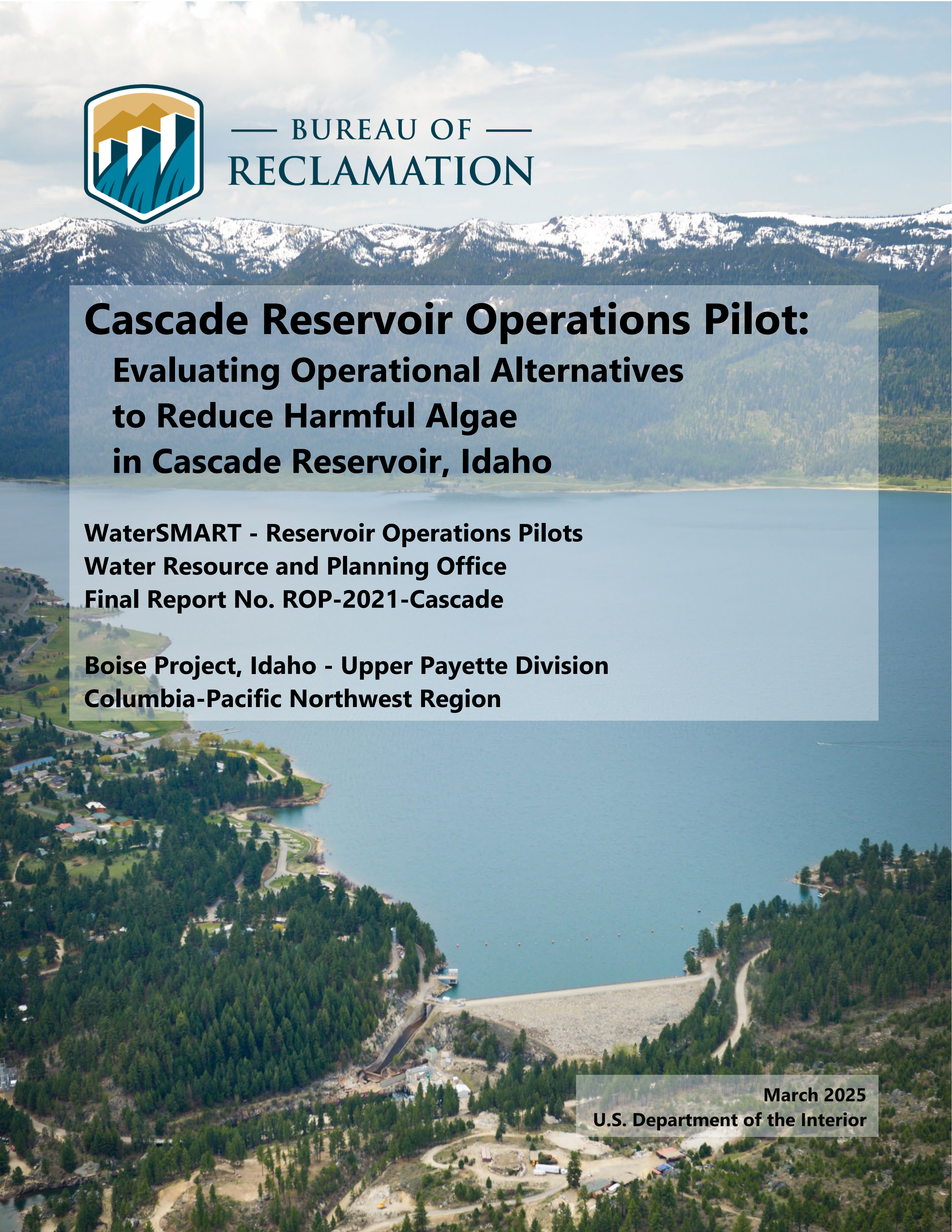

BUREAU OF RECLAMATION

# Cascade Reservoir Operations Pilot:

## Evaluating Operational Alternatives to Reduce Harmful Algae in Cascade Reservoir, Idaho

**WaterSMART - Reservoir Operations Pilots**
**Water Resource and Planning Office**
**Final Report No. ROP-2021-Cascade**

**Boise Project, Idaho - Upper Payette Division**
**Columbia-Pacific Northwest Region**

**March 2025**
**U.S. Department of the Interior**

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The changes to reservoir operations explored by this study are theoretical for research purposes and are not under consideration for actual implementation at this time.

# Acknowledgements

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Cover: Aerial photograph of Cascade Dam and Reservoir taken by Bureau of Reclamation staff May 5, 2015.

# Cascade Reservoir Operations Pilot:
## Evaluating Operational Alternatives to Reduce Harmful Algae in Cascade Reservoir, Idaho

**Final Report No. ROP-2021-Cascade**

*prepared by*

**Columbia-Pacific Northwest Regional Office**
**in coordination with the Snake River Area Office**

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Water Management, Long-term Operations and Planning

# Peer Review

## Bureau of Reclamation
## Water Resources and Planning Office
## Reservoir Operations Pilots Program

Final Report ROP-2021-Cascade

**Cascade Reservoir Operations Pilot:**
**Evaluating Operational Alternatives to Reduce Harmful Algae in Cascade Reservoir, Idaho**


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# Acronyms and Abbreviations

| Acronym or Abbreviation | Definition |
|---|---|
| cfs | Cubic feet per second |
| CSC | Cascade Dam and Reservoir |
| DED | Deadwood Dam and Reservoir |
| FRM | Flood Risk Management |
| PSU | Portland State University |
| RCP | Representative Concentration Pathway |
| Reclamation | Bureau of Reclamation |
| USGS | U.S. Geological Survey |

# Contents

# Executive Summary

Cascade Reservoir, in west-central Idaho, often experiences harmful algal blooms that negatively affect water quality and can produce toxins that are of concern for public health. Harmful algal blooms typically occur in the late summer when higher water temperatures and nutrient availability promote the rapid growth of harmful algae. This study, funded through Reclamation's Reservoir Operations Pilots program, explored how a range of theoretical changes in operations of the larger reservoir system (i.e., the Payette River basin) might affect water levels and the occurrence of harmful algae and associated toxins, while continuing to meet the authorized purposes and operational constraints of the reservoir system.

This study adapted an existing river-reservoir operations model and developed a new water quality model to assess the potential sensitivity of harmful algae to theoretical changes in reservoir operations. The river-reservoir operations model can simulate historical hydrologic inflows to the system, historical water supply requirements for various purposes (e.g., irrigation, power generation, and ecological needs), and the historical and theoretical operations of the different dams, river flows, and transmission infrastructure (e.g., canals) in the system to release water and meet the various purposes. The water quality model is capable of simulating reservoir hydrology (e.g., inflows, physical mixing, and water levels), water quality dynamics, and algae growth and toxin production. The water quality model was calibrated using historical hydrologic data and water quality measurements for the calendar years 2018 through 2022. The models provide repeatable logic to simulate operations using historical environmental conditions and create a suitable test environment where operations can be adjusted, while holding other influential factors constant (e.g., wind, cloud cover, air temperatures, and inflows), to constrain the potential effects of specific changes in operations on harmful algae.

Four reservoir operating alternatives were identified based on the operational constraints and flexibilities of the system. Within the scope of Reservoir Operations Pilots, these operational alternatives are theoretical and are not under consideration for implementation at this time, as they could have negative effects to other purposes (e.g., flood risk management, fish habitat, recreation, and power generation) or other water quality parameters not focused on in this study. These other potential effects could outweigh any potential improvements to harmful algae and would need further study when considering actual implementation of changes in operations. The operational alternatives involved changing the timing of water releases, release mechanisms, and how releases from Cascade Reservoir were balanced with releases from the other storage reservoir within the Payette River basin, Deadwood Reservoir, to meet water supply needs. The four operational alternatives can be described briefly by the following changes.

1) Changing which of Cascade Dam's structures were used to make water releases (e.g., releasing water over the spillway rather than through the intake structure and powerhouse) to withdraw water of different temperatures from different depths in the reservoir.

2) Shifting the timing of certain releases (e.g. beneficial flows for anadromous fish, such as salmon) to change the timing of reservoir drawdown.

3) Primarily releasing water to meet water supply needs from Cascade Reservoir first each season, to draft the reservoir water levels down as early as possible (i.e. minimum operating range).

4) Primarily releasing water to meet water supply needs from Deadwood Reservoir first each season to keep Cascade Reservoir as full as possible for as long as possible (i.e. maximum operating range).

The four operational alternatives were run through the models to simulate the hydrology, operations, water quality dynamics, and harmful algae growth. A baseline alternative simulating historical operations was also run through the model for comparison with the operational alternatives to quantify potential effects and understand the sensitivity of harmful algae growth to the changes in operations.

The model results showed the changes in releases and water levels for the operational alternatives resulted in relatively small changes in harmful algae concentrations (e.g., -2% to +3%) that were not considered significant within the context of related measurable model uncertainties. The study results demonstrated that harmful algae growth dynamics were not particularly sensitive to changes in operations (i.e., the timing of dam releases and reservoir water levels) within the range of theoretical operational flexibility for the Payette River basin system. The largest operational changes in reservoir water levels were small (up to around 4 feet) relative to the water depth (up to around 50 feet). The different dam release structures also were unable to affect reservoir temperatures because the intake structure, for the outlet works and powerhouse, and spillway openings are both at mid-elevations within the reservoir and generally release similar (i.e., average) temperatures of water. Note that this study looked specifically at calendar years 2018 through 2022, and it is possible different effects could be observed in other years.

The results were also interpreted within the context of potential future changes in climate and hydrology based on an ensemble of global climate models. In the future, the projected warmer temperatures could increase the potential for harmful algae growth. However, the lack of sensitivity of harmful algae to the changes in water levels in the operating alternatives suggest that changes in reservoir operations may be unable to offset these potential future effects without other measures to control harmful algal blooms (e.g., nutrient management).

# 1. Introduction

This reservoir operations pilot study explored the potential effects that changes in reservoir operations might have on harmful algal blooms at Cascade Reservoir, also known as Lake Cascade, in west-central Idaho. The intent was to identify theoretical changes in operations of the larger reservoir system (i.e., the Payette River basin; Figure 1) that could reduce the abundance of harmful algae and associated toxins, while continuing to meet the authorized purposes and operational constraints of the reservoirs. The study used a river-reservoir operations model for the Payette River basin and a water quality model for Cascade Reservoir that were calibrated for the calendar years 2018 through 2022. Operational alternatives were developed based on the operational constraints and flexibilities of the system and simulated through the models to assess the potential effects on harmful algae. Results for the operational alternatives were compared to understand the sensitivity of harmful algae to changes in operations and considered within the context of potential future changes in climate and hydrology. Note that these operational alternatives are theoretical and are not under consideration for implementation at this time, as they would entail changes that could have adverse effects to other purposes that would need to be fully explored and considered.

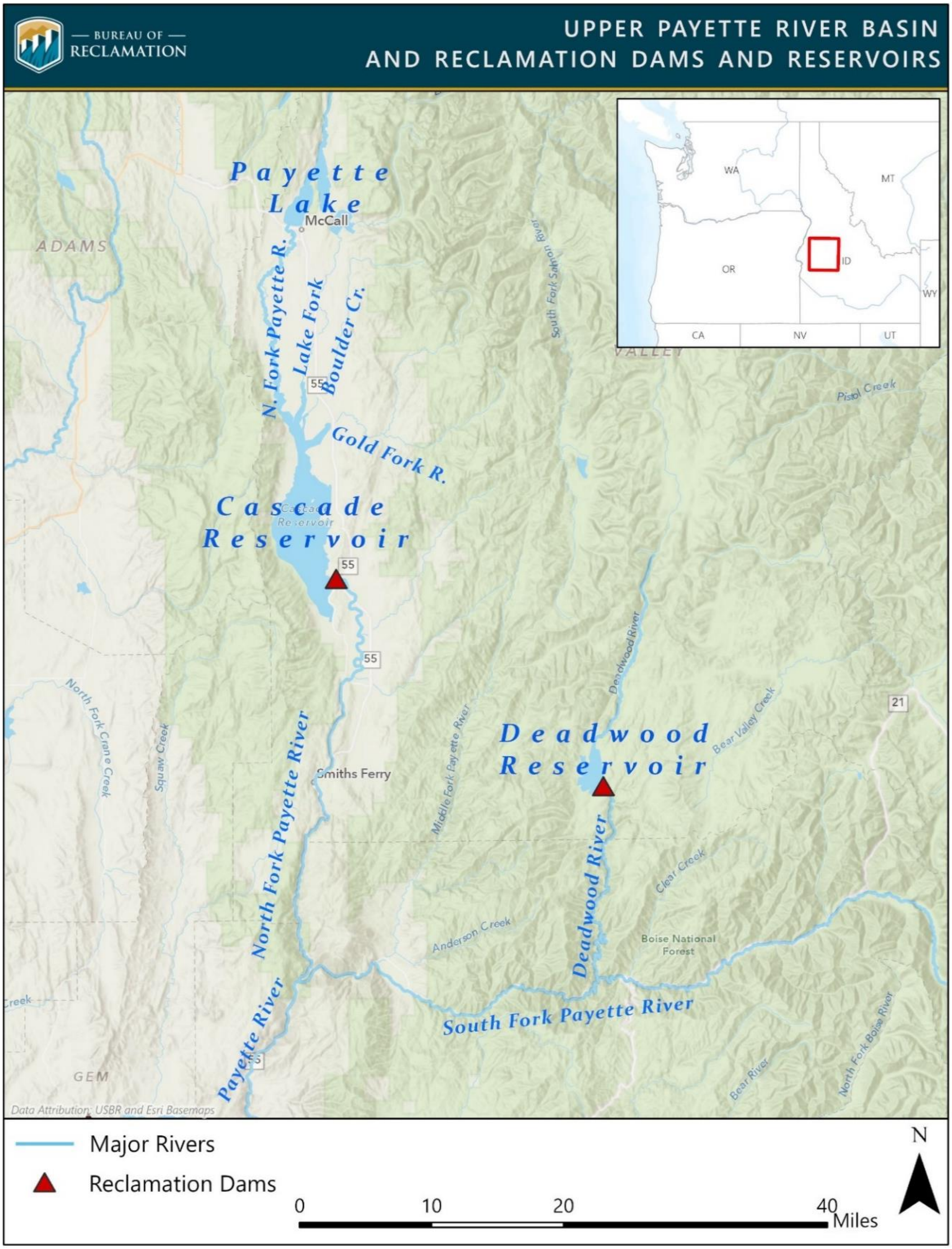


Figure 1. Map of the Upper Payette River basin with location of major rivers, dams, and reservoirs

# 2. Background

Cascade Reservoir is a man-made water body formed by the impoundment of the North Fork Payette River at Cascade Dam. Cascade Dam was authorized by Congress in 1905, built by 1948, and first filled in 1957 to provide irrigation and power production (Reclamation 2002). The reservoir is wide and relatively shallow, occupying what was formerly an incised river channel and adjacent uplands that are relatively flat (Figure 2). Cascade Reservoir receives water from an approximately 615 square mile watershed ranging in elevation from around 4,820 to 9,050 feet (5,940 feet average). The basin contributing runoff to the reservoir was summarized using the U.S. Geological Survey's StreamStats website (streamstats.usgs.gov; USGS 2019) as receiving an average of 37.9 inches of precipitation annually for 1981 through 2010, largely as snow and varying with elevation, over a landscape composed of 60 percent forest cover, 9 percent agricultural land, 0.1 percent developed land, and a remainder likely composed of sagebrush-steppe rangeland.

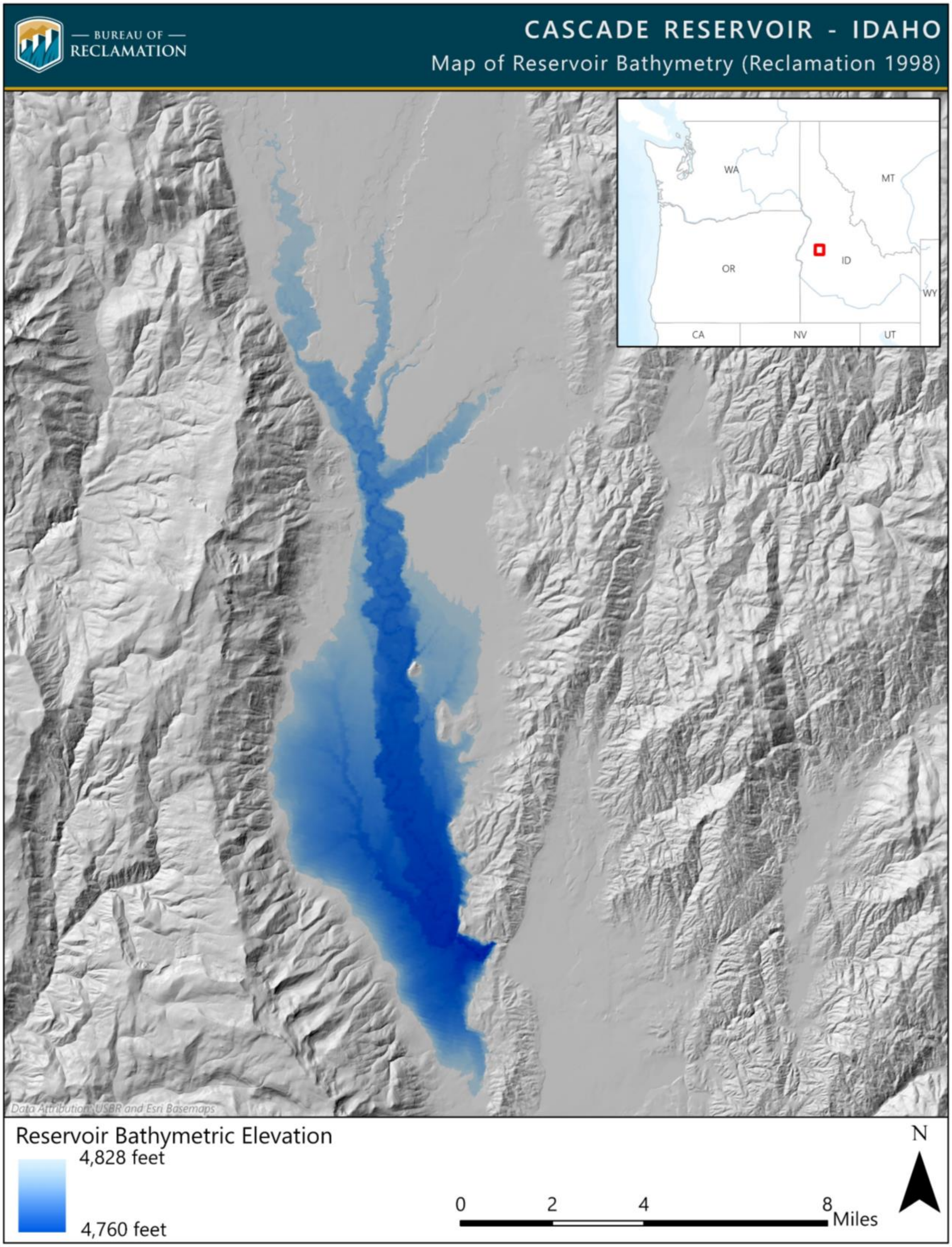


Figure 2. Map of bathymetric elevations (blue) for Cascade Reservoir from reservoir sedimentation survey (Reclamation 1998), with hill-shaded topography in background (gray shades)

The reservoir has historically experienced algal blooms (IDEQ 1998; Stuebner 2023), which typically occur when conditions (e.g., water temperatures and nutrients) are favorable to the growth of specific types of algae, some of which can produce harmful toxins (Garstecki 2021). Harmful algae (i.e., cyanobacteria, also known as blue-green algae) produce and release harmful toxins (e.g., cyanotoxins) under specific conditions. These toxins can negatively affect water quality, recreation, and the health and safety of people and animals. Not all algae produce harmful toxins, and not all algal blooms are harmful (e.g., cold-water diatoms and green algae do not produce toxins). Potentially harmful algae typically bloom following the warmer summer months (e.g., 2019 bloom in Figure 3), with larger blooms generally associated with warmer temperatures and higher nutrient loads such as nitrogen- and phosphorus-based nutrients (Garstecki 2021). This study focused on assessing the impact of reservoir operations on harmful algae during the summer months.

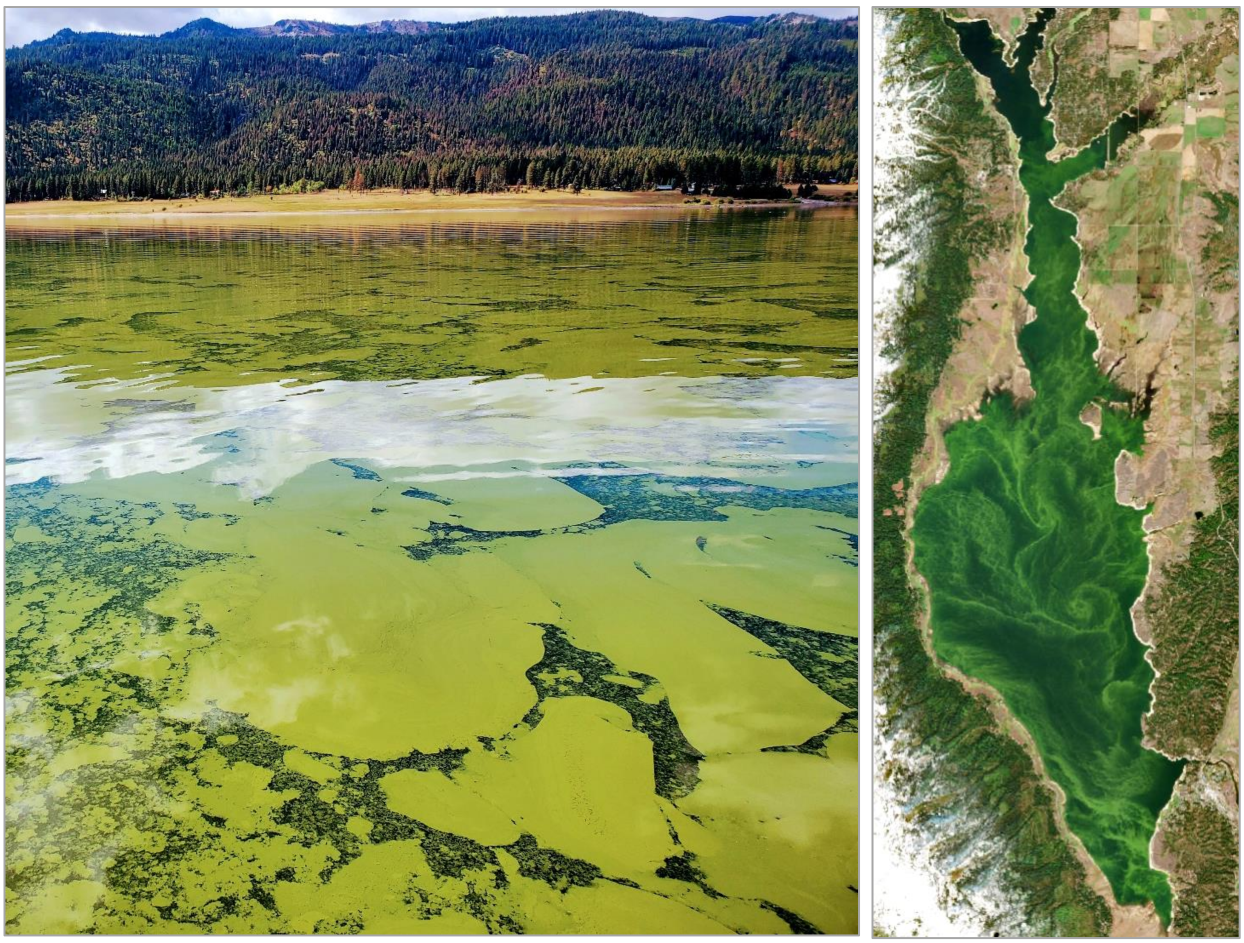

Figure 3. 2019 algae bloom (left; September 26, 2019; photo courtesy of Friends of Lake Cascade) and by satellite (right; October 6, 2019; color enhanced; Sentinel-2 image accessed December 2024 from https://dataspace.copernicus.eu/)

Since reservoir releases may affect water levels and movement within water bodies, reservoir operations have the potential to affect temperatures and water quality characteristics that influence harmful algae growth. However, it is difficult to assess the effects of changes in operations in real-world circumstances due to the complexity of numerous other factors that might affect the growth of harmful algae from one year to the next. An alternative approach is to simulate changes in operations using reservoir system models, where operations can be changed while other influential factors (e.g., wind, cloud cover, air temperatures, inflows, nutrient inputs, etc.) are held constant, effectively isolating the effects of the changes in operations. The chain of physical, chemical, and biological processes within lakes (limnology) are complex and simulating them appropriately involves calculations of hydrodynamic flow, reservoir stratification, heat fluxes, light incidence and attenuation, biochemical reactions and fluxes, and complex biological processes (e.g. respiration, metabolism, reproduction, and death). Uncertainties associated with each of these calculations and the combined effects of these uncertainties are difficult to quantify but are considered when assessing how theoretical changes in reservoir operations affect the modeled algae dynamics.

A water quality model capable of simulating these processes was developed specifically for this study by Portland State University's Water Quality Research Group, with the intent to simulate algae dynamics and toxin production using recently developed modules. Model development and calibration are detailed in their separate report (Wells et al. 2023). In this study, the model was used to explore whether changes in reservoir operations could reduce the concentrations of harmful algae and associated toxins. A public meeting was hosted by Reclamation and the Valley Soil and Water Conservation District on August 23, 2022, in the town of Cascade, Idaho, with presentation on the plans for the study and operational and modeling constraints for the Payette River system, followed by an open discussion with the public to provide input for the study (e.g., suggestions for changes in operations that might affect harmful algae). Changes to the reservoir that did not involve dam operations (e.g., changes to the water quality of inflows) were outside the scope of the study and not considered. Different reservoir operating alternatives were developed based on the ideas generated from the meeting and discussions with system operators, with consideration for operational constraints of the reservoirs and the river basin and the operations-based scope of the study. These operating alternatives are theoretical and may or may not be possible to implement and would require further assessment and consideration of other potential effects.

The operating alternatives were first simulated in a separate river-reservoir operations model to calculate the dam operations (e.g., outflows and water levels) needed as input to the water quality model. The water quality model was then run for each alternative to assess concentrations of harmful algae. The resulting harmful algae concentrations for each alternative were compared to a 'Baseline' alternative that did not include changes in operations (i.e., modeled historical operations) to evaluate their potential to reduce harmful algae.

# 3. Project Constraints

The scope of this study was limited by constraints in the physical hydrology and infrastructure, operational flexibilities, modeling capabilities, and project timelines. These factors limited the range of theoretical changes in reservoir operations, timespans (years studied), and spatial detail (model resolution) that could be explored. These limitations and constraints are discussed in more detail in the subsections that follow.

## 3.1. Physical System Constraints

This section describes the real-world physical system constraints (i.e., not modeling constraints, which follow). The reservoirs in the Payette River basin are subject to physical constraints such as the amount of inflow to the reservoirs, the available reservoir storage space, and federally authorized uses. The Bureau of Reclamation (Reclamation) is committed to operating the reservoirs to manage the water supply. Cascade and Deadwood Reservoirs are the two main storage reservoirs in the Payette River basin and are jointly operated to manage flood risk, supply water for agriculture, and support ecological functions, with the total flows needed downstream balanced between the two reservoirs depending on their relative amounts of stored water and forecasted inflows. Operations to support these priorities are determined by federal authorizations, biological opinions, natural flow and stored water rights, and intergovernmental agreements. Reservoir releases may concurrently be used to produce hydroelectric power and provide opportunities for primary and secondary contact recreation, but the dams are not authorized to operate specifically for these purposes and they are considered incidental benefits.

Other physical constraints include meteorological conditions, snowmelt, and amounts and timings of inflow to the reservoirs, which are not under Reclamation's control. For either reservoir, the total storage and capacities and configurations of release mechanisms (e.g., outlet; spillway) are fixed. Changes to infrastructure were not explored in this study.

### 3.1.1. Reservoir Inflows and Storage

Inflow to Cascade Reservoir comes from the North Fork Payette River, Lake Fork Creek, Gold Fork Creek, Boulder Creek, and numerous smaller tributaries, such as those draining into the reservoir from the mountains to the west. The North Fork Payette River is the largest source of inflows but is regulated by a dam at the outlet of Payette Lake that is operated by a private company, Lake Reservoir Company. Diversions for irrigation from upstream water sources may also return a portion of their flow to Cascade Reservoir. Flow regulation and diversion from the other tributaries to Cascade Reservoir also represent modifications to inflow that are not under Reclamation's control and were not considered as operational flexibilities in this study. Inflows from the other tributaries to Cascade Reservoir are largely unregulated but influence the water supply and operations. Likewise, inflow to Deadwood Reservoir is unregulated, but it influences and constrains water supplies and operations and must also be considered when forecasting water supplies and operating the multi-reservoir system.

#### *3.1.1.1. Cascade Reservoir Storage Allocation*

There is 693,200 acre-feet of storage space for water in Cascade Reservoir. Of that space, 46,700 acre-feet is lower in elevation than the intake for the dam and physically unavailable to release (also known as "dead space"). The remaining 646,460 acre-feet is divided among several uses (Figure 4). Existing storage space for irrigation makes up 310,387 acre-feet, and an additional 16,474 acre-feet is committed for future irrigation, municipal, and industrial contracts but currently withheld from contracting. Another 250,000 acre-feet is reserved as the conservation pool and is kept in the reservoir to maintain water quality and is not available to release. Finally, 69,600 acre-feet is storage for flow augmentation releases, which are for flows to benefit out-migrating ESA-listed fish, described below (Section 3.1.2.7).

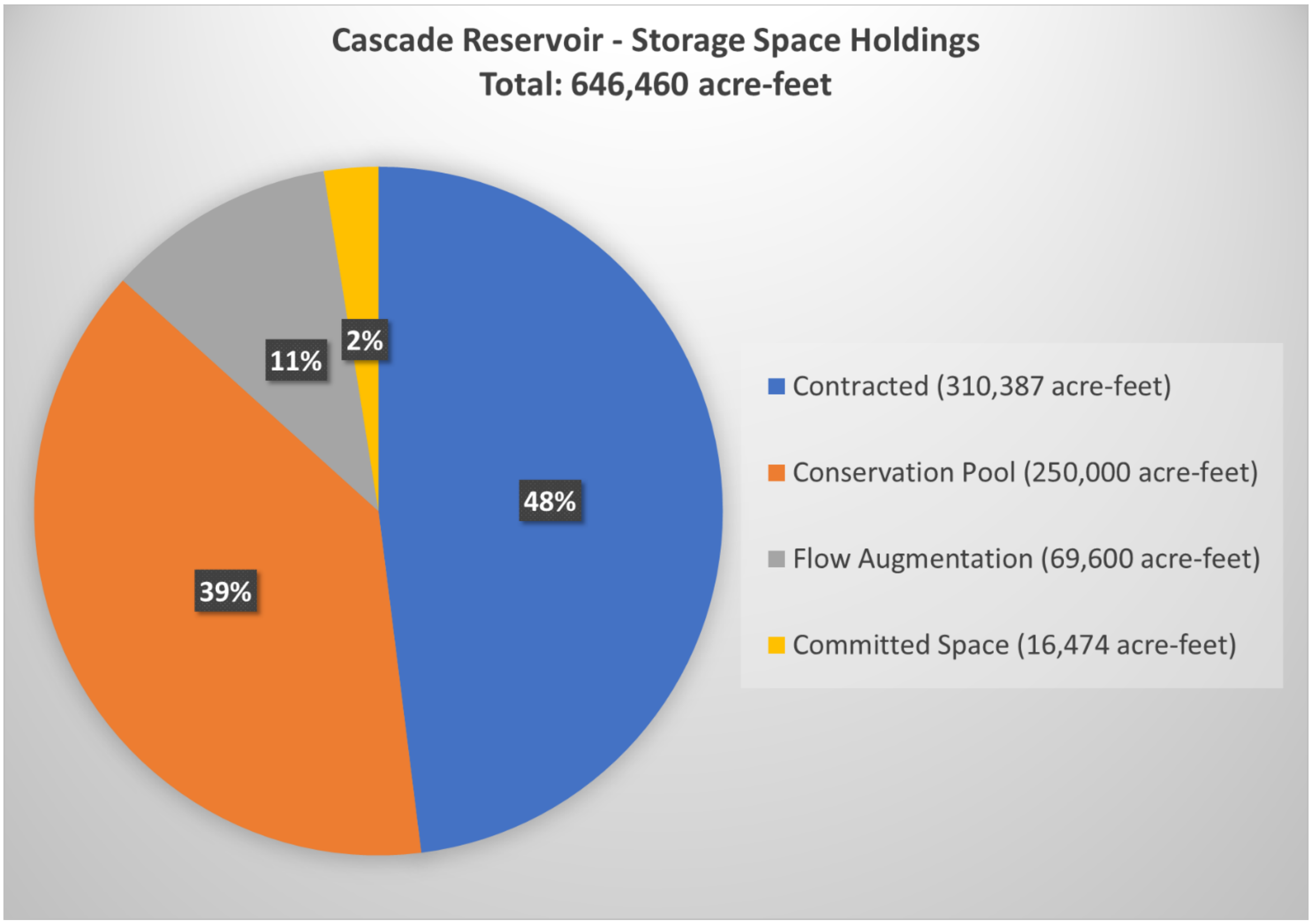


Figure 4. Storage allocation in Cascade Reservoir

#### *3.1.1.2. Deadwood Reservoir Storage Allocation*

Deadwood Reservoir is smaller than Cascade Reservoir, having a current capacity of 153,992 acre-feet with no unusable dead space at the bottom of the reservoir. Of the current capacity, 50,000 acre-feet makes up the conservation pool reserved for water quality, resident fish & wildlife, and recreation. This conservation pool volume is also used to allow bull trout listed under the Endangered Species Act to migrate up tributary streams; storage is not to go below 50,000 acre-feet. Storage space reserved for streamflow, recreation, and wildlife maintenance is 24,515 acre-feet. Flow augmentation storage is 26,008 acre-feet. The remaining 53,469 acre-feet is storage for consumptive use (e.g., irrigation).

### 3.1.2. Reservoir Outflows

Reservoir outflows are constrained by both the physical limitations of the dams impounding them and legal requirements regarding how and when water is stored and released. Cascade and Deadwood Reservoirs are jointly operated to meet these requirements, with releases balanced between them based on relative storage and water supplies. Reducing releases at one reservoir would require increasing releases at the other, assuming a constant total amount. The seasonal priorities, flow, and volume parameters for Cascade and Deadwood Reservoirs are shown in Table 1 and Table 2, respectively, and are elaborated on in the subsequent text discussions.

Table 1. Cascade Reservoir general operations timeline for a typical year

<table>
<tr><th rowspan="2">Operations</th><th colspan="12">Monthly Operations</th></tr>
<tr><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th></tr>
<tr><th rowspan="2">Flood Risk Management</th><td colspan="5">Winter flood space (e.g., around 494 KAF max fill)</td><td colspan="4">Ensure CSC/DED maintain FRM space (e.g., 80/20 split)</td><td colspan="3" rowspan="2"></td></tr>
<tr><td colspan="9">Downstream management: Ensure combined releases from CSC/DED keep flows below 14,500 cfs at EMMI and 12,500 at HRSI</td></tr>
<tr><th>Irrigation</th><td colspan="6"></td><td colspan="6">Irrigation prioritized</td></tr>
<tr><th>Flow Augment-ation</th><td colspan="7"></td><td colspan="3">Flow augmentation prioritized</td><td colspan="2"></td></tr>
<tr><th>Recreation</th><td colspan="8"></td><td colspan="4">When possible; coordinated with local stakeholders: N. Fork flows approximately 1,200-2,200 cfs</td></tr>
<tr><th>End of Irrigation - CSC/DED balancing</th><td colspan="8"></td><td colspan="4">To ensure highest probability of filling following year</td></tr>
<tr><th>Minimum Release for Hydropower</th><td colspan="12">200 cfs - year-round</td></tr>
<tr><th>Preferred Max Outflow</th><td colspan="12">5,000 cfs, depending on basin conditions</td></tr>
</table>

Acronym definitions: KAF, thousand acre-feet; CSC, Cascade Dam; DED, Deadwood Dam; FRM, Flood Risk Management; cfs, cubic feet per second; EMMI, Payette River near Emmett, ID (USGS station 13249500); HRSI, Payette River near Horseshoe Bend, ID (USGS station 13247500).

Table 2. Deadwood Reservoir general operations timeline

<table>
<tr><th rowspan="2">Operations</th><th colspan="12">Monthly Operations</th></tr>
<tr><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th></tr>
<tr><td rowspan="2">Flood Risk Management</td><td colspan="5">Winter flood space (e.g., around 116 KAF max fill)</td><td colspan="4">Ensure CSC/DED maintain FRM space (e.g., 80/20 split)</td><td colspan="3" rowspan="2"></td></tr>
<tr><td colspan="9">Downstream management: Ensure combined releases from CSC/DED keep flows below 14,500 cfs at EMMI and 12,500 at HRSI</td></tr>
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<tr><td>Flow Augment-ation</td><td colspan="7"></td><td colspan="3">Flow augmentation prioritized</td><td colspan="2"></td></tr>
<tr><td>Recreation</td><td colspan="8"></td><td colspan="4">When possible; coordinated with local stakeholders: S. Fork flows approximately 1,200-1,600 cfs</td></tr>
<tr><td>End of Irrigation - CSC/DED balancing</td><td colspan="8"></td><td colspan="4">To ensure highest probability of filling following year</td></tr>
<tr><td>Minimum Flow</td><td colspan="12">50 cfs* - year-round</td></tr>
<tr><td>Preferred Max Outflow</td><td colspan="12">1,000 cfs, depending on basin conditions</td></tr>
</table>

*Note: minimum was changed to 5 cfs in 2024 but 50 cfs was in effect during the years modeled.
Acronym definitions: KAF, thousand acre-feet; CSC, Cascade Dam; DED, Deadwood Dam; FRM, Flood Risk Management; cfs, cubic feet per second; EMMI, Payette River near Emmett, ID (USGS station 13249500); HRSI, Payette River near Horseshoe Bend, ID (USGS station 13247500).

#### 3.1.2.1. Physical Outflow Limitations of Dam Structures

Water released from Cascade Reservoir through Cascade Dam flows through a single intake structure that routes flow through the powerhouse or outlet works. When the required outflows exceed the capacity of the intake structure, water can also be released over a controlled spillway with a crest elevation of 4,808 feet. Two high-pressure gates regulating the outlet works have a capacity of 2,760 cubic feet per second (cfs) and Idaho Power Company's hydroelectric power generating plant has a capacity of up to 2,300 cfs, but the two outflow structures share a penstock and the combined outflow is limited by the penstock capacity (i.e., the 2,760 and 2,300 cfs are not additive). Usually, the outlet gates are closed to route flow through the powerhouse and optimize power production, with any additional releases in excess of the powerhouse capacity made through the spillway. The controlled spillway is regulated by two radial gates with a combined capacity of 12,500 cfs when the reservoir is full. Actual flow through the spillway is a function of both water surface elevation, relative to the spillway crest, and radial gate operation.

The outlet of Deadwood Reservoir through Deadwood Dam is through either a single intake structure and outlet or over an uncontrolled spillway with crest elevation 5,334 feet. The Deadwood Dam outlet works is regulated by two jet flow gates with a combined capacity of up to 2,800 cfs. The spillway capacity varies with reservoir water levels and is 11,300 cfs when the reservoir is full.

#### 3.1.2.2. Releases for Flood Risk Management

Flood risk in the Payette River basin is managed by reserving empty space in the reservoirs during the winter and spring so that when flows into, and downstream of, the reservoirs are high, the inflows can be stored and dam releases reduced to minimize flooding downstream. Releases for Flood Risk Management (FRM) usually occur in early spring at both Cascade and Deadwood Reservoirs. Inflow forecasts are generated by Reclamation each month from January through June that take into account, among other things, basin conditions such as snow water equivalent, precipitation, and antecedent runoff. These inflow forecasts are then used in real-time management of FRM releases while also considering water storage needs. FRM guide curves are used to suggest appropriate flood space volumes to reserve based on runoff forecasts; however, many other factors, including variability in forecasts, future weather conditions, snow data, and soil data, are considered as the reservoirs are filled. These flood space volumes are calculated for the Payette as a whole and split between Deadwood and Cascade Reservoirs, with Cascade typically accounting for a fraction in proportion to its share of annual runoff (e.g., around 80 percent on average for water years 1995 through 2024) of the flood space. The allocation of flood space to the reservoirs and FRM are not considered operational flexibilities for this study, as they are important for the safety of lives and property as well as dam safety and should have less effect on the reservoir drawdown that often precedes harmful algal blooms.

Typically, when spring runoff occurs and the reservoirs begin to fill, water operation personnel increase flows out of the reservoirs to maintain space or create space to capture future runoff. In Figure 5, which shows how Cascade Reservoir was operated in water year 2019, the gold line depicts outflow from Cascade Dam. Runoff into Cascade Reservoir for this water year was about 9 percent higher than average (e.g., about 759,000 vs. 694,000 acre-feet average during 1995-2024; see Section 3.3). Outflow is increased in late February to maintain space in the reservoir. Releases for FRM vary from year to year. It is difficult to predict any certain flow volumes early in the year. After it is determined that FRM is no longer needed, flows are adjusted to allow the reservoir to fill and later to meet flow augmentation and irrigation demands.

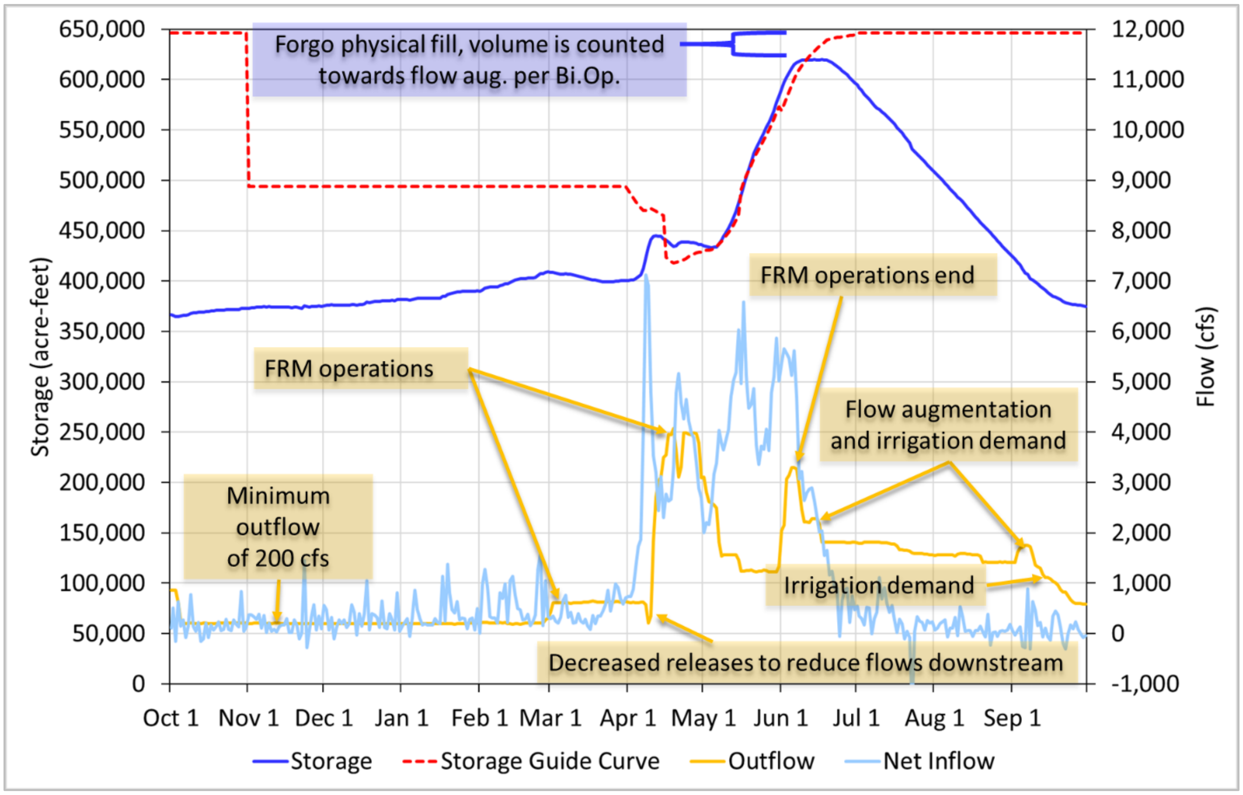



Figure 5. Typical water operations for Cascade Reservoir, showing water year 2019 time series plot of storage (dark blue), net inflow (i.e., losses subtracted; lighter blue), outflow (gold), and flood risk management (FRM) guide curve (red).

#### 3.1.2.3. Releases for Irrigation

Stored water is primarily used for meeting the irrigation demand for contracted spaceholders. Releases for irrigation demands generally begin when FRM ends. Downstream demands are met first by natural flows from unregulated tributaries to the Payette River and then by water released out of Deadwood and Cascade Reservoirs. If irrigators are not receiving enough flow to meet their demands, they contact the Water District 65 manager and "call" for more water to be released from the reservoirs. The Water District and the Idaho Department of Water Resources closely monitor water right storage and deliveries. Reclamation has contractual obligations to deliver this water if it is available and without discretion. Reclamation has no discretion over the timing and amounts released from the reservoirs specifically for irrigation, which is determined by the watermaster, irrigation districts, and water right and space holders, but Reclamation can decide how the total amount is distributed between different reservoirs. Balancing releases between reservoirs is a primary operational flexibility used to meet water requests while meeting incidental benefits (e.g., holding recreational flows at relatively constant rates) while depleting reservoirs similarly to equalize the amount of water left at the end of the year (reservoir carryover) and balance the probability of them refilling in the following year. Balancing between the reservoirs is limited by the amounts of water available in each reservoir and water level limits for conservation and ecological benefits. Reservoirs are balanced within the operational, conservation, and ecological constraints to optimize the probability that both reservoirs will fill in the following year.

#### 3.1.2.4. Releases for Recreation

Releases are not made or limited explicitly for purposes of supporting recreation, as this is outside the purposes for which the dams were authorized (e.g., irrigation and power production; Reclamation 2002). However, recreation, both on the reservoirs and downstream, is affected incidentally by reservoir operations. Water being released for flow augmentation and irrigation demand at both Cascade and Deadwood Dams effectively perpetuate flows that enhance recreational activities on the rivers. Flows out of Cascade Reservoir typically range from 1,200 to 2,200 cfs during the summer months, which allows river activity on both the North Fork Payette and the mainstem Payette Rivers. Deadwood Reservoir flow augmentation and irrigation releases incidentally provide recreational activities on the South Fork Payette River and the mainstem Payette River. Flows on the South Fork River above approximately 1,200 cfs provide adequate water for safe river recreation.

#### 3.1.2.5. Releases for Power Generation

The powerplant below Cascade Dam is owned and operated by Idaho Power Company (IPC), which holds water rights for up to 2,200 cfs of flow, with 200 cfs of the rights senior to the storage rights for the dam. During the irrigation season, all IPC's water rights can be junior to the irrigation water rights downstream, so Reclamation does not typically release stored water expressly for the purpose of electrical generation. However, hydroelectric power is generated with reservoir releases routed through the powerplant whenever feasible. As such, hydroelectric power generation is largely incidental and most of the time has little influence on the operation of Cascade and Deadwood Reservoirs. However, after the irrigation season and through the winter and early spring, when 200 cfs of their 2,200 cfs water rights come into priority, at least 200 cfs typically needs to be released for power generation; since power generation is a non-consumptive use, this effectively provides a minimum amount of flow below the dam.

Additional power can be generated incidentally when more water needs to be released for other purposes. When other releases for FRM, flow augmentation, and irrigation deliveries occur, IPC can route this additional flow through the powerplant's two generating units to meet their 2,200 cfs of non-consumptive water rights. Releases exceeding the powerhouse's capacity must either pass through the outlet works or over the spillway; typically, the spillway would be used so as to not interfere with hydraulic head for power generation.

The powerplant at Deadwood Dam only generates power for Reclamation's local use, with a flow capacity of 2.3 cfs. No power is sold or generated for use on the grid. Water is not generally released specifically for power generation at Deadwood Dam, and it is generated incidentally from releases for other purposes.

##### 3.1.2.6. Releases for Instream Flow

All instream flow releases made from Cascade and Deadwood are in accordance with the water rights contracts and are fully accounted for in Idaho's Department of Water Resources accounting database. Cascade Reservoir must maintain at least 200 cfs of flow below the dam when Idaho Power Company's water rights that are senior to the storage rights for the reservoir are in priority, but there is no dedicated reservoir storage for these releases. As noted above for power generation, these are not true minimum flows, as they are released for power generation, but they effectively provide a minimum amount of flow below the dam since power is a non-consumptive use. At Deadwood Reservoir, 24,515 acre-feet of storage is used for instream flows to benefit ecological function, but recreation also benefits from these releases. Releases to maintain at least 50 cfs of instream flow below Deadwood Dam generally occurred from the end of August through winter or early spring. Note that these minimums changed to 5 cfs in 2024, which post-dates the timespan of this study.

##### 3.1.2.7. Releases for Flow Augmentation

Water is also reserved in the reservoirs for flow augmentation, which increases flows in the Snake and Columbia Rivers when it is beneficial for out-migrating ESA-listed anadromous fish (e.g., salmon and steelhead). The volume reserved and the flow rate and timing of these flow augmentation releases are set according to the 2007 Upper Snake Biological Assessment, the 2008 Upper Snake Biological Opinion, and through coordination with the Columbia River Technical Management Team. Reclamation has committed to shifting flow augmentation releases in the upper Snake River basin to earlier in the migration season, when Snake River flows are more beneficial to federally listed fish. However, like irrigation, there is some operational flexibility over which reservoir flow augmentation is released from, to balance the system, but is also subject to the same water level limits.

Currently the Payette basin provides up to 95,608 acre-feet of storage water from uncontracted storage space for flow augmentation. Additionally, water from the rental pool is also used for flow augmentation. The volume of water provided from the rental pool fluctuates annually, typically between 40,000 and 70,000 acre-feet, and is made up of stored water that is made available for rental by the storage spaceholders in lieu of using the water. Flow augmentation releases begin in the summer and are released through August 31.

#### 3.1.2.8. System Balancing

In October, the volumes stored in Cascade and Deadwood Reservoirs are balanced to give the highest likelihood of filling both during the following refill season. This is possible because the diversion point for storage spaceholders in both reservoirs is downstream of the confluence of the North Fork Payette River and the South Fork Payette River. Typically, Cascade is kept at higher percentage (around 10 percent) of full than Deadwood at the end of the irrigation season, since it is larger and generally harder to fill.

## 3.2. Modeling Constraints

Computer modeling can be used to simulate a wide array of physical systems and management changes to those systems. Different models have different uses and capabilities, but the limitations of models may constrain their use. These limitations affect the scope of a study. Some limits are particular to the modeling software; others to the system being modeled. This study used one model to simulate river and reservoir operations, followed by a second model to simulate reservoir water quality resulting from those operations. The specific modeling constraints relevant to these models, in general, and specifically to this study are described in the subsections that follow.

### 3.2.1. Constraints for Operations Modeling in RiverWare

The river-reservoir operations model was developed in RiverWare, which is a rule-based river system modeling program. The model is configured to run with daily timesteps for 2018 through 2022. The Payette River basin is represented using a network of interconnected nodes representing river reaches, reservoir, diversions, and return flows. Water enters, leaves, and moves through the system and is allocated to water users according to programmed rules that follow logic intended to reflect real-world operations and water rights. Boundary conditions such as inflows and gains and losses for different tributaries and river reaches in the Payette River basin (e.g., north, south, middle, and main forks of the Payette River; reservoir net inflows) are set using historical gage measurements. Outputs from the RiverWare model include inflows, outflows, and water storage for reservoirs and gaged river reaches in the modeled system, as well as diversion volumes and rates. Water quality values, such as temperature and dissolved oxygen concentration, are not included in the RiverWare model.

### 3.2.2. Constraints for Water Quality Modeling with CE-QUAL-W2

CE-QUAL-W2 is a two-dimensional, laterally averaged, hydrodynamic and water quality modeling environment that can be used for rivers, estuaries, lakes, reservoirs, and river basin systems (Wells 2023; https://www.ce.pdx.edu/w2/). The model runs with varying timesteps, slowing down when necessary to achieve model stability (e.g., hydrodynamic calculations) while abiding timestep constraints specified by the user. For this study, timesteps varied from up to 60 seconds to as little as a fraction of a second. The model must be configured and calibrated individually for each system being modeled, which requires data about the reservoir, hydrology, meteorology, and water quality information.

In the CE-QUAL-W2 modeling software, water bodies are represented using a grid of vertical layers and longitudinal segments to discretize them into a series of adjacently stacked rectangular blocks that vary in lateral width to represent the volumetric shape of the reservoir (bathymetry). The model assumes that each longitudinal segment is well mixed (laterally averaged). Because the model is laterally averaged, spatial differences in the lateral direction are not simulated, which is generally appropriate in rivers and reservoirs that are longer than they are wide, such as Cascade Reservoir. The vertical and longitudinal resolutions of model outputs are also limited, as the computational intensity of a simulation increases dramatically at finer spatial resolutions and using a greater resolution sacrifices computation efficiency for diminishing returns in model precision. For example, a three-dimensional model might provide more spatial detail within a reservoir but could take longer to run and limit the scope of the study to fewer years and operational alternatives. Using a two-dimensional model is generally a justifiable tradeoff to allow for computational focus on other factors (e.g., flow dynamics, chemistry, and biological processes) while producing acceptable precision, depending on the questions being researched.

Model inputs include reservoir inflows, inflow water quality parameters, reservoir releases, water levels, and meteorology to drive reservoir hydrologic and thermal dynamics and simulate flow dynamics and water quality. Chemical and biological processes and their interactions with other water quality and physical variables can also be modeled. The water characteristics modeled in this study include water temperatures, chemistry, nutrient dynamics, sediment kinetics, and algae growth, reproduction, toxin production, death, and decay. The ability to model toxin production is a feature added recently by the Portland State University (PSU) team (Garstecki, 2021; Garstecki and Wells, 2023). These various data can be output from the model at the scale of the model grid to analyze and study how water quality varies within the reservoir and changes over time.

This study focused on how possible changes to operations might affect harmful algae concentrations in Cascade Reservoir. A CE-QUAL-W2 model for Cascade Reservoir was specifically developed and calibrated by the model developers (Wells et al. 2023) for this purpose, based upon historical hydrological, meteorological, and water quality data. This study assumed the previously calibrated model represented the best available configuration for the model and modified only the reservoir outflows and water levels using data from the RiverWare simulations of the operating alternatives. Improving or further validating the model calibration was beyond the scope of this study.

## 3.3. Project Timeline Constraints

Funding for this study was provided through Reclamation's WaterSMART Basin Study Program as part of the Reservoir Operations Pilot Initiative. A limited project timeline was a condition of this funding, with the study starting in March 2021 and being completed by December 2024. This short study time frame limited how many years and operational scenarios could be modeled. Since the water quality model was developed during the 2023 water year, only data through 2022 were available at the time, so the model timespan was limited to 2018 through 2022. The years modeled varied in annual net inflow and average temperatures during August and September, when harmful algal blooms typically occur (Table 3). The years included some years that were wetter or drier than average. Air temperatures were similar among the years but included a couple of years that were hotter than average (e.g., 2021 and 2022).

Table 3. Comparison of net inflows and air temperatures of the years modeled (2018 through 2024), summarized as annual unregulated inflow volumes for Cascade Reservoir and average air temperatures at Cascade Dam during the peak harmful algae-producing months of August and September. Results are compared to 30-year averages during 1995 through 2024.

| Year | Annual Net Inflow | | Air Temperatures in August and September | |
|---|---|---|---|---|
| | Total (acre-feet) | Percent of 30-Year Average | Average (°F) | Percent of 30-Year Average |
| 2018 | 655,069 | 94% | 62 | 100% |
| 2019 | 758,583 | 109% | 61 | 99% |
| 2020 | 590,310 | 85% | 63 | 100% |
| 2021 | 371,060 | 53% | 64 | 103% |
| 2022 | 565,976 | 82% | 66 | 105% |
| 30-year average (1995-2024) | 694,261 | -- | 62 | -- |

# 4. Data Collection and Historical Conditions

Historical data for Cascade Reservoir were used for developing and calibrating the water quality model. These data included historical hydrology, historical water quality, reservoir bathymetric data, elevation data for the surrounding topography, and historical meteorological data. These data are described in more detail in the subsections that follow. Greater detail is provided in the model documentation (Wells et al 2023).

## 4.1. Historical Hydrology

For developing the water quality model, historical hydrologic measurements from Reclamation's Hydromet database (https://www.usbr.gov/pn/hydromet/ ) were used, including historical inflows to Cascade Reservoir from the North Fork Payette River, water levels and storage for Cascade Reservoir, and historical outflows. For the operations model, the model was extended from calendar years 2018 through 2022, which required additional gage flow and reservoir measurements from Hydromet for gages throughout the basin. These measurements were used to calculate the historical net gains and losses for the different reservoirs and river reaches. Historical measurements for irrigation diversions within the Payette River basin were obtained from a data request to Idaho Department of Water Resources.

## 4.2. Water Quality Sampling and Measurements

Reclamation regularly collects measurements and water samples from Cascade Reservoir during the spring and summer. This provided a database of historical measurements used by the model developers (Wells et al. 2023) for model calibration. In general, water quality measurements and samples were taken monthly at six sampling locations across the reservoir from multiple depths, including near the surface and bottom. Following the start of this study, the existing water quality sampling plan was expanded to provide more data for calibrating the water quality model. During the first 2 years of the study (i.e., 2021 and 2022), existing sampling protocols were expanded as part of this study by assessing additional water quality characteristics, adding sampling locations, sampling at more depths, and sampling more frequently. These data were provided to the model developers for calibration purposes. The water quality lab that processed the water samples did not have the capability of specifically measuring concentrations of harmful algae or toxins.

## 4.3. Bathymetric and Elevation Data

Bathymetric data for Cascade Reservoir were available from a 1995 reservoir sedimentation survey (Reclamation 1998) and are presented visually in Figure 2. The water quality model developers used these data to define the water quality model spatial boundaries and grid. They used digital elevation data for the land surrounding the reservoir to calculate topographic shading, which affects the sunlight that the reservoir is exposed to and can affect water temperatures. They spatially defined the reservoir using a grid of regular blocks with consistent height (i.e., 1 meter, or 3.28 feet) and longitudinal length (352 meters, or 1,153 feet), relative to the flow direction, but varying in width according to the dimensions of the reservoir (Figure 6). This grid was defined such that it maintained the known bathymetric relationship between reservoir water levels and storage volumes and represented the various branches of the reservoir.

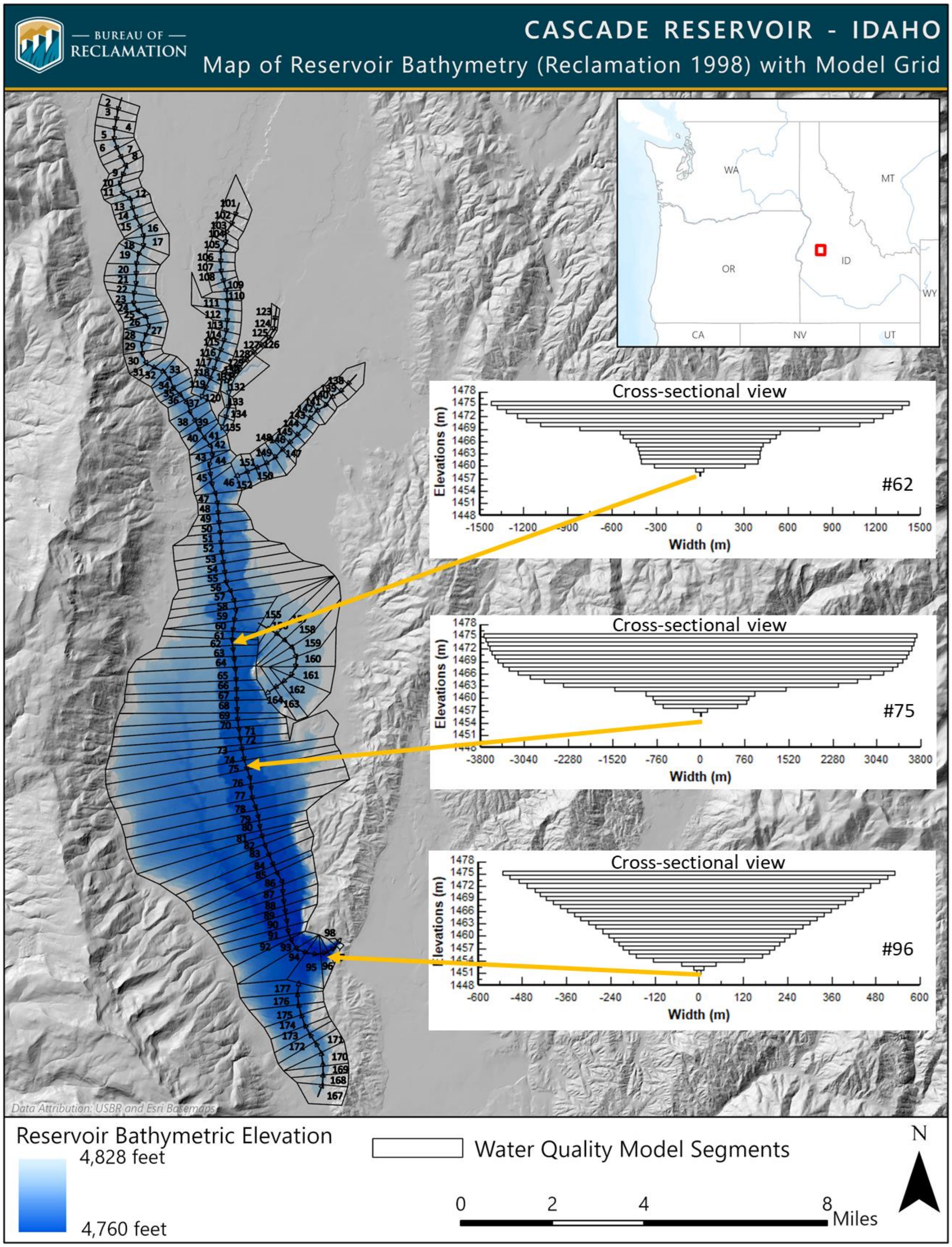



Figure 6. Map showing water quality model grid overlaying reservoir bathymetry (Reclamation 1998), with hill-shaded topography in background. Insets show example model cross-sections (i.e., side views).

## 4.4. Meteorological Data

Meteorological data were obtained by the model developers for weather stations near Cascade Reservoir. Air temperature data were primarily from a sensor at Cascade Dam (station CSC). Gaps in the CSC air temperature data were filled via interpolation for smaller (<6 hours) gaps; larger gaps (i.e., up to 1 day) were filled based on regressions with other nearby weather stations. One nearby weather station was about 1 mile north of the dam, and a second weather station was about 25 miles north. Cloud cover, dew point temperature, relative humidity, wind speed, and wind direction data used in the water quality model were obtained from a weather station near the McCall Airport (station KMYL).

# 5. Modeling Methods

This section describes the methods used to implement the reservoir operating alternatives in 1) an operations model using RiverWare to simulate system operations and calculate releases through the different dam structures, and 2) a CE-QUAL-W2 water quality model to simulate harmful algae growth dynamics. The modeling efforts were sequential, with the reservoir releases and water levels from the operations model used as inputs by the water quality model.

## 5.1. Operations Model Adaptation

A previously developed operations model for the Upper Snake basin (Reclamation 2023) was used as a starting point for developing an operations model for this study. Several changes were made to use the model for this study. The geographic scope of this model includes the whole Upper Snake River basin from Brownlee Dam upstream to the various headwaters. Since this study was focused on operations within the Payette River basin, the model was simplified to only run the Payette River portion of the model, which includes Cascade, Deadwood, and Black Canyon reservoirs, the North Fork, South Fork, and main Payette River, and water diversions from the headwater reservoirs down to the confluence of the Payette River with the Snake River. This made running the model faster, reducing the time for testing of subsequent modifications and scenario development.

Since this study was focused on recent years, 2018 through 2022, and the operations model only ran through the end of the 2018 water year, the operations model run period was extended. The model uses daily average inflows and river reach gains and losses at various points in the system. These inflows, gains, and losses are calculated using hydrologic mass balance principles in an independent model previously developed for the purpose in the MODSIM software (Reclamation 2023). This model was extended through 2022 using historical data for gage flows, reservoir water levels, and diversions (Section 4).

The full operations model also runs for more years than required for the scope of this study; the original model started with the 1928 water year. Since this study focused on 2018 through 2022, the model was limited to run during this period, with reservoir levels starting from historical values. This also increased the model speed and expedited scenario development and modification testing.

One important component of operations is the management of flow augmentation releases. In real-time operations, flow augmentation is determined based upon many different factors. For this study, the amount of flow augmentation from the Payette River basin was set to the historical volumes that were contributed each year. These volumes were distributed as the daily historical values, which were tracked by real-time operations. The daily volumes were then split with 80 percent coming from Cascade Reservoir and 20 percent coming from Deadwood Reservoir.

In addition to the above changes, the model was updated to improve the simulation of historical operations (i.e., model calibration). These changes included updating flood space calculation tables, improving operating logic, and adjusting releases for flood risk management, irrigation flow management (i.e., carriage flow managed at the gage on the Payette River near Letha), and late season irrigation releases. The balancing of releases from Cascade and Deadwood Reservoirs for the various purposes was also adjusted to better simulate historical water levels.

## 5.2. Operations Modeling and Alternatives

Several operating alternatives were simulated by the operations model. These operating alternatives were identified as theoretical operating alternatives that would not violate hard operational constraints (see Section 3). However, many of these alternatives would involve changes in operations that could affect other purposes (e.g., hydropower, flow augmentation benefits, and recreation). These operational alternatives are theoretical and are not under consideration for actual implementation at this time, as the potentially adverse effects to other purposes would first need to be fully explored and considered.

All alternatives used the 'Baseline' alternative as a starting point for model changes. The model was modified to simulate each operational alternative different, but operations were kept as consistent as possible to facilitate comparisons of the changes in operations inherent to each alternative. For example, when adjusting releases between Cascade and Deadwood Reservoirs, the logic was implemented such that the same amount of water would be delivered for each purpose; just the relative proportions from each reservoir differed. The specific changes required to implement each alternative are detailed below.

### 5.2.1. 'Baseline' Alternative

The 'Baseline' alternative is meant to represent the historical operations of the reservoir, against which the alternatives involving changes in operations were compared to assess changes. Since operations needed to be adjusted for the other alternatives, the operations needed to be represented using repeatable model logic (e.g., operating rules written in a programming language). Getting model logic to replicate real-world operations is challenging, as many factors are considered in decision making for real-time operations, including current and future forecasted weather, snowpack, soil storage, runoff forecasts, anticipated water requests, and other factors. The difference between the modeled and actual historical operations represents the model bias. To avoid incorporating model bias into the comparisons of the operating alternatives, it was necessary to first model the historical operations so that they could be adjusted for each scenario, and so the effects of those changes could be isolated. This modeled historical operation is the 'Baseline' alternative.

### 5.2.2. 'Use Spillway' Alternative

Since the dam's intake structure, which controls flow to the outlet and powerhouse, is at a lower elevation than the dam's spillway, the spillway withdraws more water from higher in the reservoir. In current operations, water is passed through the powerhouse to capacity before the spillway is used. In the summer, water near the surface of the reservoir tends to be warmer, with relatively cooler water being released when using the intake and powerhouse, leaving warmer water behind. Releasing more water via the spillway should withdraw warmer water from this surface layer more, leaving cooler water behind and potentially reducing temperatures in the reservoir and the growth of harmful algae. The 'Use Spillway' alternative was intended to test this idea. Importantly, using the spillway instead of the powerhouse would entail large potential effects to hydropower generation that would need to be fully assessed before this theoretical alternative could be considered for actual implementation.

To model the 'Use Spillway' alternative, as much of the releases as possible were routed through the spillway, except for 200 cfs for the water right for power generation, which was routed through the intake and powerhouse. The spillway was preferentially used in this way throughout the model run, during all times of year. This change in operations had no effect on the total amount of water that could be released (i.e., spillway capacity was not a limiting factor), so total daily releases were the same as for the 'Baseline' scenario. The lowest water level elevation from 2018 through 2022 was about 4,814 feet, which is 6 feet above the spillway sill (4,808 feet). As water levels drop to near the spillway sill elevation, releases over the spillway can be limited by hydraulic capacity, but water levels never fell this low. Historically, water levels have not been lowered to near the spillway sill since 1980. For these reasons, the total amount of water released by the dam was unchanged throughout the model run, and it was not necessary to adjust operations of Deadwood Reservoir from the Baseline operations.

### 5.2.3. 'Early Flow Aug.' Alternative

The 'Early Flow Aug.' alternative released the same total volume of water for flow augmentation but with more released earlier in the season (June and July) and less later in the season (August) to test the influence on harmful algae concentrations. The 2007 Upper Snake Biological Assessment (Reclamation 2007) suggested earlier flow augmentation releases from other reservoirs in the upper Snake River basin to benefit out-migrating ESA-listed fish species. Releasing flow augmentation from Cascade Reservoir earlier in the year would cause lower water levels and storage volumes earlier in the season, potentially resulting in a failure to meet water quality standards. Due to the increased concerns with a negative impact to water quality, Cascade Reservoir flow augmentation is generally released in late July through August. Assessing other potential water quality characteristics during an 'Early Flow Aug.' alternative was beyond the scope of the current study but would be important to consider for the theoretical operation. Additional impacts resulting from an 'Early Flow Aug.' alternative would include reduced summer flows for recreation, reduced summer power generation, potential irrigation operation loss, and reduced flows lower in the system. The collective impacts for this theoretical operating alternative would need to be more fully assessed before being considered for actual implementation.

For the 'Early Flow Aug.' alternative used in this study, the total annual volume of flow augmentation remained the same as the 'Baseline' but was released at a higher rate to end earlier in the summer. This additional flow was released through the intake structure, so it was not necessary to use the spillway. This change was made for both Cascade and Deadwood Reservoirs since they are operated together to meet flow augmentation requirements. The 'Early Flow Aug.' releases were set from the 'Baseline' start of the flow augmentation releases for each year through the end of July, at a constant rate, versus the 'Baseline' releases that extended through the end of August. This change to flow augmentation operations scheme was repeated in each of the 5 years modeled. The daily and total flow augmentation releases were split between the reservoirs as in the 'Baseline' alternative, with 80 percent released from Cascade Reservoir and 20 percent from Deadwood Reservoir.

### 5.2.4. 'Use Cascade First' Alternative

The 'Use Cascade First' alternative adjusted operations to preferentially use Cascade Reservoir first earlier in the year to test how earlier reservoir drawdown might affect harmful algal blooms. For this alternative, Cascade Reservoir was used first to meet flows needed for irrigation and flow augmentation. Early in the year, Deadwood Reservoir still released water for its independent operations for FRM and minimum flows; flood space was not altered for the dams, as it is related to dam safety and was considered an operational constraint (see Section 3.1). However, since Deadwood Reservoir stayed fuller, additional FRM releases were required, which were accounted for in Cascade Reservoir's releases to avoid releasing more water than necessary. Once Cascade Reservoir was lowered to around its annual historical low for each year, releases were reduced to 200 cfs for power generation, and Deadwood Reservoir was used instead to meet remaining irrigation and flow augmentation demands. The releases from the reservoirs were adjusted so that the reservoir carryover was as close to the 'Baseline' as possible. The historical reservoir carryover amounts were considered fixed constraints for operational flexibility, as changing them would affect ability to refill the reservoirs and cause over-releasing from one reservoir (e.g., Cascade) in one year to affect water levels in the subsequent year. Balancing the end of season carryover ensured that the reservoirs were used more consistently with the water rights associated with each and able to refill to avoid affecting operations in the next year. Assessing such multiyear effects was beyond the scope of this study.

Importantly, this theoretical alternative would involve reduced releases from Cascade Reservoir later in the summer, after it has reached it minimum, which could have negative effects for recreational flows on the North Fork Payette River. These potential effects would need to be fully assessed before being considered for actual implementation.

### 5.2.5. 'Use Deadwood First' Alternative

The 'Use Deadwood First' alternative tested the effects on harmful algae concentrations of preferentially using Deadwood Reservoir earlier in the year, while reducing releases from Cascade Reservoir and keeping it fuller for longer. This alternative was implemented similar to the 'Use Cascade First' alternative but was reversed so that Deadwood was used to meet demands first, until it reached it near its historical annual minimum, and then Cascade was used as much as possible. Importantly, this theoretical alternative reduced releases from Deadwood Reservoir later in the summer, after it has reached it minimum, which could have negative effects for recreational flows on the South Fork Payette River. These potential effects would need to be fully assessed before being considered for actual implementation.

## 5.3. Water Quality Modeling

The water quality modeling component of this study was conducted in two phases for 1) historical model development and calibration, and 2) implementation of the different operating alternatives to model potential effects to harmful algae. Each of these phases is described in more detail in the following subsections.

### 5.3.1. CE-QUAL-W2 Model Development

The water quality model was developed for 2018 through 2022 using the CE-QUAL-W2 software (Wells 2023) by the Water Quality Research Group in the Department of Civil and Environmental Engineering at Portland State University (PSU) (https://www.ce.pdx.edu/w2/). The model development and calibration are described in detail in a stand-alone report (Wells et al. 2023) and the process is briefly summarized below.

PSU used data and information provided by Reclamation, the Idaho Department of Environmental Quality, and online sources (e.g., meteorological stations) to develop the model. These data sources are described in Section 4. The reservoir bathymetry was defined using data from a 1995 sedimentation survey (Reclamation 1998) and combined with elevation data from around the reservoir. Elevation data for the surrounding terrain were used to calculate topographic shading, which affects the amount of sunlight the reservoir receives. Reservoir net inflows were calculated from reservoir water levels and outflows, with the total inflow split between the tributaries based on gage measurements, where available (e.g., North Fork Payette River), or split in proportion to their drainage areas (e.g., Lake Fork, Boulder Creek, and Gold Fork River). The water quality characteristics of these inflows were based on the limited measurements available (e.g., temperatures for specific periods) and adjusted during calibration based on water quality data from the reservoir branches near each tributary inflow. Dam releases were set to historical measurements of outflows, and the water balance was adjusted to ensure water levels matched historical measurements. Meteorological data from nearby weather stations were used to simulate air temperatures, wind, cloud cover, sunlight.

Water quality information from a range of locations within the reservoir was used to help calibrate the model. Although the primary output from the model used by this study was the harmful algae concentrations and toxins, it was not possible to directly calibrate the model to these variables, since the water measurement and sampling were unable to measure them directly (see Section 4.2). However, chlorophyll-a concentrations were measured, which should reflect the total concentrations of different types of algae, with concentrations during specific times of year reflecting the prevailing algae during those times (e.g., chlorophyll-a concentrations mainly reflect harmful algae during August and September). The model was calibrated to the chlorophyll-a concentrations, with a mean absolute error of about 10 micrograms per liter (i.e., 10 milligrams per cubic meter). The model was also calibrated to other water quality characteristics, with associated model error quantified, such as dissolved oxygen, pH, nitrogen-based nutrients, phosphorus-based nutrients, organic carbon, conductivity, suspended solids, alkalinity, chloride, and sulfate. See the model development report for more information (Wells et al. 2023). The developers also calibrated the model to flow and water levels (root mean square error 0.037 meters) and temperature (outflow, root mean square error 1.08 to 1.33 $^{o}$C), and other water quality information for reservoir profiles at different sampling locations and for reservoir outflow (see Wells et al. 2023 for details).

During calibration of the water quality model by PSU, the model output indicated releases were cooler than historical measurements. These releases were primarily through the intake tower to the powerhouse. In reality, the intake extends from 4,802 to 4,762 feet, but using these values withdrew water from lower in the reservoir that was too cold. Prior diving surveys suggest that a sediment mound partially blocks the lower half of the intake structure. This mound and debris accumulation on the intake structures trash racks may be restricting withdrawals to higher elevations. Based on this information, and to improve the temperature calibration of the reservoir outflows in the model, the model developers artificially raised the centerline elevation of the intake to 4,810 feet and restricted it to only withdraw water from higher within the reservoir where water is generally warmer. This limited the ability to preferentially draw water from different elevations by releasing water via the spillway versus the intake structure (which, in reality, are vertically separated by only about 6 feet). Since the model required these adjustments to match historical outflow temperatures, it was assumed that this reflected reality with the intake generally withdrawing water from higher in the reservoir. The model was not modified from the settings that the model developers used for calibration.

### 5.3.2. Modeling of Operating Alternatives

The operating alternatives were set up for water quality modeling by first modeling the 'Baseline' alternative and then using that as a starting point for the rest of the alternatives. As discussed in Section 5.2, the 'Baseline' alternative differed from the historical calibrated model in that the dam releases and water levels were modeled based on logic in the river-reservoir operations model, rather than historical releases. This was done to facilitate comparisons between the 'Baseline' and the other alternatives; holding as many operations as possible consistent helps to isolate the effects of specific changes in operations. Each alternative was modeled starting from the 'Baseline' by only modifying the logic necessary to simulate the changes in operations.

For the water quality modeling, the main changes for all of the alternatives were to set the outflows for the different dam structures (i.e., spillway and dam intake/powerhouse outlet) to those produced by the operations model for each alternative. The water quality model was then run iteratively for each alternative to adjust inflows and ensure water levels matched those for the alternative in the operations model. This water level adjustment is a necessary step for all models in CE-QUAL-W2. It was performed using Python-based automation to call the CE-QUAL-W2 water balance utility and adjust the net inflows until the amount of error in the water levels stopped decreasing for subsequent runs (e.g., root mean square error values of around 0.07 feet or lower).

For some of the alternatives, the water quality model timesteps had to be adjusted to maintain stability in the hydrodynamic calculations, which would prevent the model from running completely. Timestep adjustments usually involved slowing down the model during specific periods, when the model previously encountered errors during hydrodynamic calculations, so that it maintained stability. These adjustments did not change the timesteps beyond the 'Baseline' range (e.g., <0.1 to 60 seconds). These changes in timesteps generally have minimal effects on water quality.

# 6. Modeling Results

The modeling results are summarized here for each operating alternative, with changes shown relative to the 'Baseline' alternative. These results focus on changes in water levels and releases, and associated changes in harmful algae and toxin concentrations. Additional water quality results are summarized in Appendix A. For summarizing the temperatures, harmful algae and toxin concentrations, and other water quality information summarized in the appendix, reservoir average values were calculated by having the model produce vertically volume-weighted averages at regular time intervals for each segment, which were then processed using Python-based automation to calculate volume-weighted averages across all the segments for each time interval.

## 6.1. Results for 'Baseline' Alternative

The 'Baseline' alternative simulates historical operations and water levels using RiverWare model logic and observed historical data. The model was able to reproduce water levels and outflows for Cascade and Deadwood Reservoirs similar to the historical data (Figure 7). Differences in operations may reflect differences in real-time forecasts, flood space guide curve adherences, reservoir balancing, and operator flexibilities that are difficult to represent completely in a model.

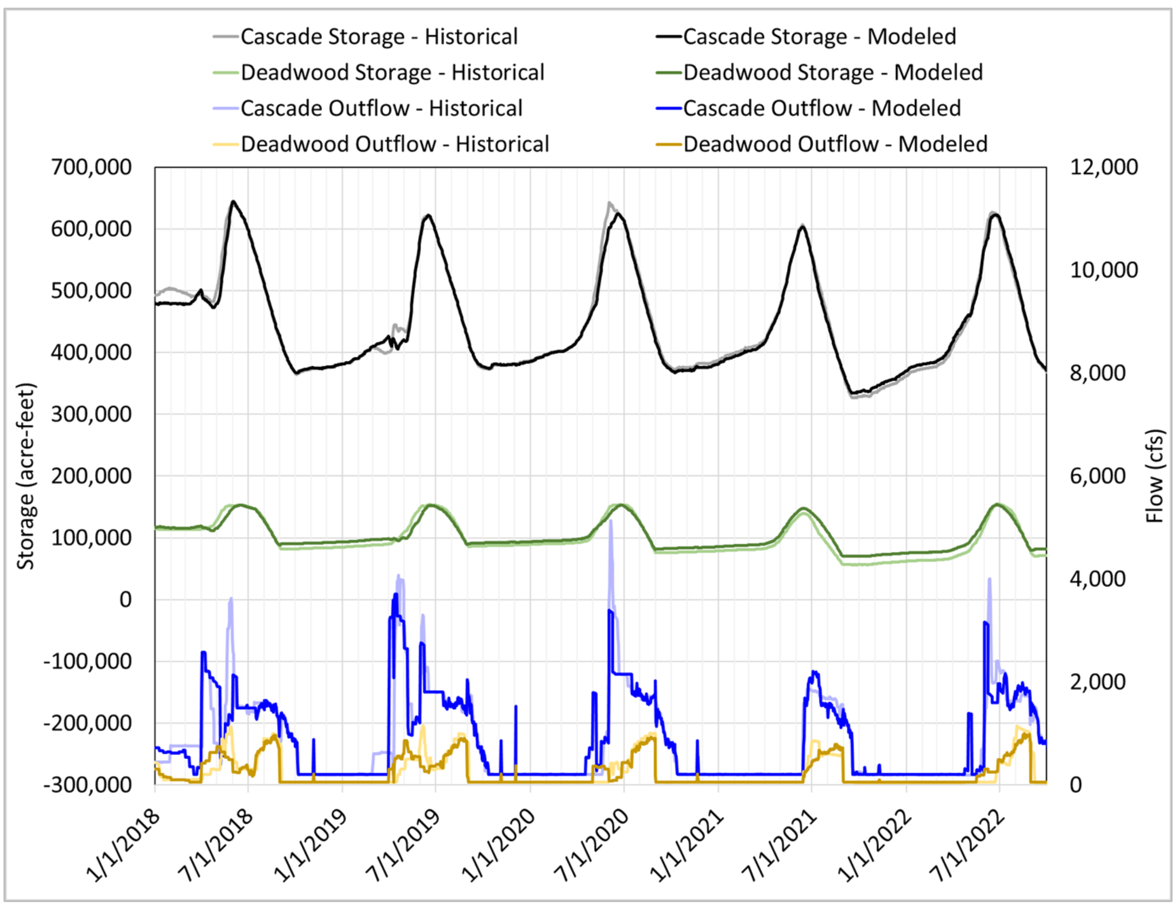



Figure 7. 'Baseline' alternative - reservoir storage and releases compared to historical measurements

## 6.2. Results for 'Use Spillway' Alternative

The 'Use Spillway' alternative routed all releases from Cascade Reservoir in excess of the 200 cfs water right for power generation through the spillway. The 200 cfs was released through the intake structure and powerhouse. For comparison, most of the release was passed through the intake structure and powerhouse for the 'Baseline' alternative. This routing had no effect on reservoir storage or the amount of water that could be released during 2018 through 2022 (Figure 8), since water levels never fell below the spillway sill and spillway outflow capacities were not a limiting factor. The lowest water surface elevation simulated in the 'Use Spillway' alternative during 2018 through 2022 was about 4,814 feet, which is 6 feet above the spillway sill (4,808 feet). Reservoir storage and total outflow from each reservoir was unchanged from the 'Baseline' alternative.

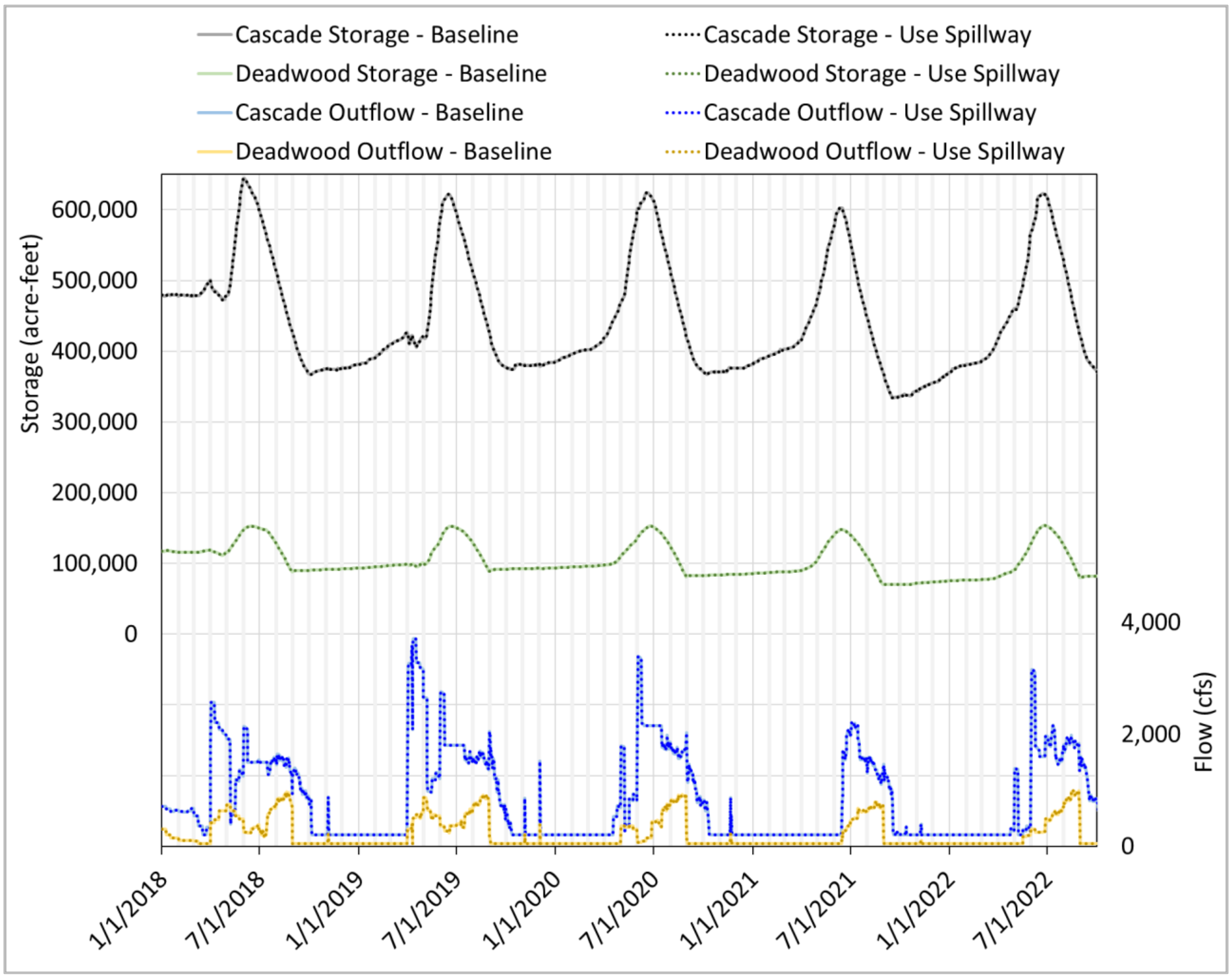


Figure 8. 'Use Spillway' alternative - changes in reservoir storage and releases. Note that the dotted and solid lines for each data type plot over each other and are the same, indicating no change in amounts released.

Although this alternative intended to selectively withdraw warmer water from higher up in the reservoir, it had little effect on armful algae concentrations (Figure 9) and toxins (Figure 10). There was also little effect on temperature, nutrients, and other water quality parameters (see Appendix A for additional results). Since the intake structure and spillway withdraw water from similar elevations (see Section 5.3.1), the lack of differences in harmful algae and toxin concentrations for this alternative are not surprising.

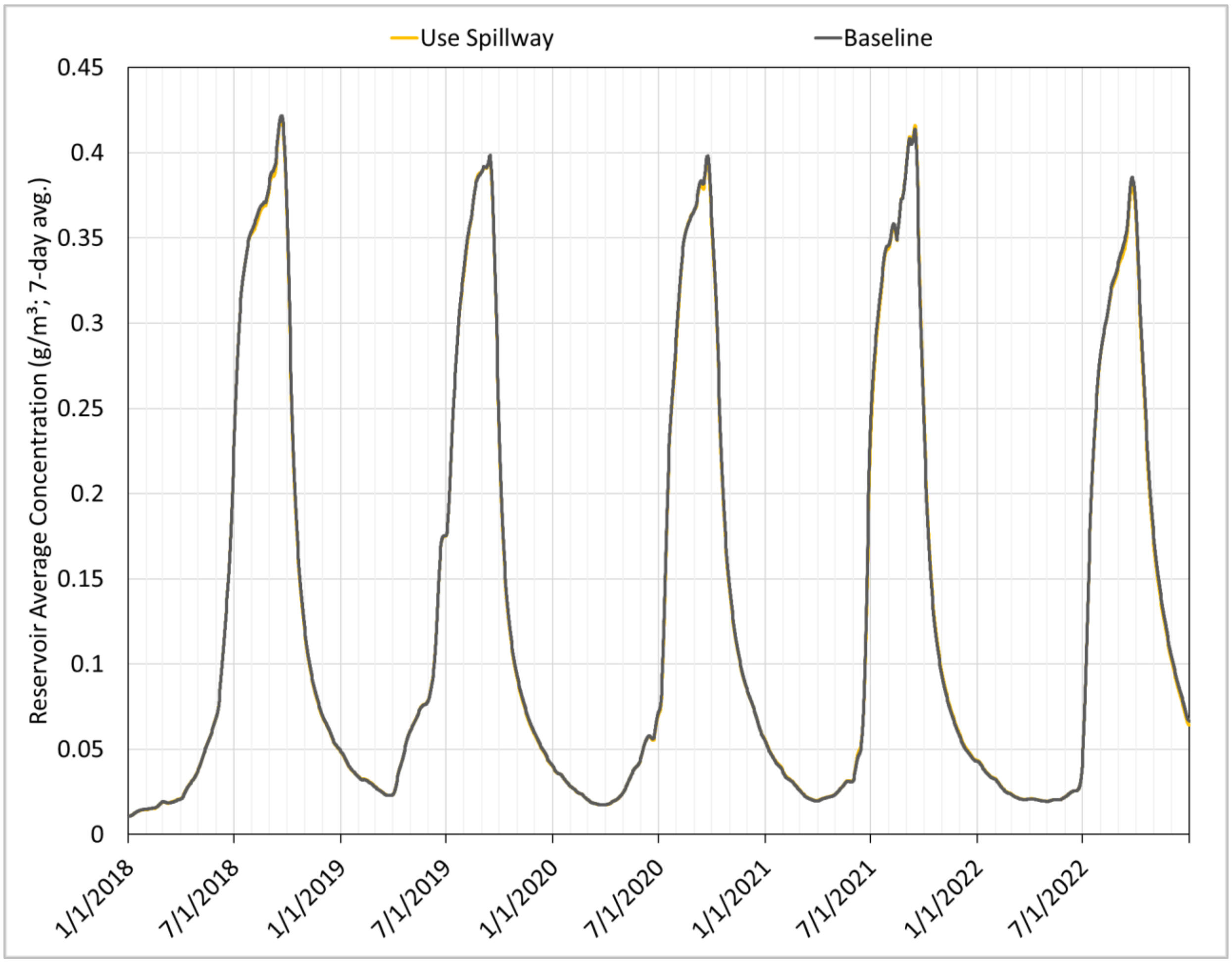



Figure 9. 'Use Spillway' alternative - changes in harmful algae concentrations

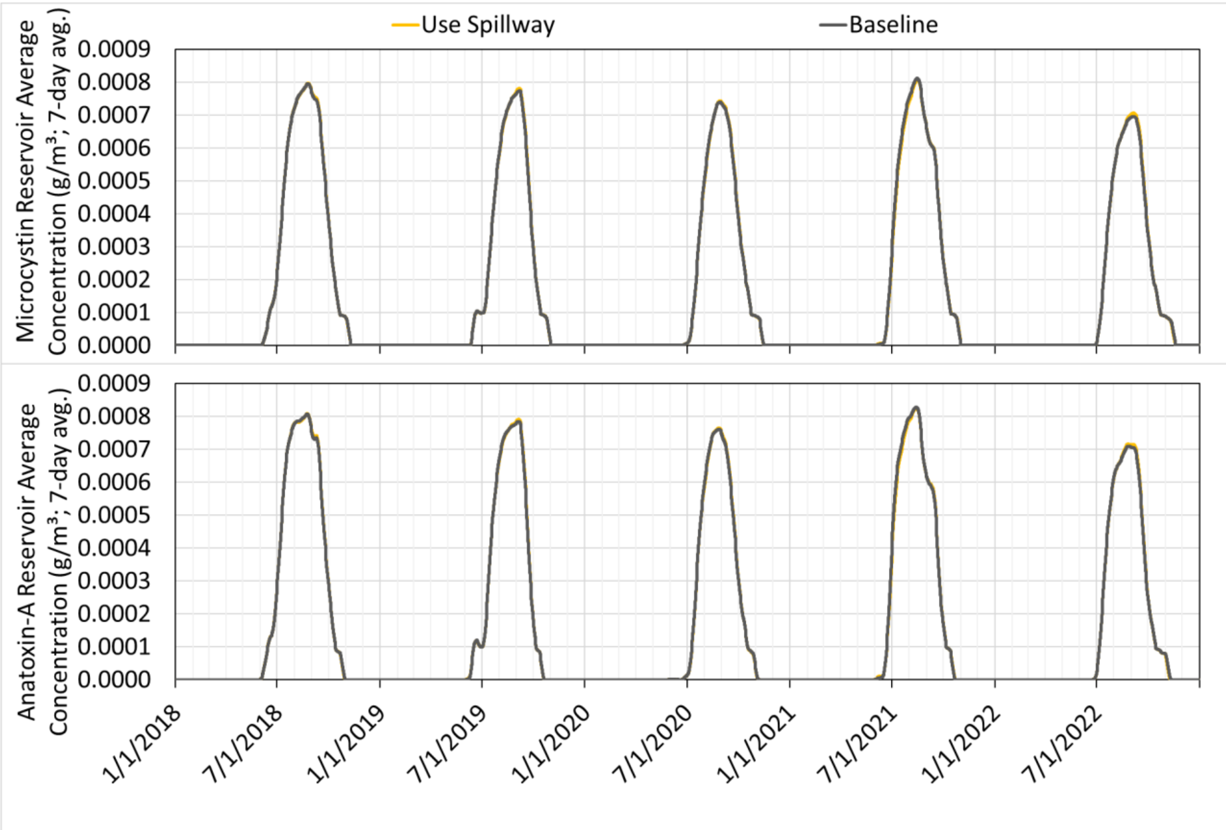


Figure 10. 'Use Spillway' alternative - changes in toxin concentrations

## 6.3. Results for 'Early Flow Aug' Alternative

The 'Early Flow Aug.' alternative generally released more water from Cascade in July and less in August (Figure 11). The increased releases in June and July were due to releasing the same total flow augmentation water volume for each year over a shorter period. This resulted in the reservoir drawing down a little faster in July but then slowing down in August when flow augmentation ceased. Additionally, the reservoir did not draft as low because the increases in releases in July were generally less than the decreases in releases in August. This effect is due to the increased flow augmentation releases in July reducing the amount of water that needed to be released for flood risk management afterwards and so reduced the overall total amount released. This caused the reservoir to carry over more water, with some improvements to refill in some years (e.g. 2021).

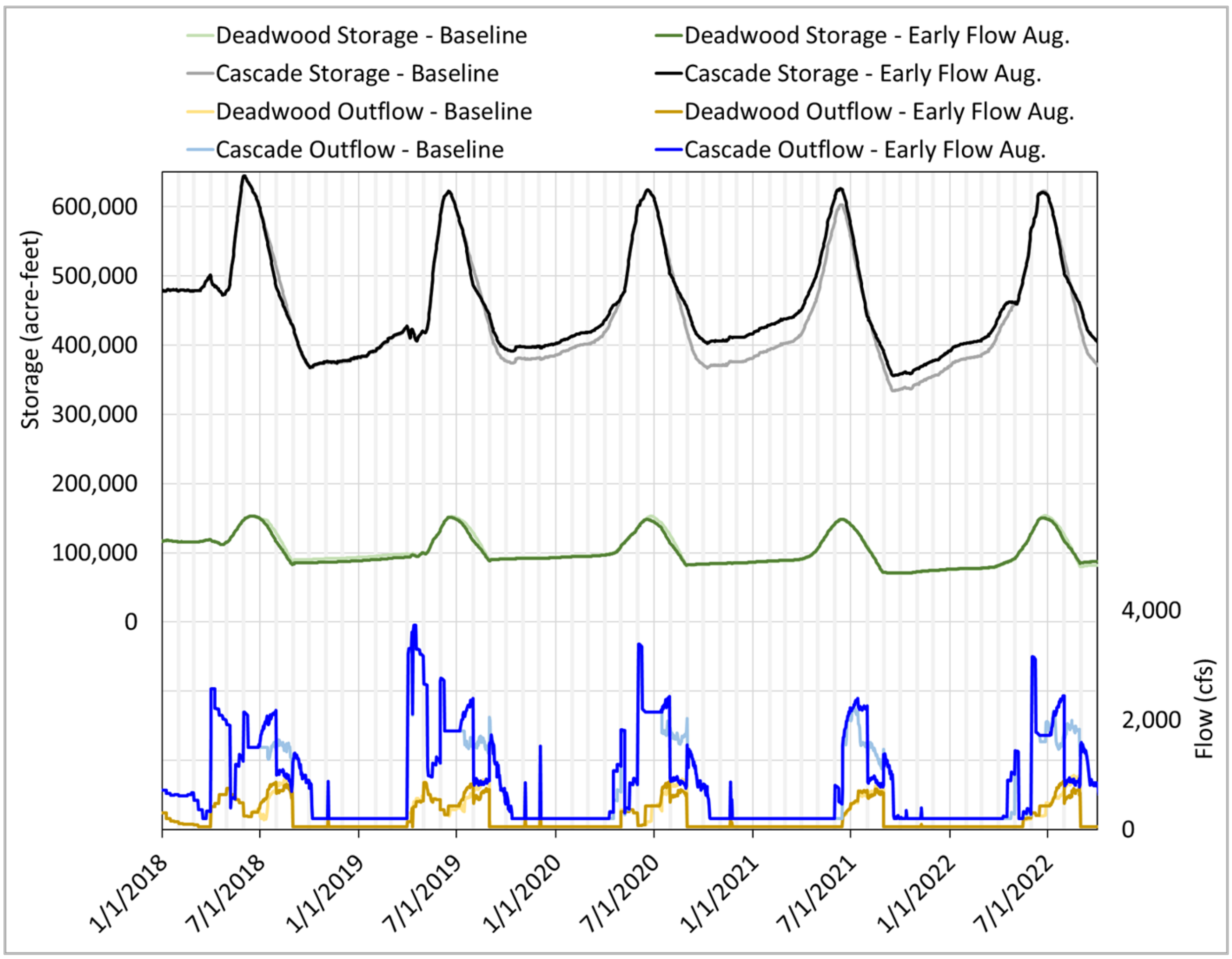



Figure 11. 'Early Flow Aug' alternative - changes in reservoir storage and releases

The changes in operations for the 'Early Flow Aug.' alternative sometimes increased or decreased reservoir average harmful algae concentrations, but these changes were small relative to the 'Baseline' average concentrations (Figure 12).

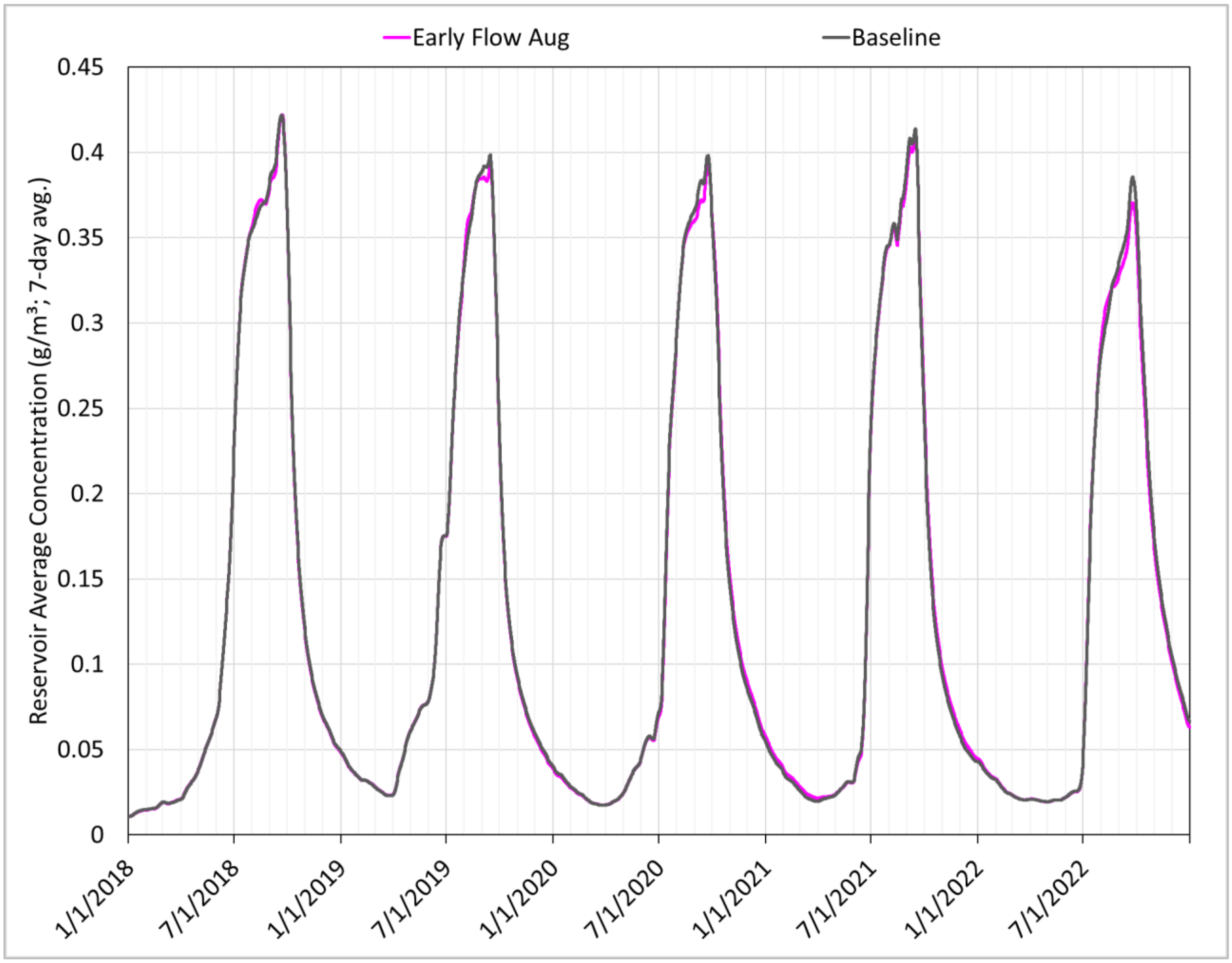


Figure 12. 'Early Flow Aug' alternative - changes in harmful algae concentrations

The 'Early Flow Aug.' alternative had little effect on the concentrations of toxins from the harmful algae, but the peak values did increase slightly (Figure 13).

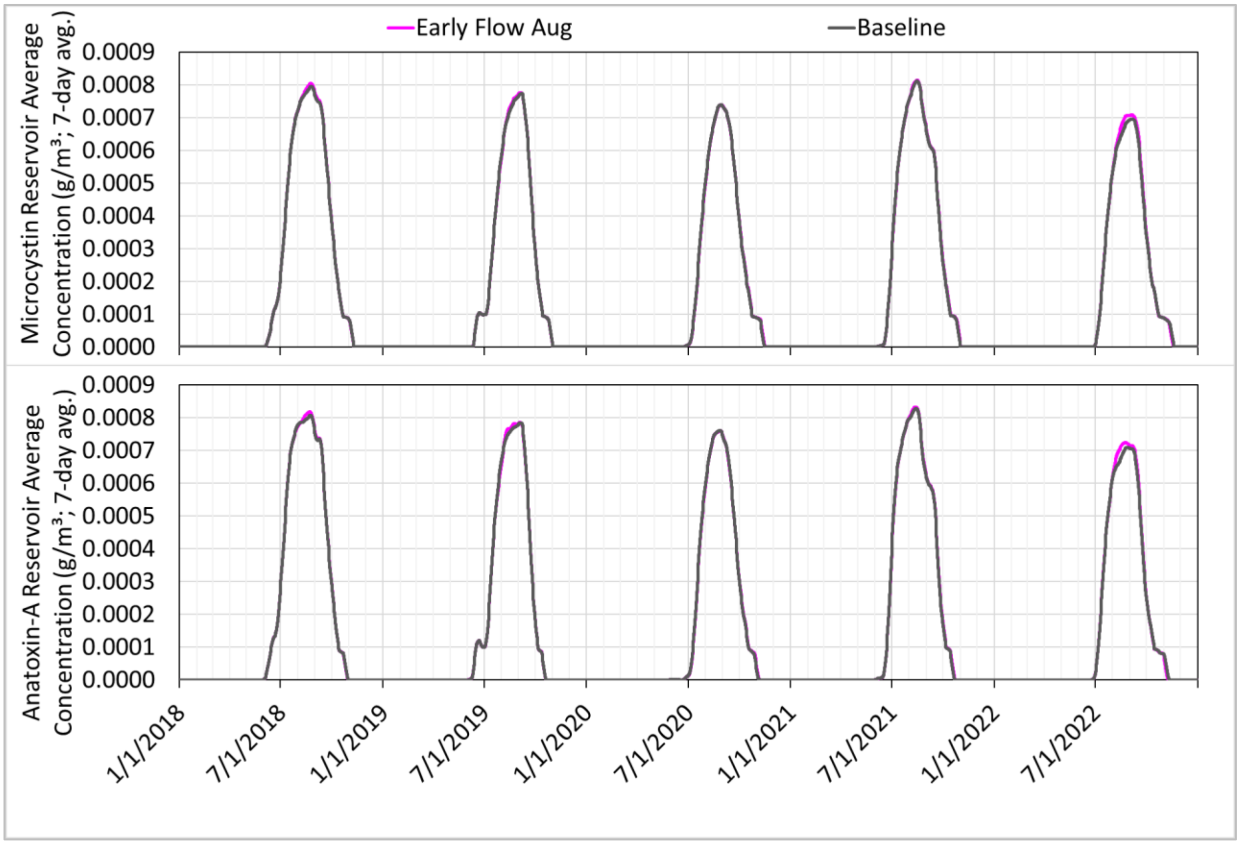



Figure 13. 'Early Flow Aug.' alternative - changes in toxin concentrations

## 6.4. Results for 'Use Cascade First' Alternative

The 'Use Cascade First' alternative increased releases from Cascade Reservoir in June through August, while reducing releases from Deadwood Reservoir (Figure 14). This caused storage for Cascade Reservoir to reach its annual low about a month earlier, while Deadwood was able to be kept full about 2 months longer.

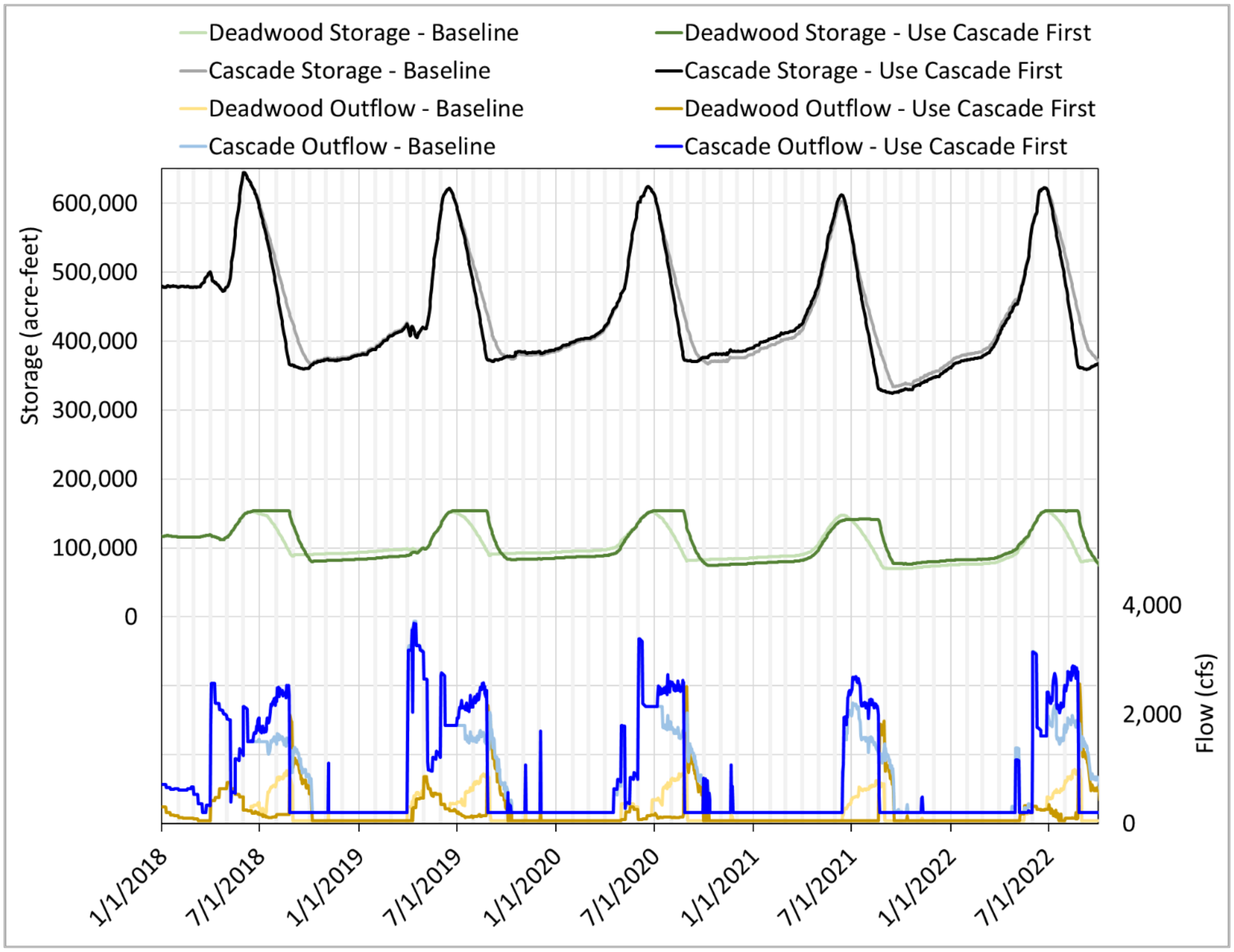



Figure 14. 'Use Cascade First' alternative - changes in reservoir storage and releases.

The changes in operations and water levels for the 'Use Cascade First' alternative increased peak harmful algae concentrations at some times, but these effects were again small relative to the total concentrations for the 'Baseline' (Figure 15).

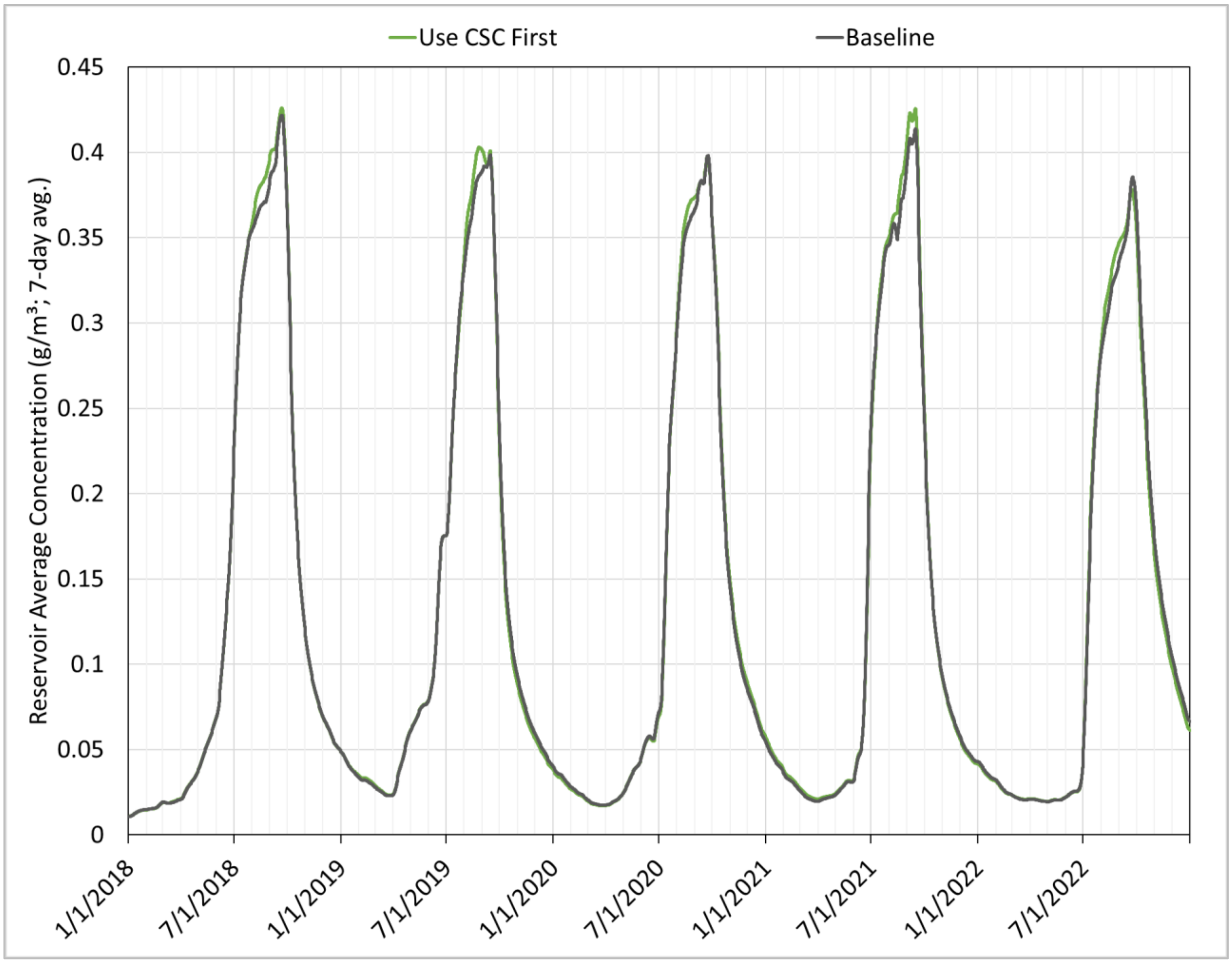



Figure 15. 'Use Cascade First' alternative - Changes in harmful algae concentrations

The 'Use Cascade First' alternative had little effect on the concentration of toxin from the harmful algae but did increase the peak values slightly (Figure 16).

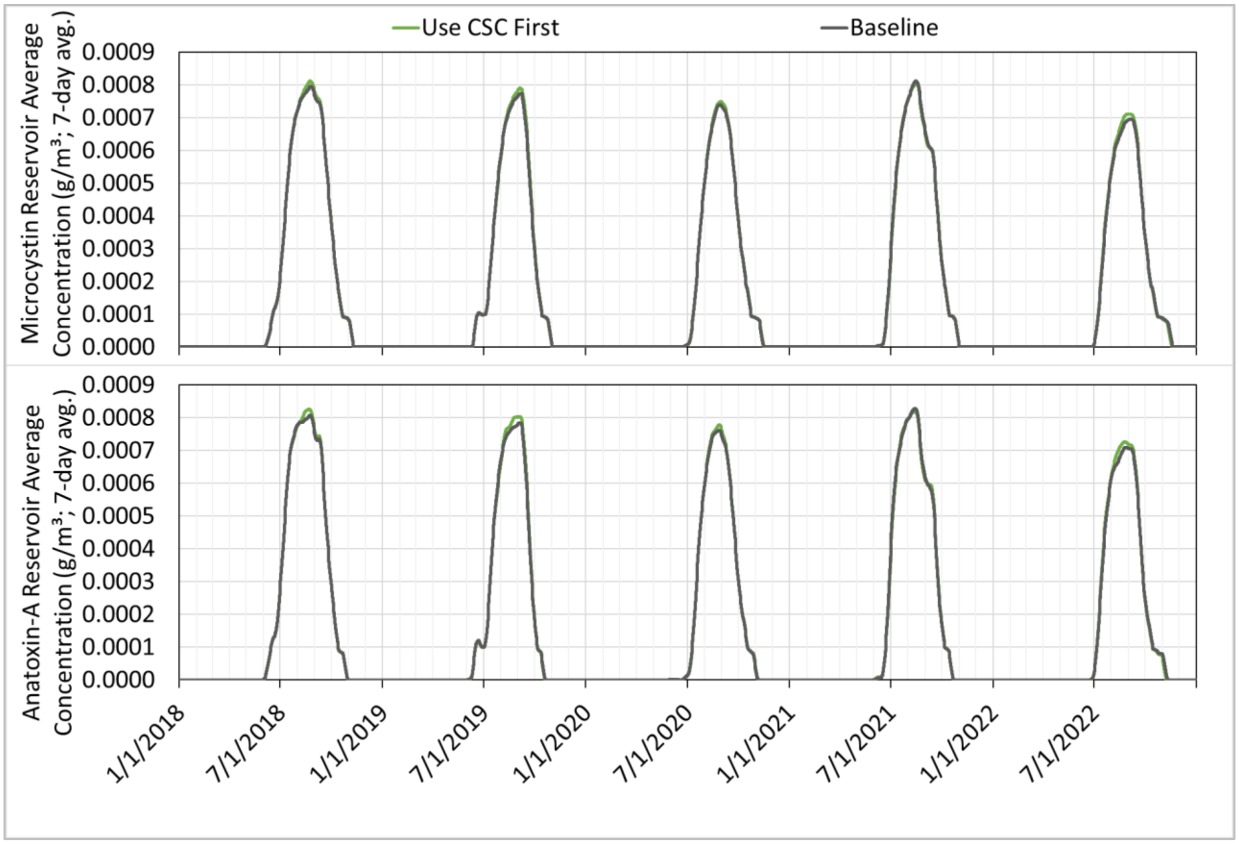



Figure 16. 'Use Cascade First' alternative - changes in toxin concentrations

## 6.5. Results for 'Use Deadwood First' Alternative

The 'Use Deadwood First' alternative increased releases from Deadwood Reservoir in June and July (Figure 17). Cascade Reservoir still needed to release water before this for FRM, so no water was needed from Deadwood until these flows diminished or did not meet irrigation needs. Cascade Reservoir was able to be kept at higher levels while Deadwood Reservoir was used, but its smaller amount of storage was quickly depleted and it reached its annual lows in a few weeks. Cascade Reservoir was needed to meet demands after that time, and the reservoir drafted at an accelerated rate since it was needed to meet the full demand. This caused storage for Cascade Reservoir to reach its annual low around the same time that it did in the 'Baseline' alternative.

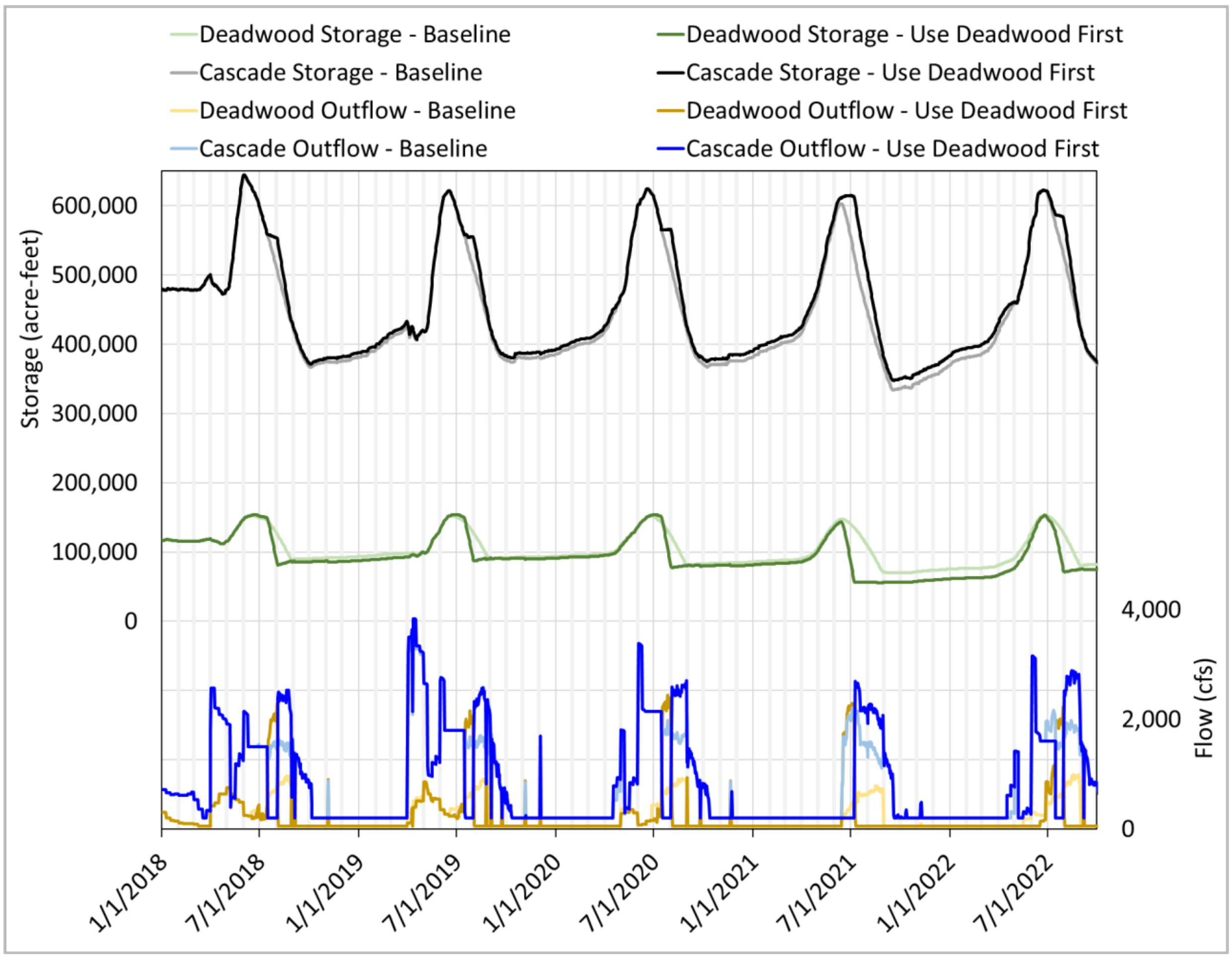



Figure 17. 'Use Deadwood First' alternative - changes in reservoir storage and releases

The changes in operations and water levels for the 'Use Deadwood First' alternative sometimes increased and sometimes decreased peak harmful algae concentrations, but these effects were again small relative to the total concentrations for the 'Baseline' (Figure 18).

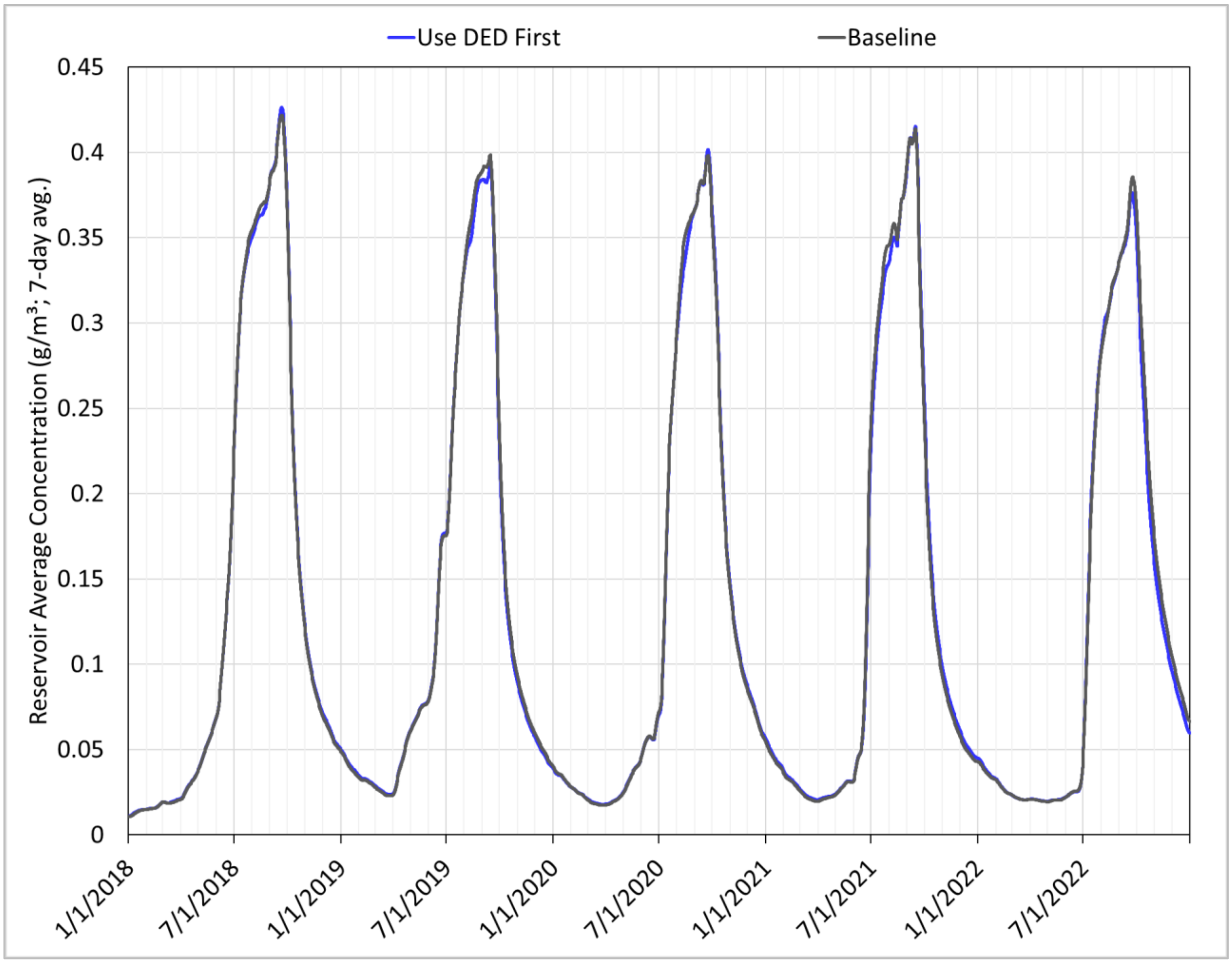



Figure 18. 'Use Deadwood First' alternative - changes in harmful algae concentrations

The 'Use Deadwood First' alternative had little effect on the concentration of toxins from the harmful algae but did increase the peak values slightly (Figure 19).

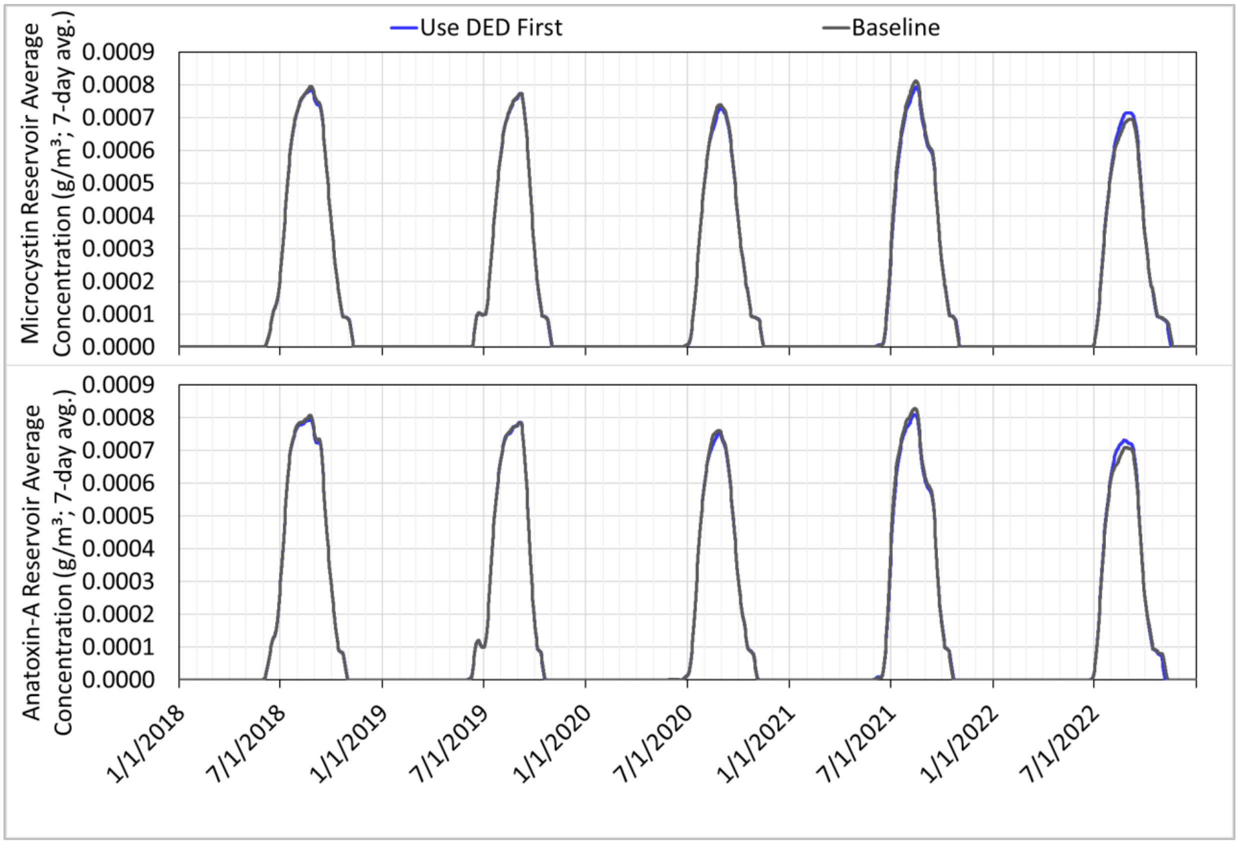


Figure 19. 'Use Deadwood First' alternative - changes in toxin concentrations

## 6.6. Comparison of Operations Alternatives

Overall, the alternatives were able to shift the timing and mechanisms (e.g., spillway) of releases, which altered water storage levels to varying degrees (Figure 20). Operational commitments limited how much flexibility there was in drawdown timing, with the different alternatives shifting this timing from the 'Baseline' alternative by up to around a month.

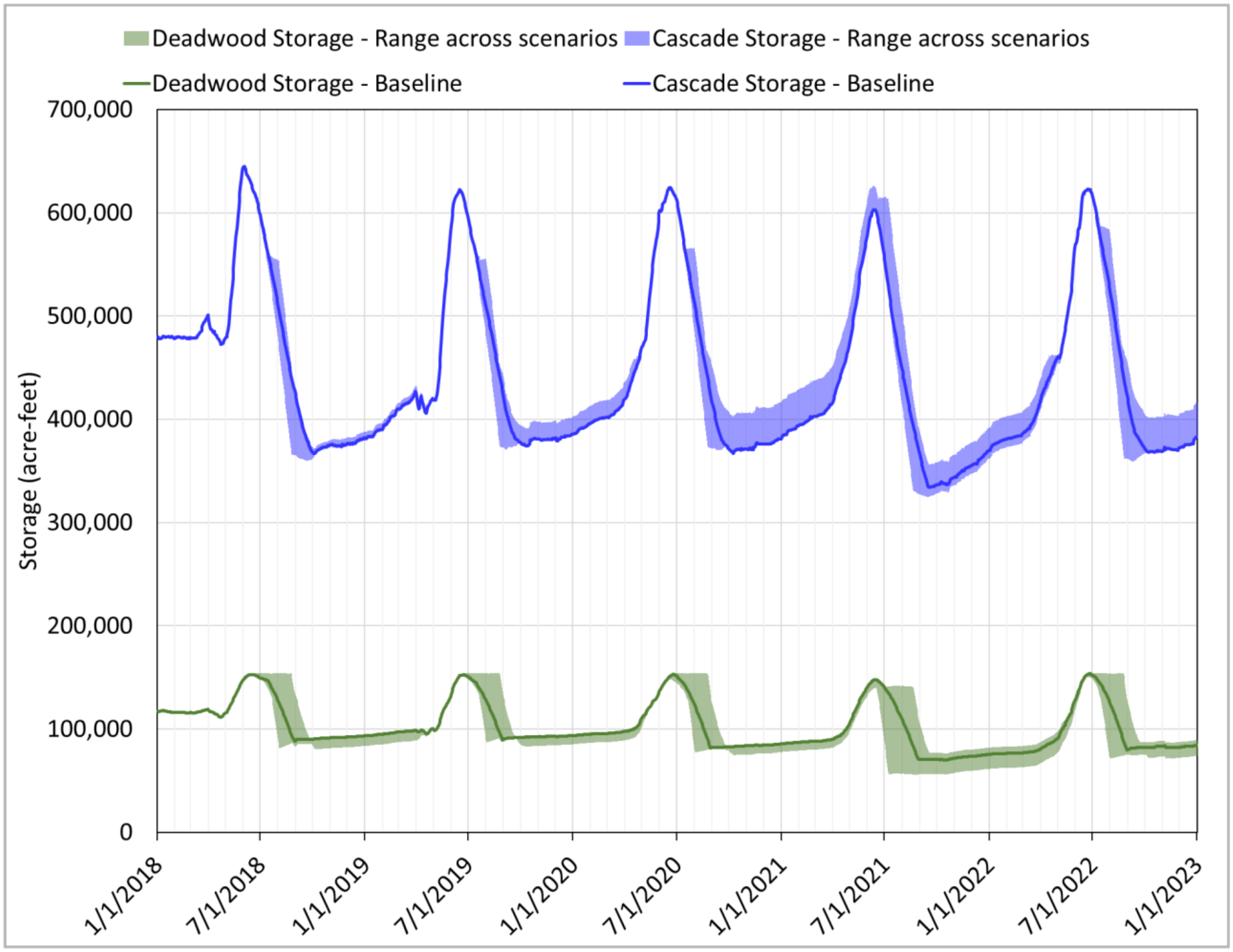



Figure 20. The simulated range in reservoir storage across the operating alternatives at Cascade Reservoir (blue) and Deadwood Reservoir (green)

Harmful algae concentrations were insensitive to the changes in operations, with concentrations changing by up to about 5 percent during the peak summer months (Figure 21).

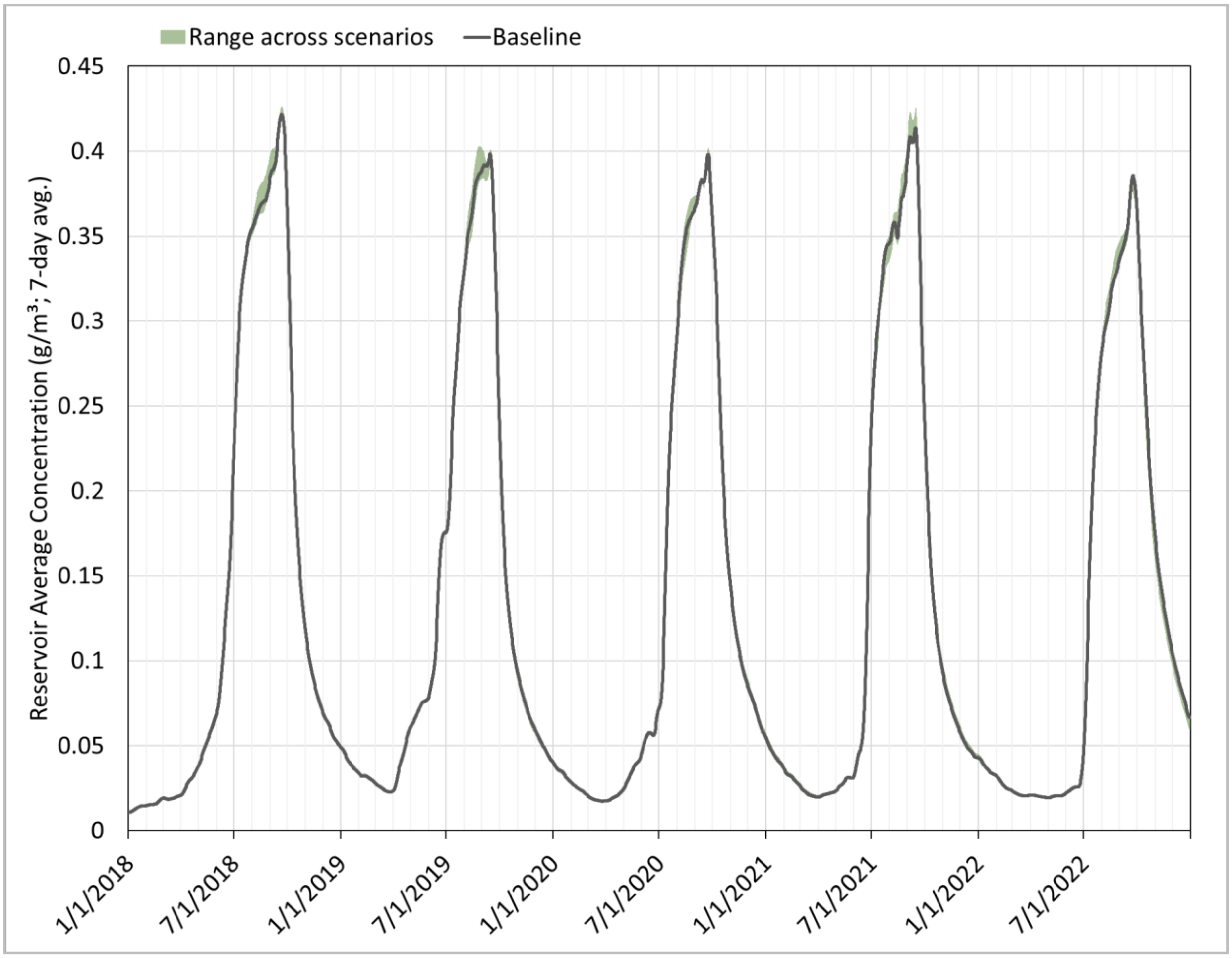


Figure 21. Simulated harmful algae concentrations in the 'Baseline' alternatives (black solid line) and the range in concentrations across all operational alternatives (green shaded area)

Table 4 shows the changes in harmful algae concentrations relative to the 'Baseline' alternative during the months of August and September when concentrations typically peak. Changes are minimal across all scenarios as compared to Baseline and range from a 3 percent increase to a 2 percent decrease in concentrations.

Table 4. Changes in harmful algae concentrations relative to 'Baseline' alternative, August through September

| Year | Use Spillway | Early Flow Aug. | Use CSC First | Use DED First |
|---|---|---|---|---|
| 2018 | -1% | 0% | 2% | 0% |
| 2019 | 0% | 0% | 2% | -2% |
| 2020 | 0% | -1% | 1% | -1% |
| 2021 | 0% | -1% | 3% | 0% |
| 2022 | -1% | -1% | 2% | -1% |
| Average | 0% | -1% | 2% | -1% |

Concentrations of toxins produced by harmful algae (i.e., cyanotoxins) likewise increased by up to 3 percent or decreased by 2 percent when comparing the operational alternatives to the 'Baseline' alternative (Table 5; Table 6). However, the changes in toxins did not always correspond with the changes in algae concentrations. This is likely due to dynamics simulated in the water quality model that control the conditions under which the harmful algae produce toxins.

Table 5. Changes in microcystin toxin concentrations relative to 'Baseline' alternative, August through September

| Year | Use Spillway | Early Flow Aug. | Use CSC First | Use DED First |
|---|---|---|---|---|
| 2018 | 0% | 1% | 1% | -1% |
| 2019 | 0% | 0% | 2% | 0% |
| 2020 | 0% | 0% | 1% | -1% |
| 2021 | 0% | 1% | 0% | -2% |
| 2022 | 1% | 3% | 2% | 3% |
| Average | 0% | 1% | 1% | 0% |

Table 6. Changes in anatoxin-a concentrations relative to 'Baseline' alternative, August through September

| Year | Use Spillway | Early Flow Aug. | Use CSC First | Use DED First |
|---|---|---|---|---|
| 2018 | 0% | 1% | 1% | -1% |
| 2019 | 1% | 1% | 3% | 0% |
| 2020 | 0% | 0% | 1% | -1% |
| 2021 | 0% | 1% | 0% | -2% |
| 2022 | 1% | 3% | 2% | 3% |
| Average | 0% | 1% | 1% | 0% |

Although it is unclear whether the changes in harmful algae and toxins are statistically significant, since the model error associated with the harmful algae and toxin concentrations could not be directly quantified without field and lab measurements of these concentrations, the chlorophyll-a concentrations that were measured can be compared to the modeled concentrations to understand model uncertainty. Chlorophyll-a concentrations generally reflect the combined concentration of the different types of algae, with the peak values in August and September primarily reflecting harmful algae. Chlorophyll-a concentrations for the operational alternatives varied by up to around 1 milligram per cubic meter (i.e., micrograms per liter). For comparison, the mean absolute error for the modeled chlorophyll-a was found to be from 7 to 10 milligrams per cubic meter, among the three reservoir profiles used for calibration (Wells et al. 2023). This suggests that the changes in chlorophyll-a concentrations, and by extrapolation the harmful algae and toxin concentrations, are not statistically significant.

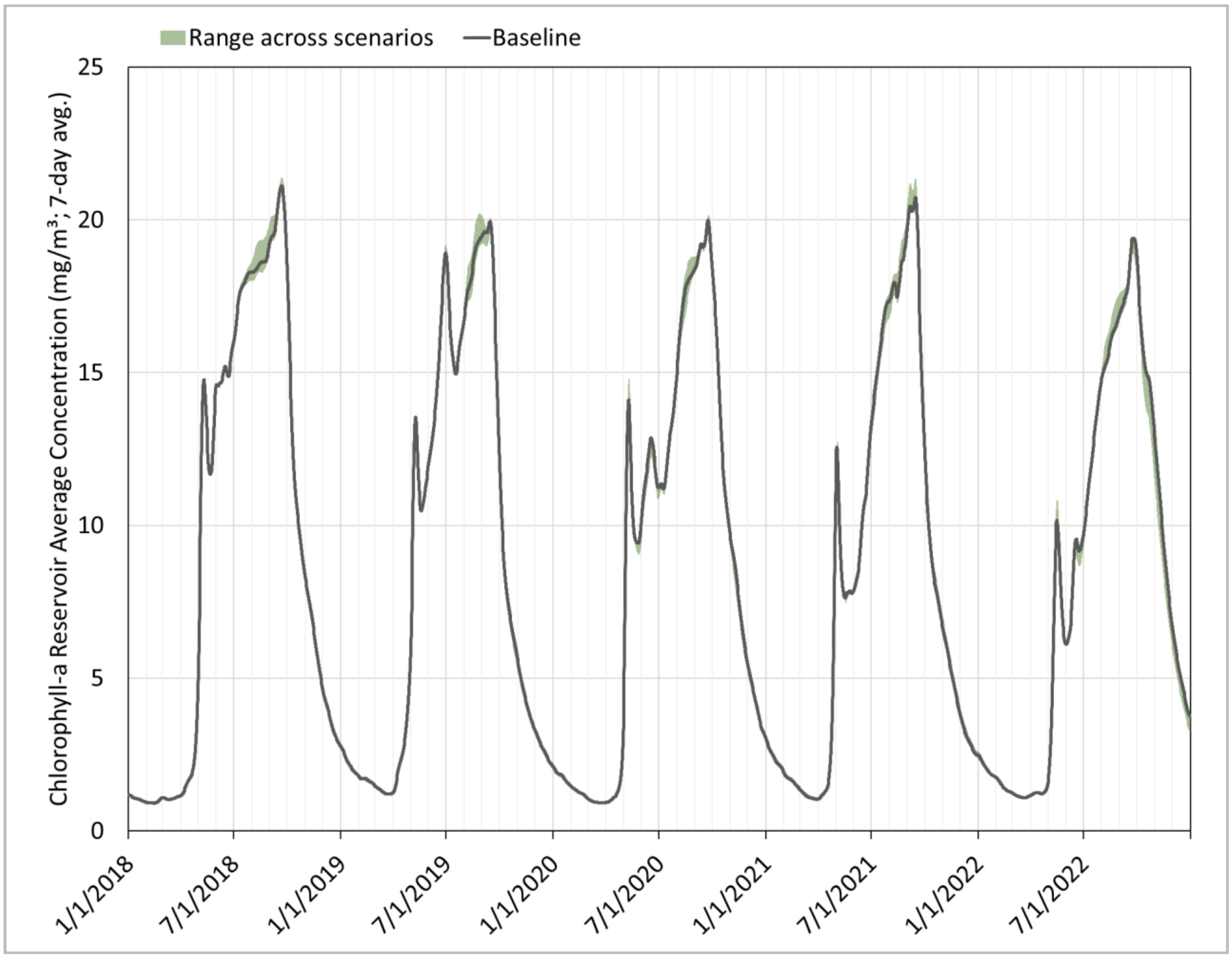



Figure 22. Simulated chlorophyll-a concentrations in the 'Baseline' alternatives (black solid line) and the range in concentrations across all operational alternatives (green shaded area). Peaks earlier in each year generally reflect non-harmful types of algae, while the last peak in each year mainly represents harmful algae.

Reservoir average temperatures were insensitive to the changes in operations for the alternatives during the summer months but showed changes up to about 2 degrees Fahrenheit during the winter (Figure 23), likely due to changes in ice cover dynamics. Even the most dramatic differences in water levels had little effect on reservoir average temperatures during the summer. This may be because the largest changes in water levels from the changes in operations are small (up to around 4 feet) relative to the water depth (up to around 50 feet). Additionally, the vertical position of the intake and spillway at mid-elevations within the reservoir generally results in average temperature water being released.

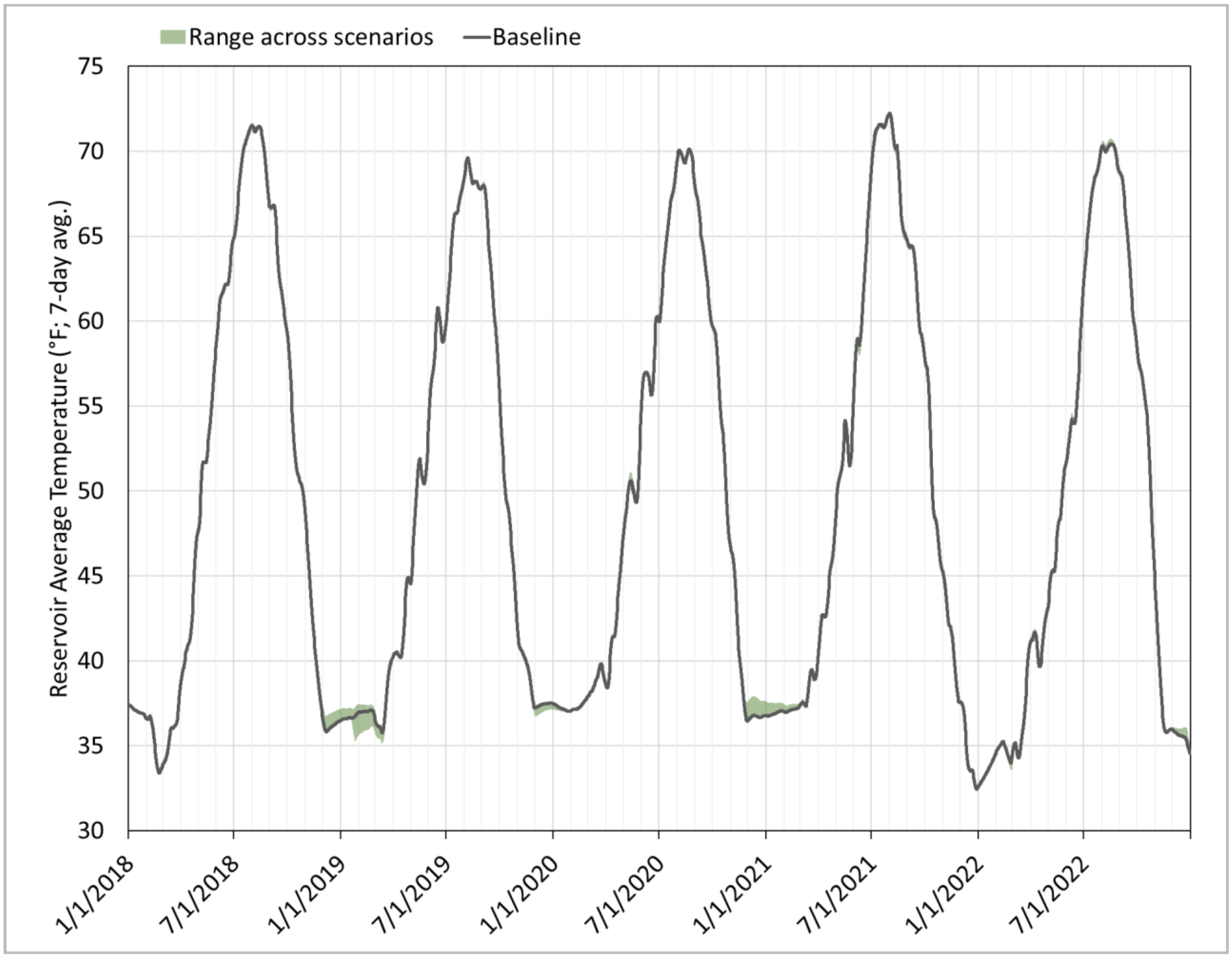



Figure 23. Range in reservoir temperature across the operating alternatives

# 7. Implications for Future Conditions

Although the scope and purpose of this study was to assess how theoretical changes in reservoir operations might affect harmful algal blooms, these changes might differ under other potential future conditions. This section considers the potential effects that future conditions could have on how harmful algae responded to the different operating alternatives.

Climate change may alter meteorological conditions, water temperatures, water supplies, and how Reclamation operates its reservoirs. These factors could influence the frequency and severity of harmful algal blooms. The main factors affecting the growth of cyanobacteria and potential for harmful algal blooms are sunlight for photosynthesis, the temperature of the water (e.g., may affect the rates of metabolic processes), and the nutrients available in the water (Garstecki 2021). Some of these factors, like increasing air temperatures, are easier to project for the future, using global climate models, than others, like inflow temperatures, cloud cover, and sunlight. Nutrient content of the water is more likely to be affected by changes in human development, land use, and land cover (e.g., fire).

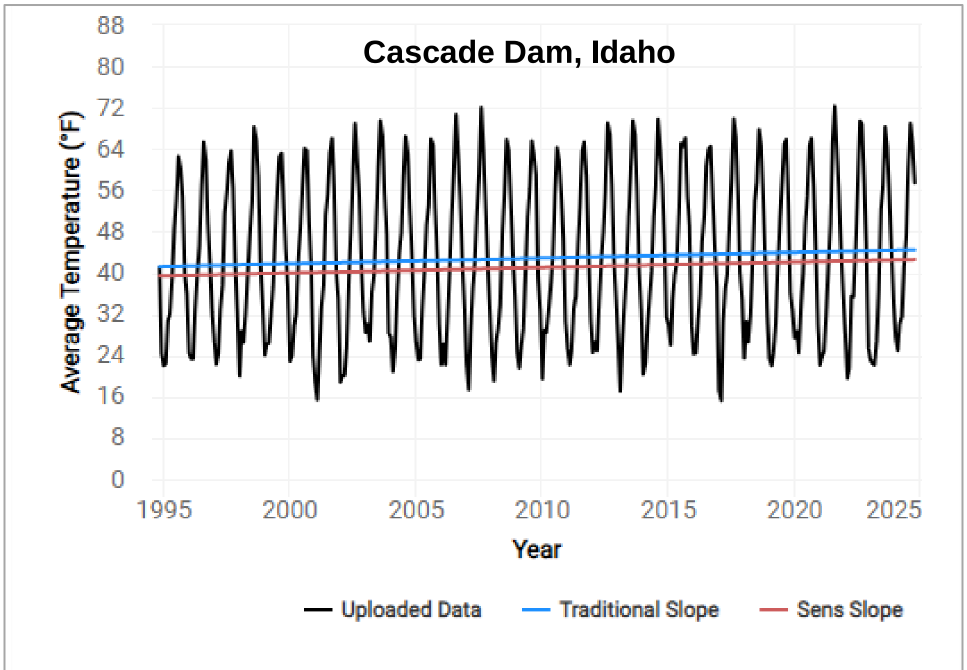
Understanding how water temperatures may change in the future is particularly important for understanding potential changes in harmful algal blooms. Harmful algae thrive in relatively warm water conditions, and if warm conditions are more frequent harmful algal blooms may also be more frequent. Changes in air temperature and precipitation within the watershed upstream of Cascade Reservoir may influence snowpack accumulation, snowmelt timing, runoff generation, and hydrologic inflows to Cascade Reservoir. Changes in inflows combined with warmer air temperatures could increase the water temperature of the inflows and influence in-situ warming of the lake. Changes in the timing and magnitude of hydrologic inflows could also affect reservoir water levels, which could affect water residence time and the reservoir dynamics that influence the growth of harmful algae. Concurrent changes in water supplies and water use could further affect water levels in the reservoir.

Historical climate data can be used to understand how the climate has already been changing. Projections of future climate conditions, based on different global climate models, can be useful to better understand where we might be headed in the future and the range of uncertainty for future conditions.

## 7.1. Historical Changes in Climate and Hydrology

Historical climate and hydrologic observations can be used to characterize how the climate has already changed. Air temperature data from a meteorological station at Cascade Dam (CSC Hydromet station) from 1995 through 2024 were used to assess changes in air temperature over time. A 30-year period of record was chosen as this duration typically captures interannual variability. Larger gaps in the data (e.g., September 2001 through May 2002) were filled based on linear regression ($r^2$=0.97) with daily air temperature values from a weather station at the McCall airport (KMYL station) 11 miles north.

The temperature data were used in an interactive web tool developed by the U.S. Army Corps of Engineers to assess trends in the climate data (climate.sec.usace.army.mil/tst_app/). For details on the summary statistics and hypothesis tests, refer to the user's guide for the interactive web tool (https://climate.sec.usace.army.mil/tst_app/TST_UserGuide.pdf). Although the tool identified a slight uptrend (Figure 24), with about 0.1 °F of warming per year, it was not considered statistically significant relative to the range of interannual variability.




Trend Line Coefficients

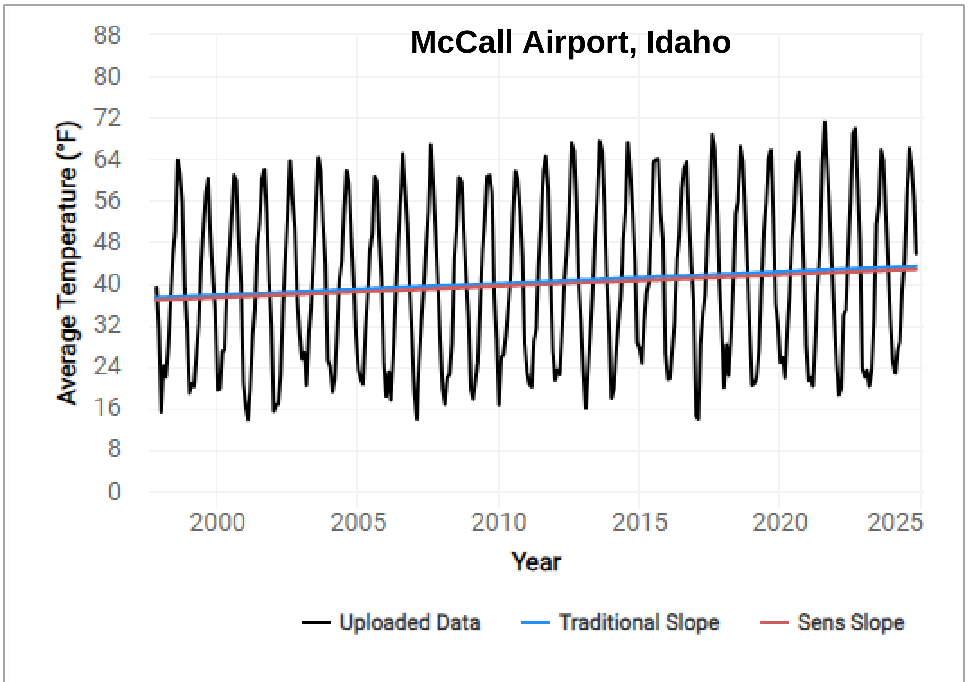
| Method | Directionality | Slope |
|---|---|---|
| Traditional Slope | Positive | 0.11 |
| Sen's Slope | Positive | 0.107 |

Trend Hypothesis Test

| Test | P-Value |
|---|---|
| t-Test | 0.237 |
| Mann-Kendall | 0.208 |
| Spearman Rank-Order | 0.224 |

Figure 24. Historical trends in average monthly air temperatures at Cascade Dam. The p-values over 0.05 indicate that the trends are not statistically significant.

Since the sensor at the dam did not show significant trends, it was thought that it may not capture as much change in temperature because of the thermal buffering effect of the nearby lake. Temperature data from a weather station at the airport near McCall, about 11 miles to the north, during the 1998 through 2024 water years were also assessed separately, although the record started with the 1998 water year and did not span a full 30 years. Similar to before (but reversed), gaps in the data were filled based on linear regression ($r^2$=0.97) with the CSC station. The resulting data were analyzed in the web application and exhibited trends that were statistically significant (i.e., $p<0.05$), with about 0.2 °F of warming per year, on average (Figure 25).




Trend Line Coefficients –

| Method | Directionality | Slope |
|---|---|---|
| Traditional Slope | Positive | 0.225 |
| Sen's Slope | Positive | 0.22 |

Trend Hypothesis Test –

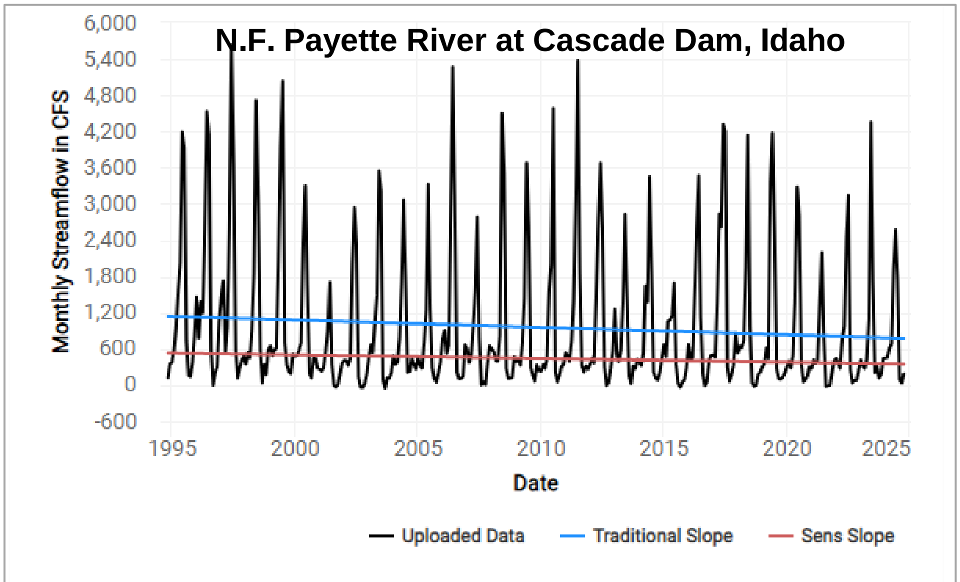
| Test | P-Value |
|---|---|
| t-Test | 0.0418 |
| Mann-Kendall | 0.0366 |
| Spearman Rank-Order | 0.0397 |

Figure 25. Historical trends in average monthly air temperatures at the McCall Airport (KMYL station), about 11 miles north of Cascade Reservoir; p-values below 0.05 indicate that the trends are statistically significant. Note that the record spans less than 30 years.

In addition to investigating the historical trends in air temperature, this study investigated historical trends in net inflows into Cascade Reservoir. Historical net inflows to Cascade Reservoir were assessed using unregulated flow data, calculated using a water balance with the measured outflows (Hydromet site CSCI; USGS station 13245000) and water storage levels for both and Cascade Reservoir (Hydromet site CSC) and Payette Lake (Hydromet site PAY; USGS station 13238500), a dam-regulated lake upstream of the reservoir. This calculation corrects for regulation of the outflows from Payette Lake to estimate what the inflows to Cascade Reservoir would have been without flow regulation by the dam, as shown below.

$$
\begin{aligned}
&Cascade\ Unregulated\ Daily\ Inflow \\
&\qquad = (Cascade\ Res.Storage[t] - \ Cascade\ Res.Storage[t-1]) + CascadeRes.Outflow[t] \\
&\qquad + (Payette\ Lk.Storage[t] - \ Payette\ Lk.Storage[t-1])
\end{aligned}
$$

Inflows showed a slight decreasing trend over the last 30 years, which was significant for two of the three tests (Figure 26). These decreasing trends may reflect a combination of factors, including changes in precipitation, runoff generation, and water use in the basin, so the exact causes are unclear.




Trend Line Coefficients

| Method | Directionality | Slope | Int |
|---|---|---|---|
| Traditional Slope | Negative | -12 | |
| Sen's Slope | Negative | -6 | |

Trend Hypothesis Test

| Test | P-Value |
|---|---|
| t-Test | 0.09 |
| Mann-Kendall | 0.0245 |
| Spearman Rank-Order | 0.0209 |

Figure 26. Historical trends in average monthly streamflow on the North Fork Payette River at Cascade Dam; p-values below 0.05 indicate that the trends are statistically significant for two of the three tests

The timing of net unregulated flows into Cascade Reservoir appeared to change historically, with a general shift in the hydrograph peak to earlier in the year by up to around a week or two (Figure 27).

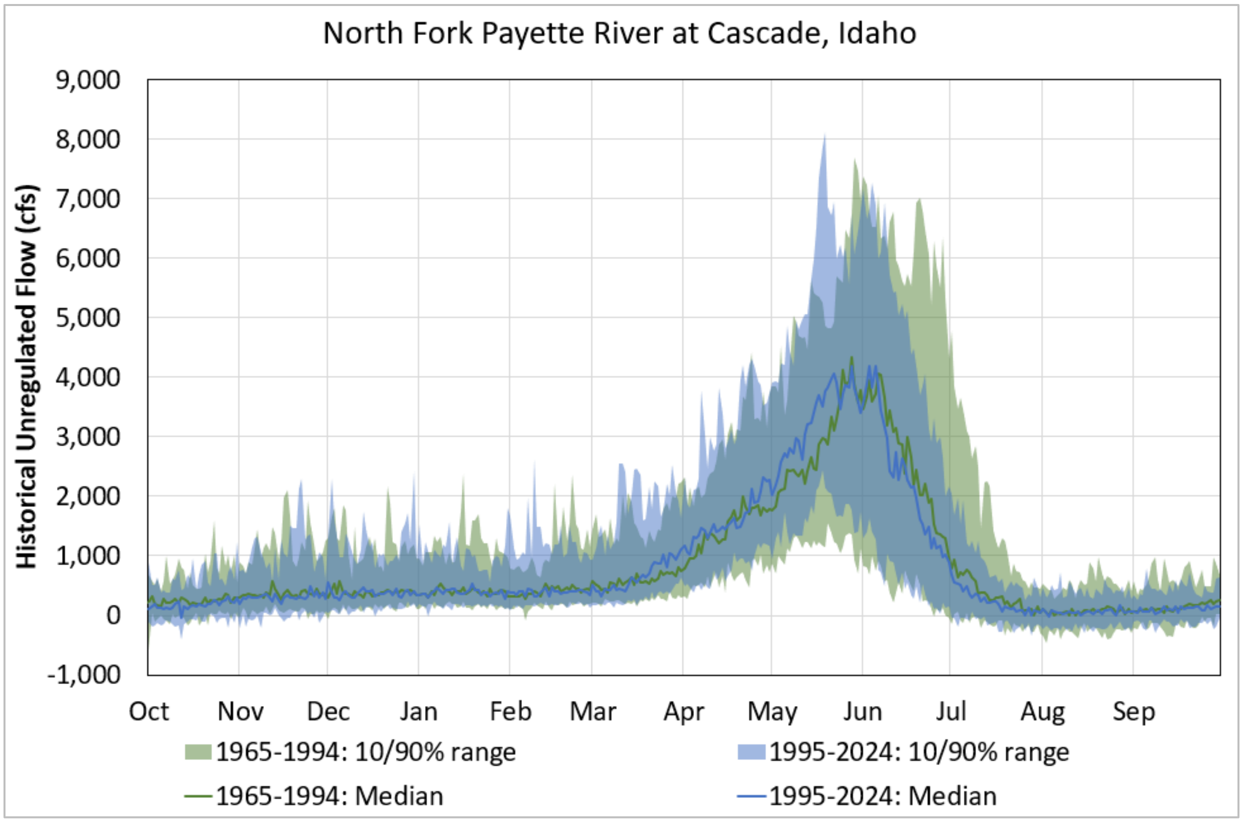
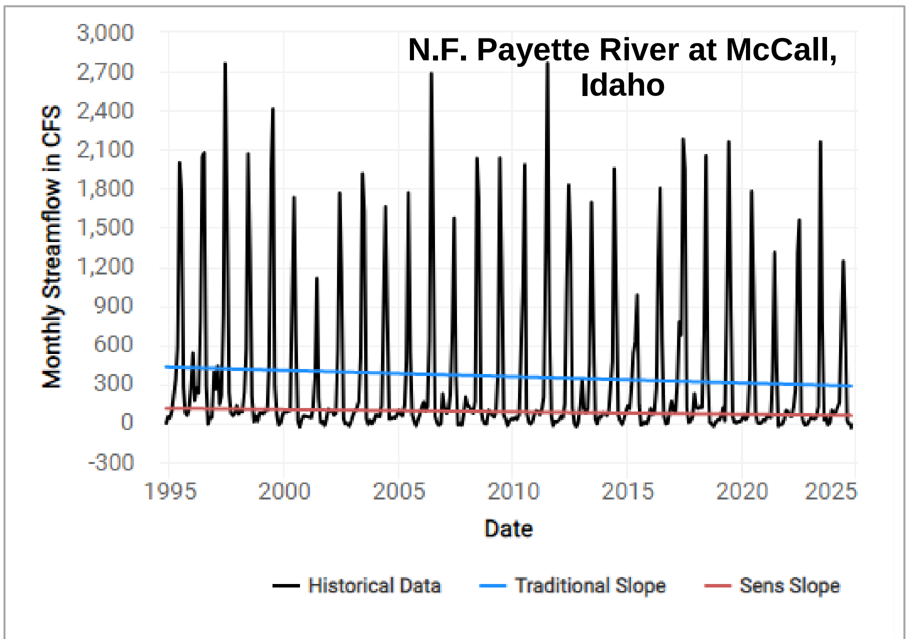



Figure 27. Changes in inflow timing at Cascade Dam from 1995 to 2024 (blue) compared to 1965 to 1994 (green). Historical unregulated flow is calculated from the water balance with historical outflows and water levels.

Historical unregulated net inflows to Payette Lake, which releases water to Cascade Reservoir, were calculated using a water balance with the measured outflows (USGS station 13239000; Hydromet ID PAYI) and water storage levels for Payette Lake (USGS station 13238500; Hydromet ID PAY) as shown below.

$$Payette\ Lake\ Unregulated\ Daily\ Inflow = Payette\ Lk.Outflow[t] + (Payette\ Lk.Storage[t] - Payette\ Lk.Storage[t-1])$$

The net inflows to Payette Lake also showed a slight decrease in flow over time, and this trend was also considered significant for two of the three tests (Figure 28). These decreasing trends may reflect a combination of factors including changes in precipitation, runoff generation, and water use in the basin, so the exact causes are unclear.




**Trend Line Coefficients**

| Method | Directionality | Slope |
|---|---|---|
| Traditional Slope | Negative | -5 |
| Sen's Slope | Negative | -2 |

**Trend Hypothesis Test**

| Test | P-Value |
|---|---|
| t-Test | 0.182 |
| Mann-Kendall | 0.00551 |
| Spearman Rank-Order | 0.00468 |

Figure 28. Historical trends in average monthly unregulated net inflow to Payette Lake, which releases water to Cascade Reservoir. The p-values below 0.05 indicate the trends are statistically significant for two of three trends.

The timing of unregulated inflows to Payette Lake also appeared to change historically, with a more pronounced shift in the hydrograph peak to earlier in the year by up to around a week to two (Figure 29).

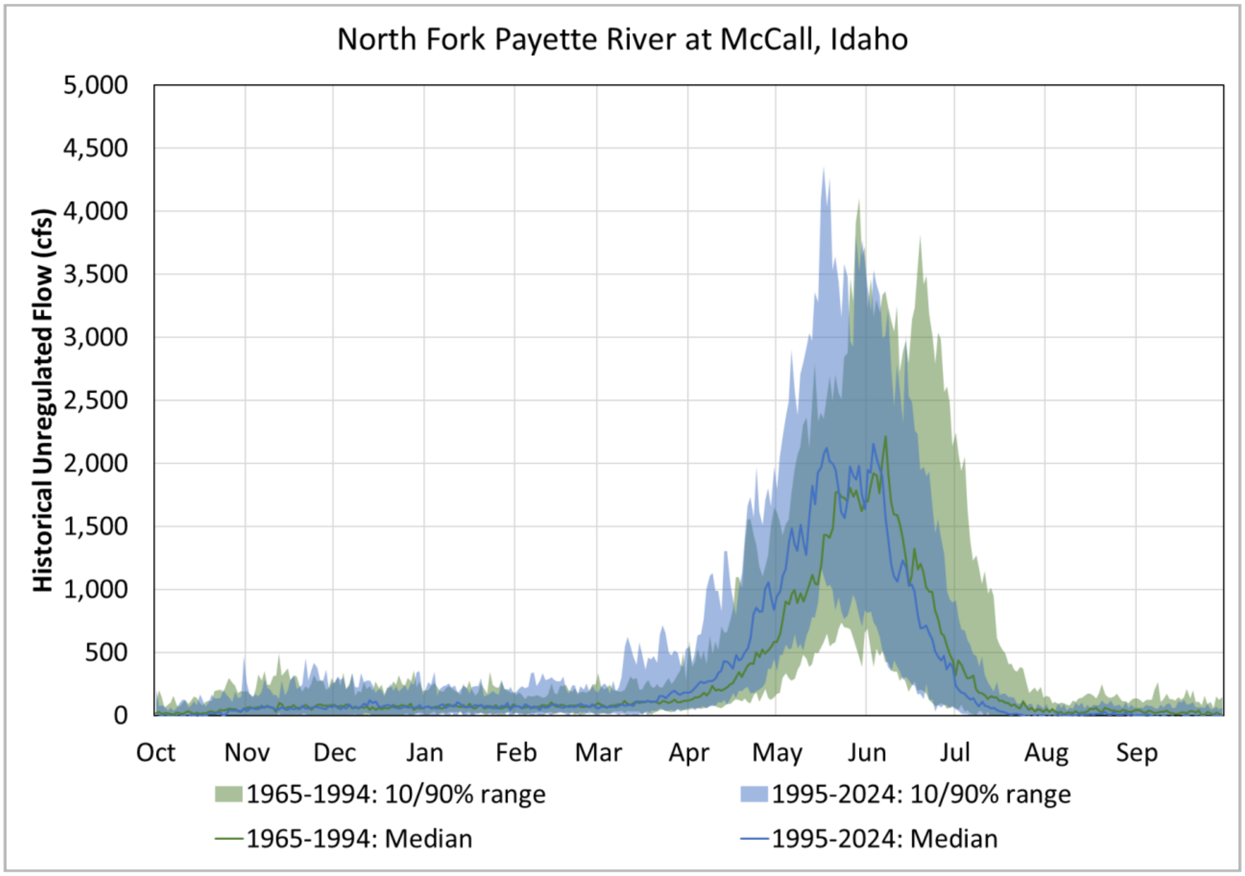



Figure 29. Changes in unregulated inflow timing for Payette Lake, which releases water to Cascade Reservoir, for years 1995 to 2024 (blue) compared to 1965 to 1994 (green)

## 7.2. Potential Future Changes in Climate and Hydrology

To understand the range of potential future climate and hydrologic conditions for Cascade Reservoir, future climate summaries were generated for the North Fork Payette River basin using the USGS National Climate Change Viewer (https://apps.usgs.gov/nccv/maca2/maca2_watersheds.html; USGS 2021; Alder and Hostetler 2013). The full report generated by this tool is included in Appendix B. The tool uses 20 future climate projections from the Coupled Model Intercomparison Project 5 (CMIP5; Taylor et al. 2012).

The climate and hydrology data are based upon projections from a range of global climate models developed by different international institutions. The global climate models were run for two different representative concentration pathways (RCPs; RCP4.5 and RCP8.5), which represent different trajectories of global greenhouse gas and aerosol emissions. RCP4.5 and RCP8.5 were identified in the Fourth National Climate Assessment (USGCRP 2018) as the core scenarios to be considered for climate impact assessment studies. RCP 8.5 represents a “higher emissions scenario” where future emissions trajectory of greenhouse gas concentrations continues to rise unchecked. RCP 4.5 represents a “lower emissions scenario” where future emissions trajectory of greenhouse gas emissions peak around 2040 and decline thereafter. RCPs do not represent forecasts or projections of future atmospheric composition; rather, RCPs represent plausible future trajectories of atmospheric composition under various assumption of population growth, economic growth, technology development, and governmental policies regarding greenhouse gas emissions. The global climate data were downscaled to better represent the effects of topography and variability at smaller scales (e.g., MACA; Abatzoglou and Brown 2012). The data were also run through a simple water balance model (METDATA; Abatzoglou 2011) to estimate runoff production, which they routed and summarized for different river and stream segments.

Projected results from the USGS National Climate Change Viewer indicate increasing air temperatures through 2099, potentially at a faster rate than has been happening historically (Figure 30). The rates of average air temperature increases vary among the models and emission scenarios, with around 5- and 10-degrees Fahrenheit of warming on average for RCP 4.5 and 8.5, respectively, by 2099.

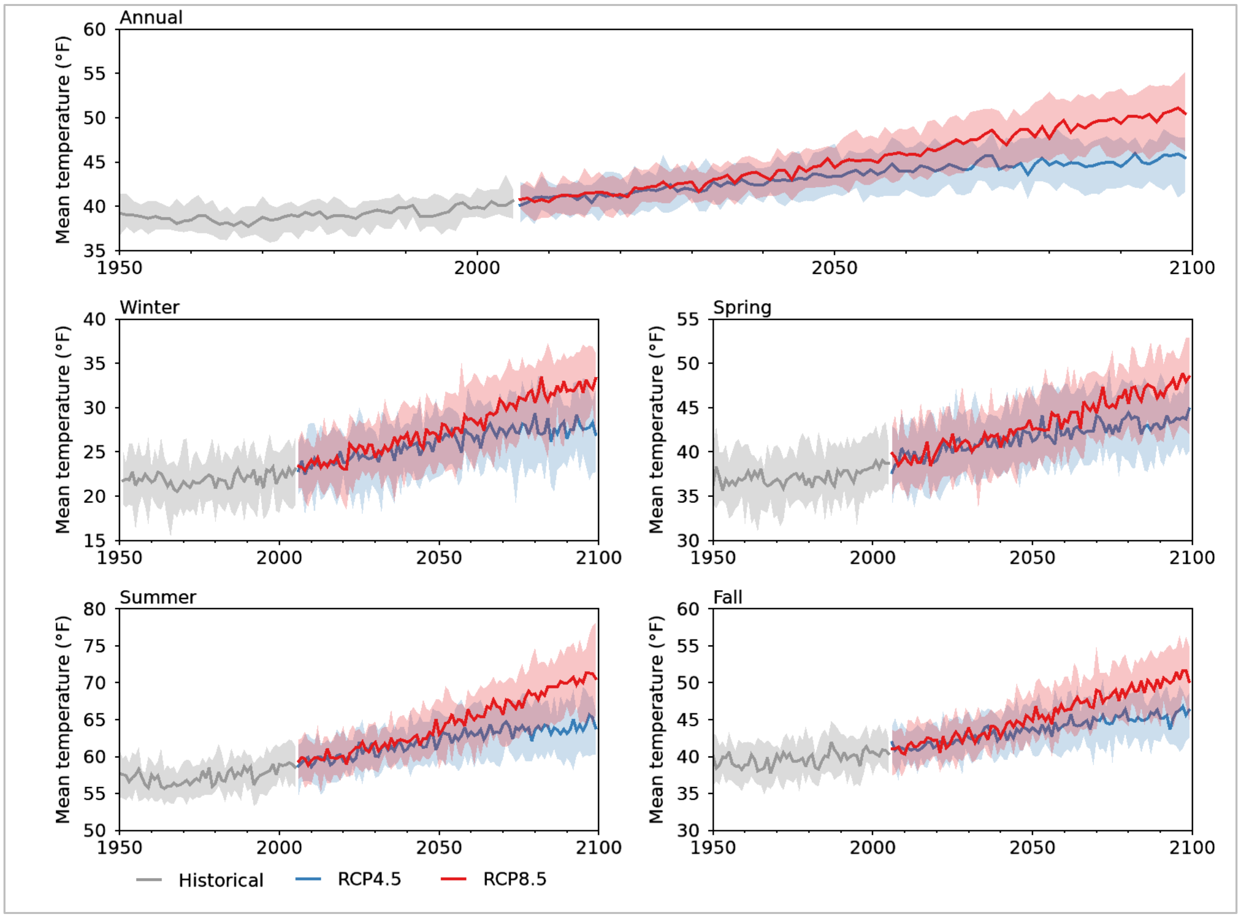



Figure 30. Future air temperature trend projections for the North Fork Payette River basin from the National Climate Change Viewer. Annual and seasonal time series of mean air temperature for historical (gray), RCP4.5 (blue), and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

Air temperatures are expected to be higher throughout the year, with some variability between months (Figure 31). The largest increases in median air temperatures occur in July and August, which could raise water temperature during periods of harmful algae production.

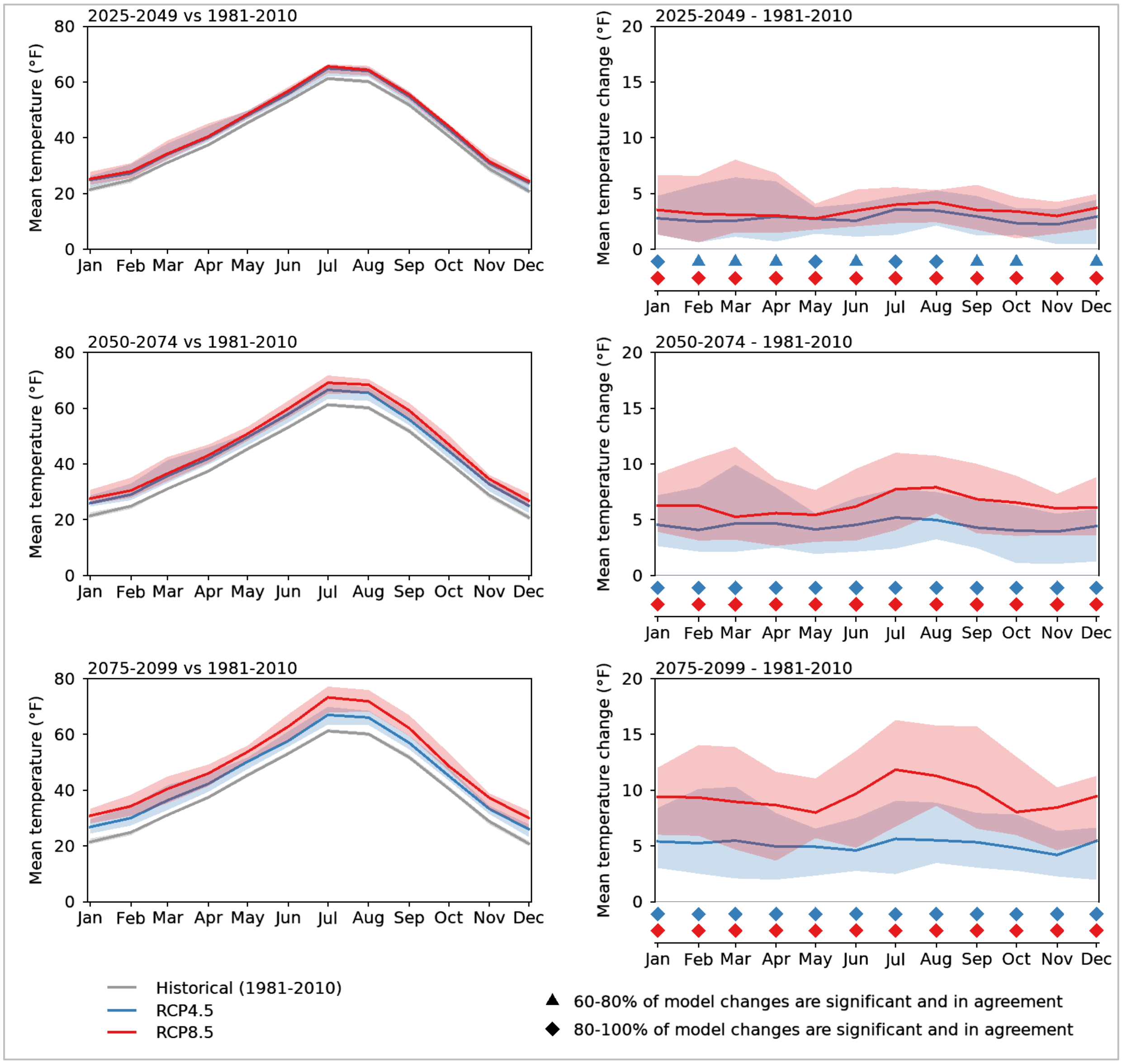



Figure 31. Future temperature seasonality projections for the North Fork Payette River basin from the National Climate Change Viewer. Monthly averages of mean temperature are shown for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10$^{th}$ to 90$^{th}$ percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($p < 0.05$).

Precipitation is not projected to change dramatically over the next century (see Appendix B), but changes in temperature could alter whether precipitation falls as snow or rain and shift the timing of snowmelt and runoff to earlier in the year. Runoff is projected to increase in the winter and decrease in the summer (Figure 32).

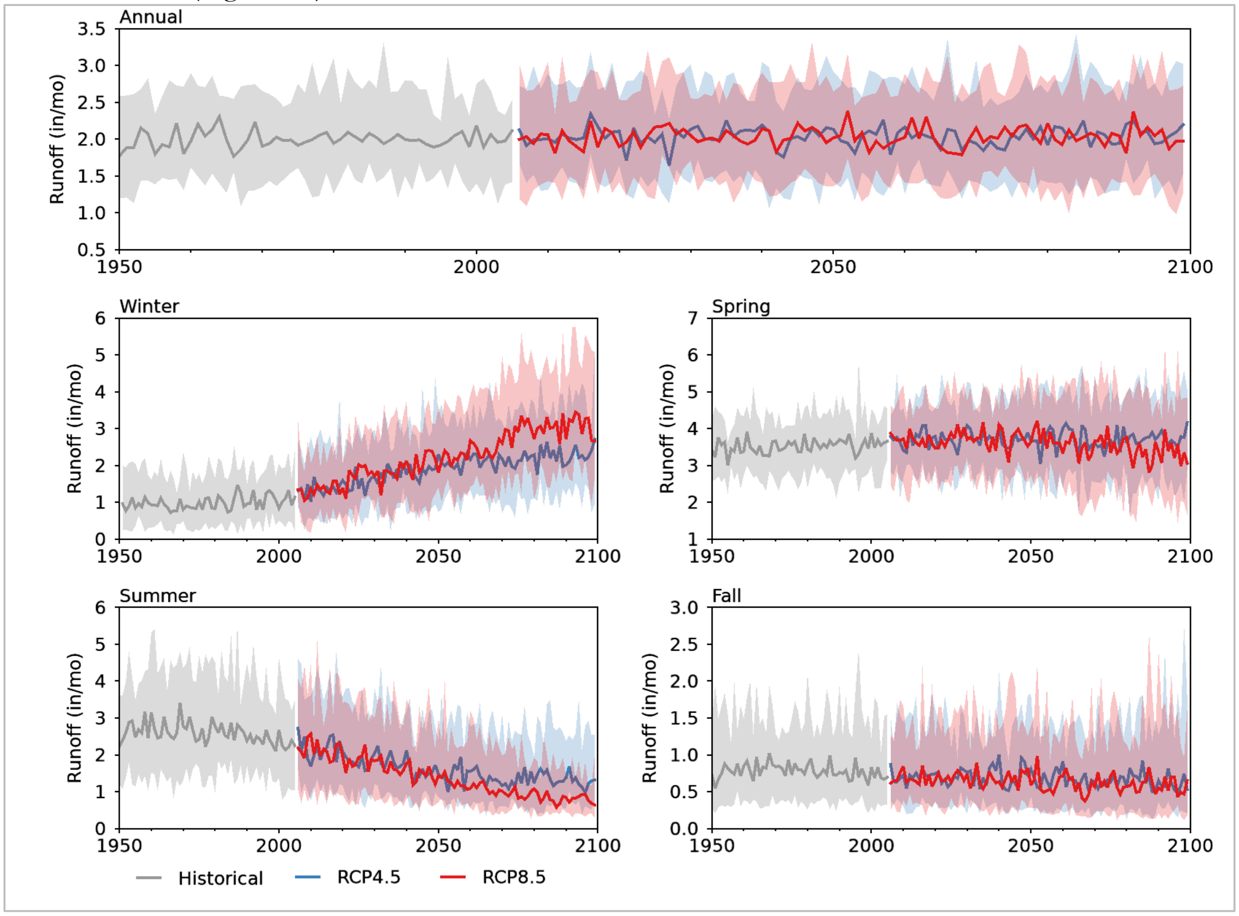



Figure 32. Future temperature trend projections for the North Fork Payette River basin from the National Climate Change Viewer. Annual and seasonal time series of runoff are shown for historical (gray), RCP4.5 (blue), and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

The changes in runoff appear shift the peak of the annual hydrographs towards earlier in the year, with lower peak flows (Figure 33).

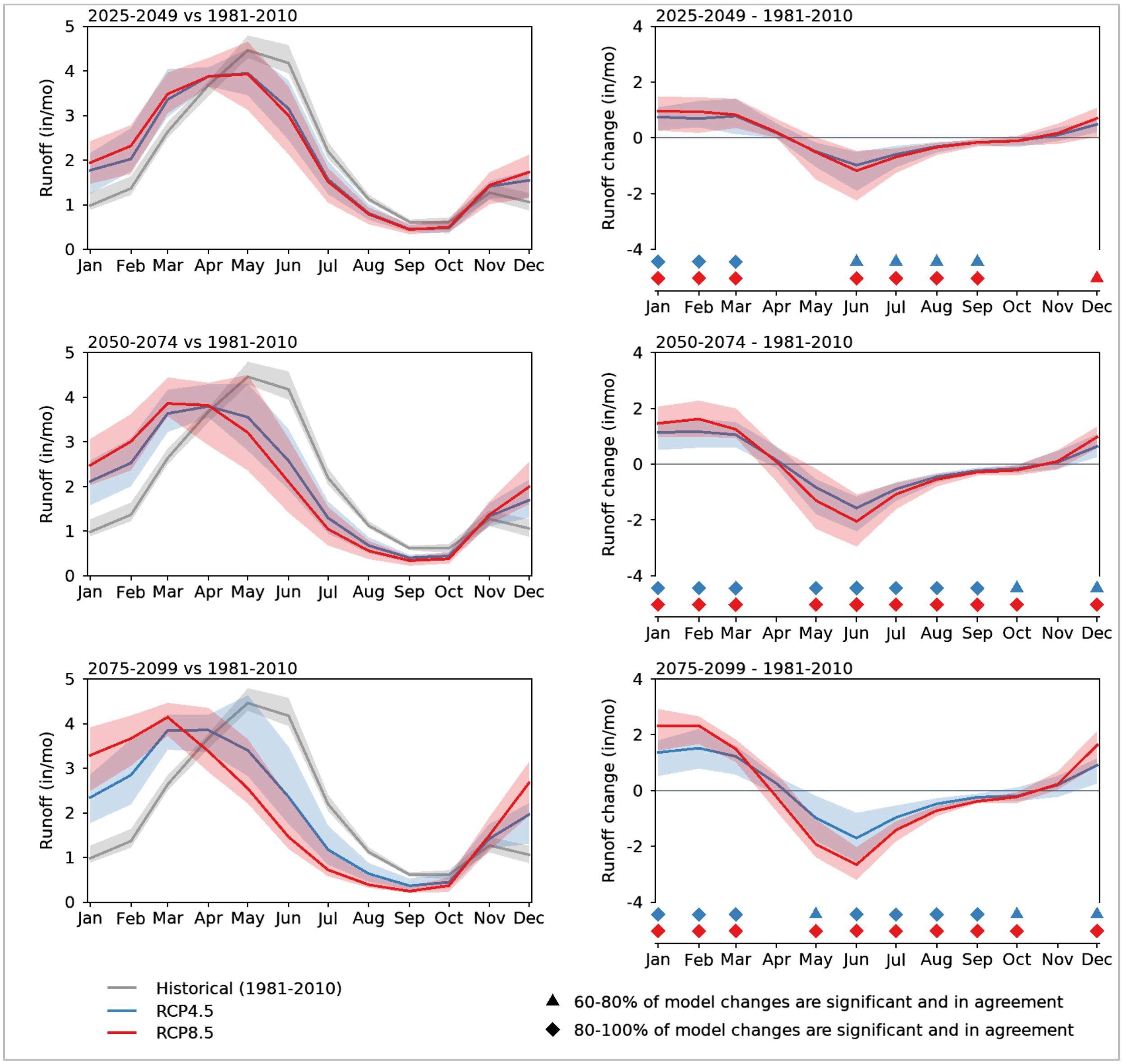



Figure 33. Future temperature seasonality projections for the N.F. Payette River basin from the National Climate Change Viewer. Monthly averages of runoff are shown for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10$^{th}$ to 90$^{th}$ percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($p < 0.05$).

## 7.3. Effects of Operating Alternatives under Potential Future Hydrology

Historical measurements and future climate projections suggest that air temperature will continue to increase until the end of the century, while runoff timing will shift towards earlier in the year. The frequency and severity of harmful algal blooms may increase under these future conditions, with warmer air temperatures leading to warmer inflow and reservoir water temperatures, which may promote harmful algae growth. Increased nutrient inputs from continued development around the reservoir could further promote harmful algae growth. However, many other factors may control how the reservoir responds to future conditions, such as competition for resources with other algal species.

From an operational perspective, the shift in timing for the runoff peak and generally decreased flows in the summer, may lead to a greater reliance on stored water to meet irrigation needs. Warmer air temperatures over crop lands may also increase evaporation and irrigation demand. This could affect water levels in the reservoirs, drawing them lower than the annual minimums during the years modeled. It is unclear how the different operating alternatives might affect algal blooms under these conditions.

Modeling the operating alternatives for different climate projections in the water quality model would be difficult because many meteorological data are required by the model that would need to be estimated for the future at the timescales needed. For example, the projections for air temperatures could be used in the model, but these projections would need to be extrapolated to estimate the effects on inflowing water temperatures. Changes in cloud cover and wind are also important factors that would be difficult to estimate for the future. Simulating the water quality model for future conditions was beyond the scope of the current study but could be considered by future studies.

The goal of this study was to explore whether changes in reservoir operations, within the range of operational flexibility, might affect concentrations of the harmful algae that cause harmful algal blooms and produce toxins. However, the lack of sensitivity of harmful algae concentrations to the changes in water levels within the operating range of the different operating alternatives suggests that changes in reservoir operations would have little ability to mitigate algal blooms if they were more frequent under future conditions.

# 8. Discussion

## 8.1. Pros and Cons of Each Alternative

The changes in harmful algae concentrations and potential changes to other resource areas are shown in Table 7. The table highlights that modeled changes in harmful algae were not considered significant and that each alternative could adversely affect other purposes, which would need to be more fully explored if actual implementation were being considered.

Table 7. Modeled changes in harmful algae concentration and associated potential effects.

| Operational Alternative | Change in harmful algae concentrations | Change in power generation | Changes in flood risk management releases | Change in summer lake levels | Change in down-river recreation flows |
|---|---|---|---|---|---|
| Use Spillway | Up to 1% reduction* | Large reduction | No change | No change | No change in flow but could alter water quality |
| Early Flow Aug. | Up to 1% reduction* | Changes in timing; potential reduction when higher releases exceed powerhouse capacity | Reductions due to larger earlier releases | Higher lake levels, due to reduced flood risk management releases | High impact due to lower flows below both dams in August |
| Use Cascade First | Up to 3% increase* | | Potential reductions for Cascade due to larger earlier releases (opposite for Deadwood) | Cascade would draft to lows earlier but not go lower (opposite at Deadwood) | High impact due to lower flows earlier in the year below Deadwood followed by lower flows below Cascade later in year |
| Use Deadwood First | Up to 2% reduction* | | Potential increases for Cascade due to lower earlier releases (opposite for Deadwood) | Cascade would draft to lows later but not go lower (opposite at Deadwood) | High impact due to lower flows earlier in the year below Cascade followed by lower flows below Deadwood later in year |

*Note: uncertainties associated with modeled chlorophyll-a concentrations, and relative amounts of change, suggest that the changes in harmful algae concentrations are unlikely to be statistically significant

The 'Use Cascade First' alternative was similar to current operations, since Cascade Reservoir has more inflow and stores more water and is generally relied on more heavily for releases. Using water from Cascade Reservoir earlier in the year would result in more rapid reservoir drawdown and reaching low water levels earlier in the year. There was no improvement in algae concentrations or toxins. This alternative could have additional effects to recreation and visual impacts due to exposed shorelines. These impacts would be similar to the 'Baseline' impacts but would occur earlier in the year.

The 'Use Deadwood First' alternative allowed Cascade Reservoir to be held at higher levels for a few weeks, but then draw down more rapidly to levels similar to the 'Baseline'. Harmful algae concentrations in August and September were reduced by up to 2 percent, but changes to toxin concentrations varied from a 2 percent reduction to a 3 percent increase, so the potential benefits of this alternative are uncertain. This alternative would also draft Deadwood Reservoir to low water levels earlier, resulting in additional potential effects to recreation and visual impacts due to exposed shorelines. At Cascade Reservoir, drawdown could be delayed in some years, potentially offering more surface area for recreation and reducing shoreline exposure.

The 'Early Flow Aug' alternative drafted Cascade Reservoir faster earlier, similar to the 'Use Cascade First' alternative but drafted more slowly when releases for flow augmentation stopped in August. This alternative showed up to a 1 percent reduction in harmful algae concentrations, but toxin concentrations were increased by up to 3 percent, for unknown reasons. This alternative could result in earlier drawdown, with potential effects to recreation and visual impacts, due to releasing more flow augmentation earlier, but tended to not draft as low, which could reduce these effects later in the year.

The 'Use Spillway' alternative did not alter the amount of water or timing of releases for Cascade Reservoir and just routed most releases through the spillway. Harmful algae concentrations were decreased by up to 1 percent in some years, but toxin concentrations were not decreased, with increases of up to 1 percent. This alternative had no effect on water levels but could have substantial effects to power production, which, although considered an incidental use to reservoir operations, might outweigh the minor changes to harmful algae concentrations.

## 8.2. Implications for Theoretical Operation Alternatives

The results for the different operational alternatives imply that changing operations within the range of operational flexibilities would affect harmful algae concentrations by less than 3 percent during the peak concentrations in August and September. The additional negative effects for some alternatives (e.g., effects to power generation and recreation; lower water levels in Deadwood) from the reduced operational flexibility implicit in these alternatives may outweigh potential benefits.

Though this study investigated alternatives, it did not intend to recommend any alternative for implementation. Implementation of any changes in reservoir operations would require further study, the development of an implementation plan, environmental compliance, and coordination with stakeholders.

## 8.3. Model Limitations and Uncertainties

The water quality model represents the best currently available tool for exploring the potential effects of the theoretical changes in operations on harmful algae. However, it is subject to limitations and uncertainties, discussed briefly below.

- As noted in Section 6.6, although the uncertainty associated with the modeled harmful algae and toxin concentrations could not be directly quantified, it was possible to characterize the model uncertainty for chlorophyll-a concentrations, which reflect the total concentrations of all the algae types. The modeled chlorophyll-a concentrations varied by only up to around 1 milligram per cubic meter among the operational alternatives, whereas the mean absolute error for the modeled chlorophyll-a ranged from 7 to 10 milligrams per cubic meter (Wells et al. 2023). This implies that the changes in harmful algae and toxin concentrations are probably not statistically significant.

- The model was calibrated and run for only 5 years of reservoir operations and water quality information. It is possible that the operations alternatives could have different effects in other water years, such as at lower water levels.

- The spatial scale and two-dimensional basis of the model makes predicting localized effects within different regions of the reservoir uncertain. It is possible that the changes in reservoir operations could produce localized effects not apparent at the whole-reservoir scale.

- The accuracy of the water quality model is largely dependent on the quality of the data that informs it; the model could benefit from additional data collection. These data are important both for defining the boundary conditions of the model (e.g., inflow characteristics) and for model calibration. It is unclear how uncertainties associated with model calibration might affect the sensitivity of harmful algae to changes in reservoir operations. Some of these uncertainties and potential improvements are described below.

    - Algae dynamics were constrained in the model based on a limited number of measurements and observations. More continuous monitoring of types of algae and concentrations, and the conditions that lead to their growth and blooms, could be used to better calibrate algae dynamics.

    - The model developers did not have data characterizing the water quality characteristics or flow rates of the different tributaries and had to make assumptions based on limited data. The inflows of the different tributaries could be better monitored and sampled to improve inflow boundary conditions.

    - Reservoir water quality, both actual and modeled, is particularly sensitive to wind and meteorological conditions (e.g., cloud cover, air temperature, etc.). Wind measurements were from weather stations located on land and near the reservoir.

However, local gusts and higher wind speeds over water can play an important role in reservoir and algae dynamics. Wind sensors on the water could improve model representation of wind dynamics.

- During model calibration, it became apparent that the ice cover dynamics were causing the ice cover to melt out too early in the model. This is likely because ice cover at Cascade Reservoir is complicated by the addition of snowfall over the ice, which the model was incapable of simulating accurately. The model developer attempted to improve this simulation but was unable to address it within the study's scope. It is unclear what effect this might have on harmful algae concentrations.

# 9. Conclusions

This reservoir operations study identified and modeled theoretical reservoir operating alternatives that could change releases and water levels for Cascade and Deadwood Reservoirs, while continuing to meet primary operational commitments. These operational alternatives could have negative effects to other purposes (e.g., recreational flows and power generation) which would need to be fully explored when considering actual implementation of changes in operations. The intent was to identify operating alternatives that might reduce concentrations of harmful algae that can produce toxins and lead to harmful algal blooms. However, when these operating alternatives were modeled in a water quality model developed for this purpose, they had minimal effects on harmful algae concentrations, with some alternatives entailing potentially negative effects to other purposes (e.g., fish habitat, recreation, and power generation). Since the changes in chlorophyll-a concentrations, which reflect all types of algae, were well within the reported range of error for the water quality model, the changes in chlorophyll-a concentrations among the alternatives were not statistically significant. By extension, the changes in harmful algae and toxin concentrations among the operations alternatives were not considered significant. In the future, although the projected warmer temperatures and other changes in water quality (e.g., continued land development) could increase harmful algae concentrations, the lack of sensitivity of harmful algae to the changes in water levels in the operating alternatives suggest that changes in reservoir operations may be unable to offset these future water quality impacts without other measure to reduce harmful algae (e.g., nutrient management).

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| Parenthetical Reference | Bibliographic Citation |
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# Appendix A - Additional Modeled Water Quality Data

This section contains additional figures showing changes in select water quality characteristics among the five reservoir operational alternatives.

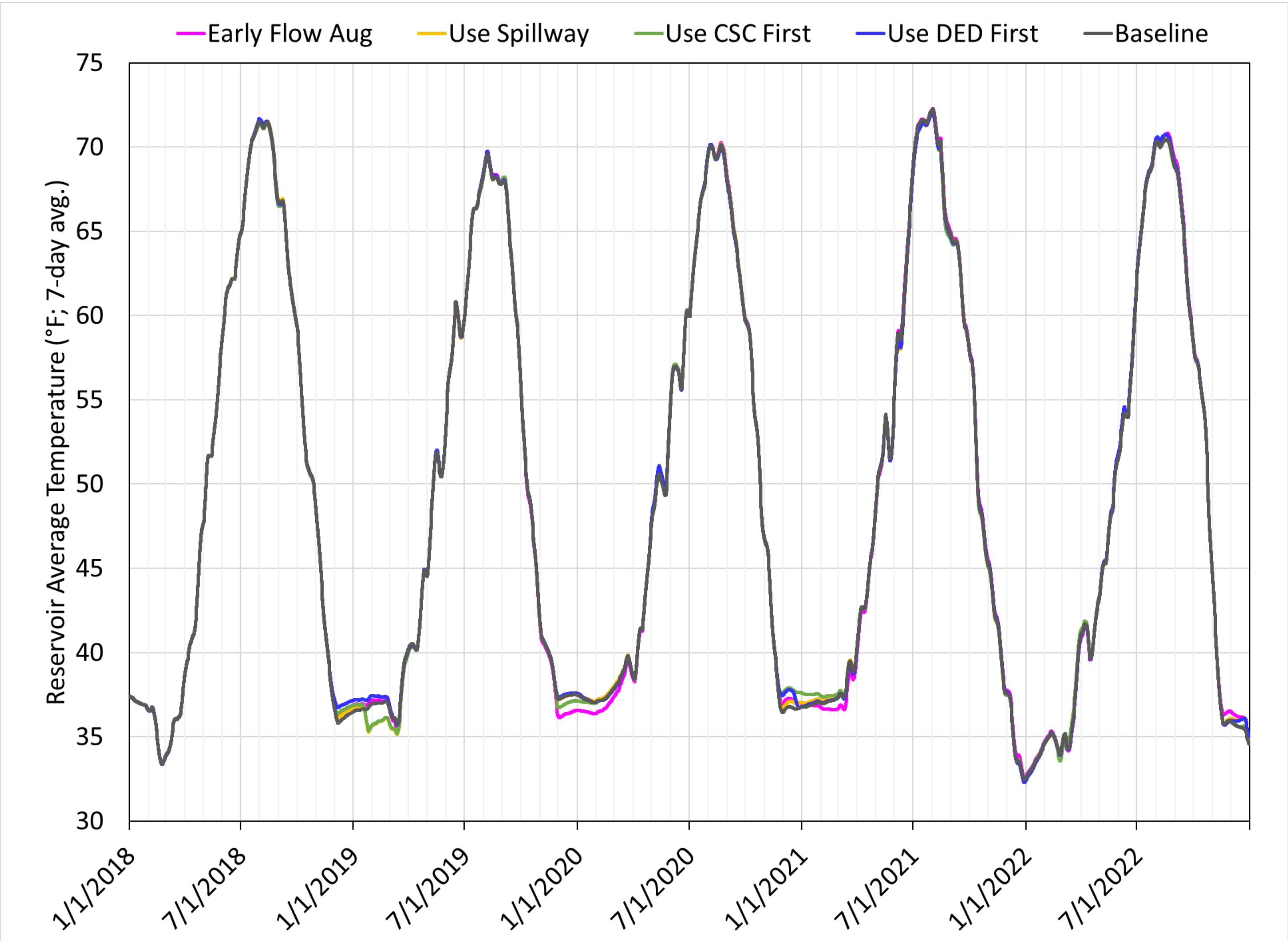



Figure A-1. Changes in reservoir average temperature over time for the reservoir operational alternatives

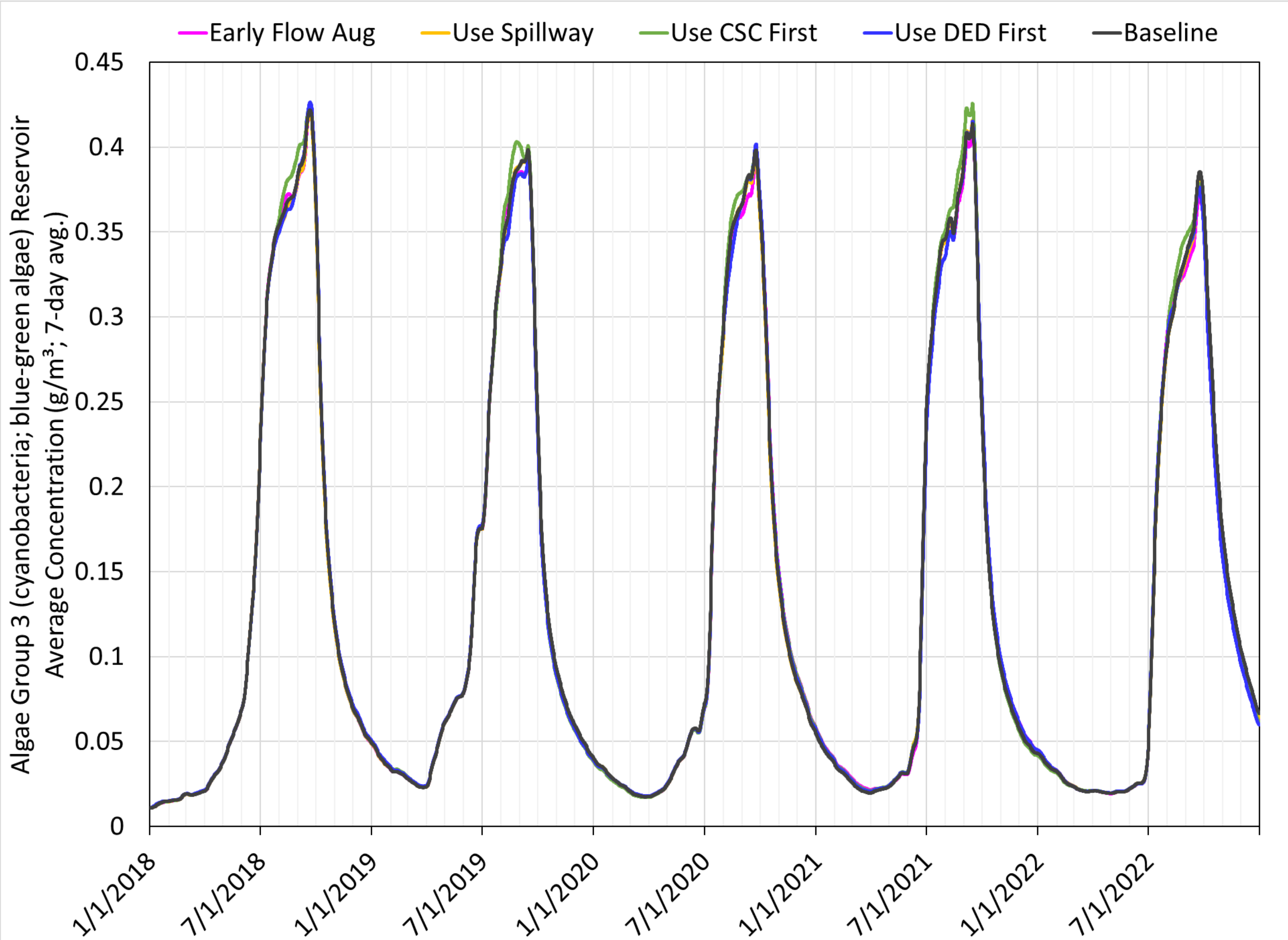



Figure A-2. Changes in reservoir average concentrations of algae group 3, which represents the harmful algae (e.g., cyanobacteria or blue-green algae), over time for the reservoir operational alternatives

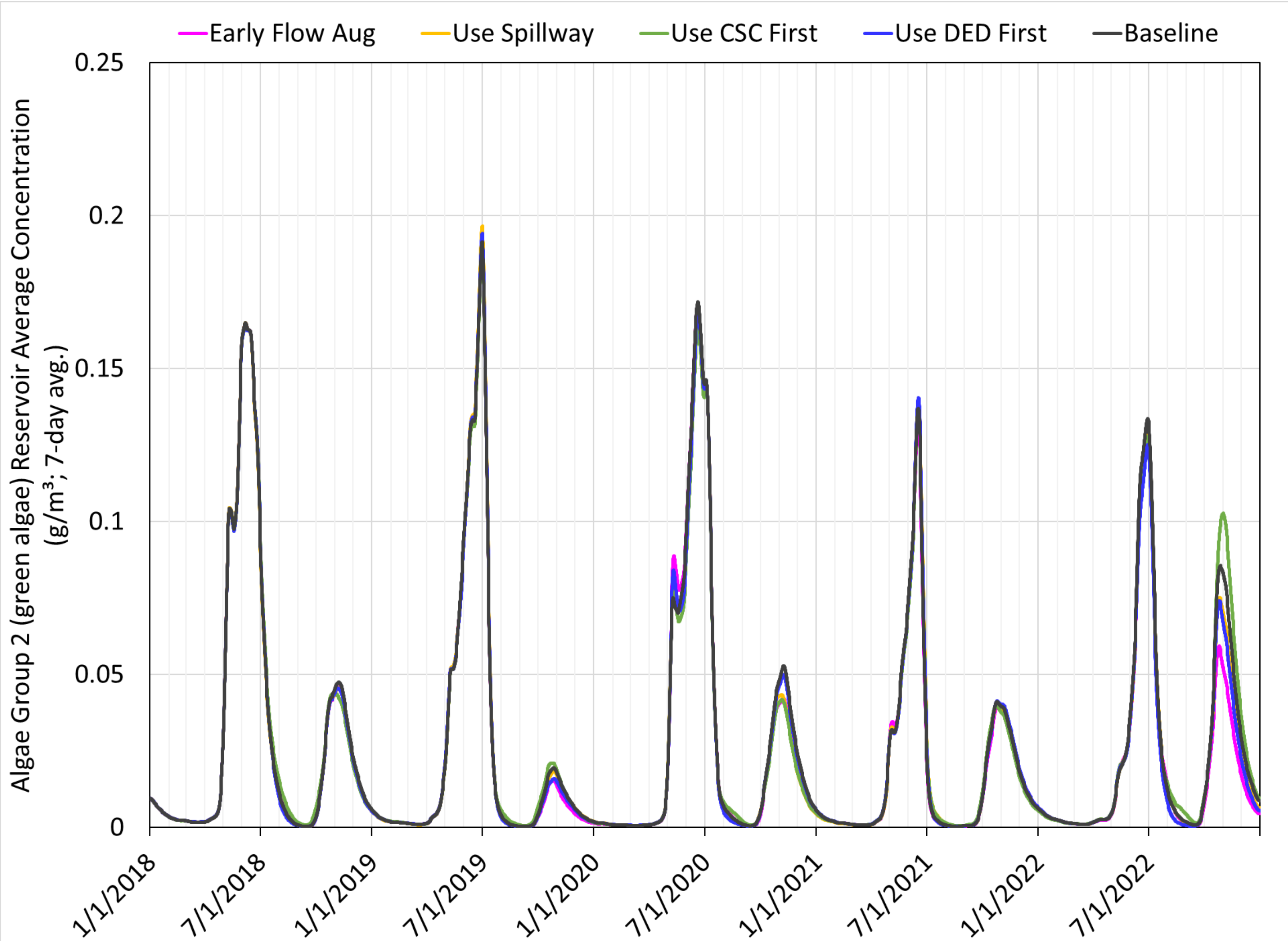



Figure A-3. Changes in reservoir average concentrations of algae group 2, which represents the non-harmful green algae, over time for the reservoir operational alternatives

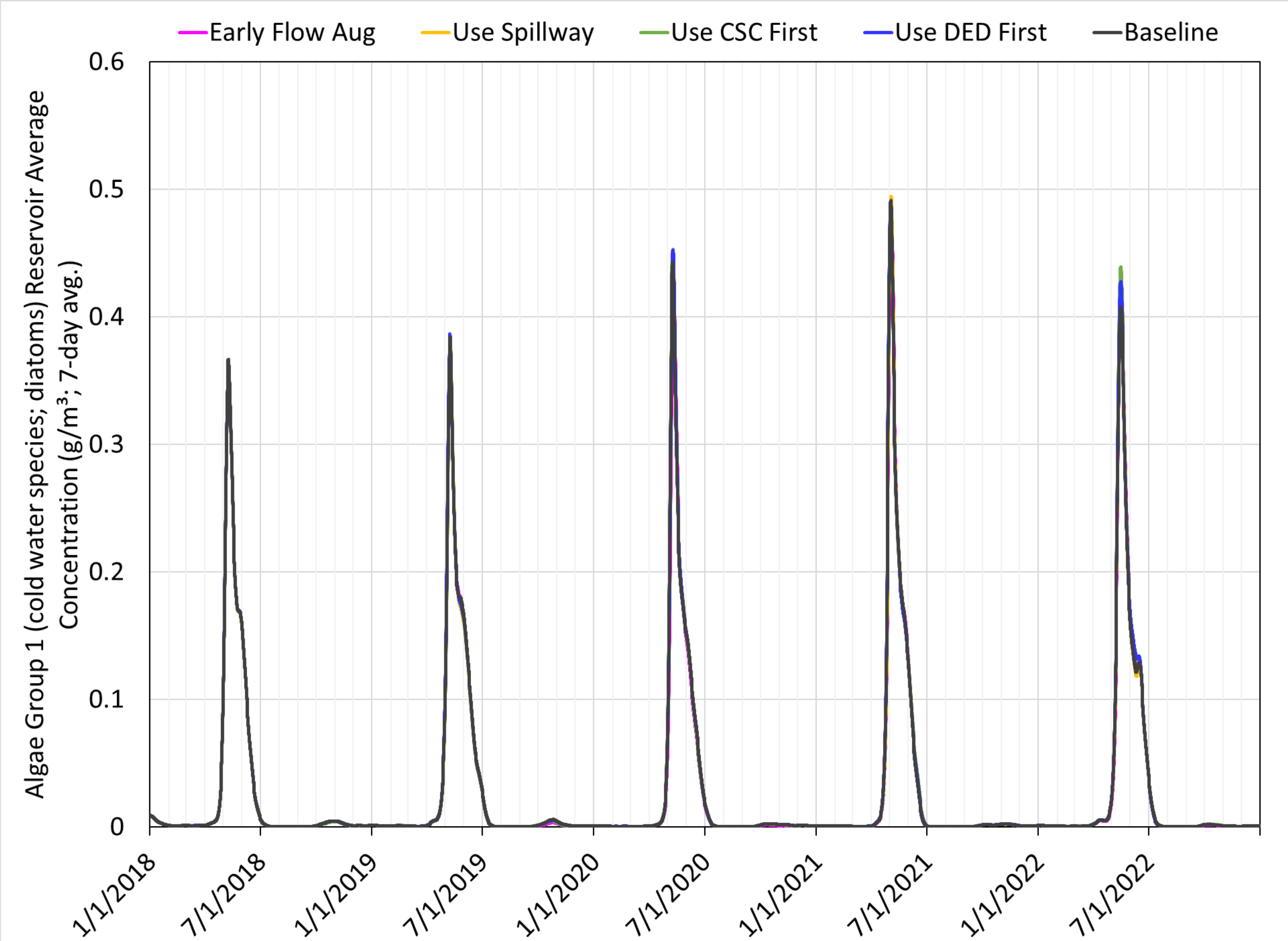



Figure A-4. Changes in reservoir average concentrations of algae group 12, which represents the non-harmful cold-water algae (e.g., diatoms), over time for the reservoir operational alternatives

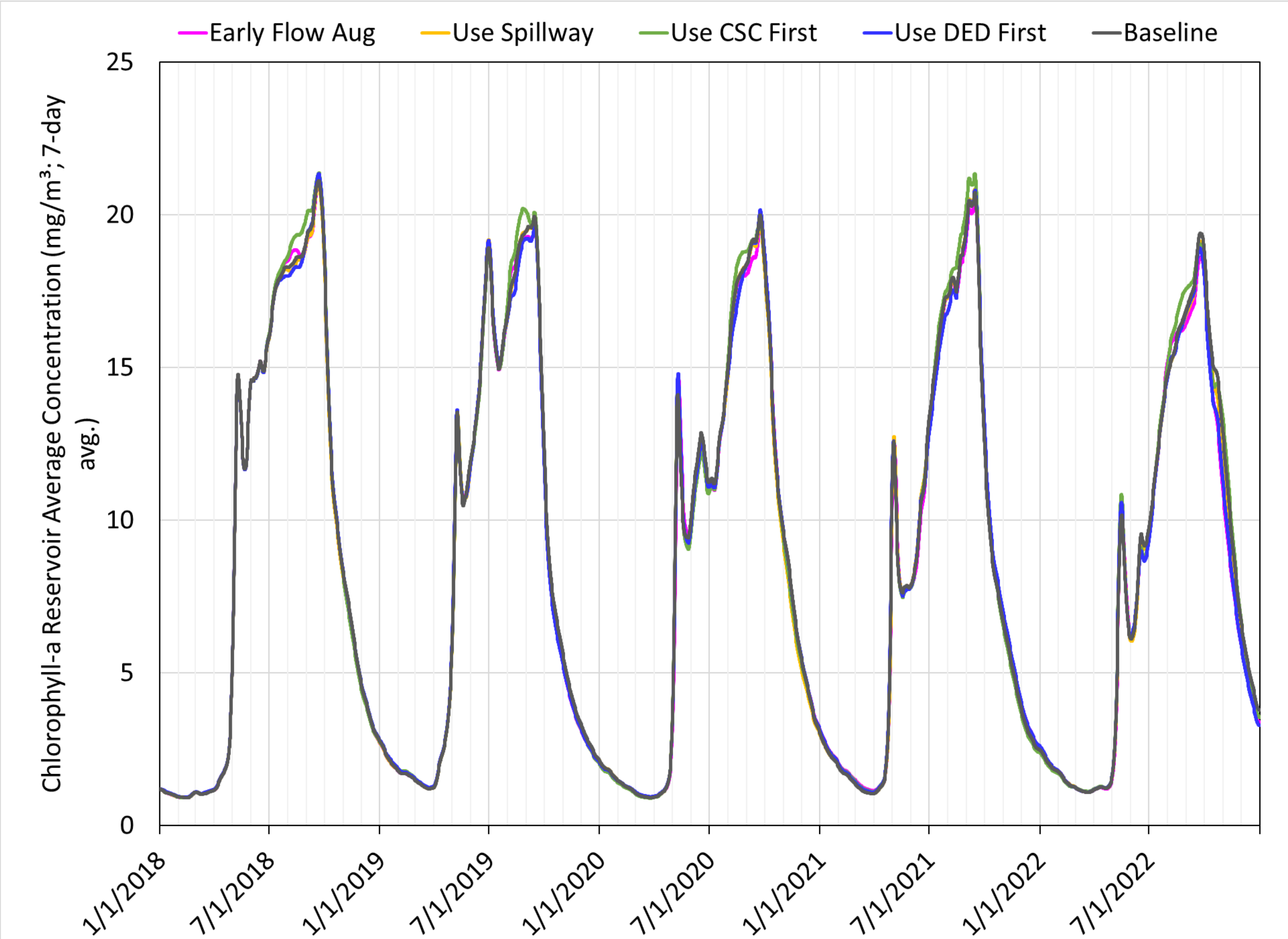



Figure A-5. Changes in reservoir average concentrations of chlorophyll-a over time for the reservoir operational alternatives

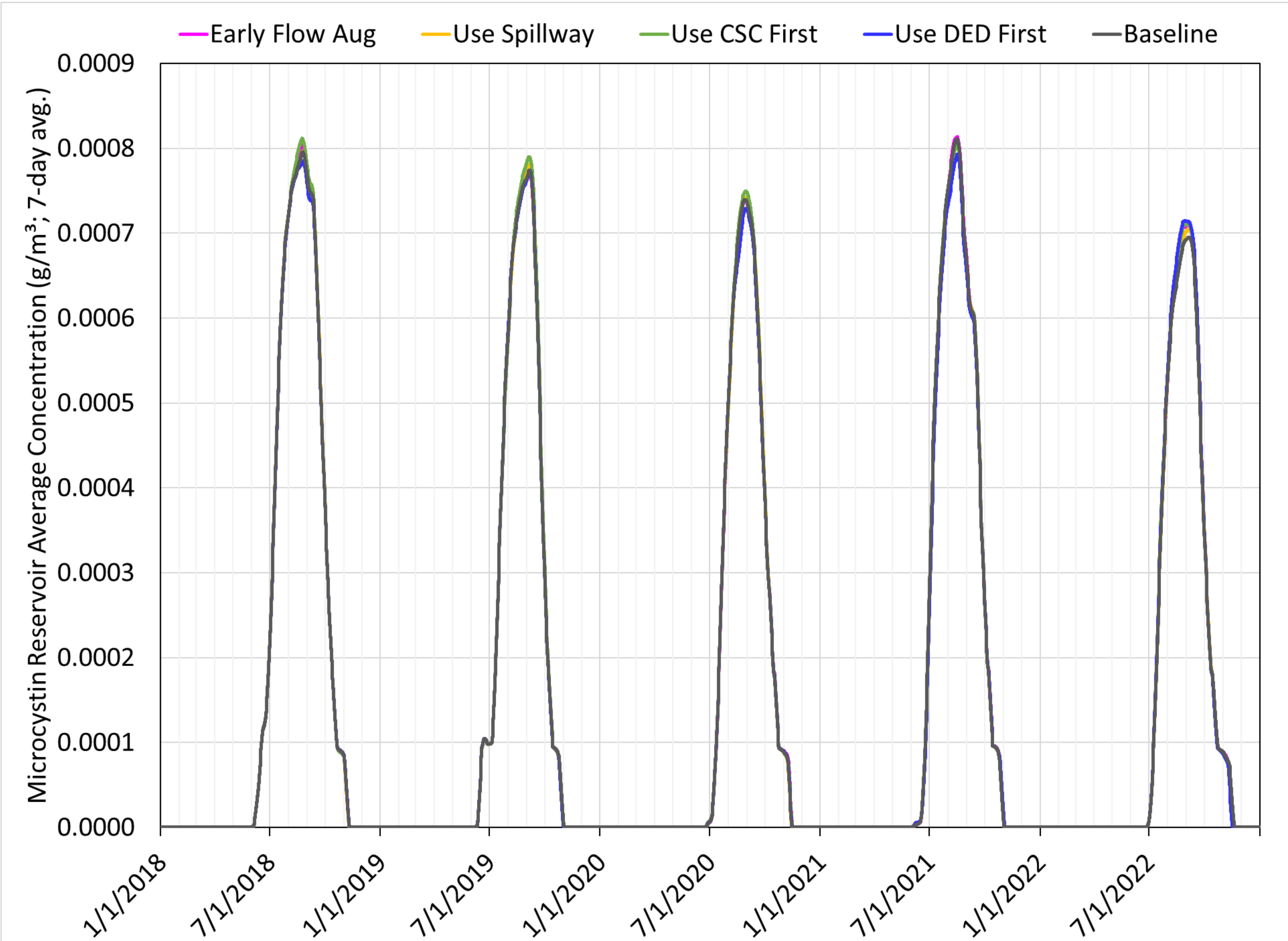



Figure A-6. Changes in reservoir average concentrations of microcystin, a toxin produced by harmful algae, over time for the reservoir operational alternatives

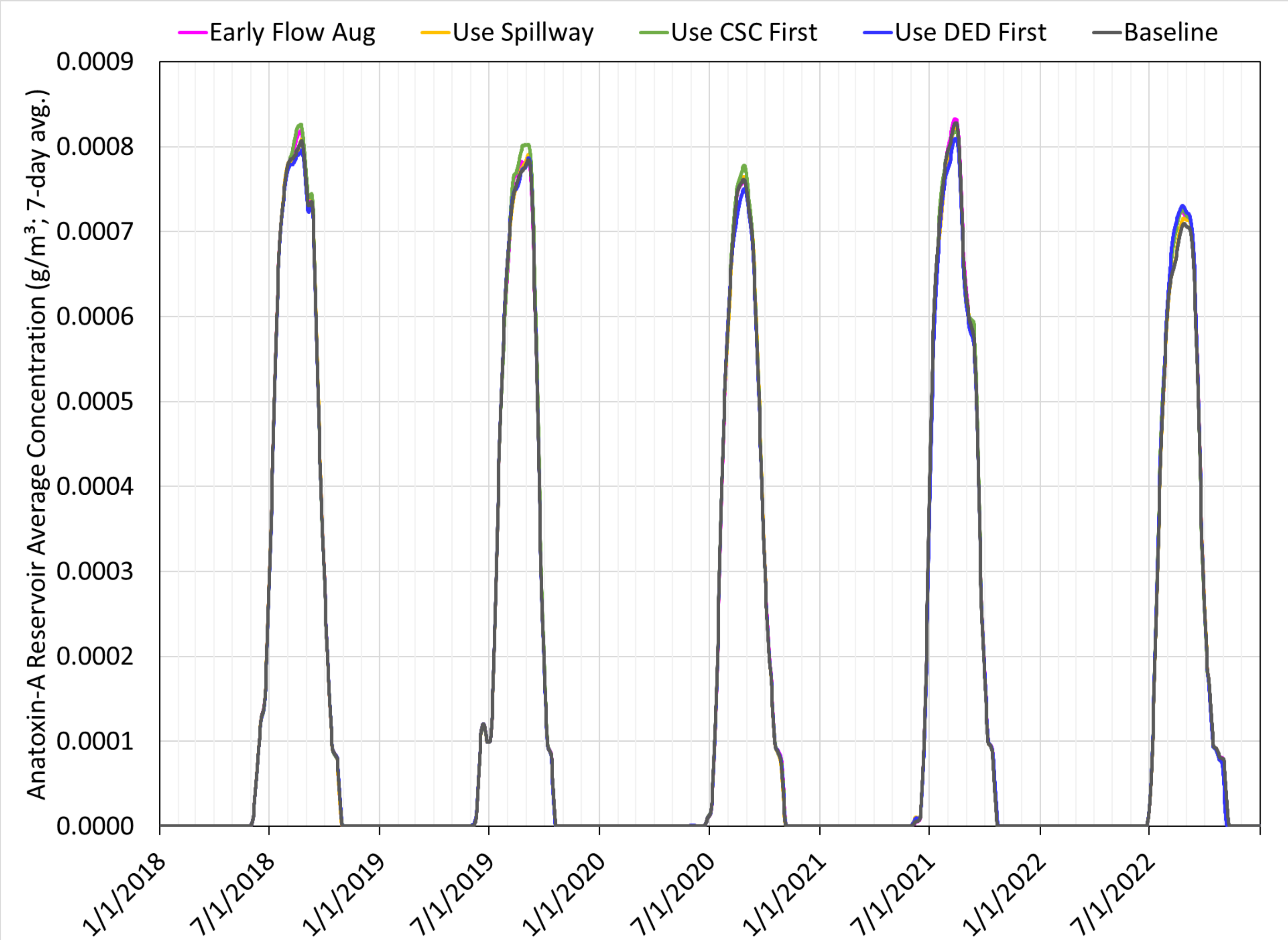



Figure A-7. Changes in reservoir average concentrations of anatoxin-a, a toxin produced by harmful algae, over time for the reservoir operational alternatives

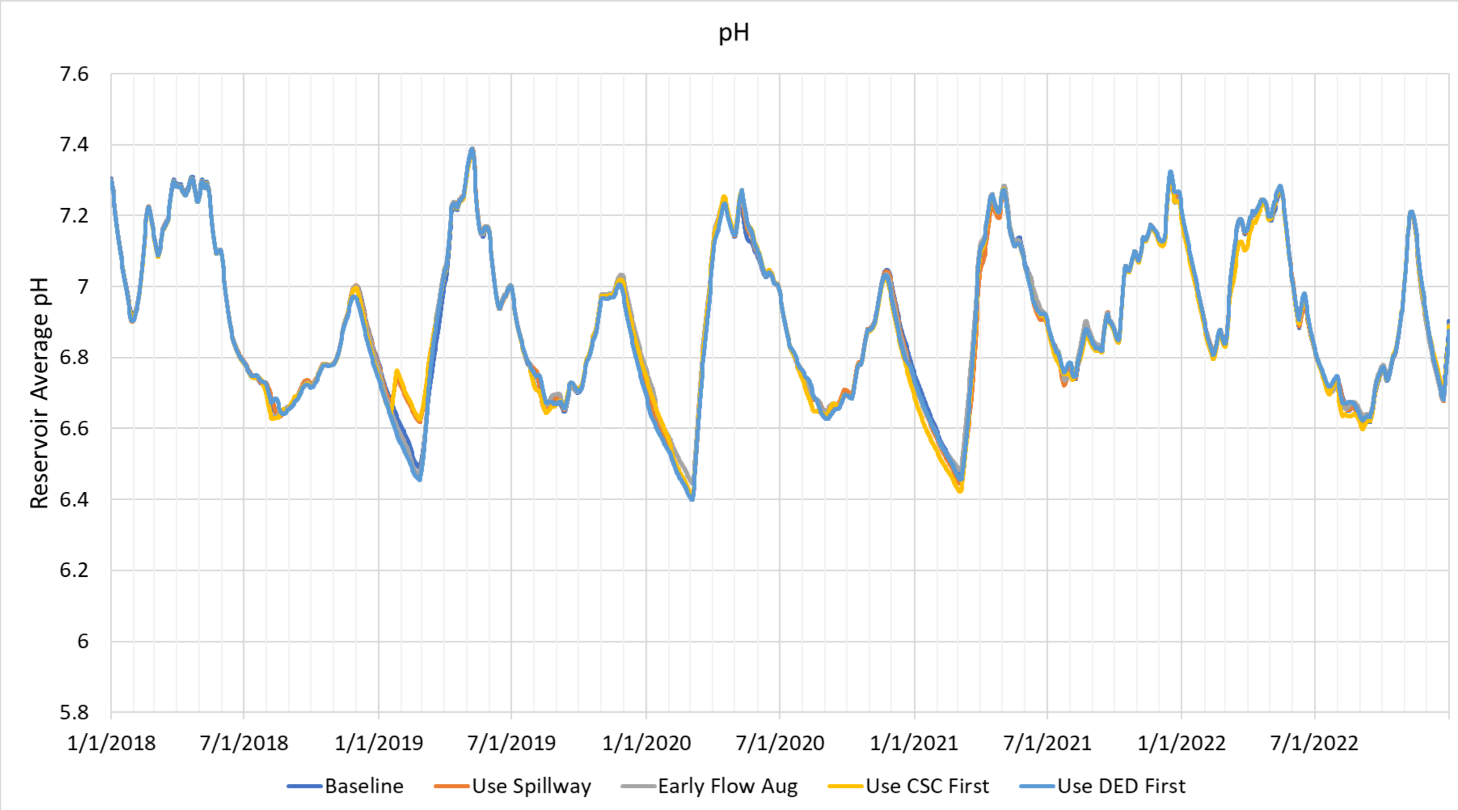



Figure A-8. Changes in reservoir average pH over time for the reservoir operational alternatives

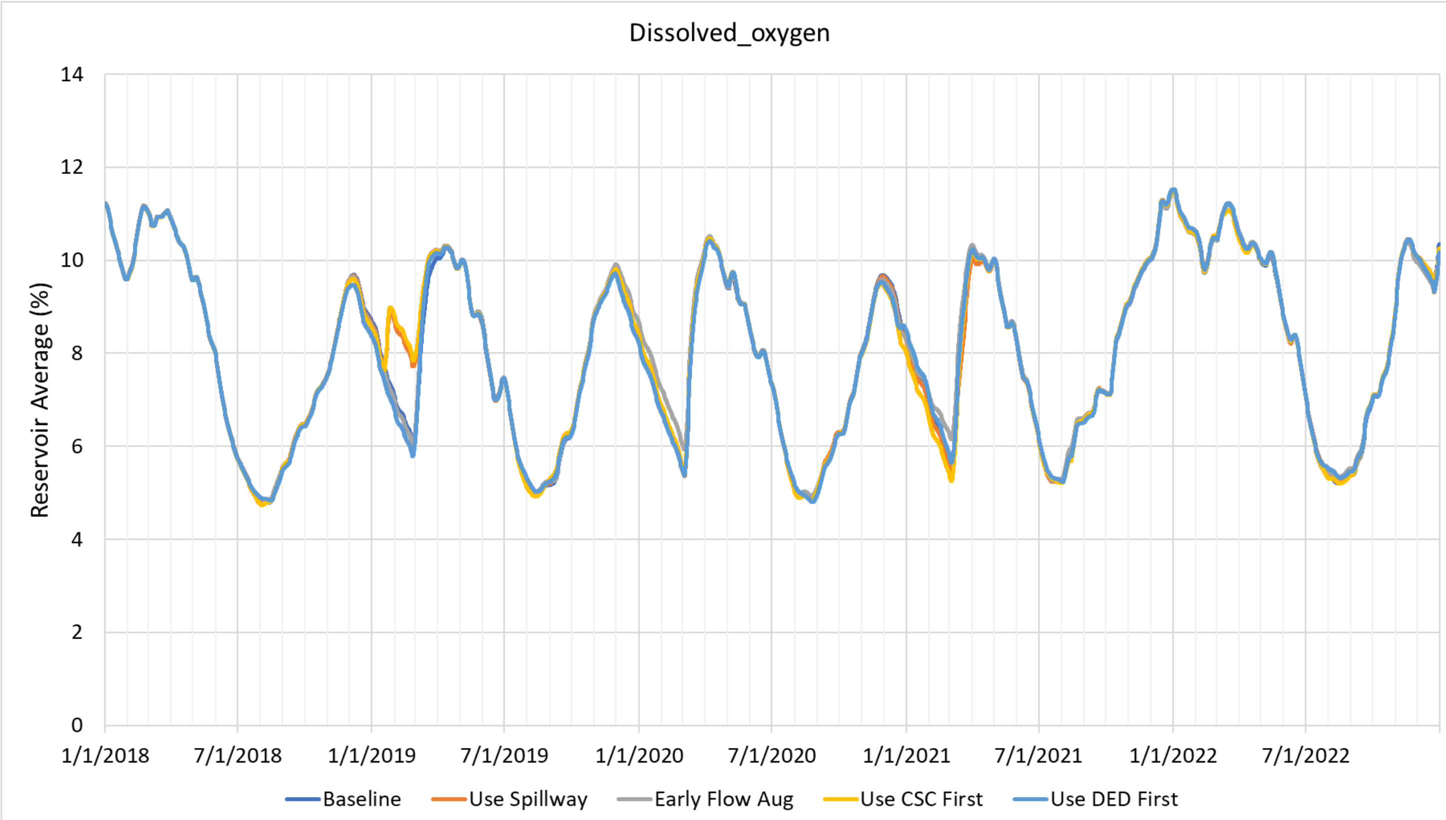



Figure A-9. Changes in reservoir average dissolved oxygen concentrations over time for the reservoir operational alternatives

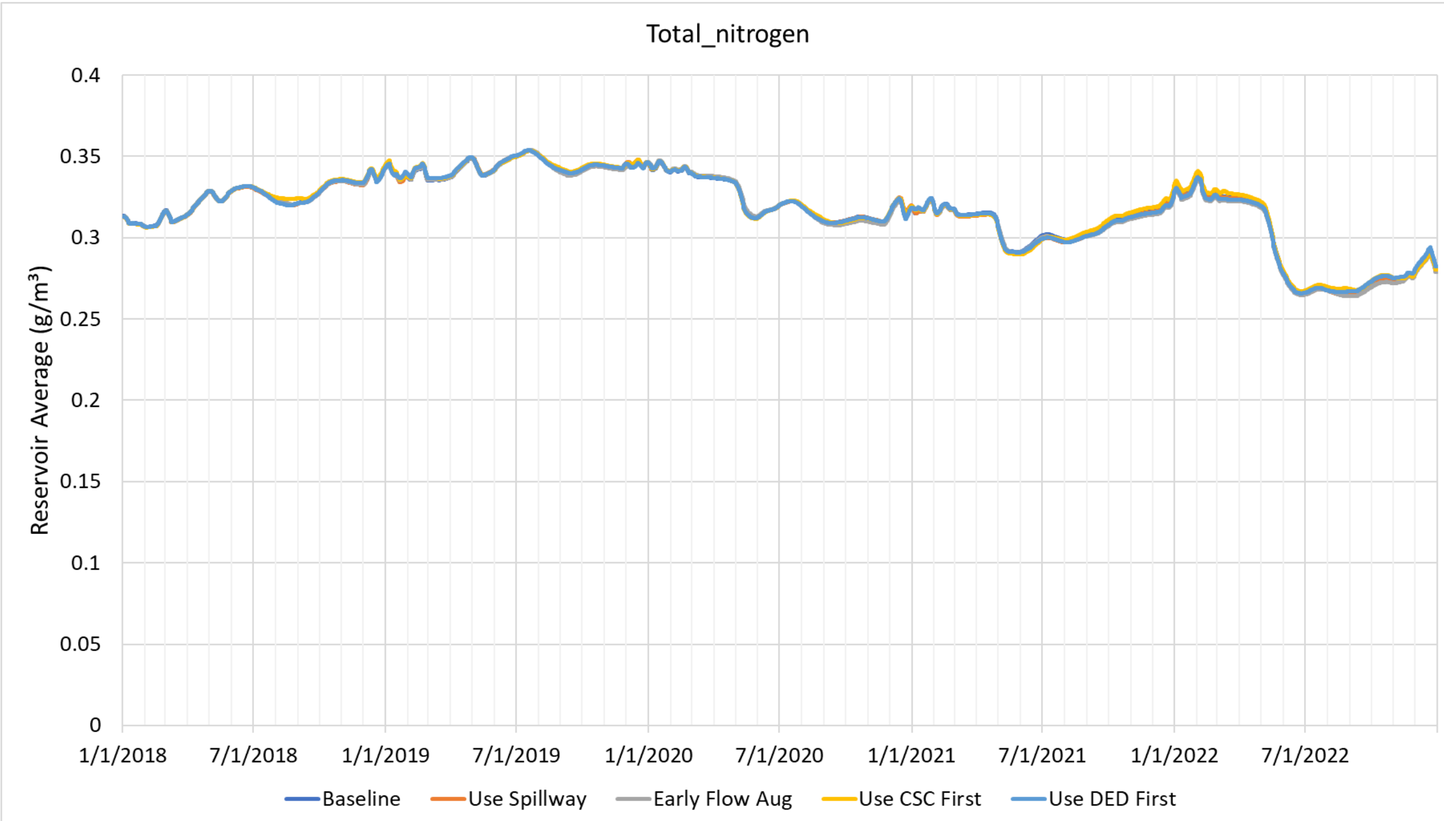



Figure A-10. Changes in reservoir average total nitrogen concentrations over time for the reservoir operational alternatives

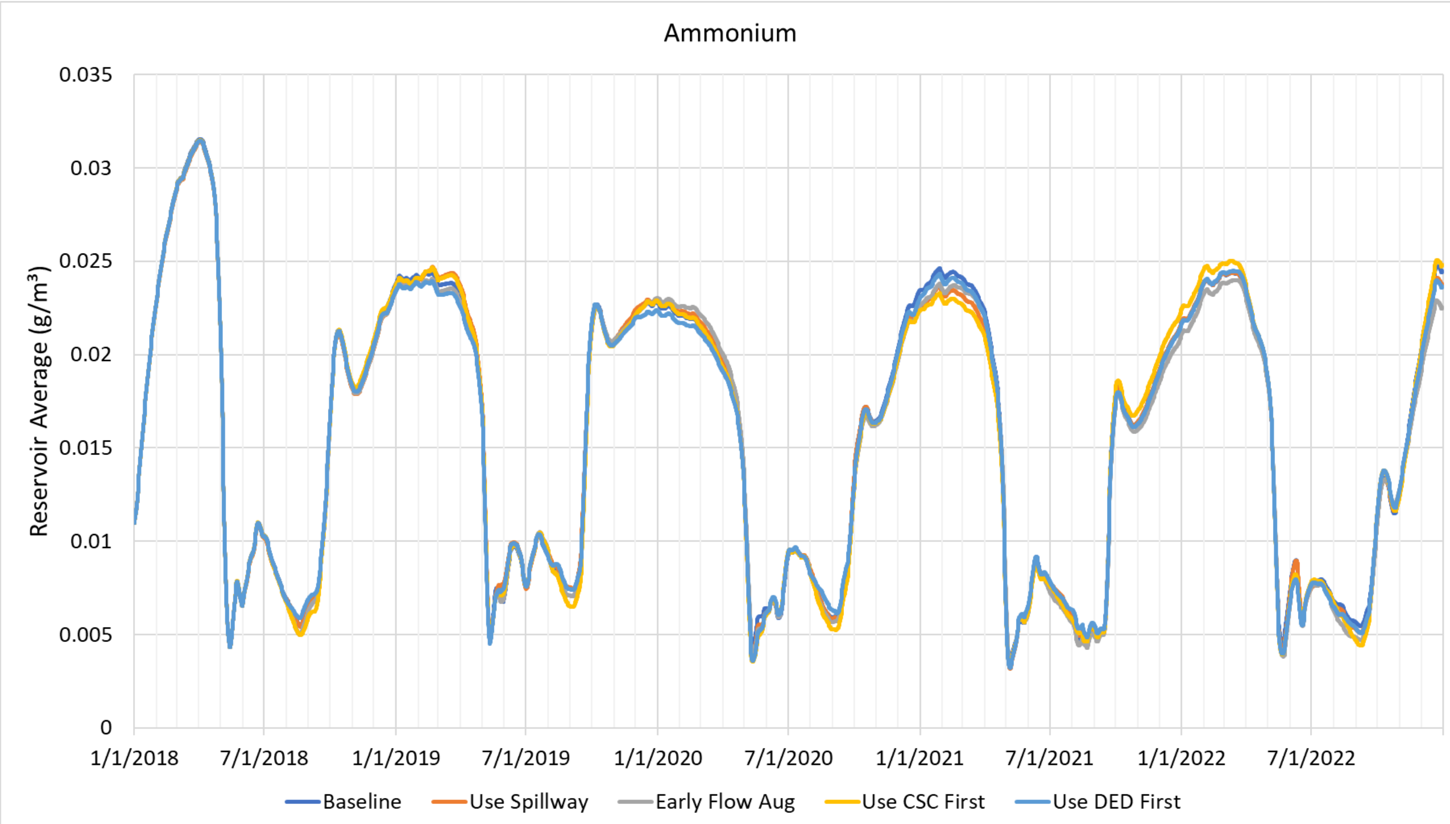



Figure A-11. Changes in reservoir average ammonium concentrations over time for the reservoir operational alternatives

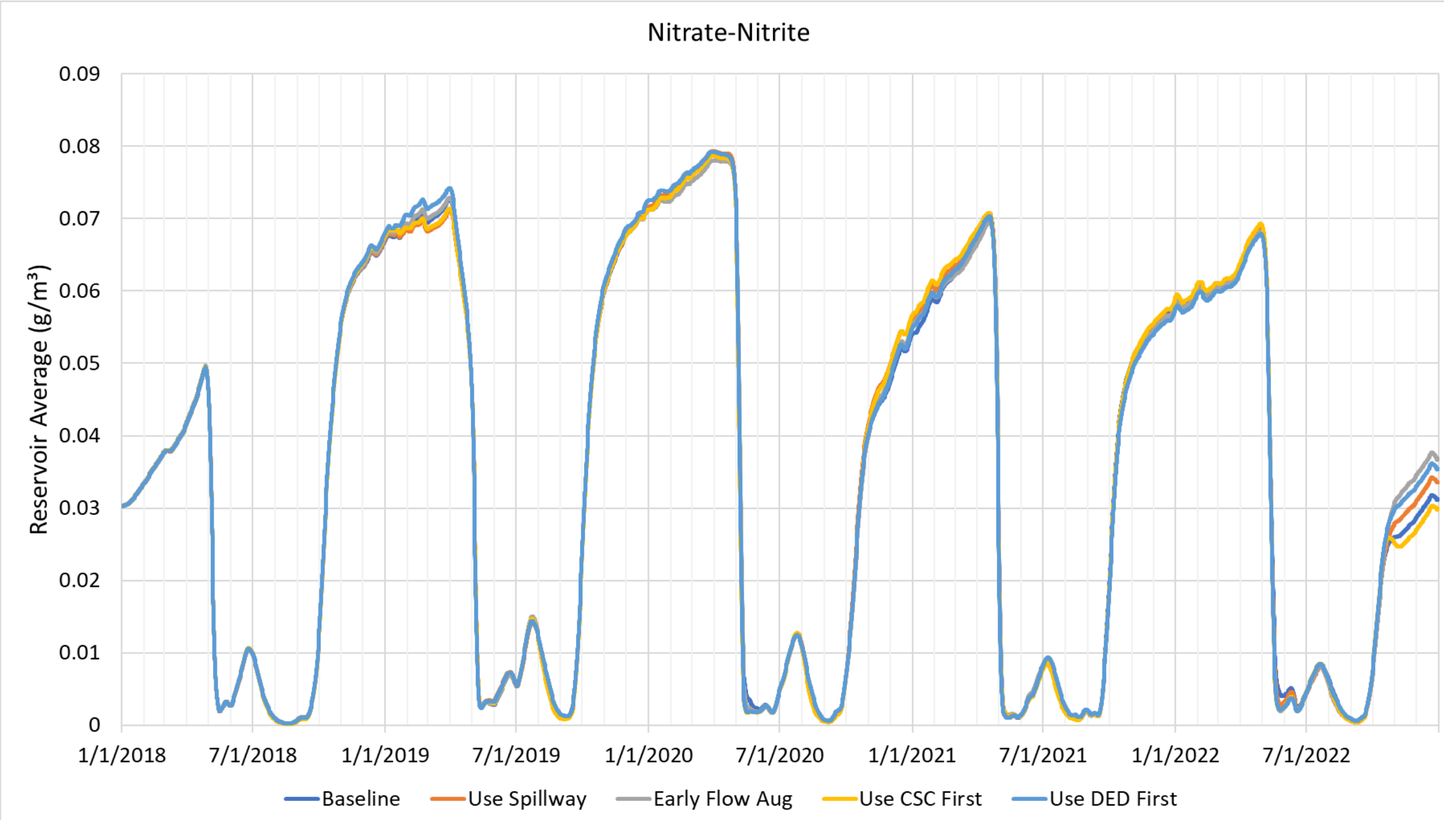



Figure A-12. Changes in reservoir average nitrate and nitrite concentrations over time for the reservoir operational alternatives

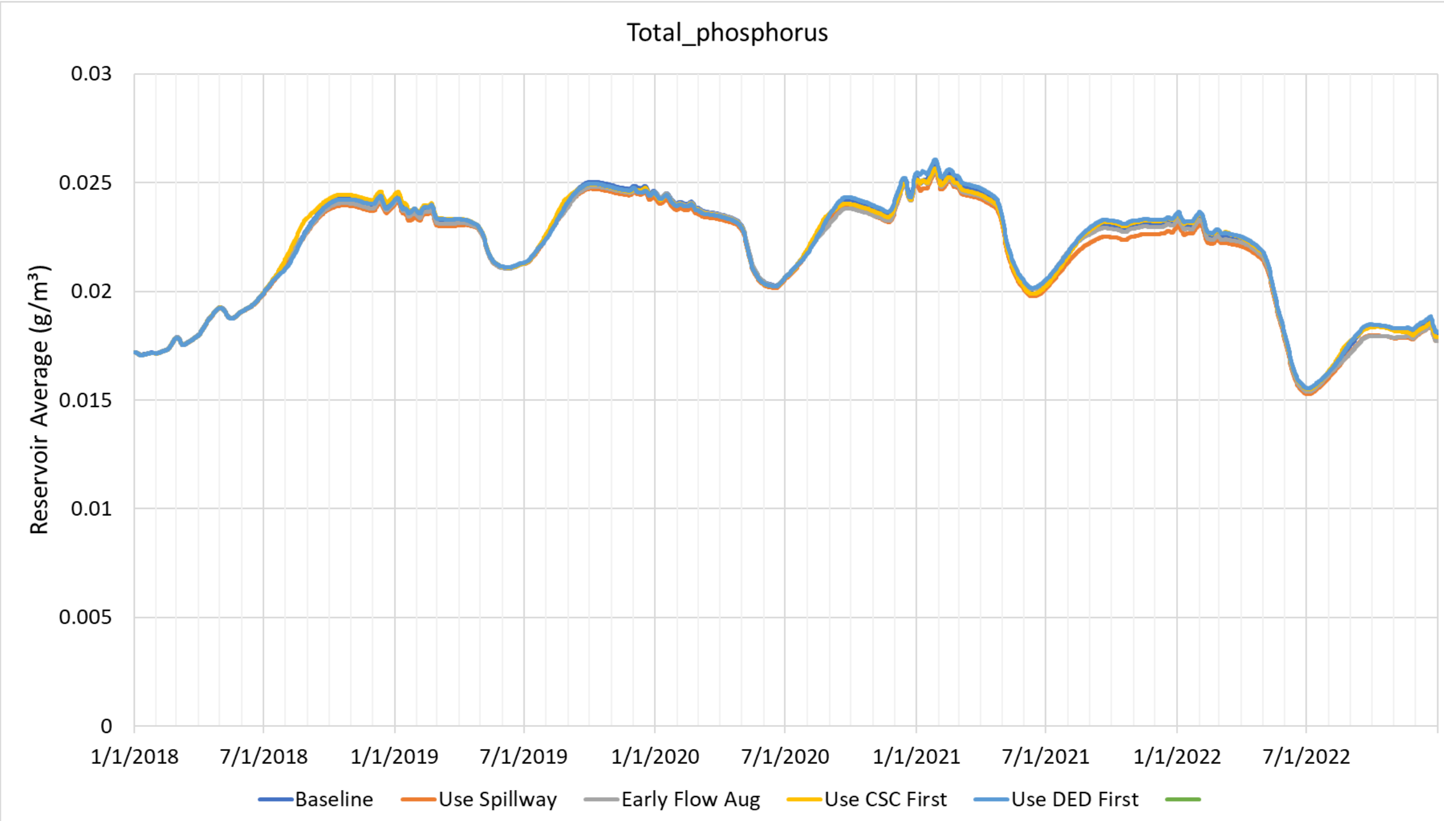



Figure A-13. Changes in reservoir average total phosphorus concentrations over time for the reservoir operational alternatives

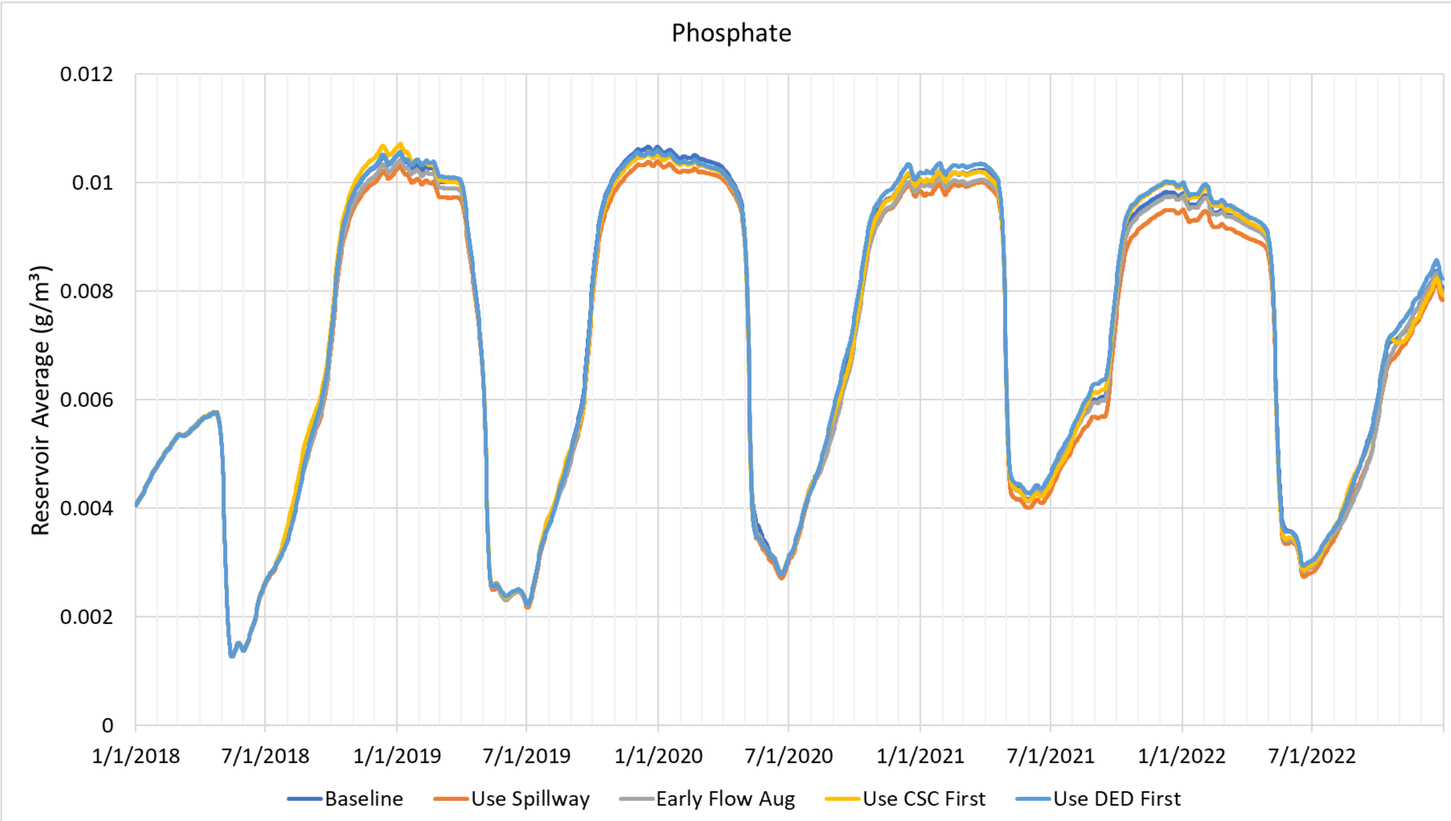



Figure A-14. Changes in reservoir average phosphate concentrations over time for the reservoir operational alternatives

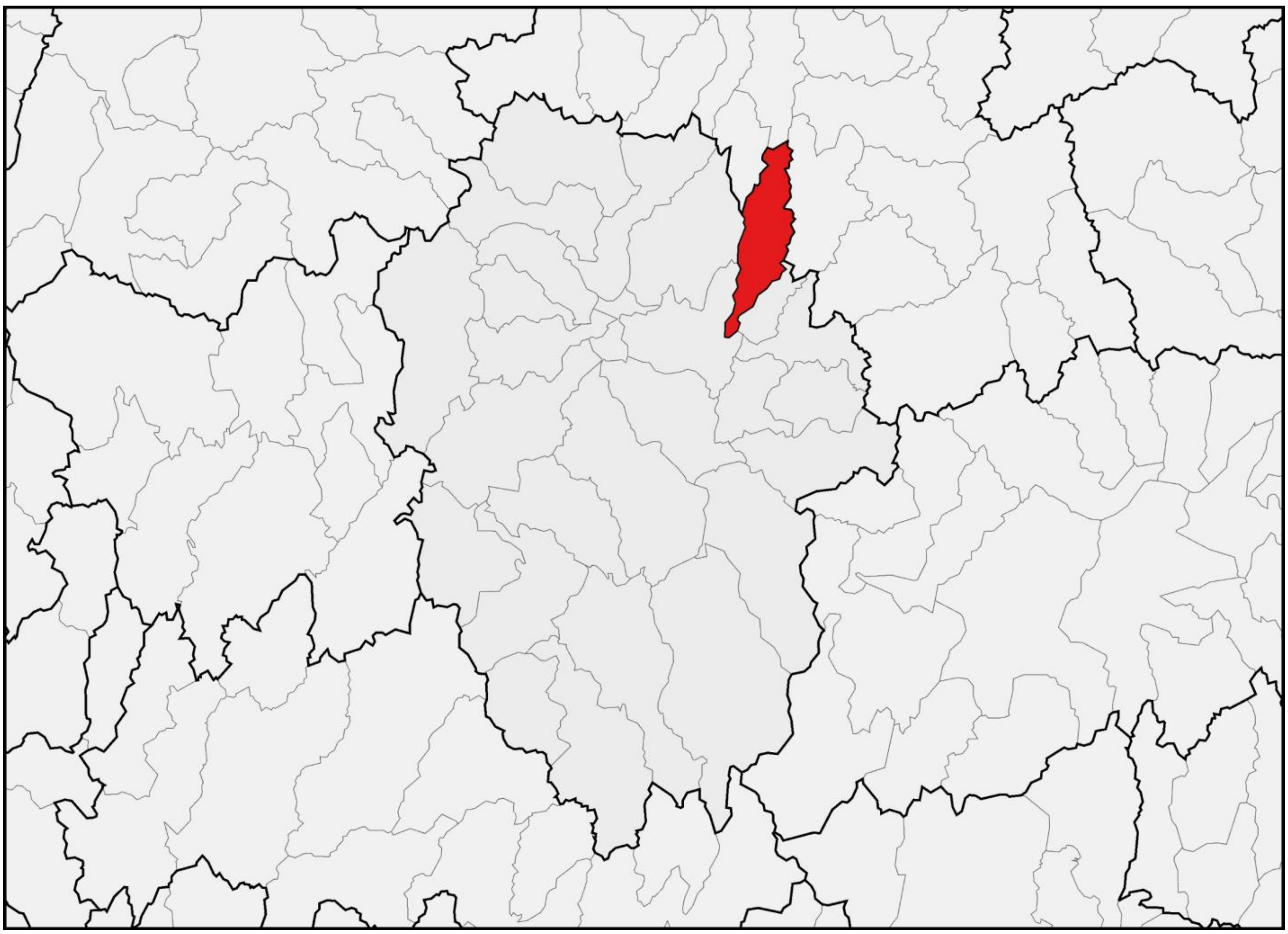
# Appendix B – National Climate Change Viewer Output

This section contains the full output from the National Climate Change Viewer for the North Fork Payette River. For more details, see source documentation (USGS 2021; Alder and Hostetler 2013; https://apps.usgs.gov/nccv/maca2/maca2_watersheds.html).

science for a changing world

U.S. Geological Survey - National Climate Change Viewer

# Summary of North Fork Payette (17050123)



May 5, 2021

# 1 Mean temperature

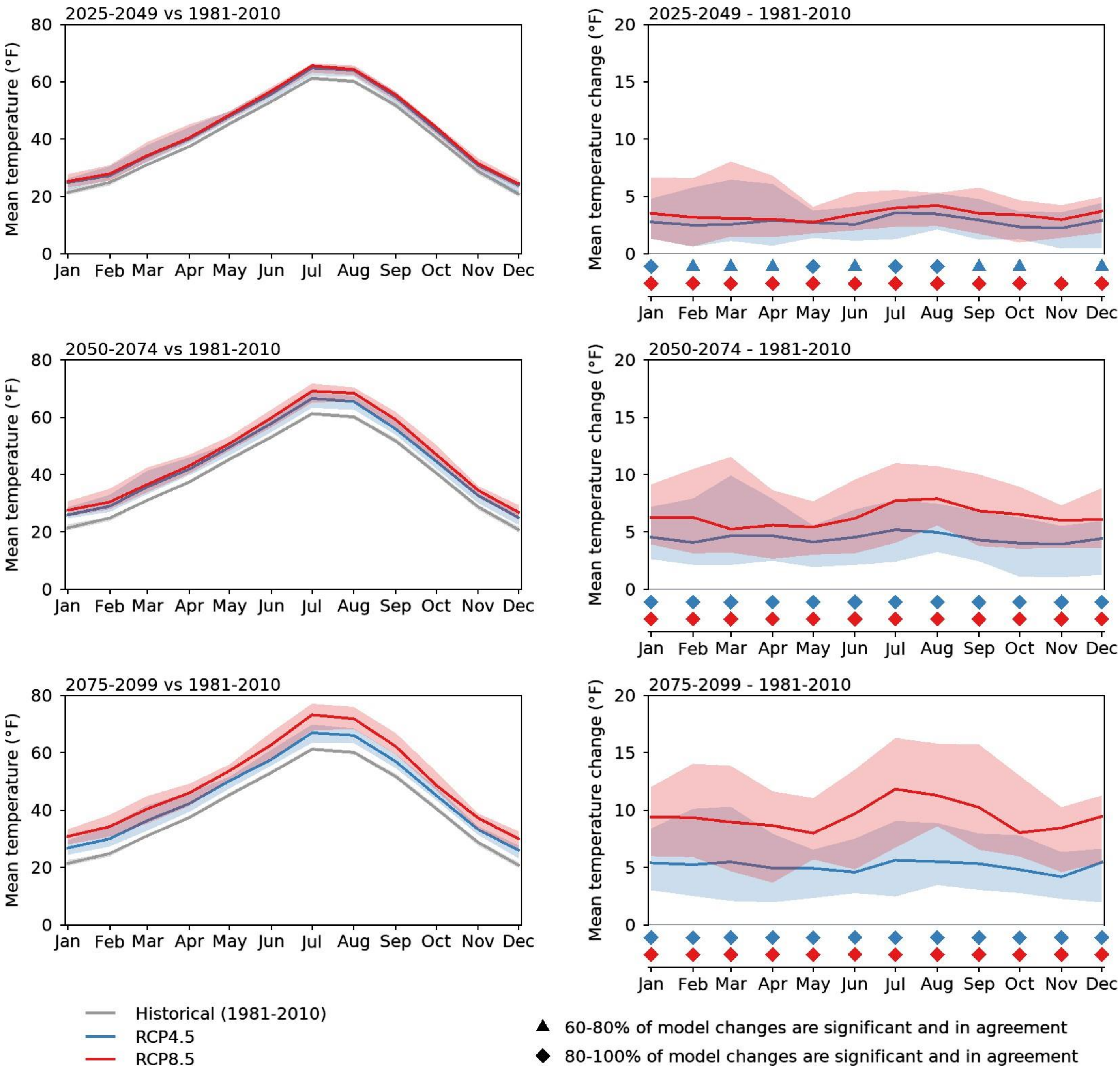



Figure 1: Monthly averages of mean temperature for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

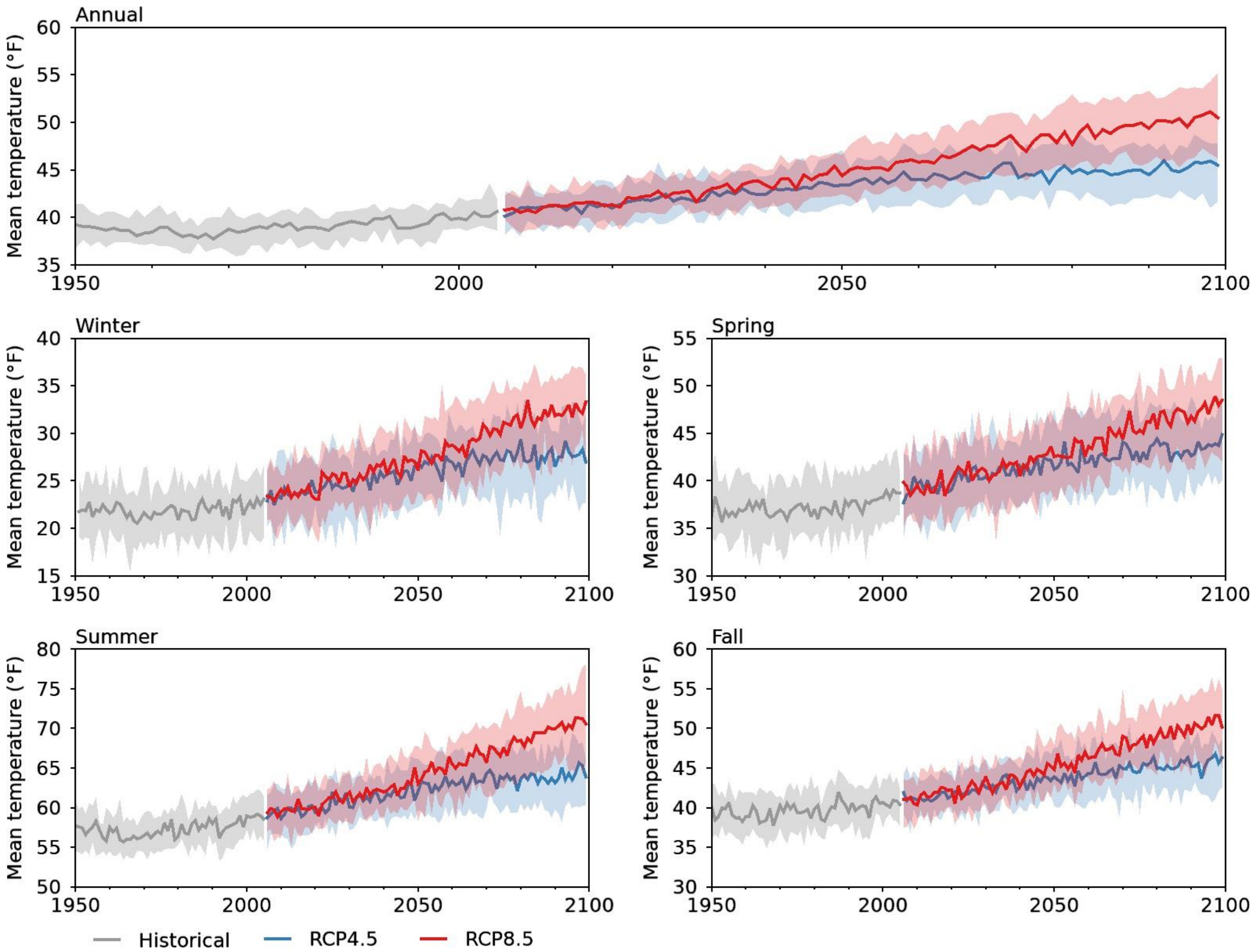



Figure 2: Annual and seasonal time series of mean temperature for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

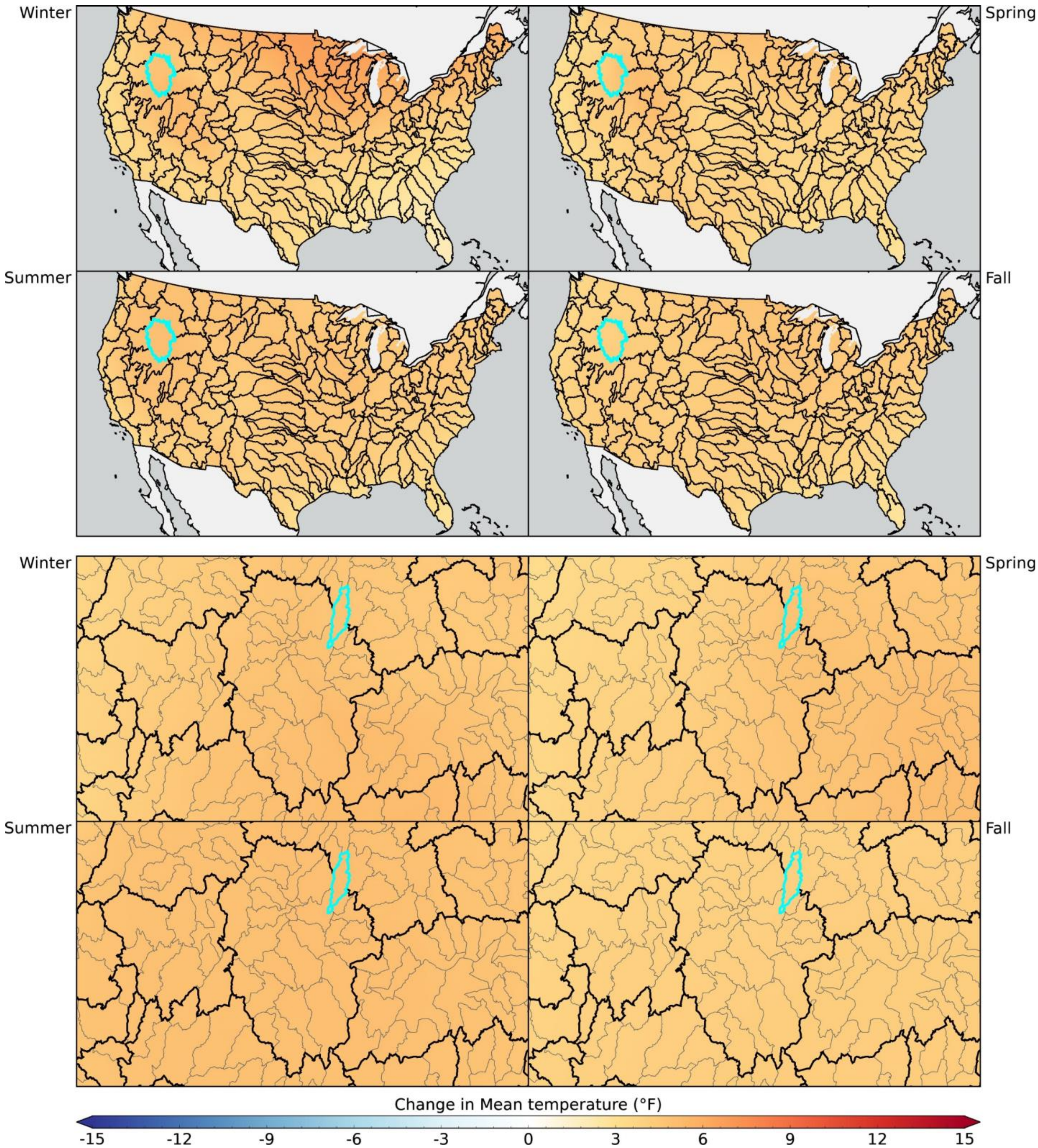



Figure 3: Seasonal maps of mean temperature for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

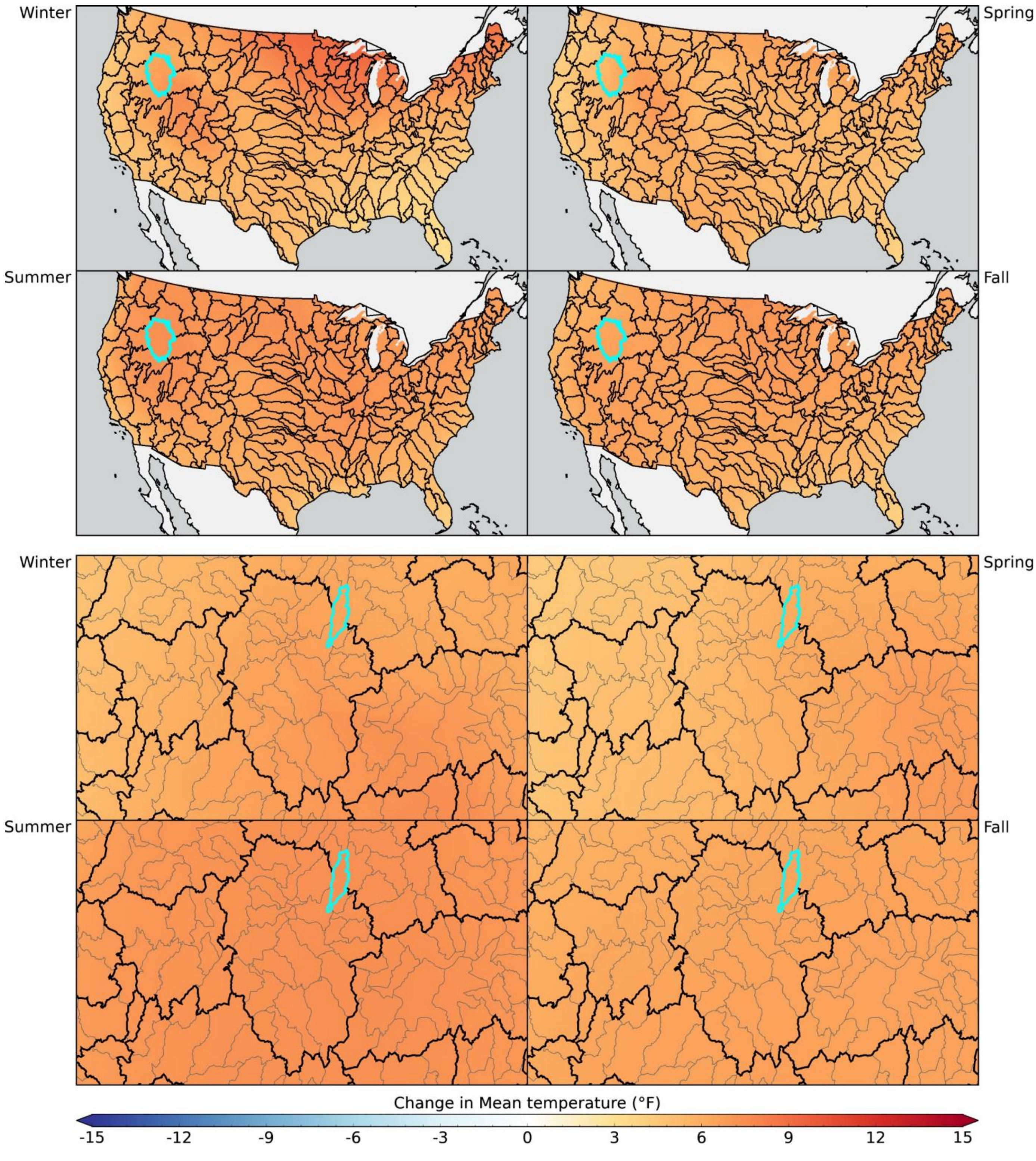



Figure 4: Seasonal maps of mean temperature for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 2 Maximum temperature

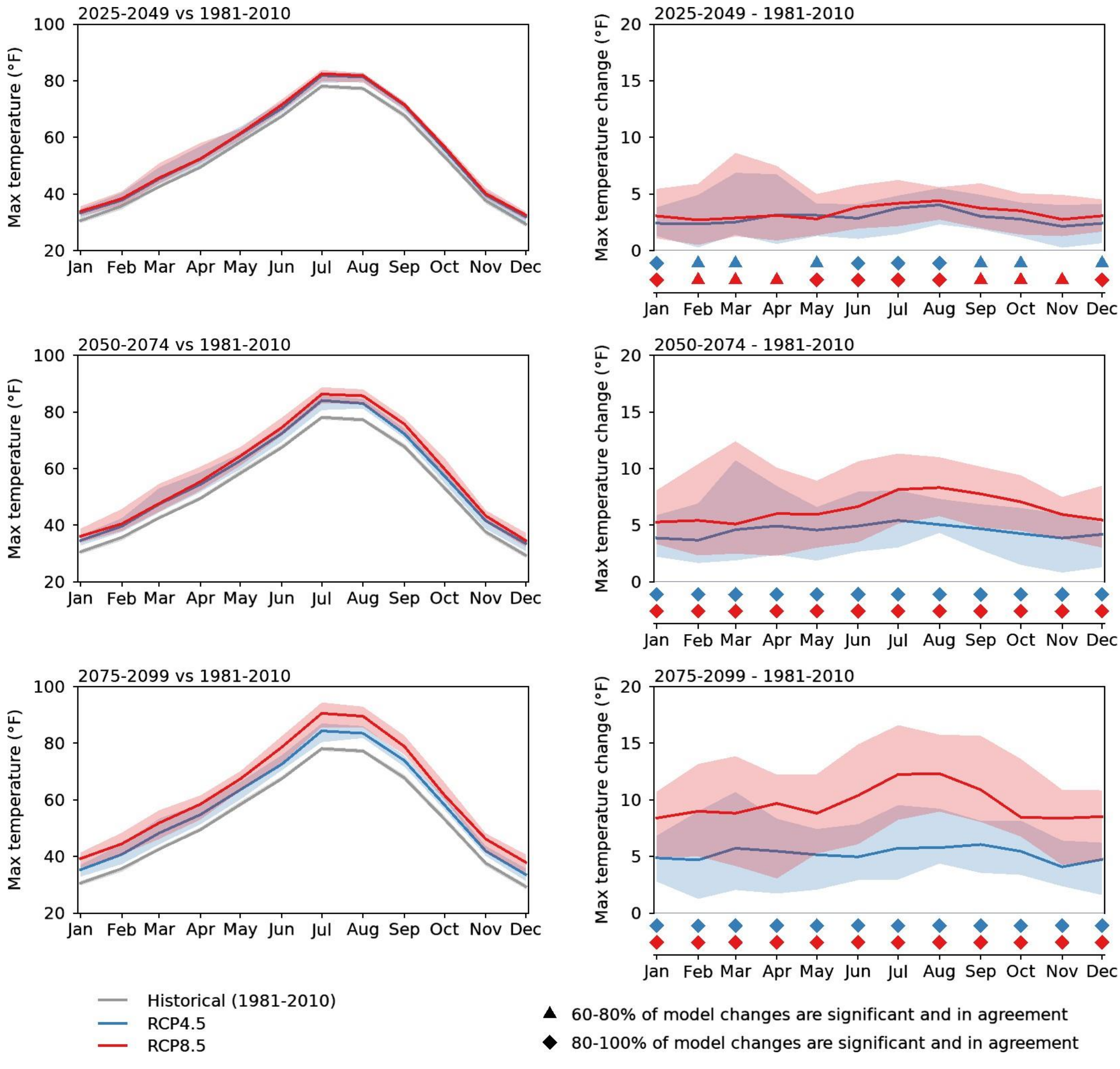



Figure 5: Monthly averages of maximum temperature for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

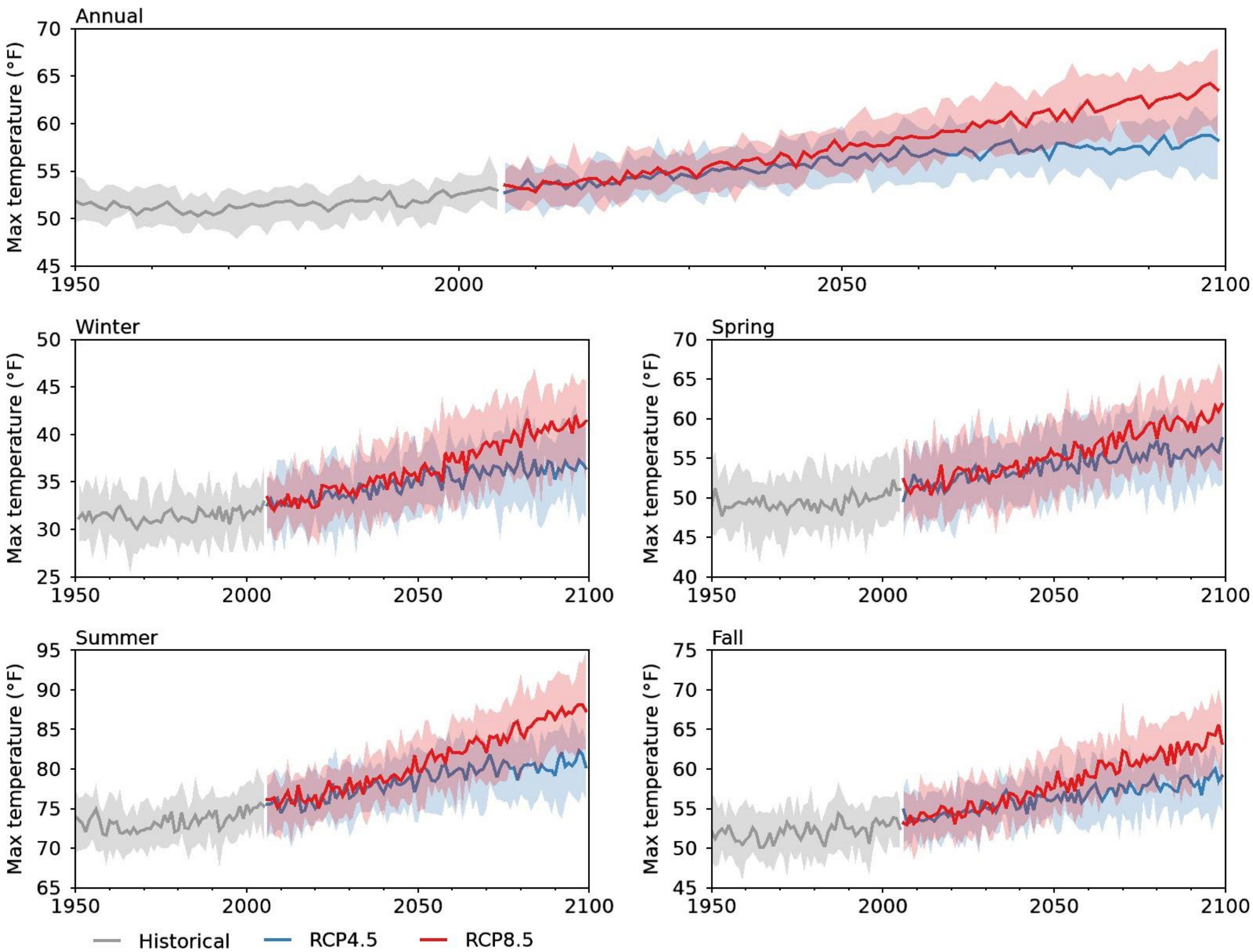



Figure 6: Annual and seasonal time series of maximum temperature for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

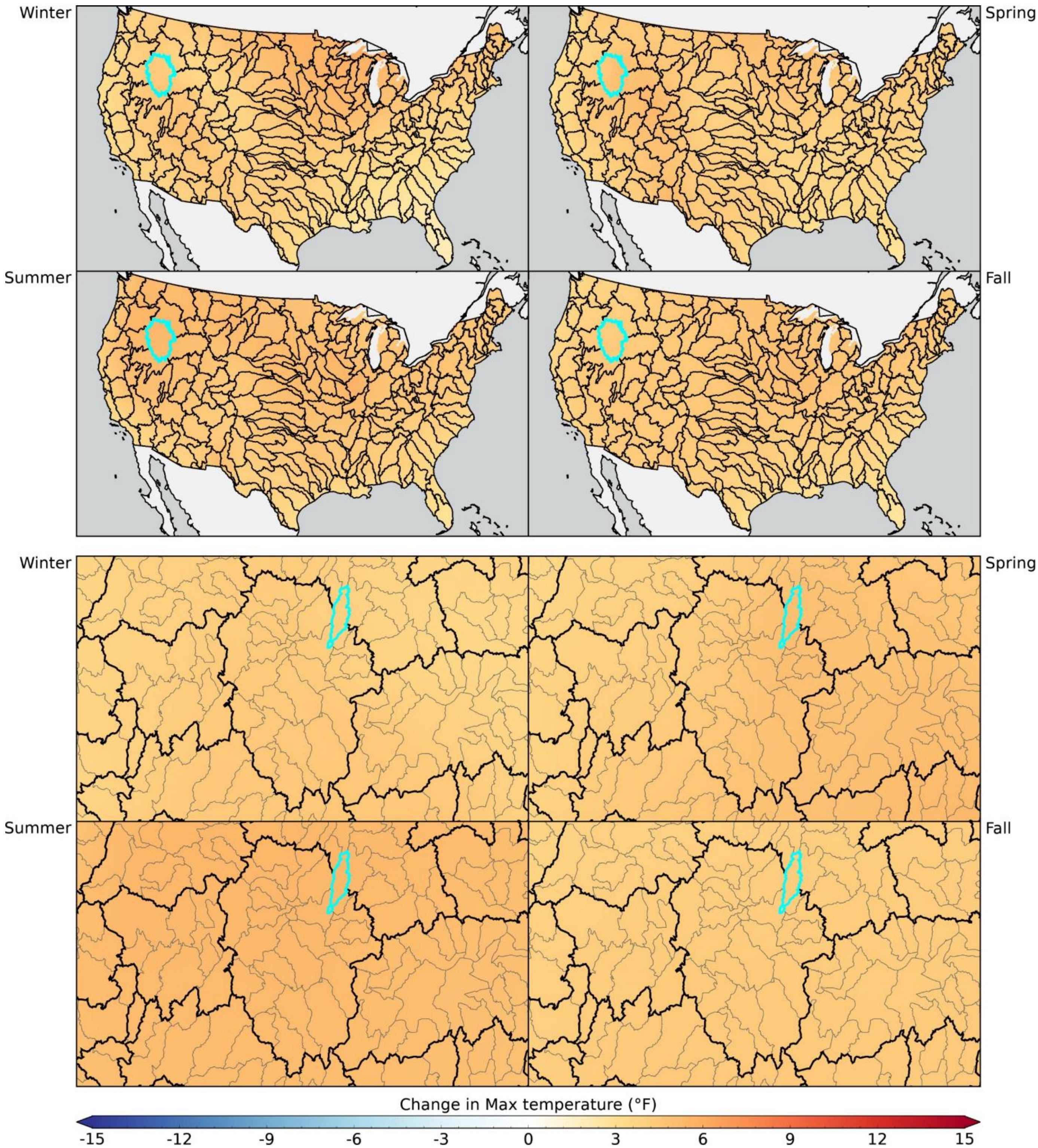



Figure 7: Seasonal maps of maximum temperature for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

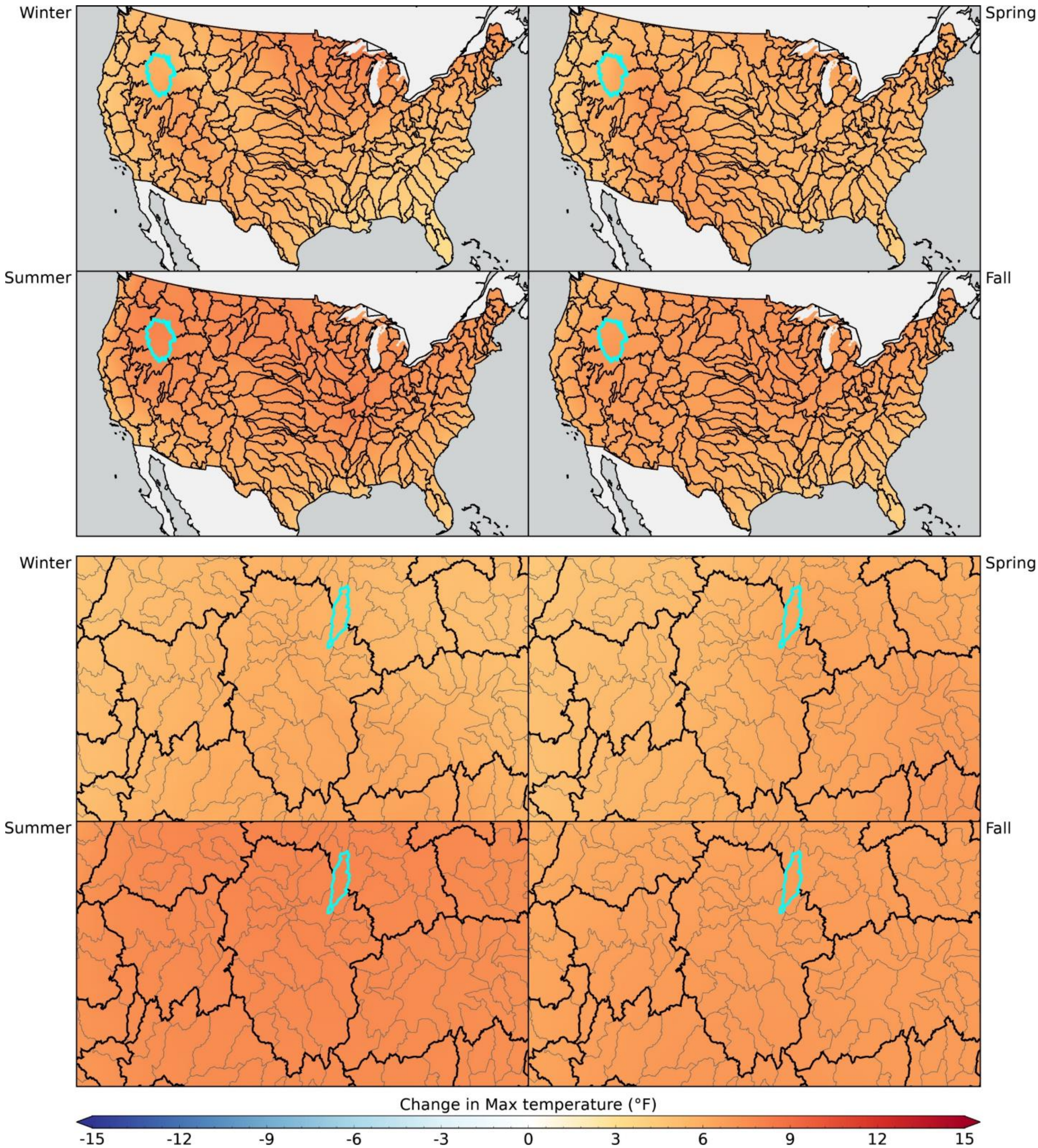



Figure 8: Seasonal maps of maximum temperature for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 3 Minimum temperature

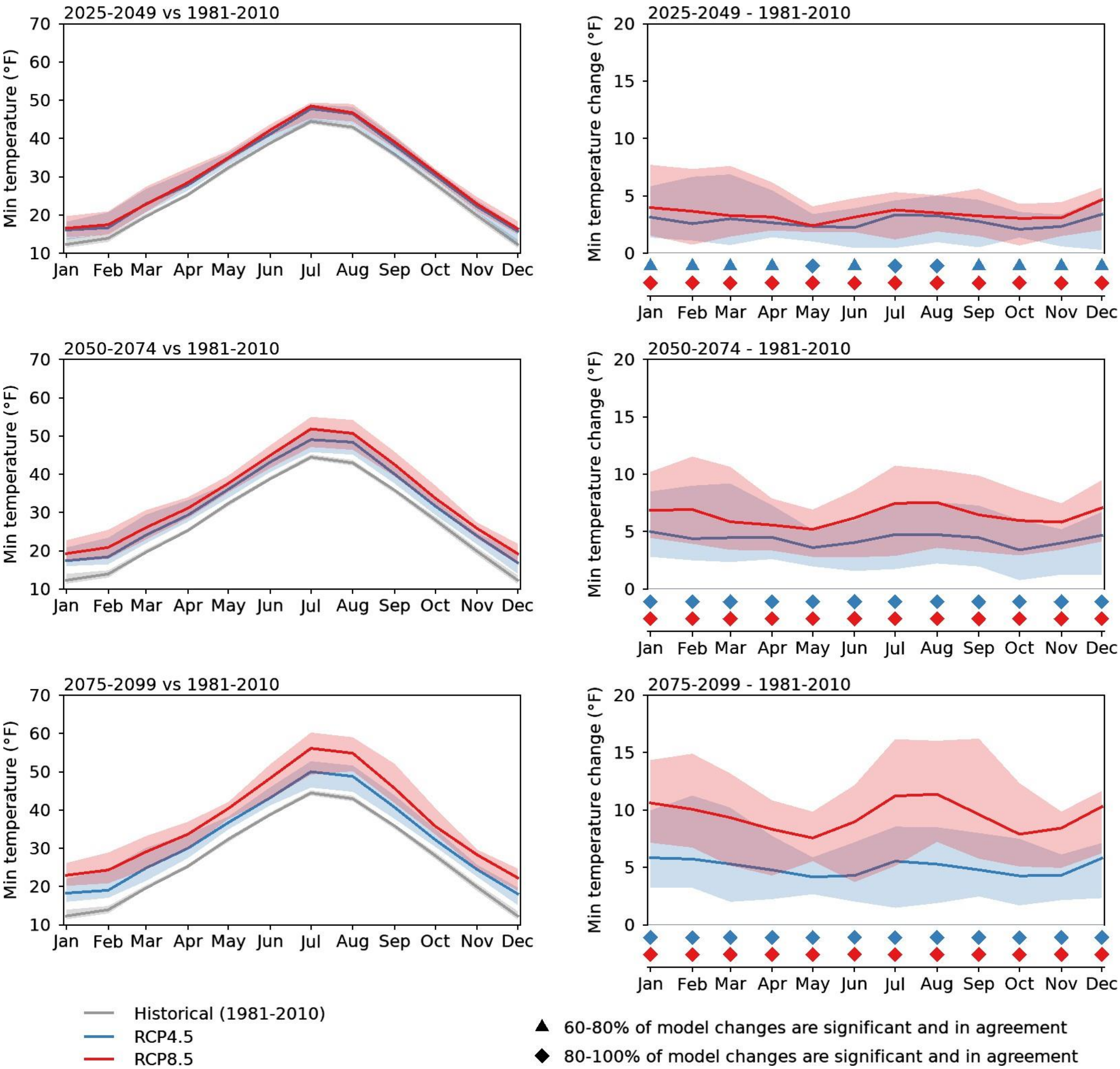



Figure 9: Monthly averages of minimum temperature for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

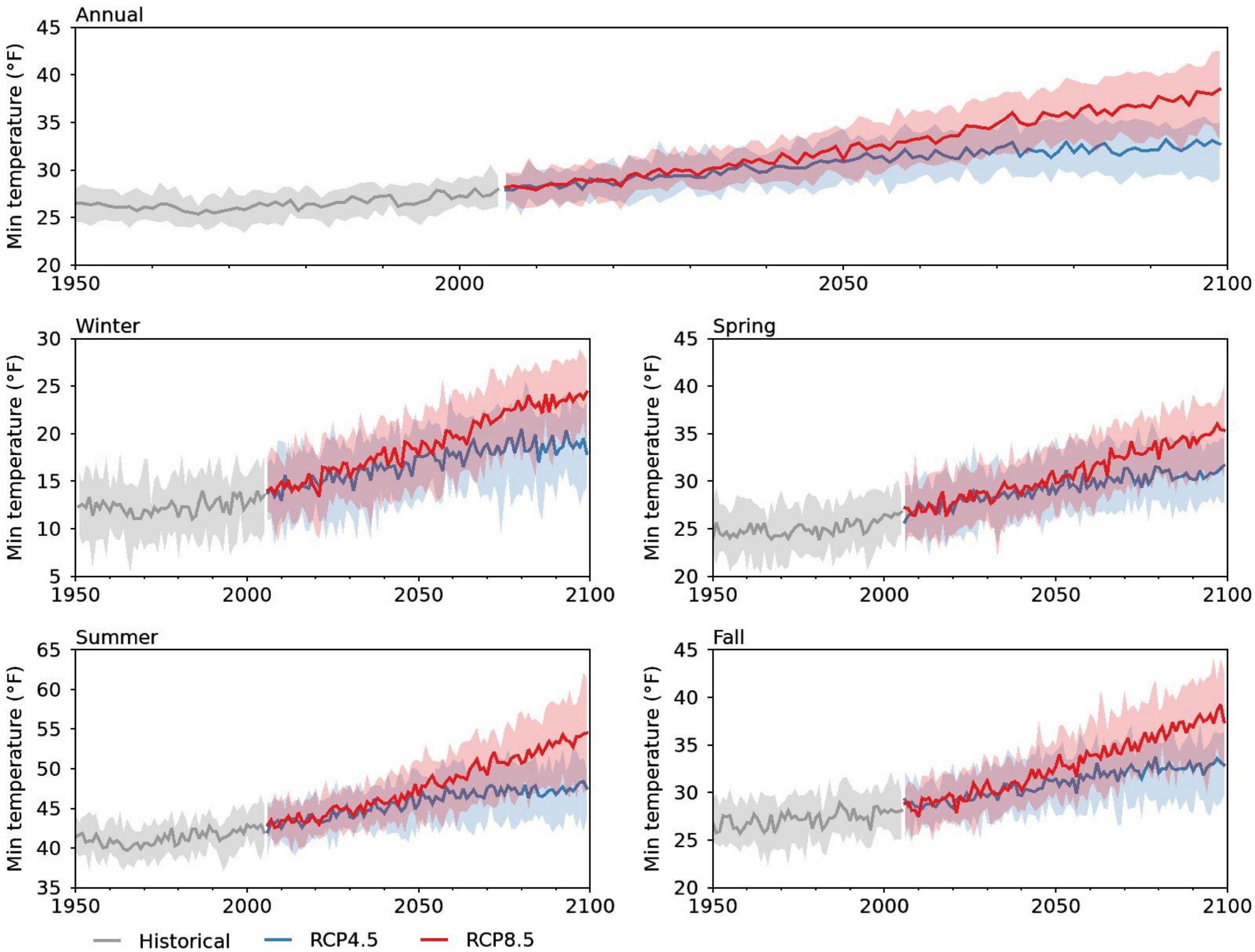



Figure 10: Annual and seasonal time series of minimum temperature for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

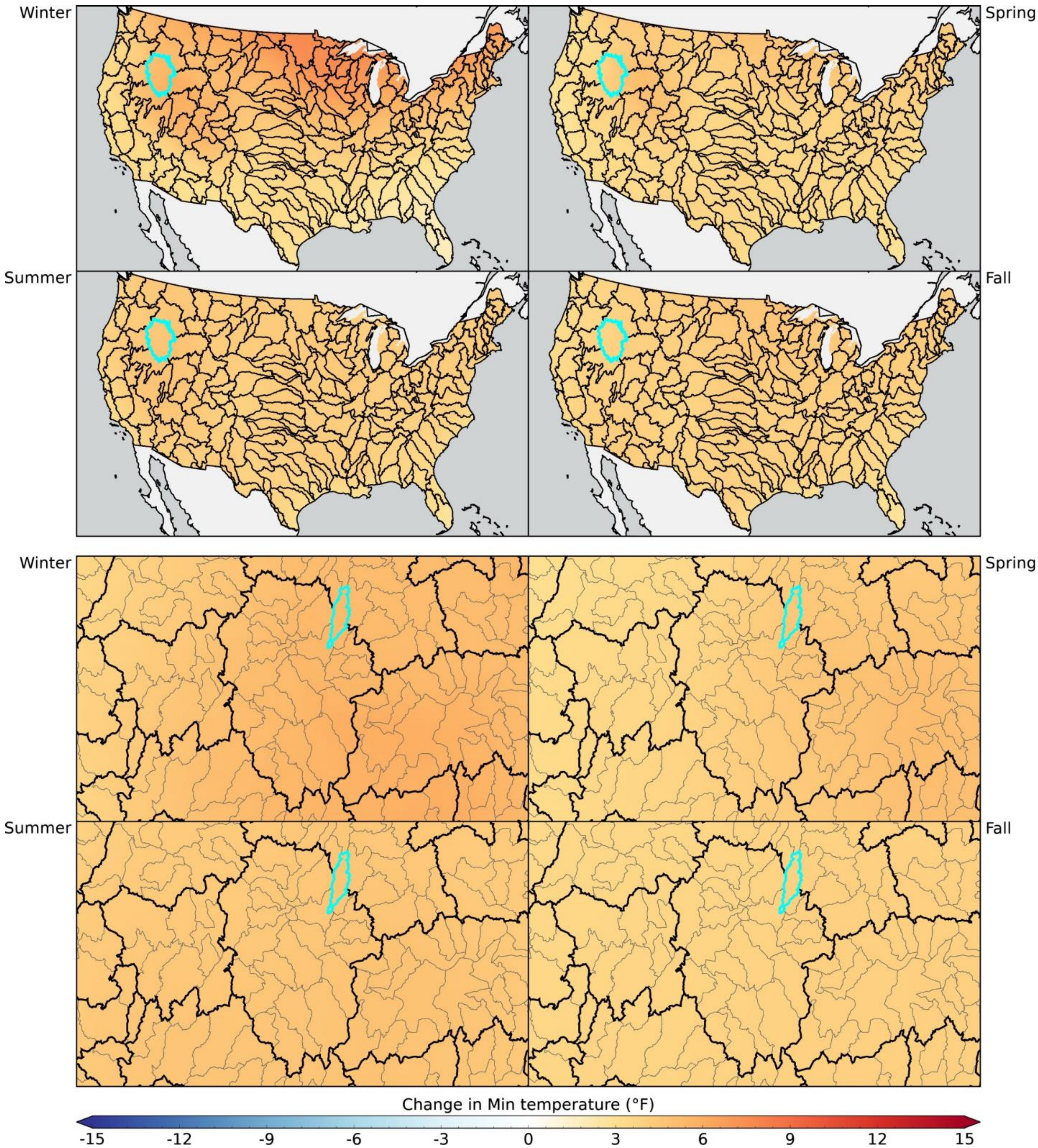



Figure 11: Seasonal maps of minimum temperature for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

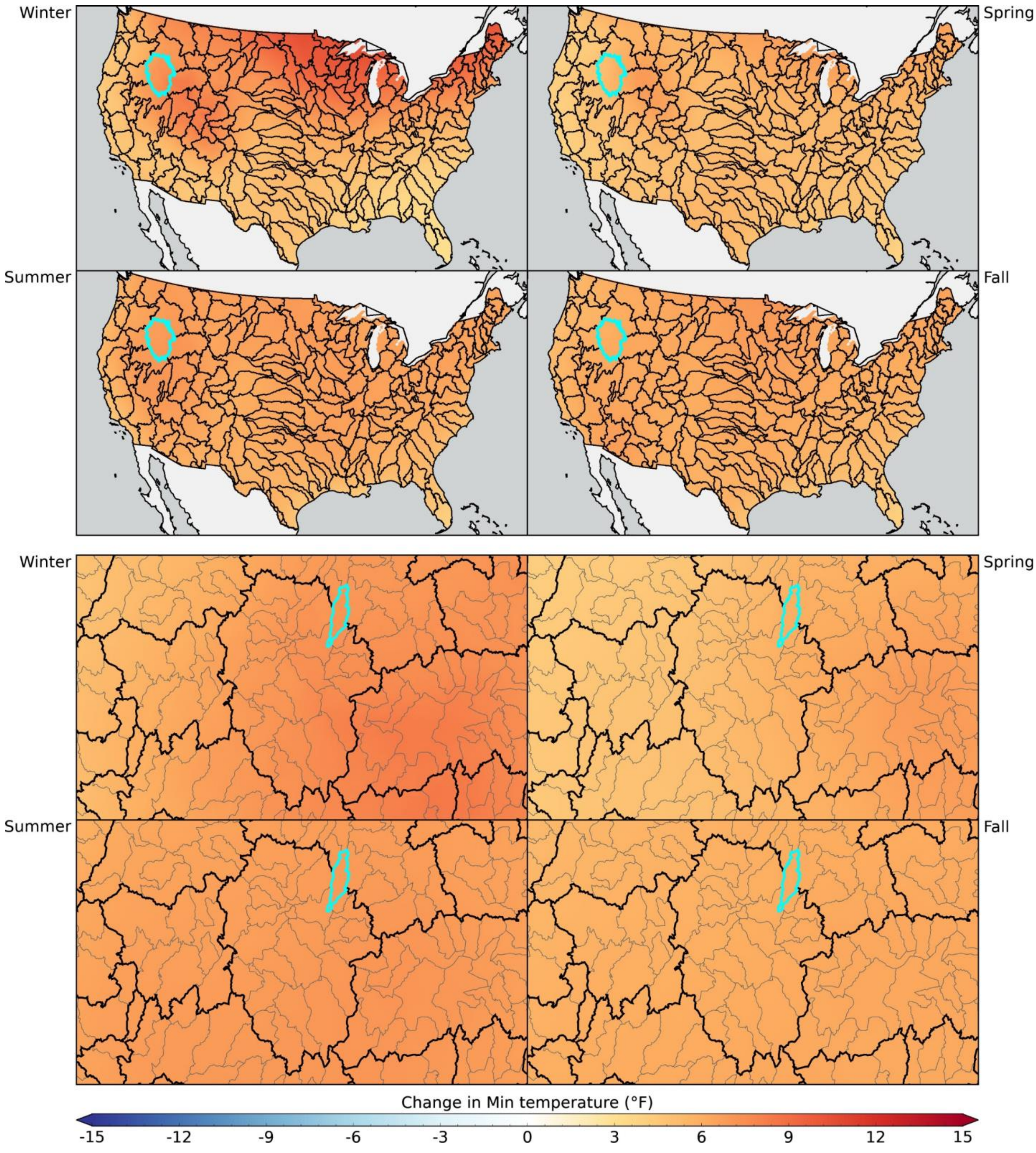



Figure 12: Seasonal maps of minimum temperature for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 4 Precipitation

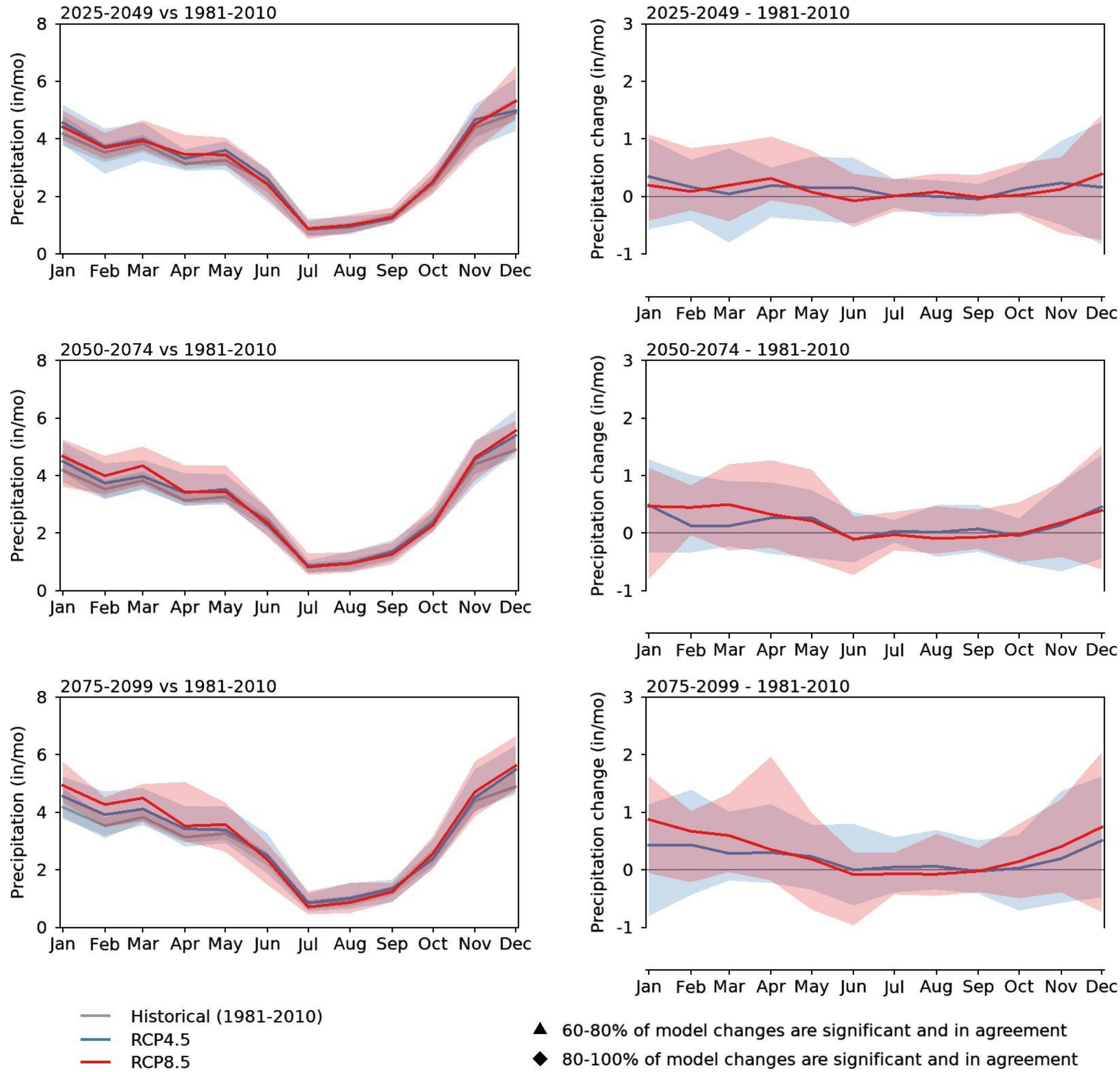



Figure 13: Monthly averages of precipitation for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

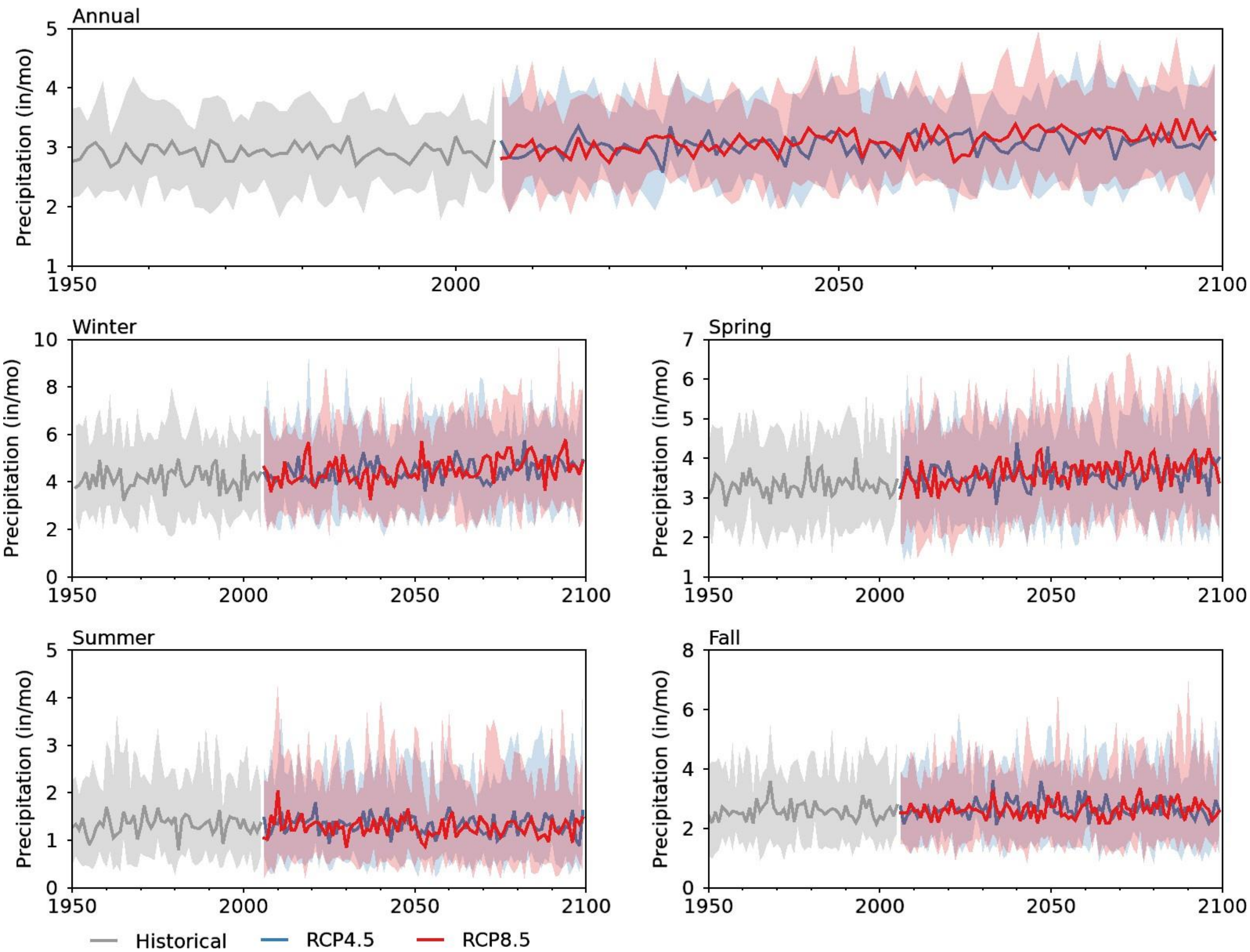



Figure 14: Annual and seasonal time series of precipitation for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

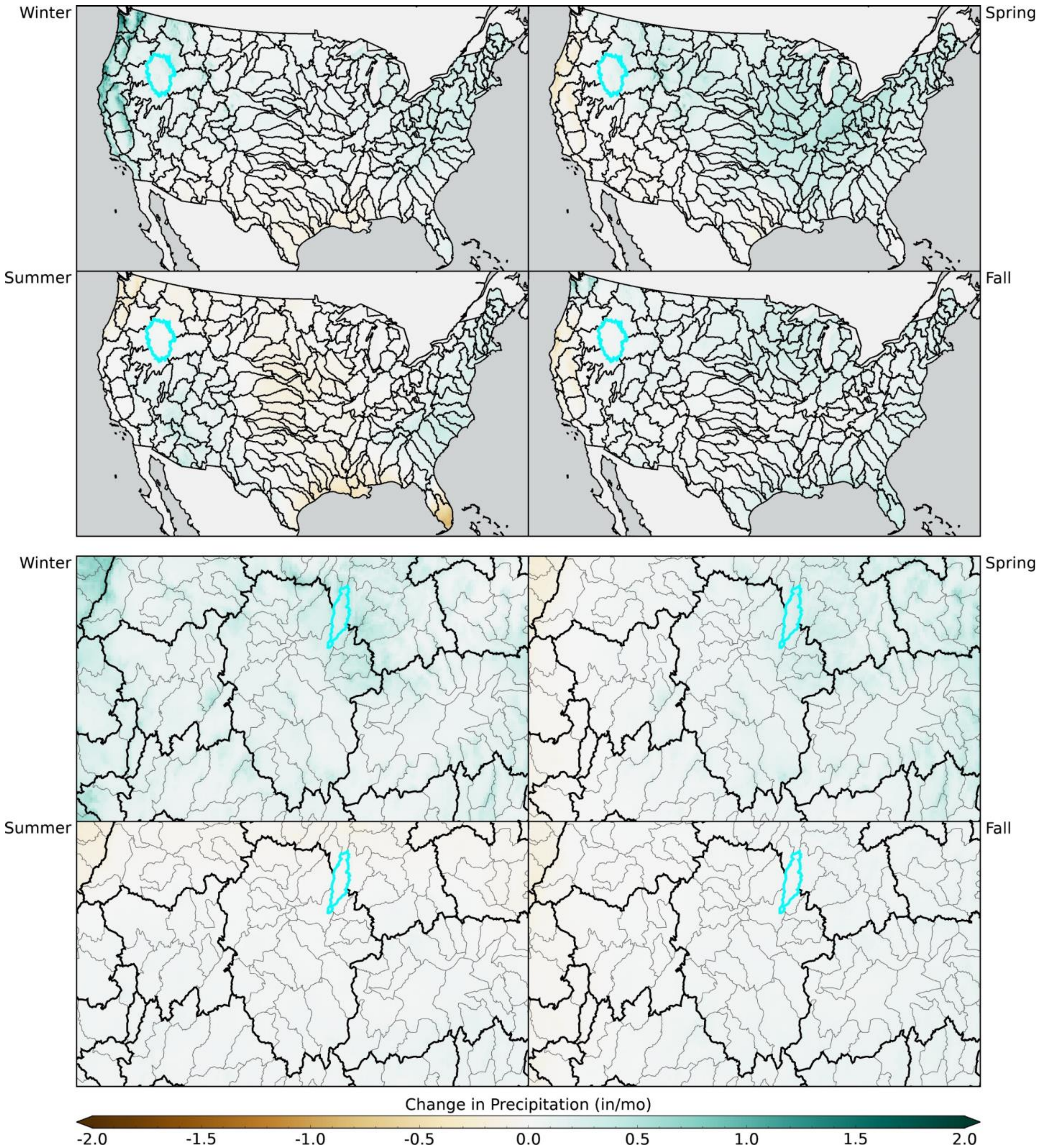



Figure 15: Seasonal maps of precipitation for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

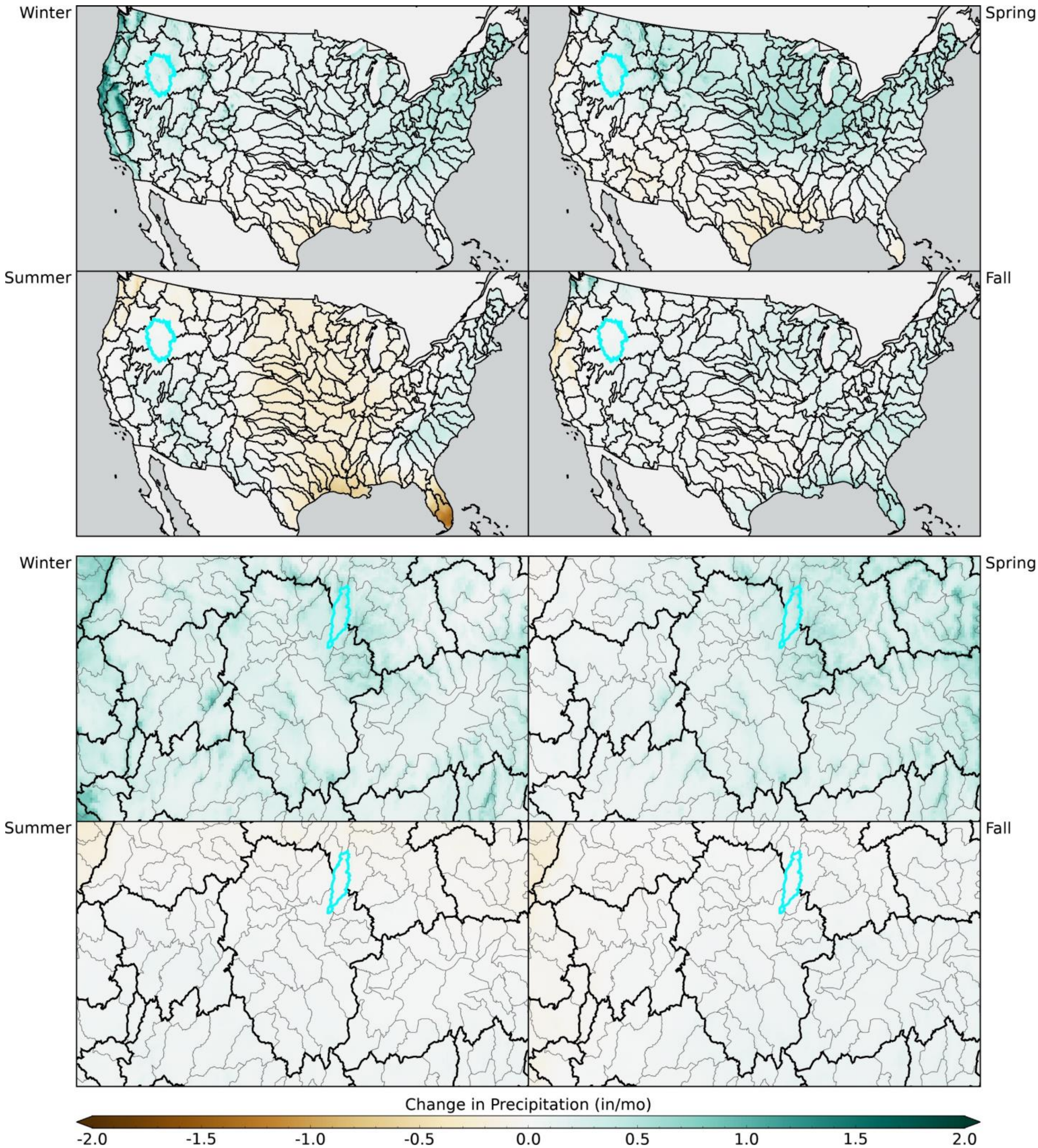



Figure 16: Seasonal maps of precipitation for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 5 Vapor pressure deficit

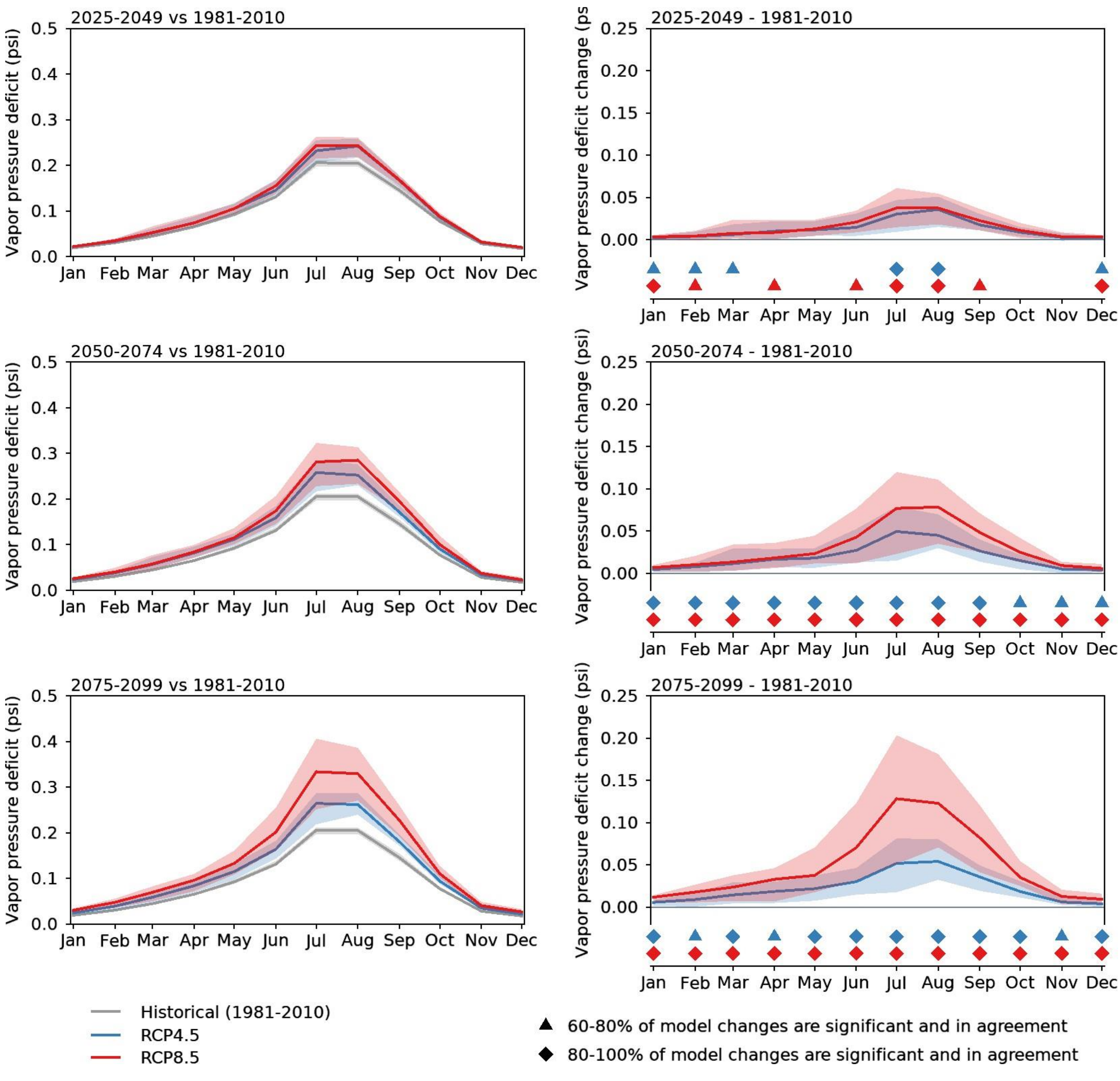



Figure 17: Monthly averages of vapor pressure deficit for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

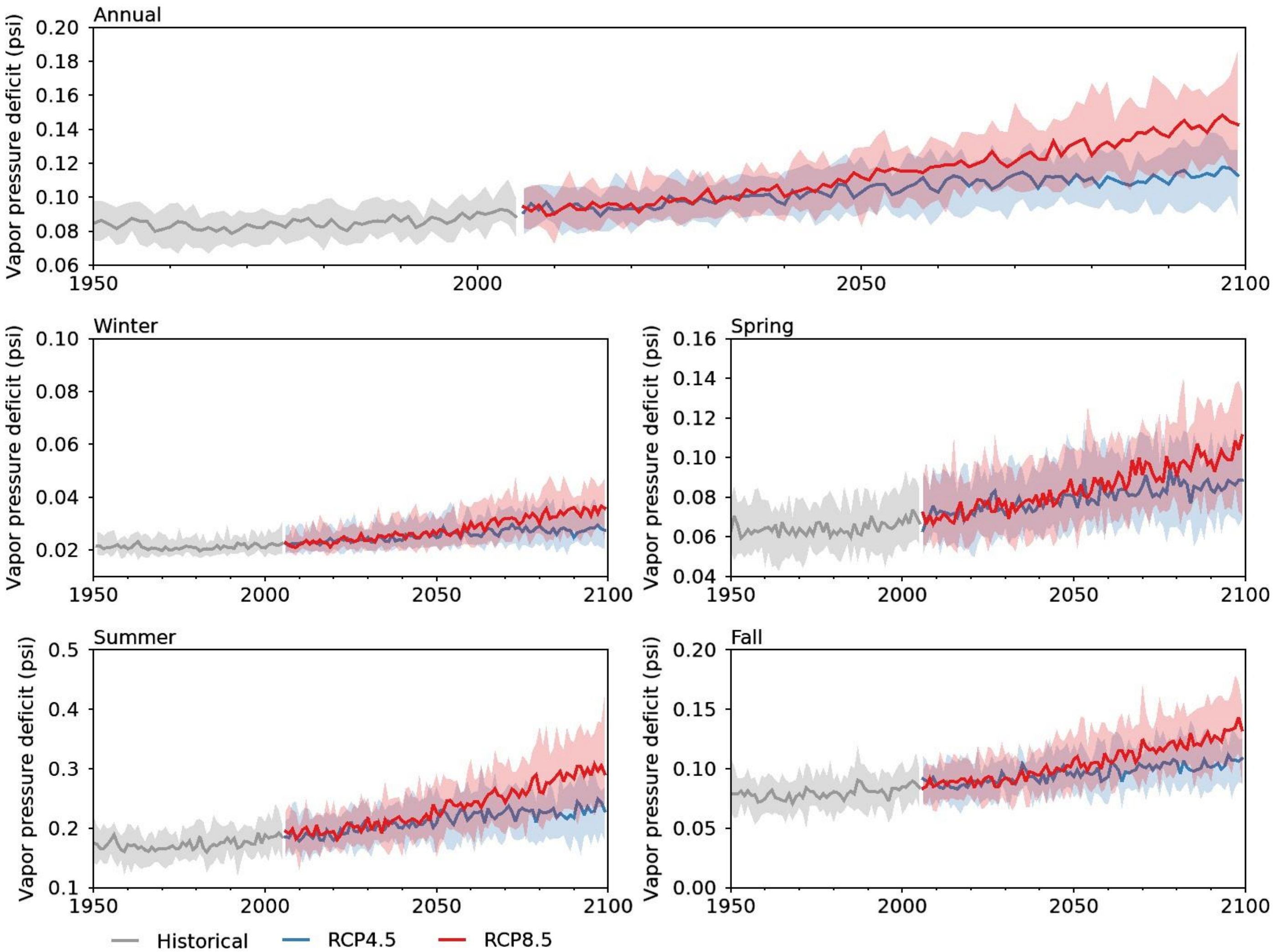



Figure 18: Annual and seasonal time series of vapor pressure deficit for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

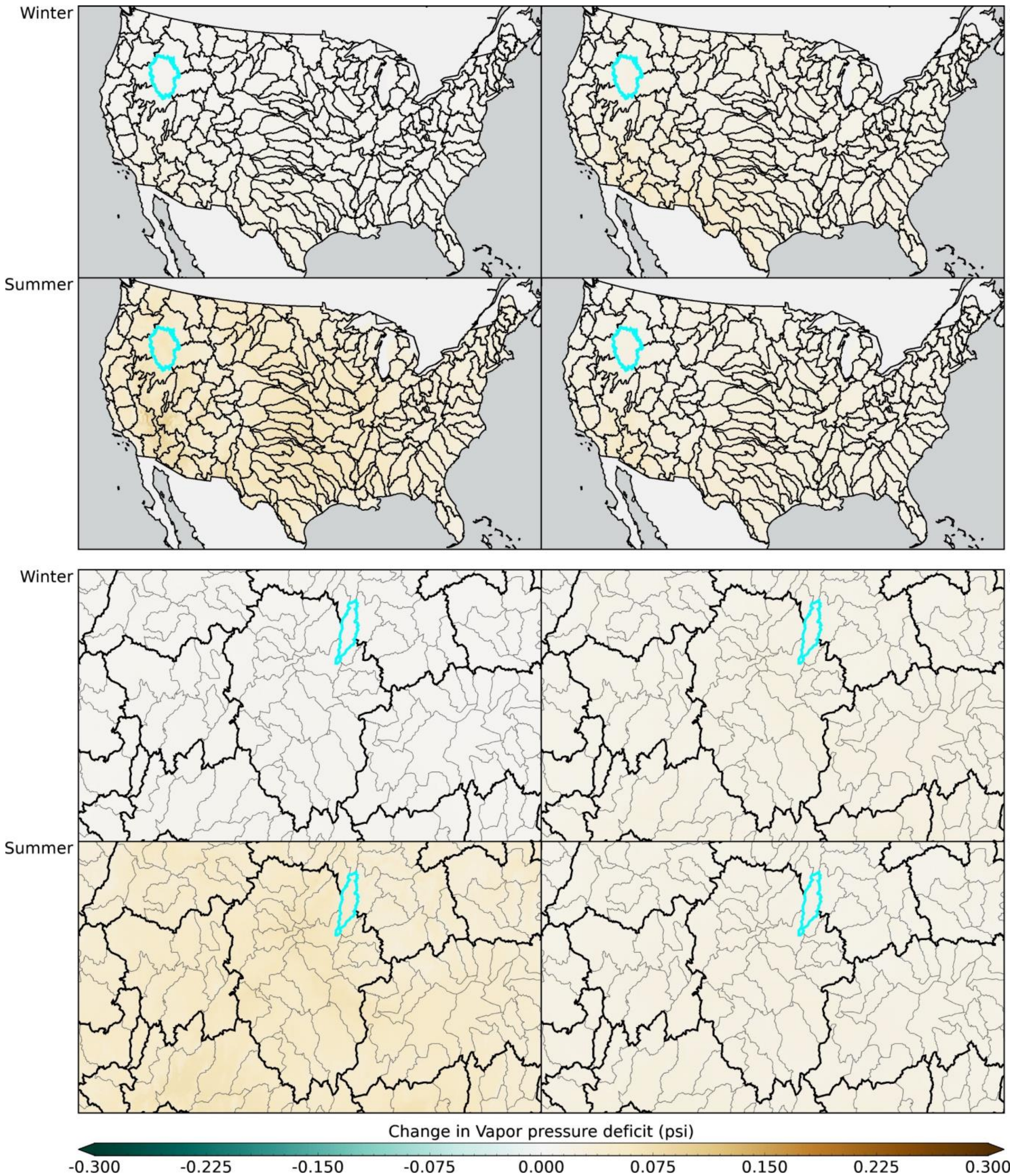



Figure 19: Seasonal maps of vapor pressure deficit for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

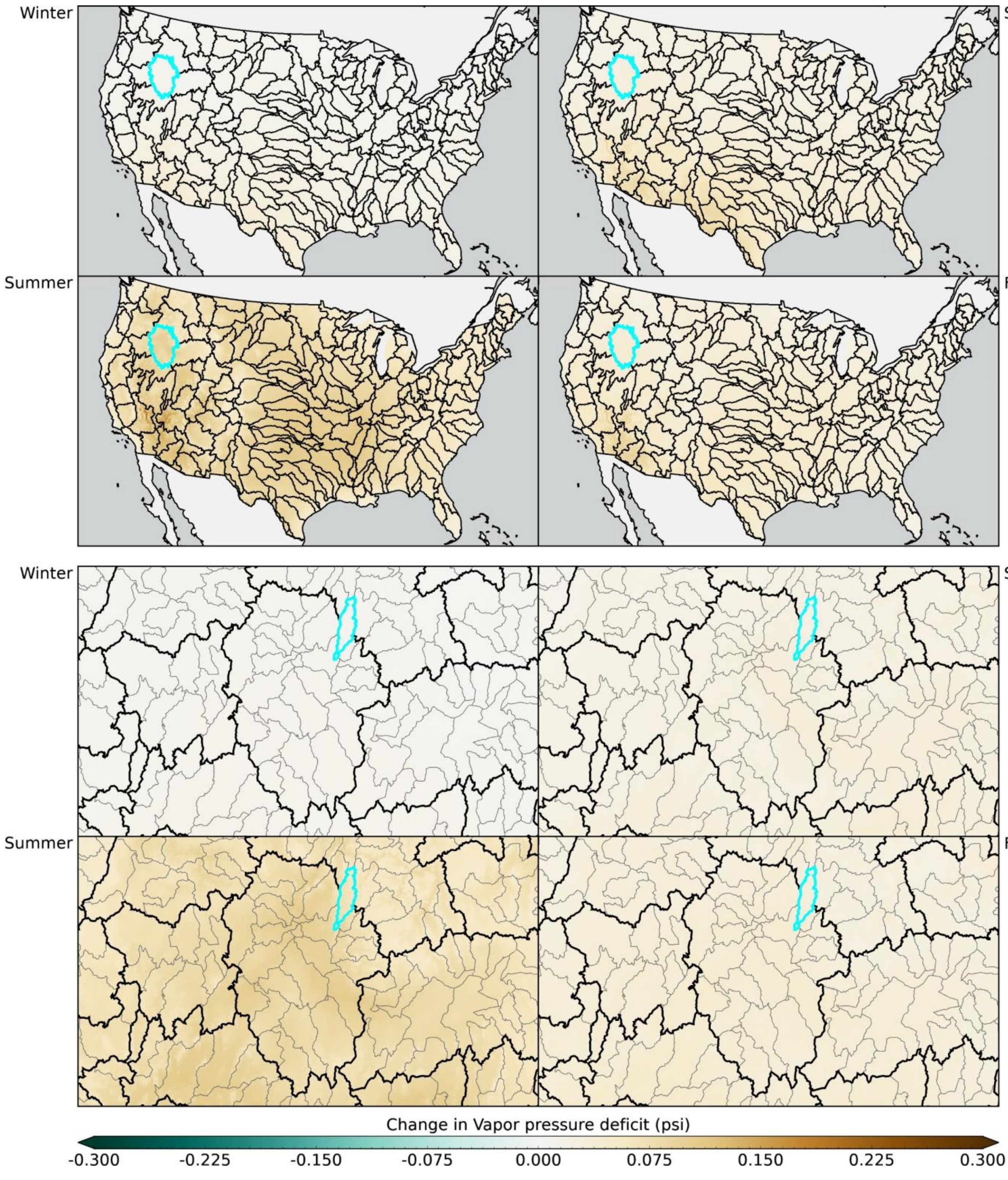



Figure 20: Seasonal maps of vapor pressure deficit for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 6 Snow Water Equivalent

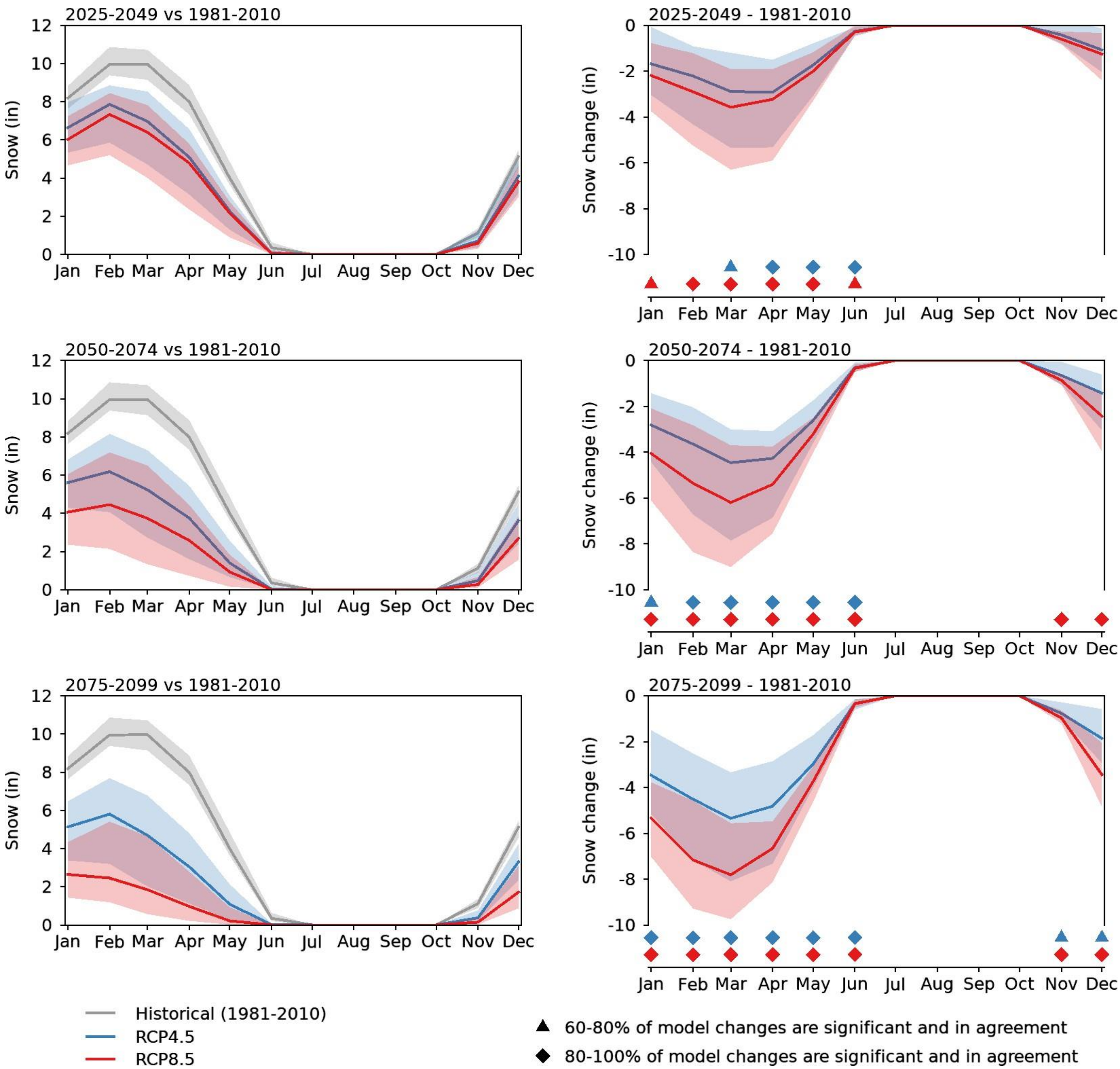



Figure 21: Monthly averages of snow water equivalent for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

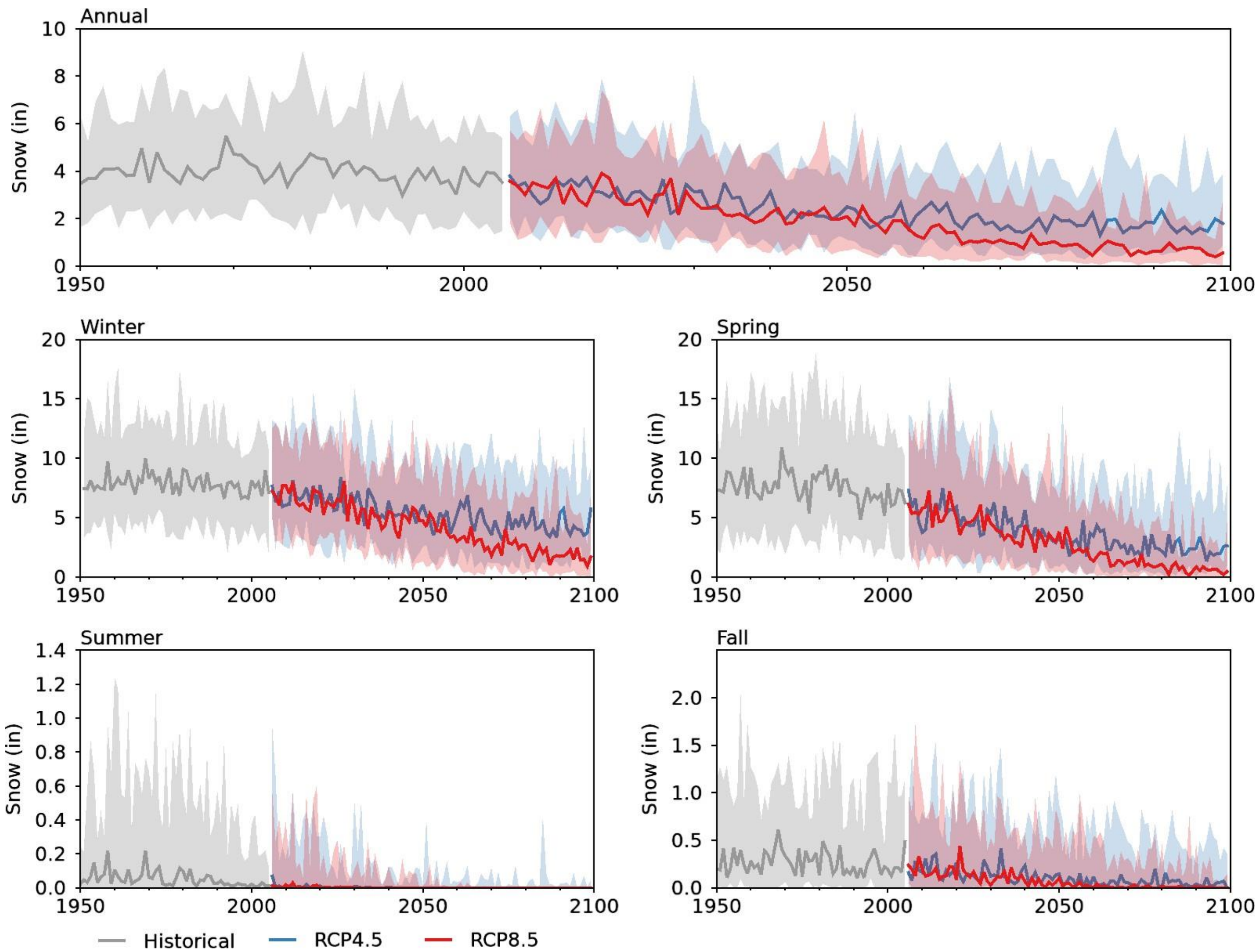



Figure 22: Annual and seasonal time series of snow water equivalent for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

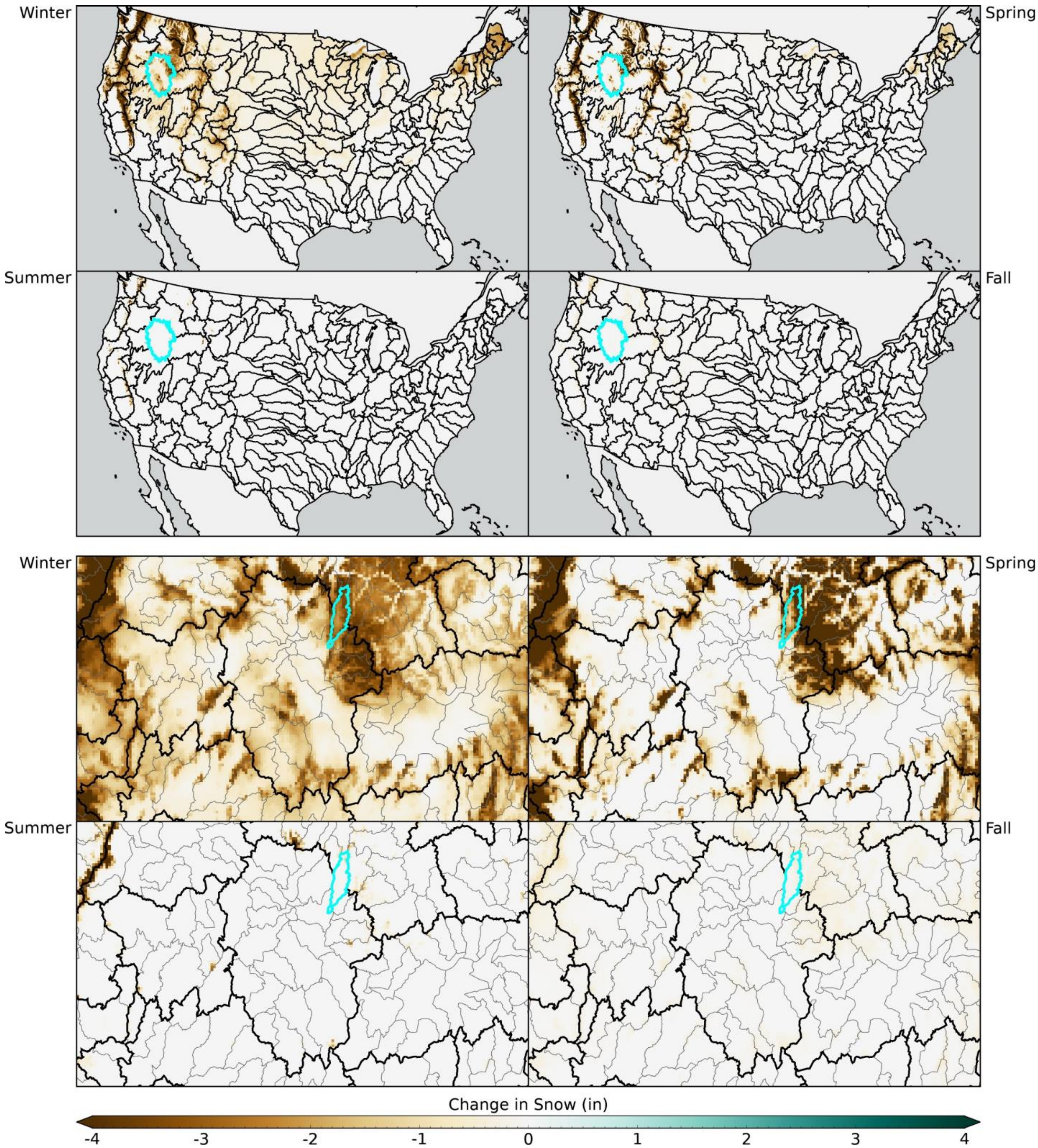



Figure 23: Seasonal maps of snow water equivalent for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

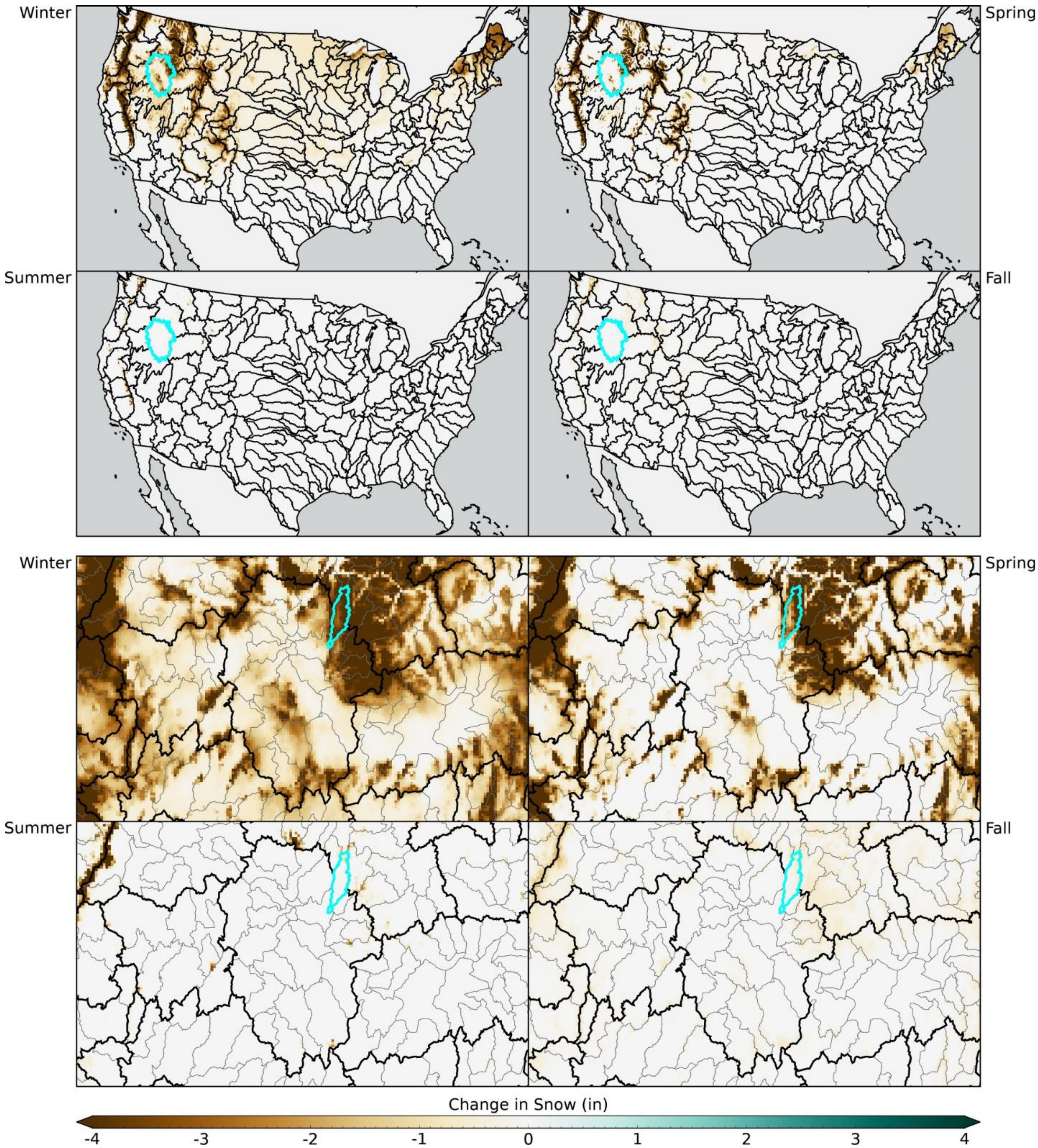



Figure 24: Seasonal maps of snow water equivalent for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 7 Runoff

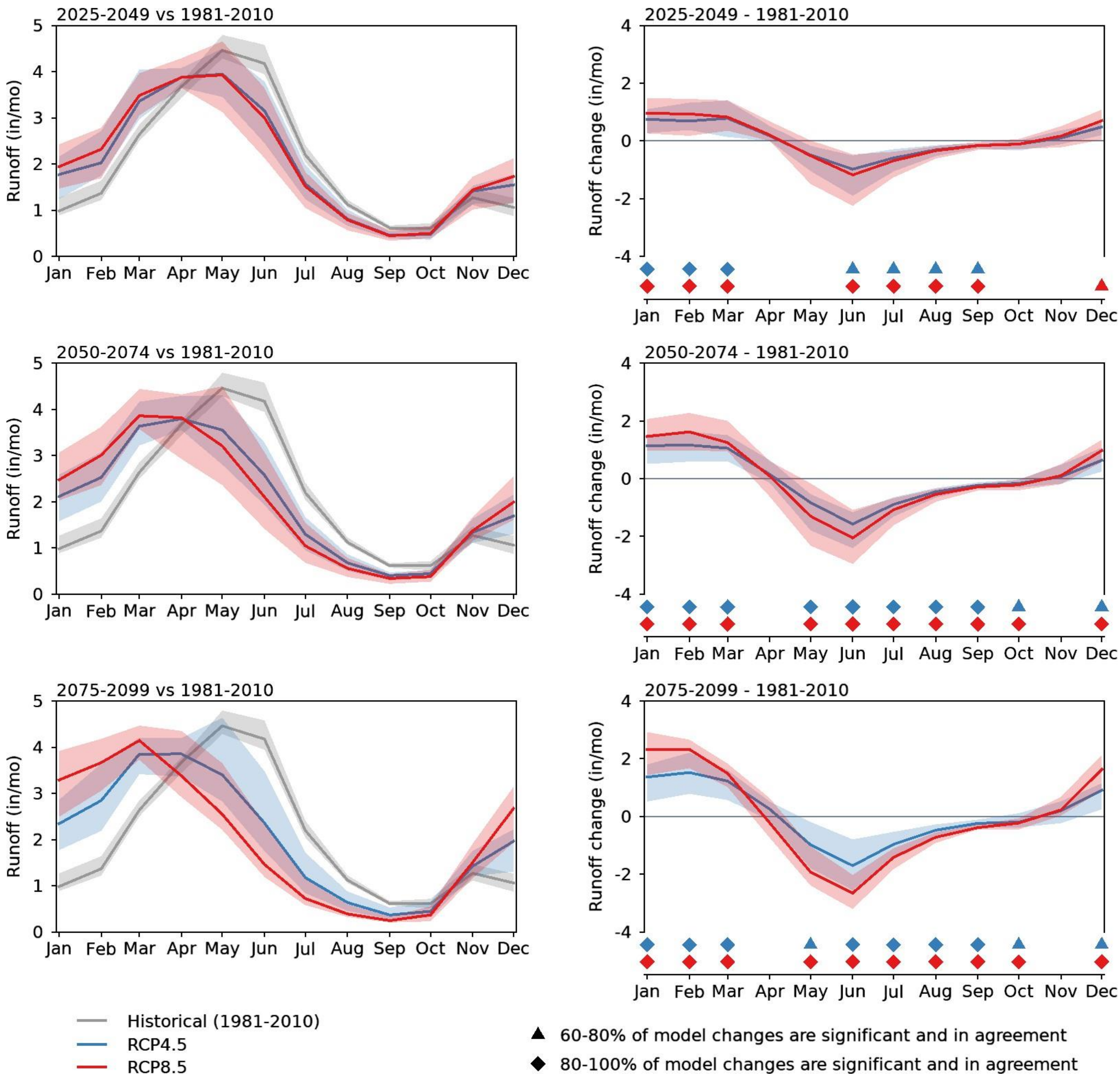



Figure 25: Monthly averages of runoff for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

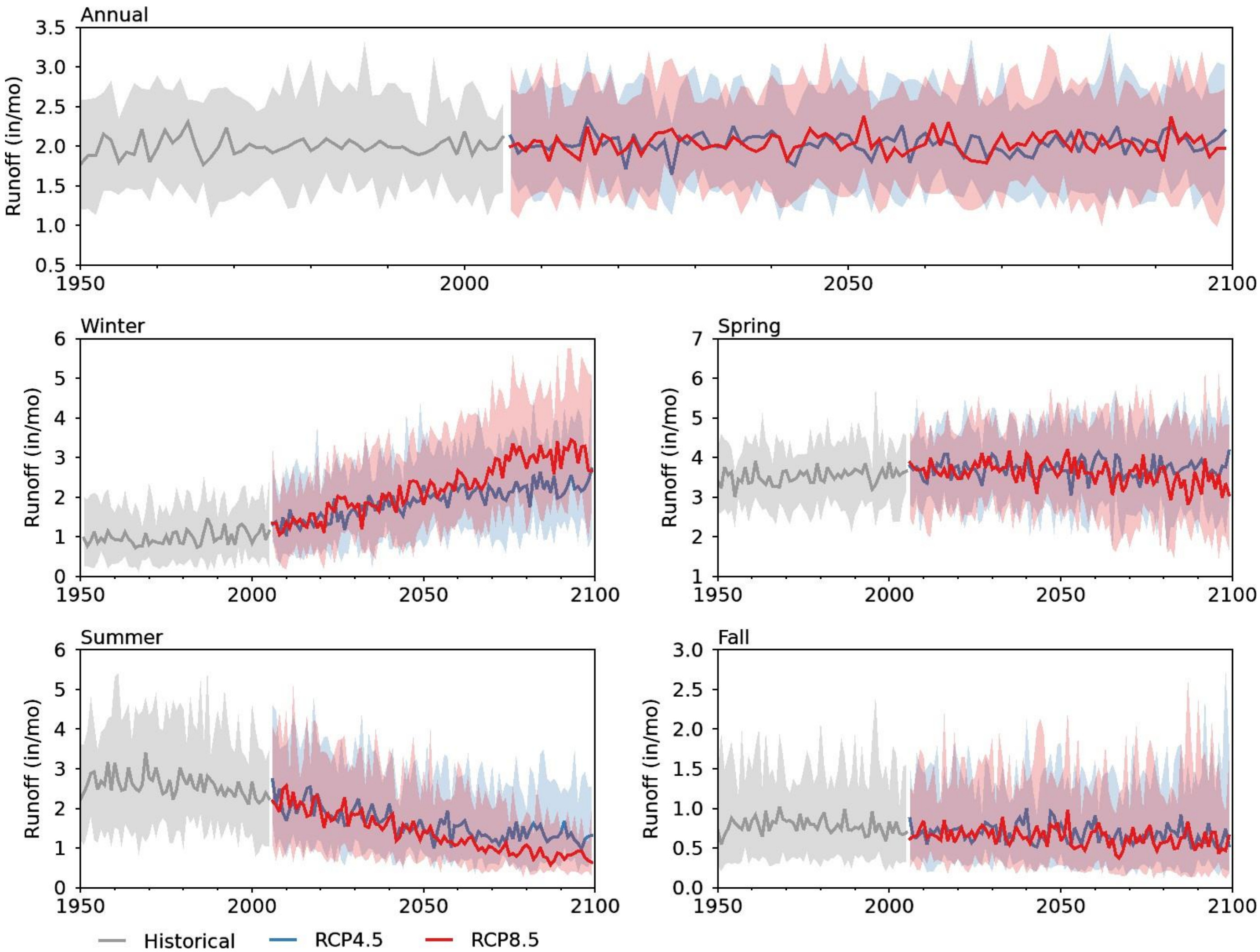



Figure 26: Annual and seasonal time series of runoff for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

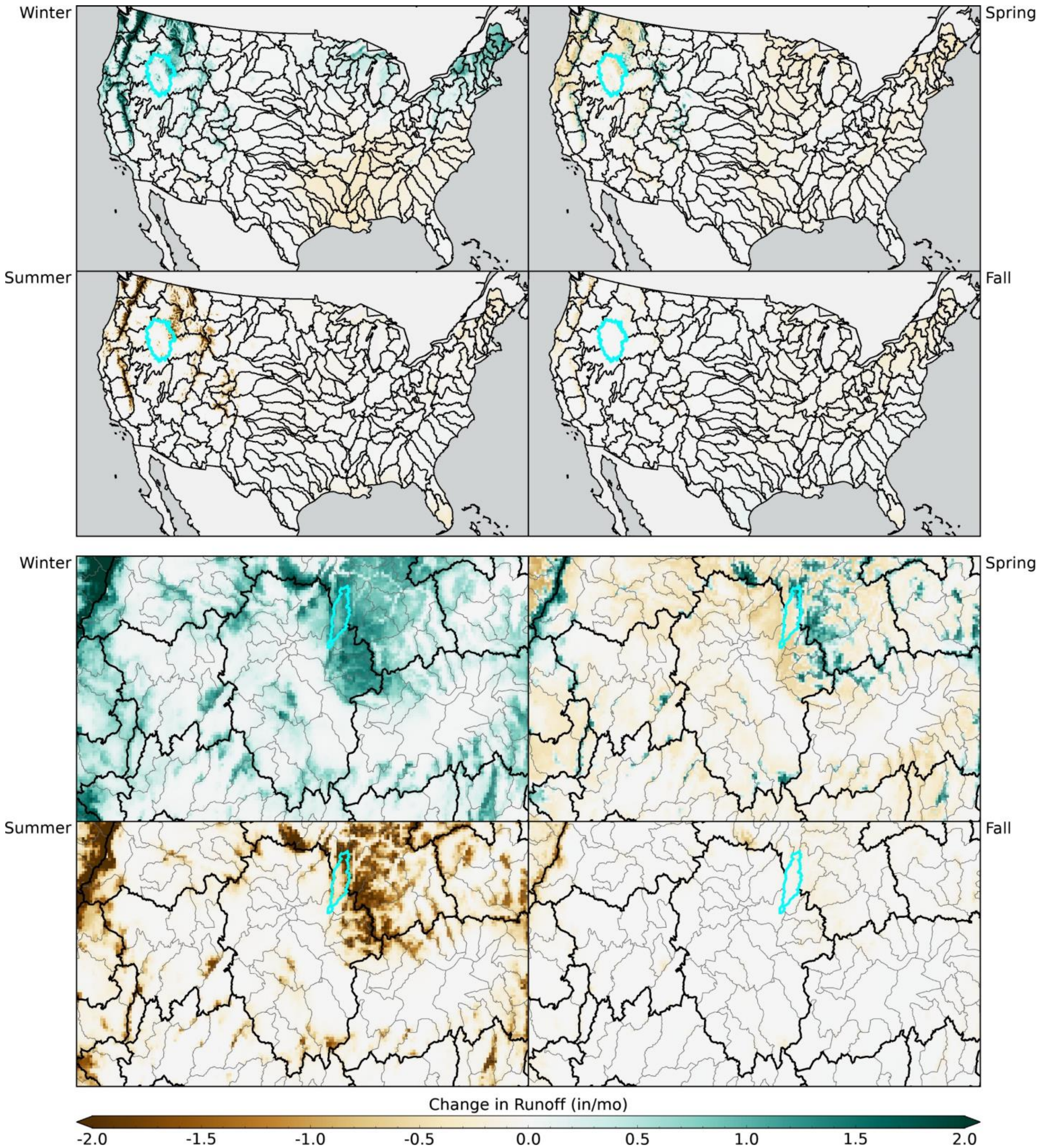



Figure 27: Seasonal maps of runoff for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

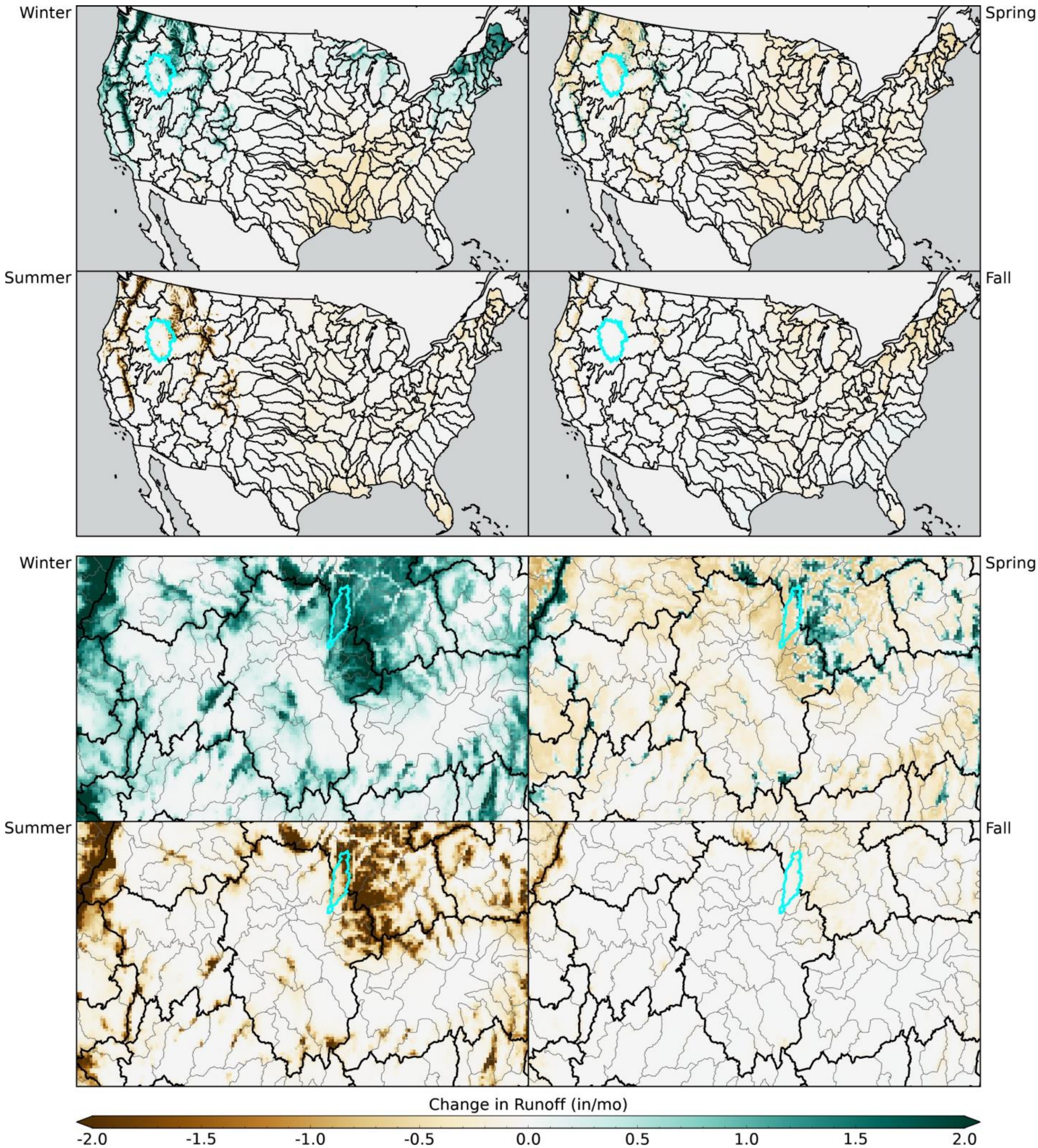



Figure 28: Seasonal maps of runoff for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 8 Soil Water Storage

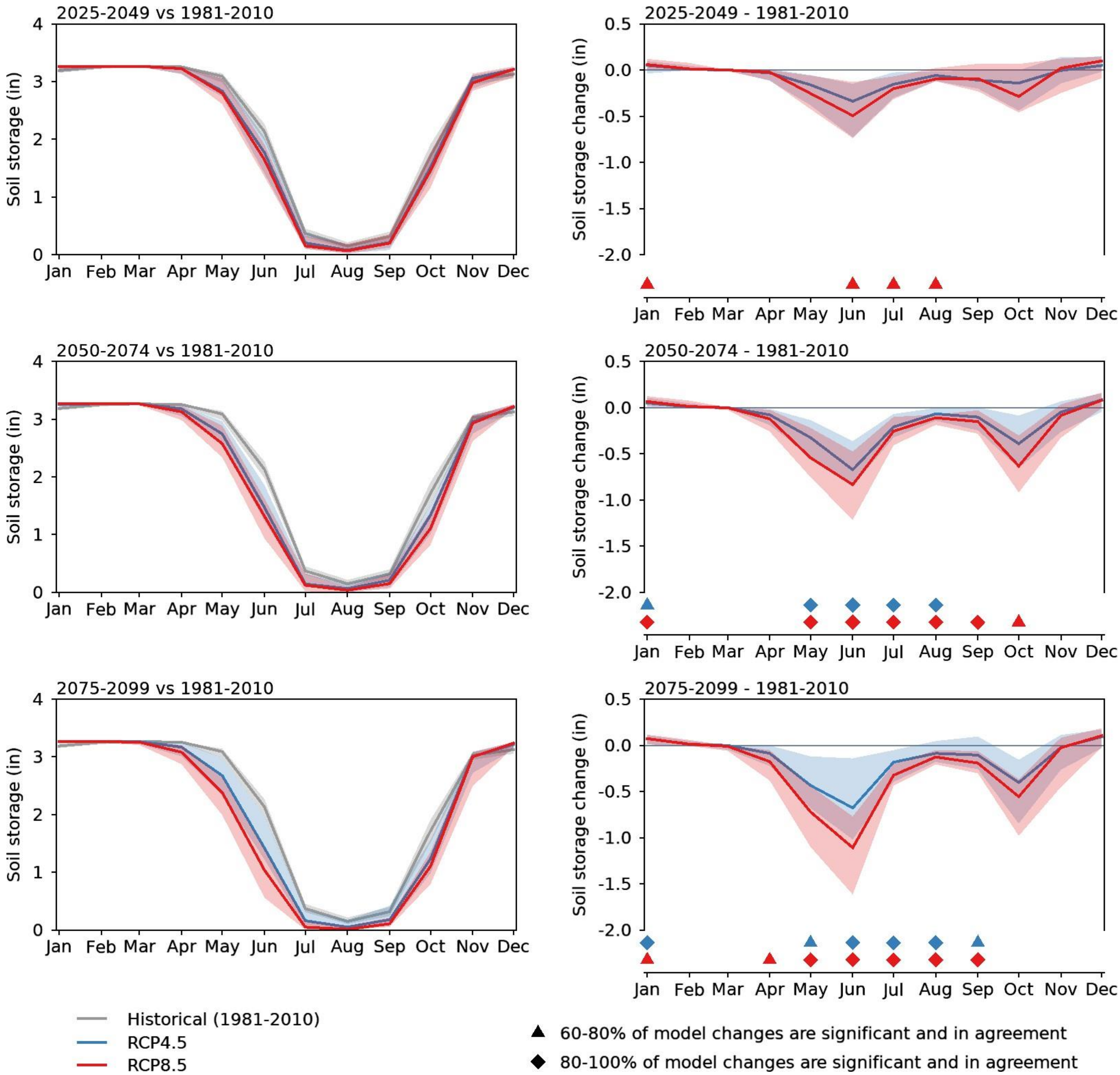



Figure 29: Monthly averages of soil water storage for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

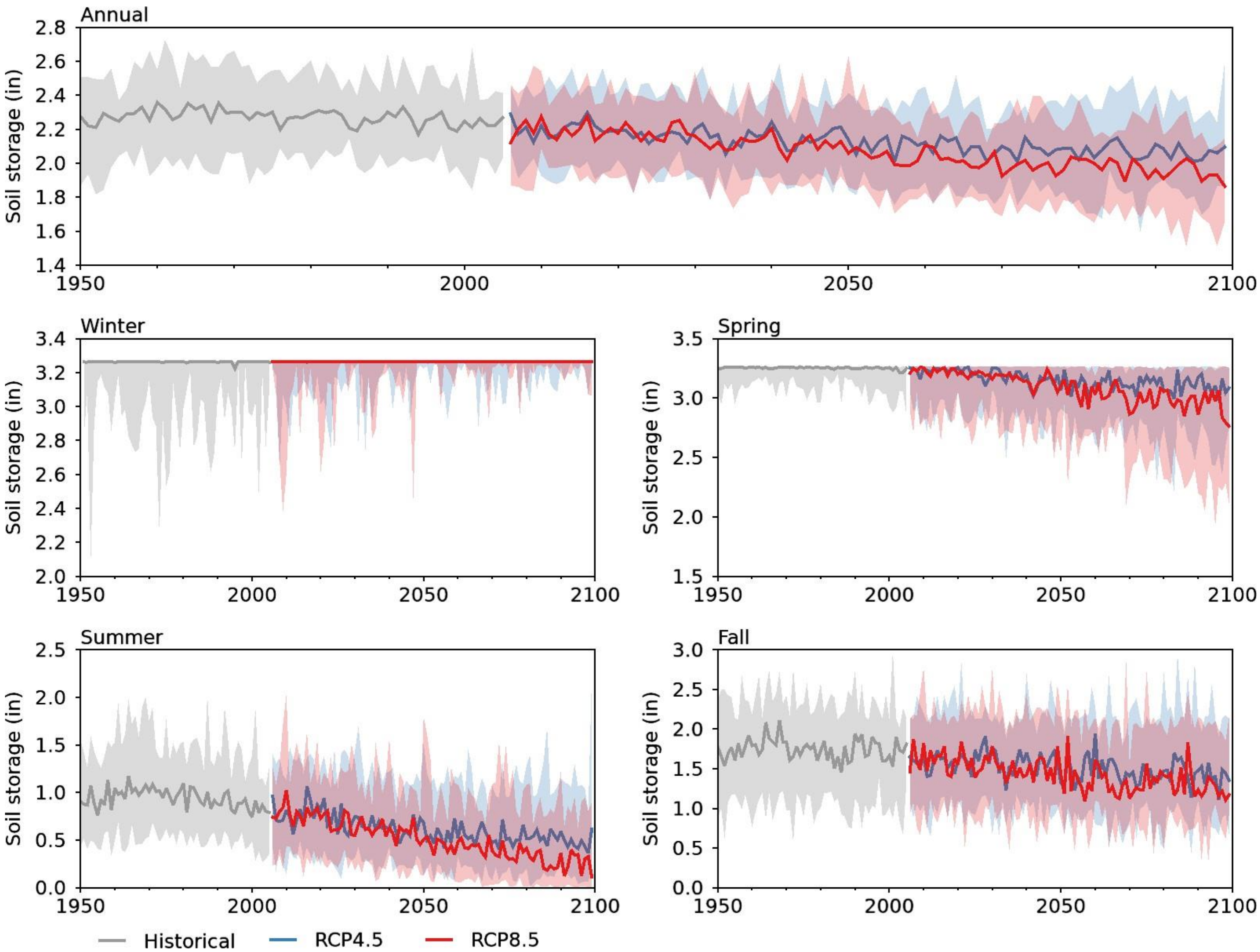



Figure 30: Annual and seasonal time series of soil water storage for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

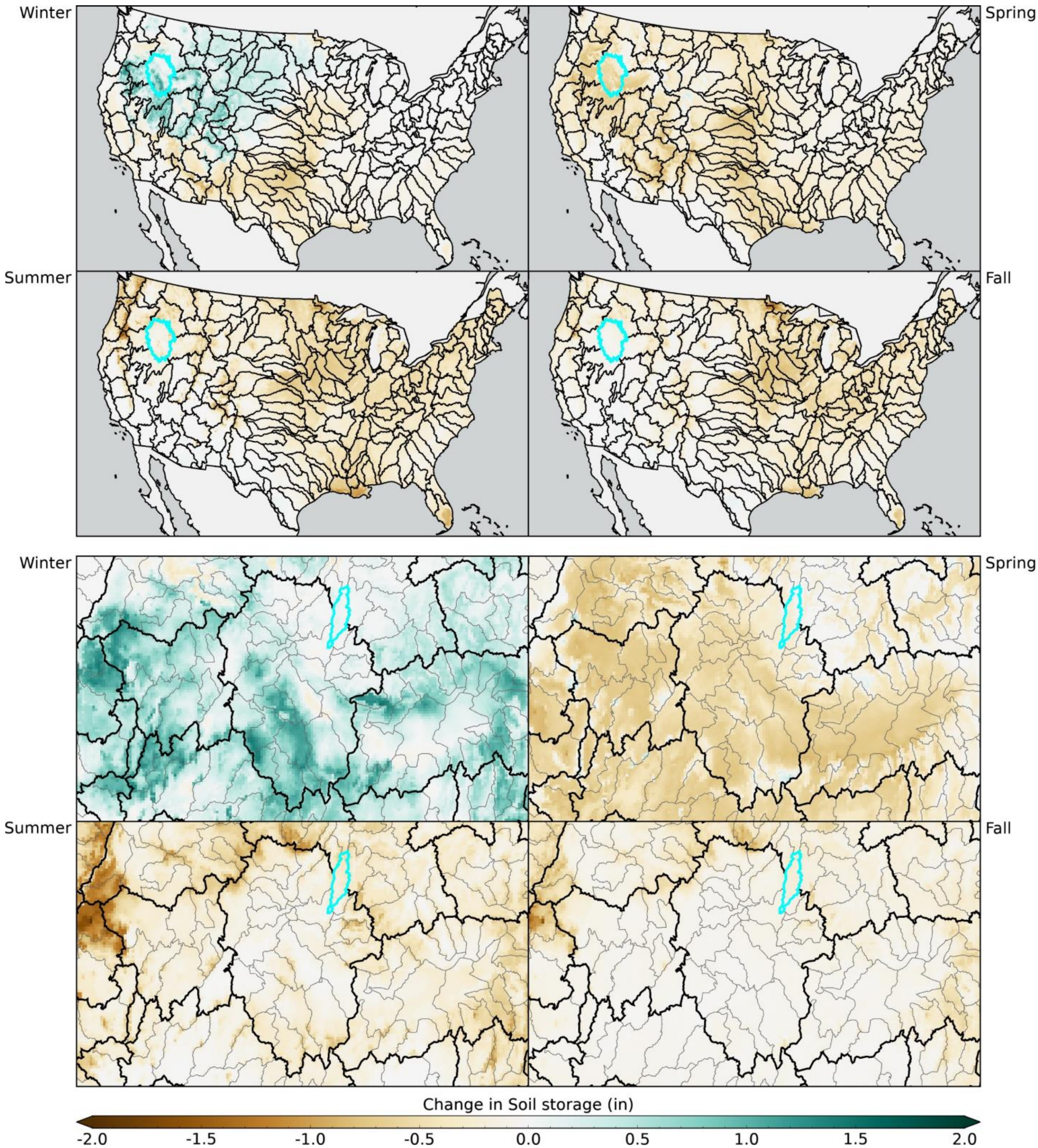



Figure 31: Seasonal maps of soil water storage for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

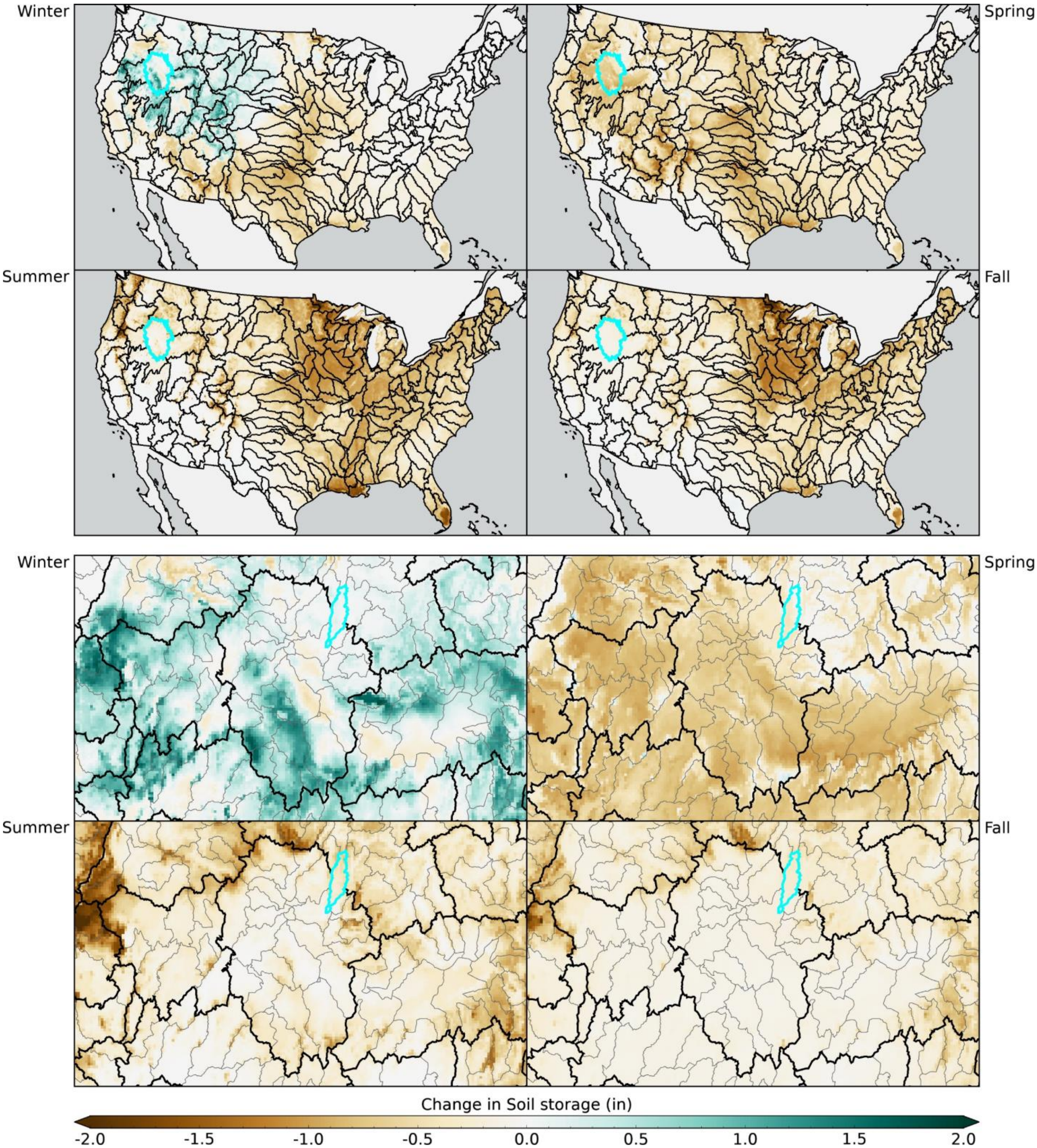



Figure 32: Seasonal maps of soil water storage for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 9 Evaporative Deficit

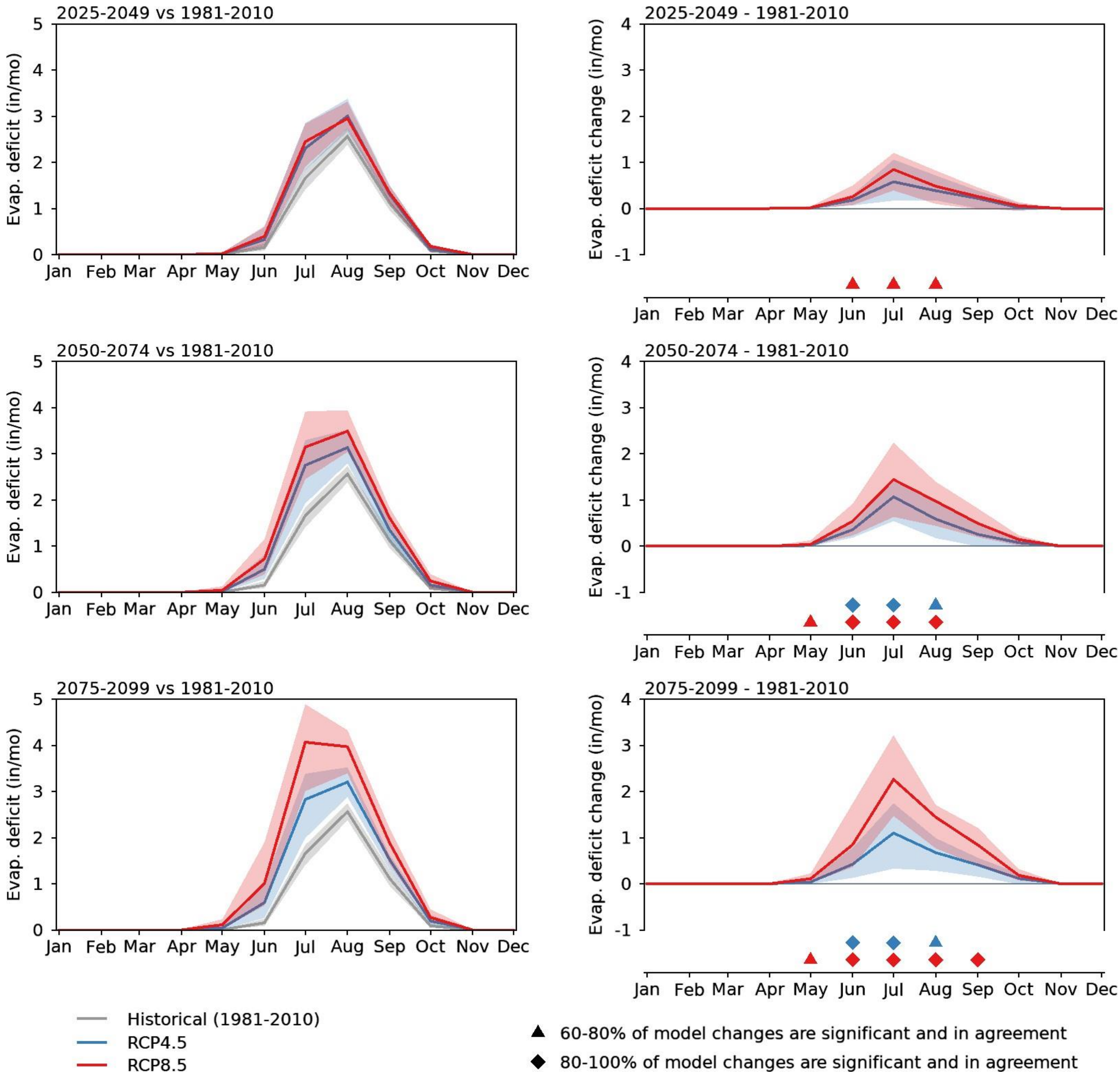



Figure 33: Monthly averages of evaporative deficit for the three future time periods for the RCP4.5 and RCP8.5 simulations. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes. Raw values relative to the historical simulation (1981-2010) are shown in the left column and future minus historical changes are shown in the right column. Triangle and diamond symbols indicate the percent of models that simulate future minus present changes that are of the same sign and significant. A Mann-Whitney rank test is used to establish significance ($\rho < 0.05$).

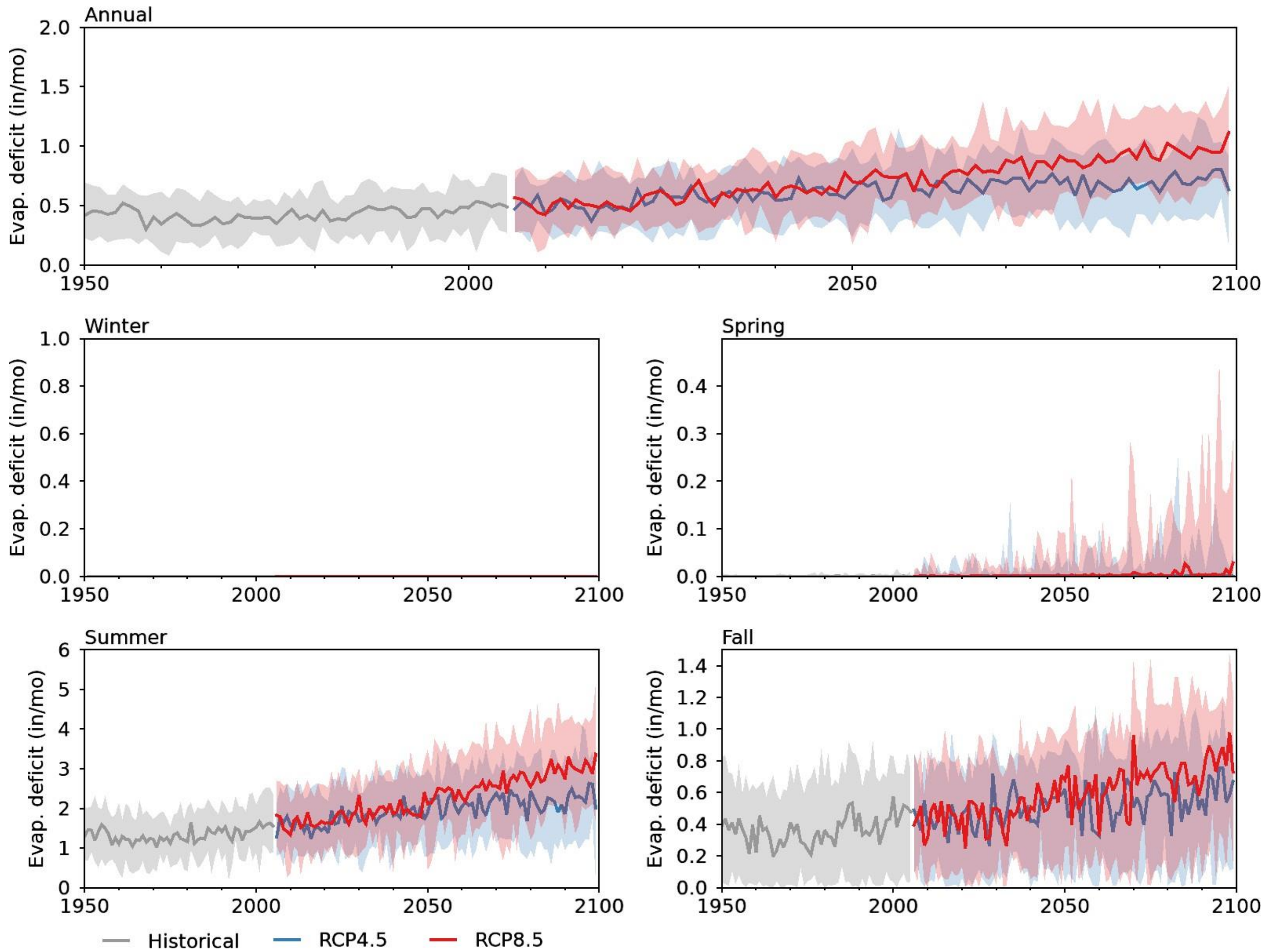



Figure 34: Annual and seasonal time series of evaporative deficit for historical (gray), RCP4.5 (blue) and RCP8.5 (red). The historical period ends in 2005 and the future periods begin in 2006. The median of 20 CMIP5 models is indicated by the solid lines and the ensemble 10th to 90th percentile range is indicated by the respective shaded envelopes.

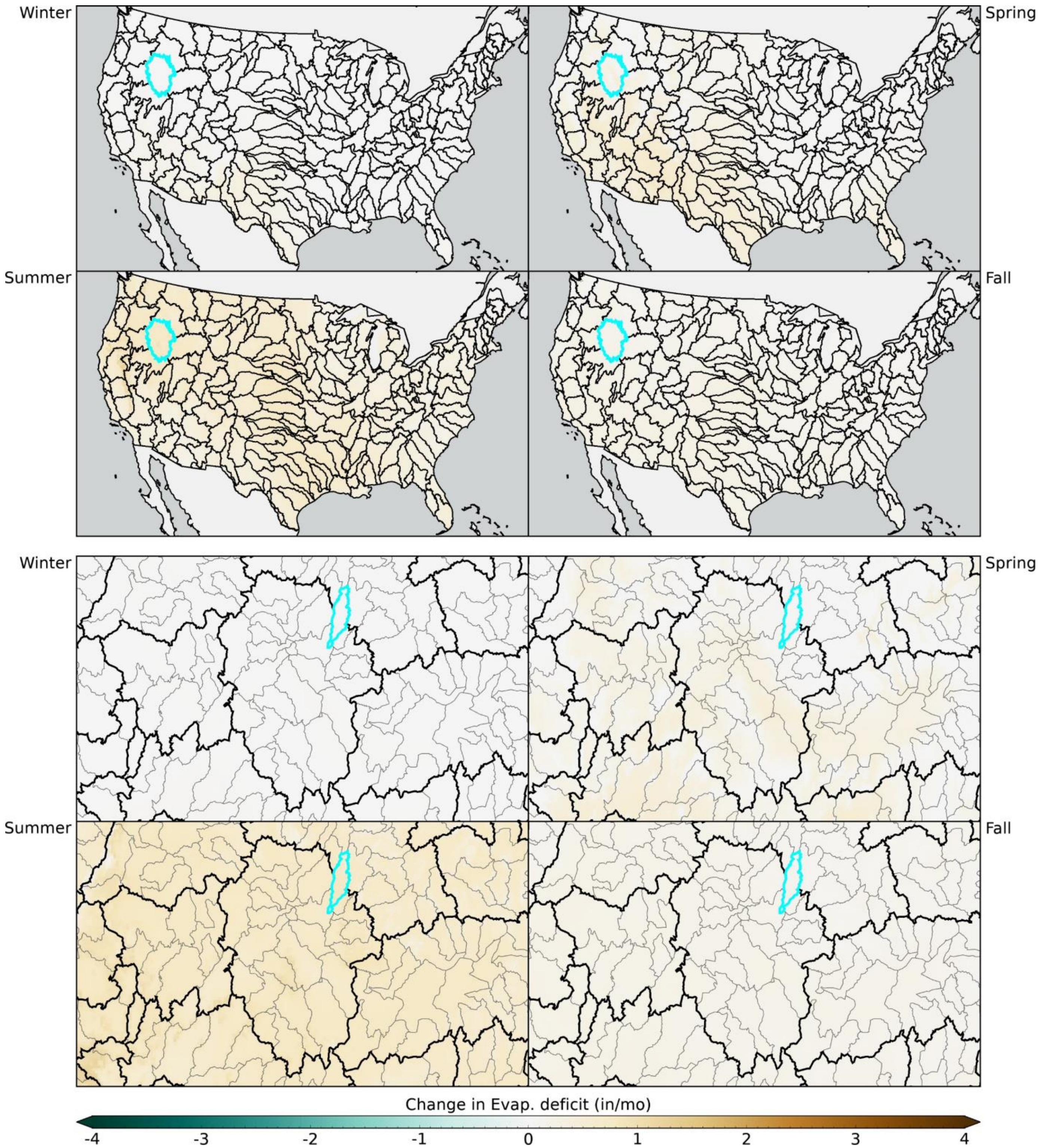



Figure 35: Seasonal maps of evaporative deficit for RCP4.5 2050-2074 minus 1981-2010 for the ensemble mean model.

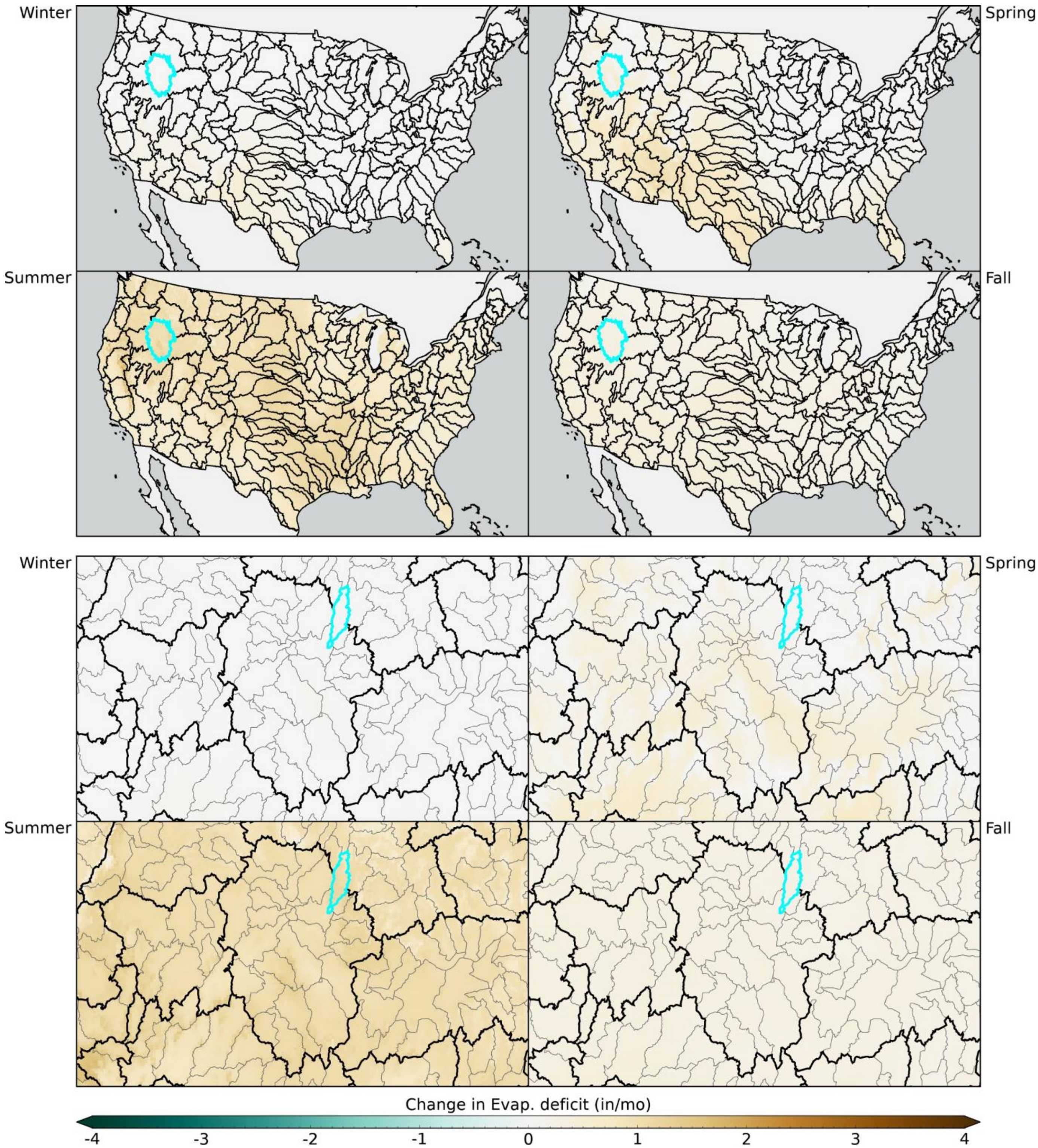



Figure 36: Seasonal maps of evaporative deficit for RCP8.5 2050-2074 minus 1981-2010 for the ensemble mean model.

# 10 Data

The temperature, precipitation, and vapor pressure deficit summaries are created by spatially averaging the MACAv2-METDATA data set (Abatzoglou and Brown, 2012). The water-balance variables snow water equivalent, runoff, soil water storage and evaporative deficit are simulated by using the MACAv2-METDATA temperature and precipitation as input to a simple model (McCabe and Wolock, 2007). The water-balance model accounts for the partitioning of water through the various components of the hydrologic system, but does not account for groundwater, diversions or regulation by impoundments.

# 11 Models

| | | | | |
|---|---|---|---|---|
| MeanModel | bcc-csm1-1-m | bcc-csm1-1 | BNU-ESM | CanESM2 |
| CCSM4 | CNRM-CM5 | CSIRO-Mk3-6-0 | GFDL-ESM2G | GFDL-ESM2M |
| HadGEM2-CC365 | HadGEM2-ES365 | inmcm4 | IPSL-CM5A-LR | IPSL-CM5A-MR |
| IPSL-CM5B-LR | MIROC5 | MIROC-ESM | MIROC-ESM-CHEM | MRI-CGCM3 |

## 7 Citation Information

Abatzoglou, J.T., 2011. Development of gridded surface meteorological data for ecological applications and modelling. International Journal of Climatology, doi: 10.1002/joc.3413.

Abatzoglou, J.T., and Brown T.J., 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology, doi: 10.1002/joc.2312.

Alder, J. R. and S. W. Hostetler, 2013. USGS National Climate Change Viewer. US Geological Survey https://doi.org/10.5066/F7W9575T.

Hostetler, S.W. and Alder, J.R., 2016. Implementation and evaluation of a monthly water balance model over the U.S. on an 800 m grid. Water Resources Research, 52, doi:10.1002/2016WR018665.

# 12 Disclaimer

These freely available, derived data sets were produced by J. Alder and S. Hostetler, US Geological Survey (Alder, J. R. and S. W. Hostetler, 2013. USGS National Climate Change Viewer. US Geological Survey https://doi.org/10.5066/F7W9575T). Climate forcings in the MACAv2-METDATA were drawn from a statistical downscaling of global climate model (GCM) data from the Coupled Model Intercomparison Project 5 (CMIP5, Taylor et al. 2010) utilizing a modification of the Multivariate Adaptive Constructed Analogs (MACA, Abatzoglou and Brown, 2012) method with the METDATA (Abatzoglou, 2011) observational dataset as training data. No warranty expressed or implied is made by the USGS regarding the display or utility of the derived data on any other system, or for general or scientific purposes, nor shall the act of distribution constitute any such warranty. The USGS shall not be held liable for improper or incorrect use of the data described and/or contained herein.