economy creates an imperative for integrated water management strategies. Critical Aquifer Recharge Areas (CARAs) and Managed Aquifer Recharge (MAR) represent essential tools for building long-term resiliency against both drought and flood hazards while protecting people, critical infrastructure, and water availability for the Yakima Basin's expansive agricultural industry.

17A.1 Critical Aquifer Recharge Areas: Regulatory Framework and Scientific Basis

Under the Washington Growth Management Act (RCW 36.70A.030(6)), Critical Aquifer Recharge Areas are designated as one of five critical area types requiring protection. The Washington Administrative Code (WAC 365-190-100) defines CARAs as "areas where an aquifer that is a source of drinking water is vulnerable to contamination that would affect the potability of the water." However, the function and value of CARAs extends far beyond drinking water protection—they are essential for maintaining agricultural water supplies, supporting groundwater-dependent ecosystems, sustaining baseflows in rivers and streams, and providing natural storage capacity that management zones against both drought and flood extremes.

The Asante-Sasu et al. (2025) study introduces a critical advancement in understanding aquifer vulnerability through the concept of "available drawdown" (ADD)—the amount of groundwater accessible to existing well infrastructure, rather than total saturated thickness. This metric reveals that even where substantial groundwater exists at depth, practical accessibility may be severely limited. In the Yakima Basin, the study found steep declines in the Grande Ronde layer (the deepest and thickest basalt aquifer), with mean declines of 1.86 feet per year and localized declines exceeding 7 feet per year. The shallower Overburden layer, while experiencing smaller absolute declines (0.22 feet per year mean), exhibits higher vulnerability due to limited available drawdown.

The heterogeneous nature of the Columbia Plateau Regional Aquifer System—described by McLarty as analogous to "a layer cake, where you have these chunks of actual cake, which is mostly fractured basalt in this case, and then there's frosting in between, the parts where water moves more easily"—means that groundwater cannot be managed as a single resource. Different aquifer layers at the same geographic location may show divergent trends, with some gaining and others losing water. This complexity underscores the need for layer-specific CARA designation and protection strategies that account for vertical and spatial heterogeneity.

Yakima County's CARA regulations must be updated to reflect current Best Available Science, including the Asante-Sasu et al. (2025) findings. Previous Growth Management Hearings Board decisions (*Hazen et al. v. Yakima County*, 08-1-0008c) found that Yakima County's CARA map, based on older science, required revision to incorporate updated hydrogeologic understanding. The 2025 WSU study provides precisely the type of observation-based, spatially resolved vulnerability assessment needed to inform science-based CARA designation and protection.

17A.2 Managed Aquifer Recharge: A Multi-Benefit Resiliency Strategy

Managed Aquifer Recharge (MAR) represents one of the most promising strategies for addressing the Yakima Basin's interconnected water challenges. MAR is defined as "the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit" (National Ground Water Association, 2022). When integrated with flood management—a strategy known as Flood-MAR—it provides simultaneous benefits for flood risk reduction, drought resilience, groundwater sustainability, and ecosystem enhancement.

The 2021 Yakima Basin MAR Assessment, conducted under the Yakima Basin Integrated Plan (YBIP) Groundwater Storage Subcommittee, identified and ranked potential MAR sites throughout the basin. The assessment found that MAR projects in the Yakima Basin could help achieve multiple YBIP objectives: increasing water supply for agriculture (particularly for proratable water users during drought years), supporting domestic use, improving instream flows, and enhancing habitat for aquatic species. Top-ranked sites include Taneum Creek, Big Creek, Tieton River, Little Creek, and Naneum Creek, with infrastructure availability and hydrogeologic suitability as key selection criteria.

California's pioneering Flood-MAR program provides a model for Yakima Basin implementation. The California Department of Water Resources' Merced River Watershed study demonstrated that Flood-MAR can concurrently reduce flood risk, improve water supply, and enhance ecosystems. Key findings applicable to the Yakima Basin include:

- Flood peak attenuation: Diverting high flows to recharge areas during atmospheric river events reduces downstream flood peaks while capturing water that would otherwise be lost to the ocean or cause flood damage.

- Drought management zone augmentation: Groundwater storage provides multi-year drought resilience, complementing shorter-term surface reservoir storage. Subsurface storage costs are typically one-third or less of surface reservoir storage costs, with significantly reduced evaporative losses.

- Agricultural water security: MAR can help offset groundwater depletion in agricultural areas, maintaining irrigation water availability during drought years when surface water allocations are reduced.

- Ecosystem co-benefits: Recharged groundwater supports baseflows in rivers and streams during critical low-flow periods, maintains wetland hydroperiods, and provides cold-water refugia for temperature-sensitive species including ESA-listed salmonids.

Research published in *Environmental Research Letters* (Scanlon et al., 2016) confirms that conjunctive use of surface water and groundwater through MAR enhances drought resilience across the western United States. The study found that "flexibility translates to resilience"—expanding the portfolio of water sources and storage options through integrated surface-subsurface management provides the adaptive capacity needed to manage increasing climate variability.

17A.3 Nature-Based Solutions for Aquifer Recharge and Flood Resiliency

Nature-based solutions (NBS) complement engineered MAR infrastructure by enhancing natural recharge processes while providing additional ecological and community benefits. Applicable strategies for the Yakima Basin include:

Floodplain Reconnection: Removing or setting back levees allows flood waters to spread across natural floodplains, increasing infiltration and groundwater recharge while reducing downstream flood peaks. Yakima County, with funding from the Washington Department of Ecology, has already purchased hundreds of acres along the Yakima and Naches Rivers for floodplain restoration. These projects—implemented through programs including Washington State Ecology Floodplains by Design, Salmon Recovery Funding Board, FEMA BRIC, and USBR WaterSmart—simultaneously improve flood conveyance, fish and wildlife habitat, and aquifer recharge.

Beaver Dam Analogues (BDAs): Constructed beaver dam analogues slow streamflow, increase channel-floodplain connectivity, and promote groundwater recharge in headwater areas. BDAs are particularly valuable in post-fire watersheds where natural beaver populations have been reduced and where enhanced water retention supports ecosystem recovery.

Riparian Management Zone Enhancement: Healthy riparian corridors with native vegetation slow overland flow, increase infiltration, filter sediments and contaminants, and provide shade that reduces stream temperatures. Enhanced riparian management zones along tributaries draining to CARA-designated areas provide both water quality protection and recharge enhancement.

Agricultural MAR: Flooding agricultural fields during the dormant season or between crop cycles allows excess surface water to infiltrate and recharge underlying aquifers. This approach, successfully implemented in California's San Joaquin Valley, could provide significant recharge volumes in the Yakima Basin's extensive agricultural lands while maintaining productive use of farmland.

Wetland Protection: Protected wetlands function as natural detention basins, storing flood waters and releasing them slowly through infiltration and evapotranspiration. Wetland restoration in groundwater-dependent areas supports both aquifer recharge and critical habitat for wildlife.

17A.4 Resiliency Benefits: Protecting People, Infrastructure, and Agriculture

Successful implementation of CARA protection and MAR programs will generate multiple, interconnected resiliency benefits for the Yakima Basin:

Drought Resiliency: The Yakima Basin has experienced three consecutive years of severe drought (2023–2025), with reservoir levels at historic lows and agricultural losses in the hundreds of millions of dollars. MAR provides a critical drought management zone by storing excess water during wet periods for recovery during dry periods. Unlike surface reservoirs, groundwater storage is not subject to evaporative losses (which can exceed 6 feet per year in the Yakima Basin's semi-arid climate) and provides multi-year carryover storage capacity. The Asante-Sasu et al. (2025) study's finding that the Spokane Aquifer is gaining water—

attributed to “very active management and monitoring efforts, including a designated Aquifer Protection Area”—demonstrates that proactive groundwater management can reverse declining trends and build drought resilience.

Flood Resiliency: Capturing atmospheric river flood flows for aquifer recharge reduces downstream flood peaks, protecting communities, agricultural lands, and critical infrastructure. As documented in earlier sections of this memorandum, AR-driven floods are increasing in frequency and intensity, with flood damages projected to increase from approximately $1 billion historically to $2.3–3.2 billion by the 2090s (Corringham et al., 2022). Flood-MAR strategies that divert peak flows to recharge areas provide a cost-effective complement to traditional flood control infrastructure while generating water supply benefits.

Agricultural Water Security: The Yakima Basin’s agricultural economy—valued at over $5 billion annually and supporting thousands of jobs—depends on reliable water supplies from both surface water and groundwater sources. Declining groundwater levels documented by Asante-Sasu et al. (2025) threaten irrigation water availability, particularly during drought years when surface water allocations are reduced. MAR can help stabilize and reverse groundwater declines, ensuring long-term water availability for the basin’s diverse agricultural operations including tree fruits, wine grapes, hops, vegetables, and livestock.

Infrastructure Protection: Groundwater depletion causes land subsidence, which damages roads, bridges, canals, pipelines, and buildings. In California’s San Joaquin Valley, subsidence rates have exceeded one foot per year in severely depleted areas. MAR can reduce or reverse subsidence by maintaining aquifer pressure and preventing the permanent compaction of aquifer materials. Additionally, by reducing flood peaks, MAR protects infrastructure from flood damage, extending the functional life of bridges, culverts, levees, and other flood-vulnerable facilities.

Ecosystem Support: Groundwater discharge to streams (baseflow) is critical for maintaining flows during summer low-flow periods when surface water is fully allocated for irrigation. Enhanced groundwater levels through MAR support coldwater refugia essential for ESA-listed salmon and steelhead, maintain wetland hydroperiods for wildlife habitat, and sustain riparian vegetation that provides shade, bank stability, and habitat complexity.

Community Protection: Flood-MAR reduces flood risk to vulnerable communities, including rural and mobile-home residents in floodplains who face disproportionate flood impacts. Drought resilience through MAR protects municipal water supplies and reduces economic hardship in agricultural communities during drought years. The integrated benefits of CARA protection and MAR implementation support community well-being across multiple dimensions.

17A.5 Implementation Framework and Policy Recommendations

Realizing the resiliency benefits of CARA protection and MAR in the Yakima Basin requires coordinated action across multiple dimensions:

Updated CARA Mapping and Designation: Yakima County should update CARA designations based on current Best Available Science, including the Asante-Sasu et al. (2025) aquifer vulnerability assessment. Updated mapping should account for vertical heterogeneity across aquifer layers and incorporate the "available drawdown" metric to identify areas of greatest vulnerability.

MAR Site Prioritization: Building on the 2021 Yakima Basin MAR Assessment, the County should work with YBIP partners to advance priority MAR projects through feasibility assessment, design, permitting, and implementation. Priority should be given to sites that provide multiple benefits across flood reduction, drought resilience, and ecosystem enhancement.

Regulatory Integration: CARA protection and MAR implementation should be integrated with Critical Areas Ordinance updates, Shoreline Master Program revisions, and flood hazard management regulations. Performance standards should require developments in CARA-designated areas to maintain or enhance recharge capacity through low-impact development techniques, stormwater infiltration, and impervious surface limits.

Water Rights Coordination: MAR implementation in the Yakima Basin requires coordination with the Bureau of Reclamation (which holds senior storage rights), the Washington Department of Ecology, and the Yakama Nation. The regulatory pathway for securing water for MAR projects—whether through negotiation with Reclamation, adding purposes of use to existing water rights, or capturing artificially recharged irrigation return flows—must be clarified and streamlined.

Monitoring and Adaptive Management: Robust monitoring of groundwater levels, recharge rates, and water quality is essential for effective MAR implementation. The WSU study's call for improved groundwater data collection should be heeded, with expanded monitoring networks in data-sparse areas. Monitoring data should inform adaptive management of MAR operations to optimize recharge timing, volumes, and locations.

Funding and Partnerships: MAR implementation should leverage available federal and state funding sources, including FEMA BRIC, EPA Enhanced Aquifer Recharge programs, USBR WaterSmart, Washington State Ecology Floodplains by Design, and Salmon Recovery Funding Board grants. Public-private partnerships with irrigation districts, agricultural producers, and conservation organizations can expand implementation capacity and share costs and benefits.

The urgency of action is underscored by the Asante-Sasu et al. (2025) finding that the Odessa Subarea—which shares similar characteristics with portions of the Yakima Basin—is projected to lose 10% of available drawdown by 2040 and 50% within 70 years if current trends continue. As McLarty observed, "This gives a quantitative target of how much water needs to be either put back into the ground or needs to be managed around to bring us back to some sort of steady condition." CARA protection and MAR implementation provide the tools to achieve that steady condition while building multi-benefit resiliency for the Yakima Basin's people, infrastructure, and agricultural economy.

SECTION 18. UNCERTAINTY, RISK, AND SCENARIO PLANNING

Environmental Change introduces significant uncertainty into hydrologic forecasting, infrastructure design, and long-term planning. Traditional methods that rely on historical data are no longer sufficient because the Yakima Basin now exhibits nonstationary hydrology, characterized by shifting baselines, extreme variability, and increased frequency of compound events (Milly et al., 2008; National Academies, 2023). Scenario-based planning provides a robust framework for assessing risk across a range of plausible future conditions.

18.1 Sources of Uncertainty

Uncertainty in future hydrologic behavior arises from several factors:

- Variability in emissions scenarios and global climate sensitivity
- Regional climate model differences
- Changes in atmospheric river (AR) frequency and intensity
- Unpredictability of wildfire extent and severity
- Soil moisture feedback loops
- Reservoir operations and water demand changes
- Ecological thresholds and species sensitivity

Despite these uncertainties, the overall trend toward warmer, more variable hydrology is unequivocal.

18.2 Risk Amplification Under Compound Events

Risk increases dramatically when multiple hazards coincide. Examples include:

- AR storms striking saturated soils
- Rain-on-snow (ROS) events in mid-elevation snow zones
- AR storms following wildfire in upstream basins
- Multi-storm clusters overwhelming reservoir systems
- Heatwaves following droughts, reducing water availability

Compound events produce outsized impacts and are expected to increase significantly under changing conditions and extreme weather events and trends.

18.3 Scenario Planning for Flood and Drought Management

Scenario planning allows managers to test decisions under a wide range of future conditions. For the Yakima Basin, recommended scenarios include:

1. High-AR, high-rainfall winters
2. Low-SWE, early runoff years
3. Extreme ROS years
4. Severe drought years

5. Wildfire + AR compound events

6. Hydrologic whiplash: wet-to-dry sequences

These scenarios inform reservoir operations, infrastructure design, floodplain planning, and emergency preparedness.

18.4 Adaptive Management as a Core Strategy

Adaptive management uses monitoring and iterative adjustments to reduce uncertainty over time. Key components include:

- Continuous monitoring of SWE, soil moisture, and AR forecasts
- Regular updates to hydrologic models
- Real-time reservoir operational adjustments
- Post-event analysis and refinement of flood-risk assumptions
- Expanded use of probabilistic forecasting tools

Agencies should treat planning documents as **living frameworks** updated regularly based on new data.

18.5 Incorporating Climate Projections into Policy and Infrastructure Design

Best Available Science (BAS) now requires the use of forward-looking rather than backward-looking data. For infrastructure planning, this means:

- Designing for future peak flows
- Including ROS and AR storms in design criteria
- Accounting for sediment loading in post-fire settings
- Using updated recurrence interval calculations that incorporate climate trends

For regulatory planning, it means:

- Incorporating climate scenarios into CAO and SMP updates
- Evaluating long-term land-use exposure under shifting flood and drought regimes
- Prioritizing nature-based, flexible hazard-reduction strategies

18.6 Thresholds, Tipping Points, and Nonlinear Responses

Hydrologic systems respond nonlinearly to warming. Examples include:

- Abrupt increases in ROS flooding when freezing levels exceed key elevations
- Rapid shifts in sediment loads following high-severity wildfires
- Sudden loss of cold-water habitat as temperature thresholds are crossed

- Step-changes in water availability during multiyear droughts

Recognizing these thresholds is essential for designing robust adaptation strategies.

18.7 Planning for Deep Uncertainty

Deep uncertainty arises when stakeholders cannot agree on problem definitions, models, or probability distributions. Under deep uncertainty, planning must focus on:

- Robustness (strategies that perform well under many futures)
- Flexibility (ability to adjust as conditions change)
- Redundancy (multiple systems providing similar functions)
- No-regrets actions (investments beneficial under all scenarios)

Such strategies are central to ensuring Yakima County's long-term resilience.

SECTION 19. SYNTHESIS AND KEY FINDINGS

The Yakima Basin is undergoing rapid and profound hydrologic transformation. Environmental Change is reshaping precipitation patterns, snowpack dynamics, flood behavior, drought severity, sediment transport, wildfire regimes, and ecological conditions. These changes challenge long-standing assumptions about water supply reliability, flood hazards, and watershed management. Based on the synthesis of Best Available Science (BAS), several key findings emerge (National Academies, 2023; CIG, 2021; Webb et al., 2025).

19.1 Intensification of Winter Flood Hazards

Flooding is increasingly driven by winter rainfall, atmospheric rivers (ARs), rising freezing levels, and rain-on-snow (ROS) events. Flood peaks are becoming larger, more frequent, and faster-rising than those of the historical record. Traditional flood-frequency analyses underestimate future flood risk.

19.2 Declining Snowpack and Earlier Runoff

Snow water equivalent (SWE) is declining across all elevations, especially mid-elevation zones. Earlier snowmelt results in reduced spring flows and diminished summer water availability, increasing drought vulnerability and stress on agricultural, municipal, and ecological systems.

19.3 Hydrologic Whiplash

The basin increasingly oscillates between extremes—floods and droughts occurring in rapid succession. This volatility strains water management, damages ecosystems, and complicates reservoir operations.

19.4 Rising Soil Moisture and Enhanced Runoff Efficiency

Soils remain wetter throughout the winter due to increased rainfall and midwinter snowmelt events. High antecedent soil moisture amplifies flood magnitude and increases sensitivity to back-to-back AR storms.

19.5 Increased Wildfire–Flood Coupling

Wildfire frequency and severity are increasing, creating conditions conducive to sediment-laden floods, debris flows, and geomorphic instability during post-fire storms. These compound hazards significantly escalate downstream risk.

19.6 Sediment and Channel Dynamics Increasing Flood Exposure

Burned watersheds, intensified runoff, and warmer storms contribute to increased sediment yields, channel aggradation, and channel migration. These geomorphic changes exacerbate flood hazards and reduce infrastructure resilience.

19.7 Reservoir Systems Under Operational Stress

Reservoirs face conflicting demands: storing enough water for summer needs while maintaining sufficient flood-space during increasingly volatile winters. Earlier runoff and larger winter inflows challenge traditional operational rules and design assumptions.

19.8 Ecosystem Vulnerability and Loss of Cold-Water Habitat

Warming waters, altered flow timing, and increased sediment loads degrade habitat for ESA-listed salmonids. Cold-water refugia are shrinking, migration cues are shifting, and redd scour risks are increasing.

19.9 Infrastructure at Elevated Risk

Transportation, utilities, water delivery systems, and critical facilities face rising exposure to flooding, debris flows, and channel migration. Post-fire hazards and undersized drainage structures intensify vulnerability.

19.10 Need for Climate-Informed Policy and Regulatory Reform

Nonstationary hydrology requires updates to CAO, SMP, floodplain mapping, and long-range planning. Modernized regulatory frameworks should incorporate scenario-based analyses, nature-based solutions, and coordinated regional approaches.

19.11 Importance of Equity and Community Resilience

Climate impacts disproportionately affect rural, tribal, and low-income communities. Planning must integrate equity principles, ensure accessible hazard information, and prioritize community-led resilience strategies.

19.12 The Urgency of Integrated, Basin-Wide Climate Adaptation

Hydrologic change cannot be addressed through isolated measures. Integrated floodplain management, wildfire mitigation, climate-informed reservoir operations, and habitat restoration are all required to build basin-wide resilience.

SECTION 20. CONCLUSIONS

The Yakima Basin is entering a new hydrologic era defined by increased variability, higher extremes, and rapidly shifting climate conditions. Traditional assumptions about snowpack, runoff timing, flood frequency, drought behavior, and watershed response no longer hold. Instead, the basin is shaped by intensifying atmospheric rivers (ARs), rising freezing levels, declining snowpack, more frequent rain-on-snow (ROS) events, heightened wildfire activity, and an overall amplification of hydrologic extremes (National Academies, 2023; Webb et al., 2025).

20.1 A Basin Under Accelerated Hydrologic Change

The cumulative scientific evidence shows that:

- Winter flood hazards are increasing and will continue to intensify.
- Snowpack decline and earlier melt are reducing natural storage capacity.
- Summer droughts are becoming hotter, longer, and more severe.
- Soil moisture patterns and watershed responsiveness are changing.
- Wildfire–flood interactions are producing compound hazards.
- Reservoir systems face increasing operational complexity and uncertainty.

These shifts represent a fundamental departure from 20th-century hydrology.

20.2 Implications for Water Resources, Ecosystems, and Communities

Climate-driven hydrologic changes have cascading impacts on:

- Water supply reliability, especially for agriculture
- Flood risk, including both peak flows and geomorphic hazards
- Ecosystems, particularly ESA-listed salmonids
- Infrastructure, including roads, culverts, bridges, utilities, and irrigation networks
- Communities, especially those with limited resources or high geographic exposure

Collectively, these impacts underscore the need for integrated planning and adaptive management.

20.3 Necessity of Climate-Informed Management and Policy

To remain effective and legally defensible, Yakima County's regulatory frameworks—including the Critical Areas Ordinance (CAO), Shoreline Master Program (SMP), and related flood hazard codes—must incorporate Best Available Science (BAS) that reflects nonstationary hydrologic conditions.

Policy updates must:

- Embrace scenario-based approaches
- Integrate forward-looking climate projections
- Shift toward nature-based, multi-benefit solutions
- Enhance data collection, monitoring, and forecasting
- Strengthen regional partnerships and coordination

20.4 Pathways to Resilience

Building long-term resilience requires:

- Investing in modernized infrastructure capable of handling future extremes
- Protecting and restoring floodplains and cold-water habitats
- Supporting climate-adaptive agricultural practices
- Prioritizing equity in hazard mitigation and recovery
- Expanding emergency preparedness for ARs, ROS events, droughts, and post-fire hazards

These strategies must be implemented at multiple scales—from site-specific projects to basin-wide coordination.

20.5 Final Perspective

The Yakima Basin has a long history of adapting to hydrologic challenges. However, the accelerating pace of Environmental Change requires more proactive, integrated, and forward-looking planning than ever before. By grounding decisions in robust science, investing in resilient natural and built systems, and fostering strong partnerships among agencies, tribes, communities, and water users, Yakima County can chart a path toward sustainable resilience in the face of growing climate uncertainty, changing conditions, extreme weather events, and trends

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APPENDIX A. FIGURES

Figure 1. Yakima Basin Overview Map

Description: A basin-wide reference map illustrating major hydrologic features, including the Yakima River, key tributaries (Naches, Tieton, Cle Elum, Kachess, Bumping), reservoirs, population centers, and physiographic regions.

Intended Data Sources: USGS National Hydrography Dataset (NHD); USGS StreamStats; USDA NRCS SNOTEL; WA DNR elevation datasets.

Figure 2. Yakima Basin Digital Elevation Model (DEM)

Description: A 10–30 m resolution DEM showing elevation bands, topographic complexity, mid-elevation snow zones (2,500–5,500 ft), and areas sensitive to freezing-level rise.

Intended Data Sources: USGS 3DEP LiDAR; WA DNR LiDAR Portal; USGS DEM.

Figure 3. Historical vs. Projected Snow Water Equivalent (SWE) Decline

Description: A line chart comparing observed SWE trends (1981–2020) with projected declines under moderate and high emissions scenarios.

Intended Data Sources: CIG (2021) downscaled climate projections; NRCS SNOTEL SWE datasets; Mote et al. (2018).

Figure 4. Seasonal Runoff Shift and Earlier Snowmelt Timing

Description: Hydrographs comparing historical (1960–1990) and modern (1990–2020) runoff timing.

Intended Data Sources: USGS stream gauge records; Vano et al. (2010) hydrologic modeling outputs.

Figure 5. Atmospheric River (AR) Frequency and Intensity Trends

Description: A bar or line chart showing increasing AR occurrence and intensity over the last ~40 years.

Intended Data Sources: NOAA ESRL/PMEL AR Catalog; Gershunov et al. (2017); Warner et al. (2020).

Figure 6. Freezing-Level Rise and ROS Vulnerability Zones

Description: Raster or contour map identifying elevation bands most sensitive to freezing-level rise.

Intended Data Sources: NOAA snow-level reanalysis; WA State Climatologist; Kampf et al. (2021).

Figure 7. Soil Moisture Trends and Antecedent Saturation Conditions

Description: Map or time series showing early-winter and mid-winter soil moisture anomalies.

Intended Data Sources: PRISM soil moisture climatology; NASA SMAP; Webb et al. (2025).

Figure 8. Post-Fire Burn Severity and Debris Flow Potential

Description: Map depicting burn scars from recent Yakima Basin wildfires and debris-flow susceptibility.

Intended Data Sources: USGS Burned Area Emergency Response (BAER); USFS MTBS.

Figure 9. Sediment and Debris Loading Pathways

Description: Conceptual diagram illustrating sediment mobilization from burned slopes into tributaries.

Intended Data Sources: Riggins et al. (2020); field geomorphology studies.

Figure 10. Reservoir System Schematic

Description: Diagram of the Yakima Basin reservoir system showing storage capacities and operational flow paths.

Intended Data Sources: USBR Yakima Project Operations Manual; Vano et al. (2010).

Figure 11. Channel Migration Zones (CMZs) Under Future Flow Regimes

Description: Map highlighting areas with high CMZ susceptibility based on geomorphic mapping.

Intended Data Sources: WDFW CMZ mapping guidance; USGS geomorphic change detection.

Figure 12. Projected Summer Low-Flow Declines and Temperature Stress

Description: Plot showing projected summer 7Q10 declines and stream temperature exceedances.

Intended Data Sources: CIG hydrologic projections; Mantua et al. (2010).

Figure 13. Flood Hazard Pathways Diagram

Description: A systems diagram showing how AR storms, soil moisture, ROS, wildfire, and reservoirs interact.

Figure 14. Social Vulnerability and Community Exposure Map

Description: Map overlaying flood hazard zones with community vulnerability indicators.

Intended Data Sources: CDC Social Vulnerability Index (SVI); Yakima County GIS hazard layers.

Figure 15. Climate Adaptation Strategy Framework

Description: Flow chart showing relationships among adaptation strategies and governance pathways.

APPENDIX B. TABLES

Table 1. Key Climate Drivers Influencing Yakima Basin Hydrology

Climate Driver	Mechanism of Influence	Primary Hydrologic Effects	References
Atmospheric Rivers (ARs)	High-intensity warm rain events	Larger winter peak flows; flooding	Dettinger (2013); Warner et al. (2020)
Freezing-Level Rise	More precipitation falling as rain	Increased ROS events; reduced SWE	Kampf et al. (2021)
Declining Snowpack	Loss of natural cold-season storage	Earlier runoff; reduced summer flows	Mote et al. (2018); CIG (2021)
ENSO / PDO Variability	Alters storm track patterns	Flood/drought cycles; whiplash	NOAA PMEL (2023)
Wildfire Regime Shift	Drier fuels; hotter summers	Increased debris flows; sediment	Abatzoglou & Williams (2016)

Table 2. Flood Hazard Pathways and Contributing Factors

Hazard Pathway	Primary Drivers	Secondary Amplifiers	Resulting Impacts
AR + Saturated Soil	Warm intense rain	High antecedent soil moisture	Rapid large floods
ROS Flooding	Mid-elevation snowpack	Freezing-level rise	Compound melt–rain runoff
Post-Fire Flooding	Burned slopes	Channel aggradation	Debris flows, culvert blockage
Multi-Storm Clusters	Back-to-back ARs	Limited reservoir flood-space	Overtopping, levee stress
Sediment & Wood Loading	Wildfire + AR	High flows mobilizing debris	Bridge scour, channel shifts

Table 3. Yakima Reservoir System — Climate Vulnerability Profile

Reservoir	Elevation Zone	Climate Stressors	Operational Vulnerabilities	Notes
Kachess	Mid-elevation	Early snowmelt, ROS	Reduced refill reliability	High drought sensitivity

Reservoir	Elevation Zone	Climate Stressors	Operational Vulnerabilities	Notes
Keechelus	High-elevation	AR storms, warming	Winter inflow spikes	Key flood-space reservoir
Cle Elum	High-elevation	Sediment from upper tributaries	Flood-space vs. refill conflict	Managed under YBIP
Rimrock	Mid-elevation	Wildfire → sediment	Debris loading	Significant post-fire risk
Bumping	High-elevation	Declining SWE	Earlier, flashier runoff	Cold-water ecological value

Table 4. Environmental Change Impacts on Ecological Systems

Impact Category	Mechanism	Species Affected	Expected Outcome
Stream Temperature Increase	Lower summer flows	Salmonids, bull trout	Habitat loss above thermal limits
Redd Scour	Higher peak flows	Spring Chinook	Increased egg/alevin mortality
Sediment Deposition	Wildfire + AR	Steelhead, coho	Loss of spawning gravel
Migration Timing Shifts	Changed hydrographs	All anadromous fish	Mismatches with ocean entry
Habitat Simplification	Channel incision	Juvenile rearing species	Lower survival rates

Table 5. Policy and Regulatory Requirements Affected by Environmental Change

Policy Domain	Required BAS Updates	Climate-Relevant Considerations
CAO – FWHCA	Updated hydrology; CMZ expansion	ESA species temperature & flow needs
CAO – Geologic Hazards	Debris-flow modeling	Post-fire instability
SMP	Shoreline management zone recalibration	Channel migration acceleration
Flood Hazard Code	Climate-adjusted recurrence intervals	AR & ROS scenarios

Policy Domain	Required BAS Updates	Climate-Relevant Considerations
Comprehensive Plan	Integrated climate resilience	Long-term nonstationarity

Table 6. Community Vulnerability Indicators

Vulnerability Factor	At-Risk Populations	Climate Hazard Linkage	Planning Relevance
Housing In Floodplains	Rural, mobile-home residents	Increasing AR/ROS floods	Hazard mitigation effort
Water Supply Dependence	Agricultural workforce	Snowpack loss	Irrigation reliability
Transportation Access	Rural communities	Debris flows, washouts	Emergency planning
Income & Resource Constraints	Low-income households	Recovery difficulty	Equity requirements
Cultural Resource Dependence	Tribal communities	Salmon declines	Treaty rights implications

BAS COMPLIANCE SUMMARY

This technical memorandum meets the Best Available Science (BAS) standards required by RCW 36.70A.172 and WAC 365-195-900 through 925 by:

1. Using authoritative, peer-reviewed sources
2. Incorporating Environmental Change and nonstationary hydrology
3. Addressing local ecological and geophysical conditions
4. Applying scientifically defensible methods
5. Acknowledging uncertainties
6. Providing directly applicable regulatory insights

It is appropriate for use in Critical Areas Ordinance updates, Shoreline Master Program revisions, flood hazard planning, and the Horizon 2046 Comprehensive Plan process.

UPDATE NO. 1: 12162025: (need to incorporate and get into BAS Portal Database/Library)

I found numerous publications on hydrologic sensitivities of runoff to climate changes published after 2010. Highlighted have best geographical relevance.

Major Follow-up Work by Vano et al.:

Vano, J. A., Das, T., & Lettenmaier, D. P. (2012). Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature. *Journal of Hydrometeorology*, 13(3), 932-949.

Vano, J. A., & Lettenmaier, D. P. (2014). A sensitivity-based approach to evaluating future changes in Colorado River discharge. *Climatic Change*, 122(4), 621-634.

Vano, J. A., Nijssen, B., & Lettenmaier, D. P. (2015). Seasonal hydrologic responses to climate change in the Pacific Northwest. *Water Resources Research*, 51(3), 1959-1976.

- This is a major follow-up to the 2010 paper, focusing specifically on Pacific Northwest with seasonal analysis

Lehner, F., Wood, A. W., Vano, J. A., Lawrence, D. M., Clark, M. P., & Mankin, J. S. (2019). The potential to reduce uncertainty in regional runoff projections from climate models. *Nature Climate Change*, 9(12), 926-933.

Recent Work on Precipitation Elasticity & Climate Sensitivity:

Dierauer, J. R., Allen, D. M., & Whitfield, P. H. (2018). Climate controls on runoff and low flows in mountain catchments of Western North America. *Water Resources Research*, 54(10), 8021-8044.

Gupta, A., Gerber, F., Siderius, C., & Mondal, P. (2022). Spatiotemporal variations in the elasticity of runoff to climate change and catchment characteristics with multi-timescales across the contiguous United States. *Journal of Water and Climate Change*, 13(3), 1408-1429.

Anderson, B. J., Brunner, M., Slater, L., & Dadson, S. (2024). Elasticity curves describe streamflow sensitivity to precipitation across the entire flow distribution. *Hydrology and Earth System Sciences*, 28(7), 1567-1586.

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He, M., & Pomeroy, J. W. (2022). The sensitivity of snow hydrology to changes in air temperature and precipitation in three North American headwater basins. *Journal of Hydrology*, 606, 127460.

Ban, Z., Barnhart, T. B., Feng, X., Musselman, K. N., Middleton, R., & Xu, M. (2025). Decelerating response of Western US runoff to shrinking snowpacks. *Geophysical Research Letters*, 52, e2025GL114629.

Lai, Y., Cayan, D., & Peterson, D. (2025). Inferring trends and temperature sensitivities using regression-based unimpaired runoff to San Francisco Estuary, 1872-2022. *JAWRA Journal of the American Water Resources Association*, 71(1), 70057.

Modeling & Methodological Advances:

Elkouk, A., Partridge, T., & Kumar, P. (2024). Toward understanding parametric controls on runoff sensitivity to climate in the land component of an Earth System Model. *Water Resources Research*, 60, e2024WR037718.